GEOCHEMISTRY OF GROUND WATER IN THE GALLUP, DAKOTA, AND MORRISON AQUIFERS, SAN JUAN BASIN, NEW MEXICO

By William L. Dam

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U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, *Secretary*
U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, *Director*

For additional information write to:

District Chief
U.S. Geological Survey
Water Resources Division
4501 Indian School Road NE, Suite 200
Albuquerque, New Mexico 87110

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY TERMS

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon (gal)	3.785	liter (L)
gallon per minute (gal/min)	0.06309	liter per second (L/s)

Temperature in degrees Celsius (°C) can be converted to temperature in degrees Fahrenheit (°F) by using the equation:

$$^{\circ}F = 1.8 \times {}^{\circ}C + 32$$

Sea level: In this report, sea level refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Al	Aluminum, in micrograms per liter
Ag	Silver, in micrograms per liter
Ar	Argon, in milligrams per liter
As	Arsenic, in micrograms per liter
B	Boron, in micrograms per liter
Ba	Barium, in micrograms per liter
Be	Beryllium, in micrograms per liter
Br^-	Bromide, in milligrams per liter
$\delta^{13}C$	Carbon-13/carbon-12 ratio, in per mil PDB (Peedee belemnite, Cretaceous Peedee Formation of South Carolina)
^{14}C	Carbon-14, in uncorrected percent modern carbon
$CaCO_3$	Calcium carbonate, in milligrams per liter
Ca^{2+}	Calcium, in milligrams per liter
Cd	Cadmium, in micrograms per liter
Cl^-	Chloride, in milligrams per liter
$^{36}Cl/10^{15}Cl$	Atomic ratio of ^{36}Cl atoms to 10^{15} atoms of Cl^{35} and Cl^{37}
Co	Cobalt, in micrograms per liter
CO_2	Carbon dioxide, in milligrams per liter
CO_3^{2-}	Carbonate, in milligrams per liter
Cr	Chromium, in micrograms per liter
Cu	Copper, in micrograms per liter
D	Deuterium
DO	Dissolved oxygen, in milligrams per liter
F^-	Fluoride, in milligrams per liter
Fe	Iron, in micrograms per liter
g	Gram
δD	Deuterium/hydrogen ratio, in per mil V-SMOW (Vienna-Standard Mean Ocean Water)
^3H	Tritium, in tritium units
HCO_3^-	Bicarbonate, in milligrams per liter
Hg	Mercury, in micrograms per liter
T	
HS^-	Bisulfide
I^-	Iodide, in milligrams per liter
K^+	Potassium, in milligrams per liter
Li	Lithium, in micrograms per liter
Mg^{2+}	Magnesium, in milligrams per liter
meq/L	Milliequivalents per liter
mg/L	Milligrams per liter
mmol/L	Millimoles per liter
Mn	Manganese, in micrograms per liter
Mo	Molybdenum, in micrograms per liter
N	Nitrogen, in milligrams per liter

Na^+	Sodium, in milligrams per liter
Ni	Nickel, in micrograms per liter
NO_3^-	Nitrate, in milligrams per liter
NO_2^-	Nitrite, in milligrams per liter
$\delta^{18}O$	Oxygen-18/oxygen-16 ratio, in per mil V-SMOW (Vienna-Standard Mean Ocean Water)
P	Phosphorus, in milligrams per liter
Pb	Lead, in micrograms per liter
pCi/L	Picocuries per liter
pCO_2	Partial pressure of carbon dioxide
pH	Negative log activity of hydrogen ion
PO_4	Phosphorous, in milligrams per liter
$\delta^{34}S$	Sulfur-34/sulfur-32 ratio, in per mil Canyon Diablo meteorite standard
SiO_2^0	Silica, in milligrams per liter
SO_4^{2-}	Sulfate, in milligrams per liter
Se	Selenium, in micrograms per liter
Sr^{2+}	Strontium, in micrograms per liter
µg/L	Micrograms per liter
µm	Micron
V	Vanadium, in micrograms per liter
Zn	Zinc, in micrograms per liter

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GEOCHEMISTRY OF GROUND WATER IN THE GALLUP, DAKOTA, AND MORRISON AQUIFERS, SAN JUAN BASIN, NEW MEXICO

By William L. Dam

ABSTRACT

Ground water was sampled from wells completed in the Gallup, Dakota, and Morrison aquifers in the San Juan Basin, New Mexico, to examine controls on solute concentrations. Samples were collected from 38 wells primarily from the Morrison aquifer (25 wells) in the northwestern part of the basin. A series of samples was collected along ground-water flow paths; dissolved constituents varied horizontally and vertically.

The understanding of the flow system changed as a result of the geochemical analyses. The conceptual model of the flow system in the Morrison aquifer prior to the study reported here assumed the Westwater Canyon Member of the Morrison aquifer as the only significant regional aquifer; flow was assumed to be two dimensional; and vertical leakage was assumed to be negligible. The geochemical results indicate that the Westwater Canyon Member is not the only major water-yielding zone and that the flow system is three dimensional. The data presented in this report suggest an upward component of flow into the Morrison aquifer. The entire section above and below the Morrison aquifer appears to be controlled by a three-dimensional flow regime where saline brine leaks near the San Juan River discharge area.

Predominant ions in the Gallup aquifer were calcium bicarbonate in recharge areas and sodium sulfate in discharge areas. In the Dakota aquifer, predominant ions were sodium bicarbonate and sodium sulfate. Water in the Morrison aquifer was predominantly sodium bicarbonate in the recharge area, changing to sodium sulfate downgradient.

Chemical and radioisotopic data indicate that water from overlying and underlying units mixes with recharge water in the Morrison aquifer. Recharge water contained a large ratio of chlorine-36 to chlorine and a small ratio of bromide to chloride. Approximately 10 miles downgradient, samples from four wells completed in the Morrison aquifer were considerably different in composition compared to recharge samples. Oxygen stable isotopes decreased by 2.8 per mil and deuterium decreased 26 per mil, relative to recharge. Carbon-14 radioisotope activities were not detectable. Chloride-36 radioisotope ratios were small and bromide to chloride concentration ratios were large. These results suggest two potentially viable processes: ion filtration or trapping of ancient dilute water recharged under a humid climate. For water samples near the San Juan River, pH decreased to about 8.0, chloride concentrations increased to more than 100 milligrams per liter, and ratios of chlorine-36 to chlorine and bromide to chloride were small. Leakage of deep basin brine into the fresher water of the Morrison aquifer appears to control ion concentrations.

INTRODUCTION

In October 1984, the U.S. Geological Survey (USGS) began a regional assessment of the San Juan structural basin aquifer systems in New Mexico, Colorado, Arizona, and Utah as part of its national Regional Aquifer-System Analysis (RASA) program (Bennett, 1979).

The San Juan Basin is located in New Mexico, Colorado, Arizona, and Utah, covering an area of approximately 21,600 mi^2 (fig. 1). The basin, a structural depression in the eastern part of the Colorado Plateau, is approximately 140 mi wide by 200 mi long, and land-surface altitudes range from about 4,500 ft in the northwest to about 11,000 ft in the southeast.

The San Juan Basin is an arid region where development of energy and water resources is essential to the economy. Surface-water resources are fully allocated, so ground-water resources are vital to industries, municipalities, and ranchers.

Purpose and Scope

This report presents geochemical and isotopic data used in examining sources of solutes and hydrologic and chemical controls that affect the concentration and distribution of solutes in aquifers in the San Juan Basin. The Gallup, Dakota, and Morrison aquifers were chosen for detailed geochemical analysis because of available water wells having known completion data, ground-water modeling results, and mineralogical analyses. These aquifers are equivalent stratigraphically to the Gallup Sandstone, Dakota Sandstone, and Morrison Formation. These aquifers are used extensively as water supplies for industry, communities, and livestock.

The report examines in detail the geochemistry of the three aquifers. The scope is constrained primarily to the northwestern part of the basin due to limited areal distribution of wells completed in a single aquifer and disturbances to the natural ground-water system by mining and petroleum industries in other parts of the basin. The main focus of this report is on the Morrison aquifer from the communities of Sanostee to Shiprock. Data for the Gallup and Dakota aquifers are provided for purposes of comparison and examination of vertical changes in flow and water quality. Hydrologic and water-quality data for the underlying Entrada Sandstone also are evaluated for the effects that water from this unit may have had on the Morrison aquifer.

Previous Studies

The hydrogeology of the San Juan Basin was described comprehensively by Stone and others (1983). USGS Hydrologic Investigations Atlases (HA 720-A through 720-J) have been published for 10 major aquifers in the basin (Craigg and others, 1989, 1990; Kernodle and others, 1989, 1990; Dam and others, 1990a, b; Levings and others, 1990a, b; and Thorn and others, 1990a, b). Data are presented on maps and in tables to describe the geology, hydrology, and water quality for each aquifer.

The only previous study that examined the regional San Juan Basin ground-water geochemistry of Jurassic and Cretaceous aquifers was performed by Berry (1959). He collected physical and chemical data from water wells, producing oil or gas wells, and drill-stem tests.

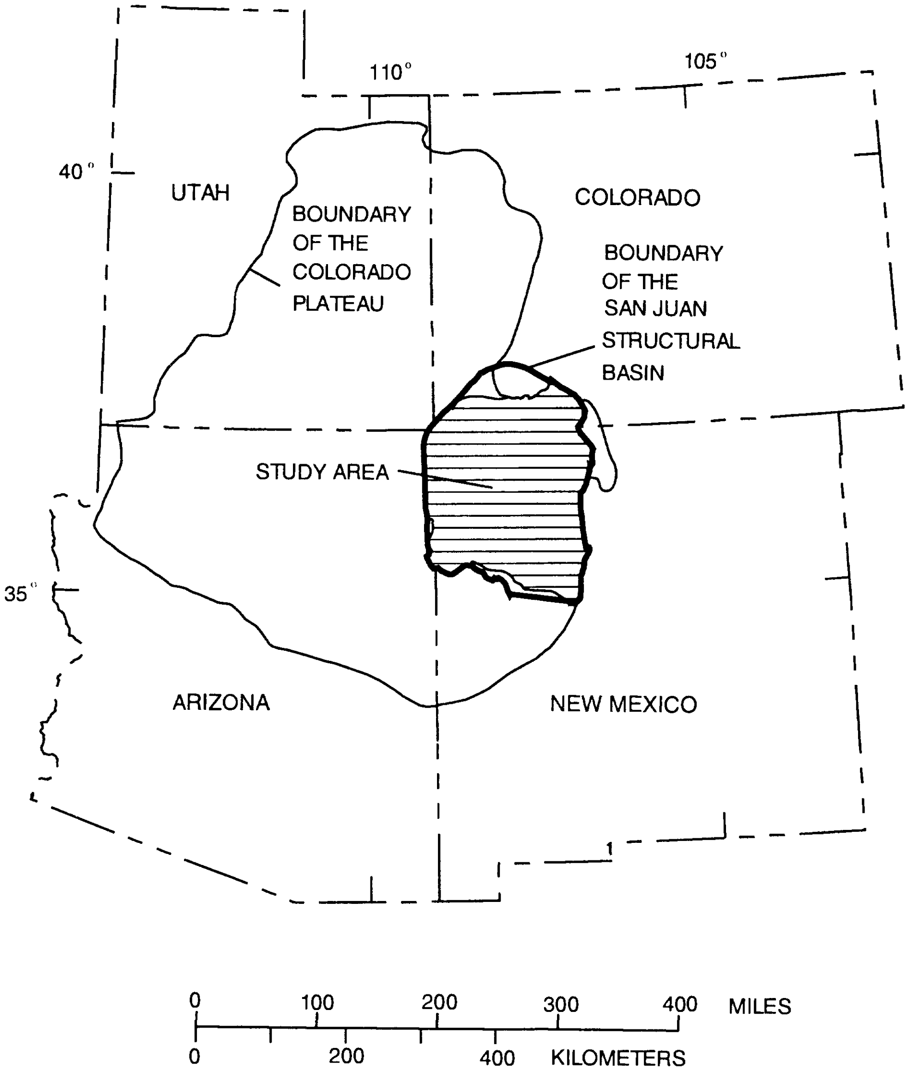


Figure 1.--Location of the San Juan structural basin, Colorado Plateau, and study area.

The direction of ground-water flow in Jurassic and Cretaceous aquifers, according to Berry (1959), was predominantly toward the lowest outcrop in the northwestern part of the basin. Normal hydrodynamic conditions existed along the flanks of the San Juan Basin. Conversely, in the central San Juan Basin, referred to by Berry as the "Inner Basin," hydraulic-pressure sinks and increased salinities were observed in all Cretaceous aquifers. Berry hypothesized that saline water containing dissolved-solids concentrations ranging from 30,000 to 270,000 parts per million entered the Entrada Sandstone from dissolved evaporite minerals such as halite contained in the overlying Todilto Limestone Member of the Wanakah Formation. The saline water in the Entrada Sandstone moved to the west and was trapped on the western side of the central basin due to the synclinal structures of the basin. Saline water in the Entrada Sandstone and freshwater in the Dakota aquifer were separated by the Brushy Basin Member of the Morrison Formation; this shale, acting as a semipermeable membrane, created an osmotic pressure system. Osmotic pressure, Berry proposed, caused the relatively dilute water from the Dakota aquifer to pass through the Brushy Basin Member. This caused a decrease in hydraulic pressure and left behind solutes that increased the salinity in the Dakota. The dilute water flowed into sandstones of the Morrison aquifer and Entrada Sandstone, increasing the hydraulic pressure and decreasing the dissolved-solids concentration. Similar osmotic-pressure phenomena for all Cretaceous sequences of sandstones and shales in this basin were observed (Berry, 1959).

Phillips and others (1986b) evaluated stable and radioactive isotopic data obtained from the Ojo Alamo and Nacimiento aquifers (in rocks of Paleocene age) in the central San Juan Basin. They found that waters collected from the two aquifers were of Pleistocene age and contained lighter oxygen and deuterium isotopes than modern precipitation and ground water. They proposed trends of decreased mean annual temperature and increased winter precipitation as factors affecting the stable-isotope contents.

Acknowledgments

The author acknowledges the people of the Navajo Nation who allowed and assisted in collection of water samples from their wells. Officials with ARCO Oil and Gas Company and El Paso Natural Gas Company also permitted access to wells, and Exxon Company, USA supplied well information. The Bureau of Land Management and the National Park Service provided access and information on selected wells. Information on oil and gas injection wells was obtained from the New Mexico Oil Conservation Division. Dr. Fred Phillips and Geoff Jones provided chlorine-36 results through a cooperative agreement with the New Mexico Institute of Mining and Technology. Several professors at the University of New Mexico provided assistance and technical advice in data collection and interpretation, including Drs. Laura Crossey, Douglas Brookins, and Crayton Yapp.

GEOLOGY AND HYDROLOGY

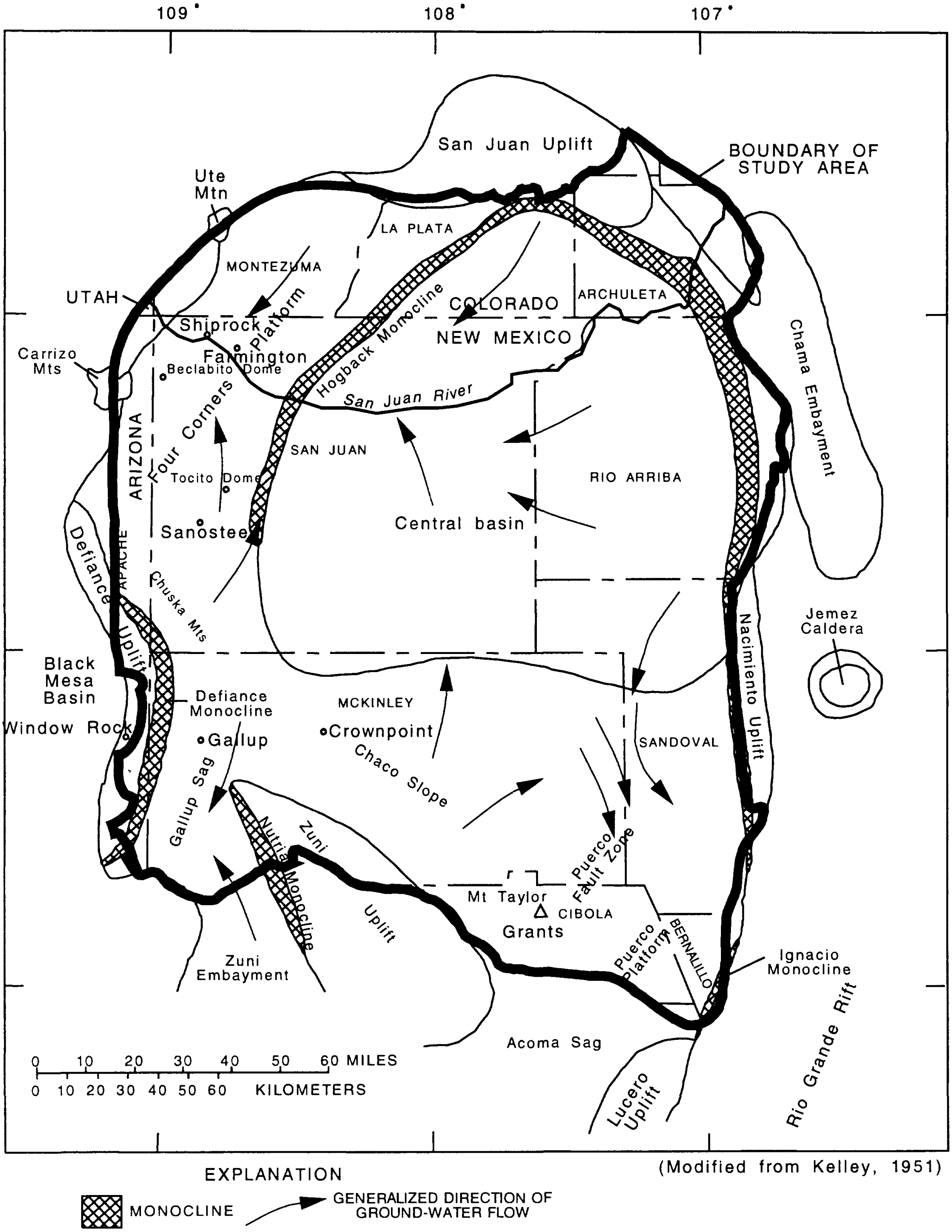
The San Juan Basin is a northwest-trending, asymmetric structural depression formed during the Laramide orogeny (Late Cretaceous-early Tertiary age) at the eastern edge of the Colorado Plateau (fig. 1). In many places, structural boundaries of the basin are well defined, whereas in other places, the basin merges gradually into adjacent depressions or uplifts (Kelley, 1951, p. 124-127). The structural boundaries consist principally of large, elongate, domal uplifts; low, marginal platforms; and abrupt monoclines as shown in figure 2. Faulting is common especially in the southeastern part of the basin. Maximum structural relief in the basin is about 10,000 ft. The Hogback Monocline, Nacimento Uplift, and Chaco Slope bound the central San Juan Basin.

The San Juan Basin contains a thick sequence of nearly horizontal beds of sedimentary rocks, ranging in age from Cambrian through Tertiary, but principally from Pennsylvanian through Tertiary (fig. 3). The maximum thickness of this sequence of rocks is about 14,000 ft at the trough-like structural center of the basin (Fassett and Hinds, 1971, p. 4). The sedimentary rocks, primarily sandstone and shale, dip from the basin margins toward the center of the basin. Volcanic rocks of Tertiary age and various deposits of Quaternary age also are present in the basin.

Ground-water flow directions for Jurassic and Cretaceous aquifers are shown in a generalized areal form in figure 2. Recharge occurs along outcrops in mountainous regions along the basin boundaries; ground water circulates toward major discharge areas in the northwestern, southwestern, and southeastern parts of the basin (Frenzel and Lyford, 1982, p. 7).

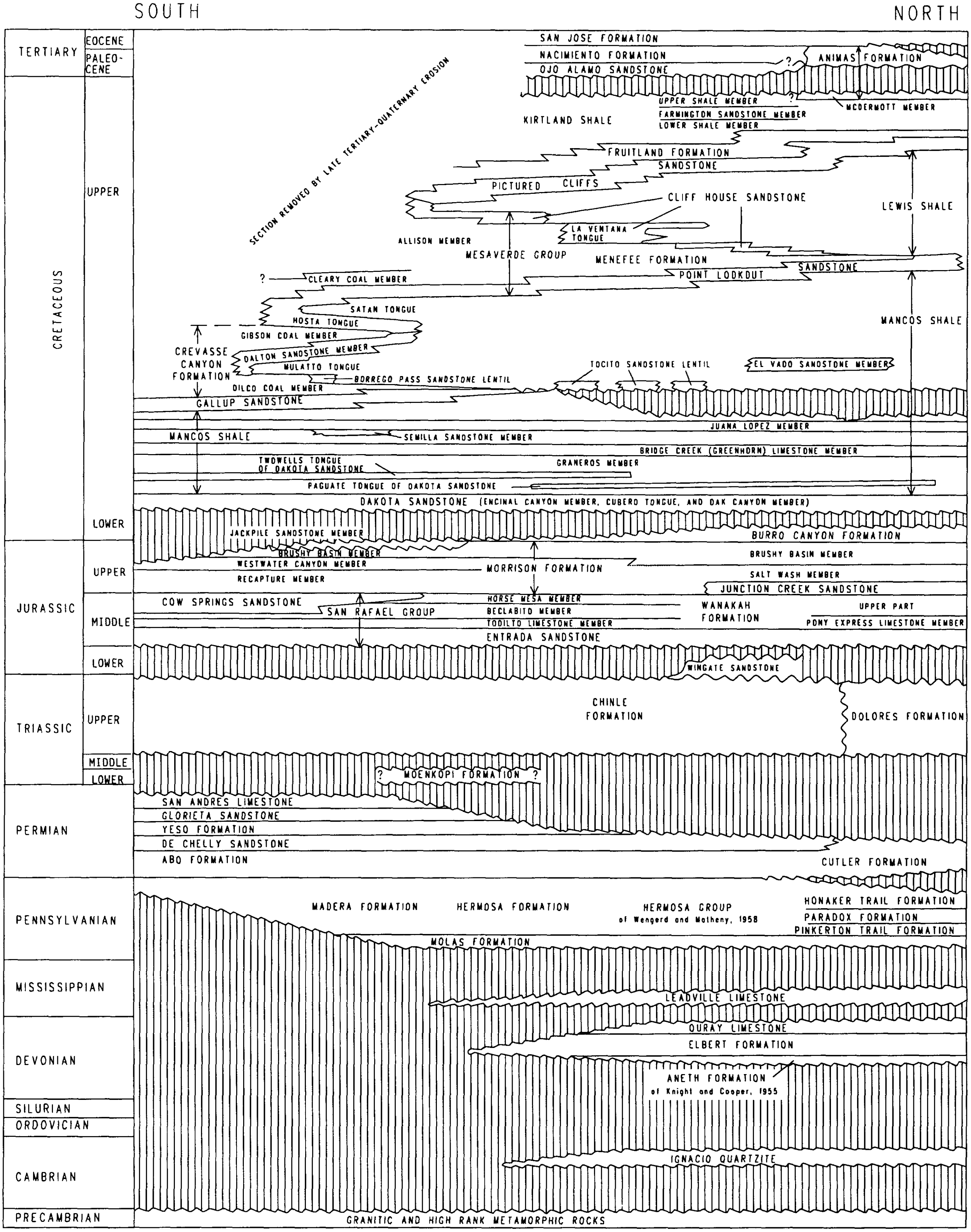
A diagrammatic hydrogeologic section showing major aquifers, confining layers, and direction of ground-water flow is shown in figure 4. Major aquifers include the rocks of Tertiary age, undivided; Kirtland Shale and Fruitland Formation; Pictured Cliffs Sandstone; Mesaverde Group, undivided; Gallup Sandstone; Dakota Sandstone; Morrison Formation; Entrada Sandstone; and San Andres Limestone and Glorieta Sandstone. Thick shale beds act as confining layers between the sandstone aquifers. Ground water generally flows from the recharge areas at the outcrops downdip through permeable zones. Vertical leakage between aquifers is known to occur; however, the magnitude is not known and leakage rates through intervening shale beds probably are small in most areas (Stone and others, 1983, p. 23). Large upward vertical leakage rates are thought to occur along the Hogback Monocline in the northwestern part of the basin and in the Puerco Fault Zone in the southeastern part of the basin (fig. 2) (Stone and others, 1983, p. 23).

The geology and hydrology of the Gallup, Dakota, and Morrison aquifers are described briefly, including the structure, stratigraphy, depositional environment, petrology, mineralogy, ground-water flow patterns, water levels, and hydraulic characteristics. Additional information can be found in Stone and others (1983); Craigg and others (1989); Kernodle and others (1989); and Dam and others (1990a).



(Modified from Kelley, 1951)

Figure 2.--Structural elements of the San Juan structural basin and adjacent areas and generalized pattern of ground-water flow in rocks of Jurassic and Cretaceous age.



(Modified from Molenaar, 1977a,b, and 1989)

Figure 3.--Time- and rock-stratigraphic framework and nomenclature. Ruled lines indicate a hiatus in the sequence of beds.

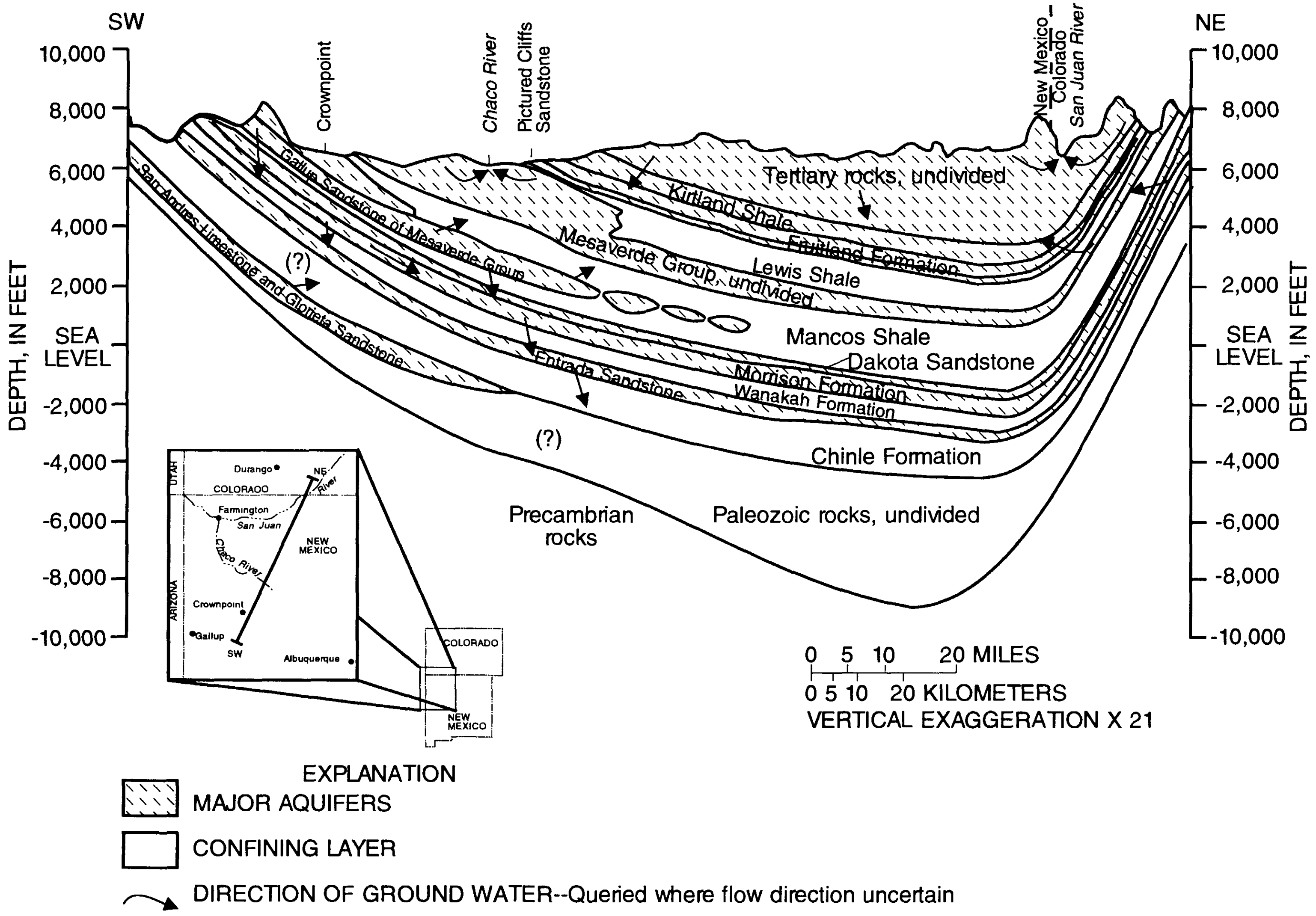


Figure 4.--Diagrammatic hydrogeologic section of the San Juan Basin (modified from Stone and others, 1983).

Gallup Aquifer

The Gallup aquifer is a hydrogeologic unit corresponding to the Gallup Sandstone. The Gallup Sandstone is of Late Cretaceous age (Molenaar, 1973, 1974). The unit has a smaller areal extent than the other major Upper Cretaceous sandstones in the San Juan structural basin and occurs only in New Mexico and a small part of Arizona. The Gallup crops out in an arcuate pattern around the western and southern margin of the basin where it typically forms erosion-resistant cliffs and dip slopes. Thickness of the Gallup decreases from about 600 ft near the outcrops along the margin of the basin to zero along the northwest-trending pre-Niobrara erosion limit. Depth to the top of the Gallup Sandstone ranges from zero in areas of outcrop to about 4,500 ft in an area about 20 mi south of the town of Farmington (Kernodle and others, 1989). The altitude of the top of the Gallup decreases from a maximum of about 7,500 ft northeast of Window Rock, Arizona, to about 1,500 ft above sea level southwest of Farmington. The Gallup represents the first major regression of the Upper Cretaceous sea in the San Juan structural basin and also represents deposition in marine and nonmarine environments. As originally defined by Sears (1925) and discussed in detail by Dane and others (1957), the Gallup consists of various rocks including sandstone (the predominant rock type), conglomerate, shale, carbonaceous shale, and coal. Minerals found in the Gallup include quartz (70-90 percent), feldspar (5-25 percent), glauconite, chlorite, sericite, chert, zircon, tourmaline, hematite, limonite, magnetite, ilmenite, dolomite, and ankerite (Kaharoeddin, 1971).

The Gallup aquifer is a source of water for domestic, livestock, municipal, and industrial uses. Recharge to the aquifer is from infiltration of precipitation and streamflow on outcrops and from vertical leakage of water through confining beds. Areas of recharge are in the southwestern and northeastern parts of the basin. Ground-water flow from these areas moves generally toward the central part of the basin and to the west, northwest, and southeast parts (fig. 2). However, the remaining body of the Gallup aquifer is cut off in a northwest-southeast pattern such that flow of water is not continuous throughout the entire basin (fig. 3). The Gallup aquifer occurs under both water-table and artesian conditions. Water wells generally are near the western and southern margins of the basin and primarily in McKinley County; flowing wells are mostly in the northern part of the county. The reported or measured discharge from 32 water wells completed in the Gallup aquifer ranges from 1 to 645 gal/min and the median is 30 gal/min (Kernodle and others, 1989). Water levels significantly below land surface were found in the Grants mineral belt near Crownpoint and near Gallup, New Mexico, and Window Rock, Arizona.

Dakota Aquifer

The Dakota aquifer is a hydrogeologic unit corresponding to the Dakota Sandstone. The Dakota Sandstone generally is thought to be of earliest Late Cretaceous age, although the lowermost part may be of latest Early Cretaceous age (Fassett, 1977, p. 225). The Dakota crops out around the basin margins where it typically caps mesas and forms erosion-resistant dip slopes and hogbacks. The Dakota Sandstone unconformably overlies the Morrison Formation (Late Jurassic age) throughout much of the basin; however, it unconformably overlies the Burro Canyon Formation (Early Cretaceous age) in the northern part of the basin (fig. 3). The upper contact of the Dakota is conformable with the Mancos Shale, and intertonguing of these two units is common near the contact. Stratigraphy of the Dakota is complex. The unit consists of a main sandstone body in the north, which branches into various members and tongues depending on location in the San Juan Basin. Thickness of the Dakota generally ranges from a few tens of feet to about 500 ft; Stone and others (1983, p. 37) reported that a range of 200 to 300 ft probably is common. Data reported by Molenaar (1977b, p. 160-161) and Stone and others (1983, fig. 66) and data obtained from Petroleum Information Corporation, Denver, Colorado, indicate that the thickness of the Dakota generally increases from the western, northwestern, and northern margins of the basin toward the eastern, southeastern, and southern margins. Depth to the Dakota ranges from zero in areas of outcrop to about 8,500 ft in the northeastern part of the basin. The top of the Dakota decreases from a maximum altitude of about 9,500 ft along the northern basin margin to about 1,500 ft below sea level in the northeastern part of the study area (Craigg and others, 1989).

The Dakota was deposited on an erosional surface in this region; the strata represent a transition from nonmarine alluvial-plain deposition in the lower part of the aquifer to marine shorezone deposition in the upper part. Marine and nonmarine depositional environments were interpreted by Walters and others (1987); the primary depositional area for nonmarine rocks was along the west side of the present basin. The Dakota contains three principal lithologies in different parts of the basin. It typically consists of a sequence of buff to brown, crossbedded, poorly sorted, coarse-grained conglomeratic sandstone and moderately sorted, medium-grained sandstone in the lower part; dark-gray carbonaceous shale with brown siltstone and lenticular sandstone beds in the middle part; and yellowish-tan, fine-grained sandstone interbedded with gray shale in the upper part (Owen, 1973, p. 39-48; Merrick, 1980, p. 45-47). Mineralogy, in mean percentage, as determined by Walters and others (1987, p. 269), for the marine (first number) and nonmarine (second number) deposits consists of the following: quartz (28 percent, 26 percent), illite (22 percent, 32 percent), kaolinite (16 percent, 22 percent), calcite (8.3 percent, 0.87 percent), dolomite (7.3 percent, 0.42 percent), mixed clay (5.7 percent, 9.8 percent), smectite (4.4 percent, 2.9 percent), potassium feldspar (4.2 percent, 4.7 percent), chlorite (2.7 percent, 0.29 percent), and plagioclase (2.4 percent, 1.3 percent).

The Dakota aquifer is a source of water for domestic, livestock, and industrial uses, and water wells generally are near the margins of the basin. Water in the Dakota aquifer occurs under both water-table and artesian conditions. Recharge to the aquifer is from infiltration of precipitation and streamflow on outcrops and from vertical leakage of water through confining beds. Within the basin, areas of stress from ground-water development in the Dakota aquifer are localized. These areas may represent oil or gas production, injection for disposal of brine, secondary recovery or repressurization of producing zones, or uranium-mine dewatering of the underlying Morrison aquifer that induces downward flow in the Dakota. The reported or measured discharge from 29 water wells completed in the Dakota aquifer ranged from 1 to 200 gal/min and the median is 13 gal/min (Craigg and others, 1989). Water levels in numerous wells were several hundred feet below land surface. Only one well, in the northwestern part of the basin, was flowing.

Morrison Aquifer

The Morrison aquifer is a hydrogeologic unit corresponding to the Morrison Formation. The Morrison Formation is of Late Jurassic age (Cadigan, 1967, p. 6) and crops out around the basin margins. Major sandstones in the Morrison typically form erosion-resistant cliffs and dip slopes, whereas shale units form topographic saddles. The Morrison is present throughout the San Juan Basin (Green and Pierson, 1977, p. 151) and conformably overlies the Wanakah Formation or Cow Springs Sandstone of Late Jurassic age (Condon and Peterson, 1986, p. 24) throughout most of the basin. In the northern part of the basin, the Morrison conformably overlies and probably intertongues with the Junction Creek Sandstone of Late Jurassic age (fig. 3). In the San Juan Basin, the Morrison Formation consists of five members (Gregory, 1938; Craig and others, 1955; Cadigan, 1967; Green and Pierson, 1977; Owen, 1984). These members, in ascending order, are: the Salt Wash Member, Recapture Member, Westwater Canyon Member, Brushy Basin Member, and Jackpile Sandstone Member. The thickness of the Morrison ranges from about 200 ft near Grants to about 1,100 ft in the northwestern part of the basin (Dam and others, 1990a). Depth to the top of the Morrison ranges from zero in areas of outcrop to about 8,500 ft in the northeastern part of the basin (Dam and others, 1990a). The top of the Morrison decreases from a maximum altitude of about 10,000 ft along the northern basin margin to about 1,500 ft below sea level in the northeastern part of the basin. Morrison Formation strata were deposited in various continental environments including eolian, stream channels, flood plains, and lakes (Green and Pierson, 1977, p. 151; Turner-Peterson and others, 1986). A semiarid to arid climate existed during deposition of the Morrison (Turner-Peterson and Fishman, 1989).

The Morrison Formation generally consists of yellowish-tan to pink, fine- to coarse-grained, locally conglomeratic sandstones, which are interbedded with sandy siltstones and green to reddish-brown shales and claystones; minor limestone beds also are in the aquifer (Woodward and Schumacher, 1973, p. 3-5; Green and Pierson, 1977, p. 151; Stone and others, 1983, p. 38). The Salt Wash Member was deposited by meandering and braided streams and consists of very fine to medium-grained sandstone interbedded with mudstone (Hansley, 1990, p. H4). The Recapture Member was deposited in fluvial, lacustrine, and eolian environments; lithology consists of very fine to fine-grained sandstones interbedded with mudstones and claystones. The Westwater Canyon Member was deposited by braided streams draining source areas in the western and southwestern parts of the basin. Sandstones are fine to medium grained and locally conglomeratic; interbedded mudstones and claystones are bentonitic (Hansley, 1990). The Brushy Basin Member consists of thick bentonitic to zeolitic mudstones interbedded with thin fluvial sandstones that were deposited in a saline, alkaline lake. The Jackpile Sandstone Member was deposited in the southeastern part of the basin by braided streams; sandstones are fine to medium grained and locally conglomeratic.

Hansley (1986 and 1990) described in detail the mineralogy and diagenesis of members of the Morrison Formation. Minerals from core samples in the southern part of the basin and from outcrop samples along the rim of the basin include amorphous silica, potassium feldspar, albite, calcite, anhydrite, barite, hematite, pyrite, garnet, staurolite, and zeolite. Whitney and Northrop (1987, p. 357) examined clay mineralogy and found smectite, interstratified illite/smectite, chlorite, and kaolinite. Crossey (1989) recognized two groups of clay minerals on the basis of grain size in the Westwater Canyon Member: (1) coarse-grained lithologies contain a mixed-layer illite/smectite that is highly expandable, kaolinite, and chlorite; and (2) fine-grained lithologies contain a more illitic mixed-layer illite/smectite with traces of chlorite.

The initial interpretation of the ground-water flow system in the Morrison aquifer is based on work by Kelly (1977), Frenzel and Lyford (1982), Stone and others (1983), and data from the files of the U.S. Geological Survey, Albuquerque, New Mexico. The conceptual model of the flow system in the Morrison aquifer assumed the Westwater Canyon Member to be the only significant regional aquifer (Kelly, 1977); the other members were considered important only as local aquifers. The Brushy Basin and Recapture Members were thought to serve as semiconfining layers above and below the Westwater Canyon throughout the basin except in the southwestern part where the Brushy Basin is absent.

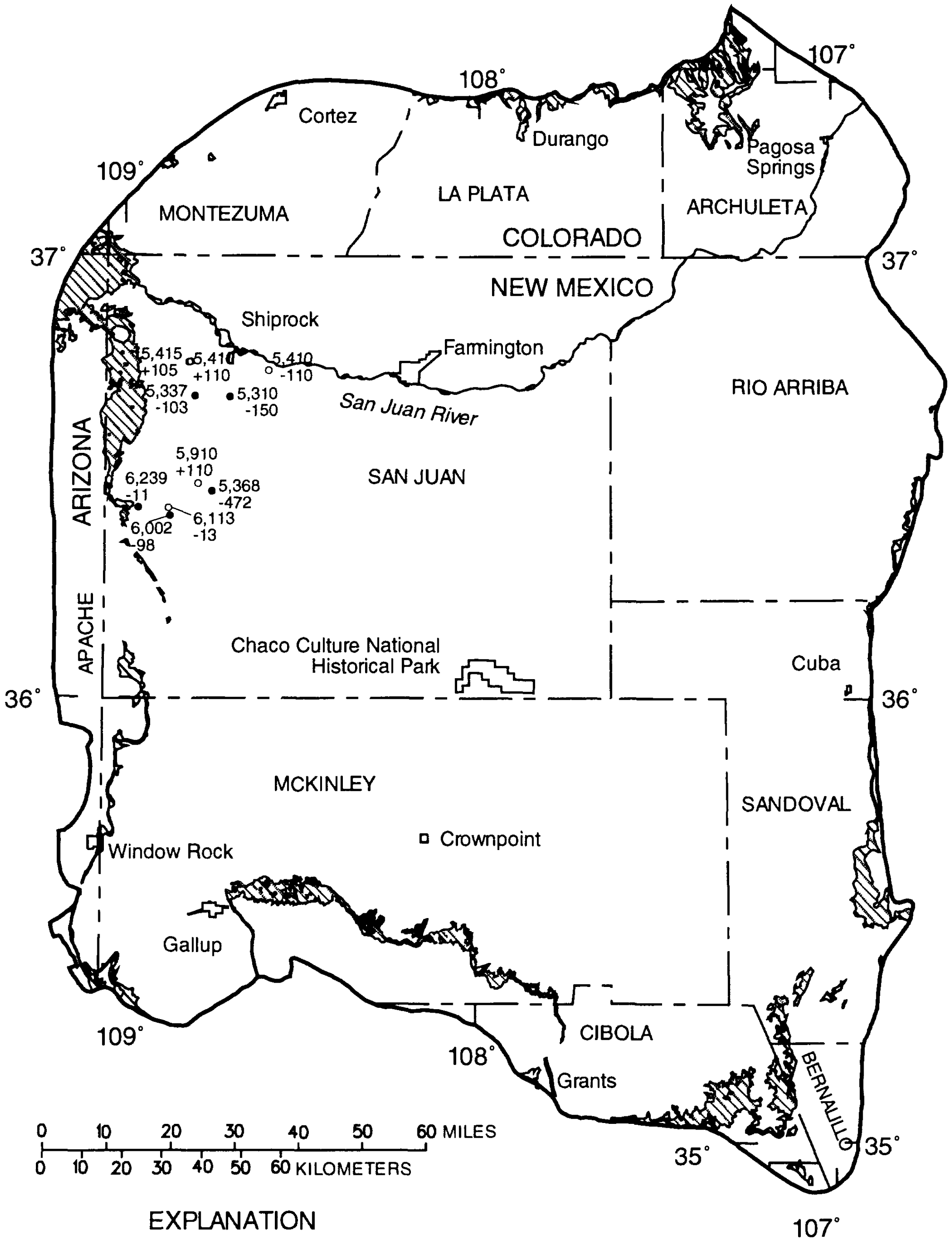
Flow in the Morrison aquifer previously was assumed to be two dimensional. Vertical leakage into the Morrison from above or below was unknown and assumed to be negligible (Stone and others, 1983, p. 23). Minimal hydraulic-head data not representing a single time period were available for units overlying and underlying the Morrison to determine vertical flow components. Data for the Dakota and Morrison aquifers were for 1985-86 and data for the Entrada Sandstone were pre-1959. Figure 5 shows a comparison of hydraulic heads for the Dakota aquifer and the Entrada relative to the Morrison aquifer. Hydraulic heads for the Dakota aquifer and Entrada were measured in the well, whereas hydraulic heads for the Morrison aquifer were interpolated from the Morrison potentiometric-surface map for that well site. The heads for wells in the Dakota (for 1985-86) generally are lower than those interpolated from the Morrison potentiometric surface.

Underlying the Morrison aquifer is the Wanakah Formation; however, no hydraulic-head data were available for this formation. The Entrada Sandstone underlies the Wanakah Formation. The only head data available for the Entrada were obtained from a dissertation by Berry (1959), which contains a potentiometric-surface map of the Entrada with five data points. The dates of measurement for these wells are unknown, but they were made prior to 1959. The head values for the Entrada indicate a northerly flow direction similar to the Morrison aquifer. Figure 5 shows the estimated hydraulic-head differences between the Entrada Sandstone and the Morrison aquifer at the locations of five wells. Comparison of heads in the Entrada (pre-1959) with those in the Morrison (1985-86) (fig. 5) shows that the Entrada heads in four wells were from 13 to 110 higher than in the Morrison. Because hydraulic-head values in the Morrison had declined, pre-1985 water levels in the Morrison were sought for comparison with pre-1959 water levels. Hydrographs for three wells completed in the Morrison aquifer that span the period 1957-90 were used to determine water-level trends in the Morrison during this time. These hydrographs, shown in figure 6, indicate a decline in hydraulic head in the Morrison during this period. The declines range from approximately 4 feet to more than 70 feet. Although the declines in the Morrison are shown for almost a 30-year period, the declines are believed to have occurred after the mid- to late 1970's when uranium test drilling was conducted and many of the test holes were completed as wells in the Morrison aquifer and allowed to flow continuously. On the basis of these tentative comparisons, even with the declines in the Morrison of as much as 70 feet, the head in the Entrada would still be several tens of feet higher than the head in the Morrison. Therefore, an upward component of flow into the Morrison aquifer is assumed.

The potentiometric contours shown in figure 7 indicate that recharge to the Morrison aquifer north of the Chuska Mountains along the New Mexico-Arizona State line has a significant component that is north, parallel to the north-trending outcrop. Along the north flanks of the Chuska Mountains, the Morrison dips primarily to the east, but northward the easterly dip flattens and a northerly dip develops toward the Four Corners Platform (fig. 2). This change in dip accounts for the much larger outcrop area, and recharge in this area moves north parallel to the outcrop to the discharge area near Four Corners.

The discharge areas for the Morrison are considered to be in the northwestern part of the area near Four Corners where the San Juan River has breached the Morrison aquifer, the southwestern part of the area southwest of Gallup, and the southeastern part of the area northeast of Grants (see fig. 2 for general areas of discharge as indicated by converging arrows). In the northwestern part of the basin north of the Chuska Mountains, the general gradient is to the north (fig. 7); in the area northeast of the city of Gallup, areas of localized dewatering for uranium mining have resulted in substantial head declines.

The reported or measured discharge from 53 water wells completed in the Morrison aquifer ranges from 1 to 401 gal/min; the median discharge is 32 gal/min (Dam and others, 1990a). Heads of wells completed in the Morrison Formation are typically above land surface in San Juan County and below land surface in McKinley and Cibola Counties.



EXPLANATION

▨ OUTCROP OF MORRISON AQUIFER, JURASSIC ROCKS, UNDIVIDED; WANAKAH FORMATION; ENTRADA SANDSTONE; AND SAN RAFAEL GROUP-- From Dane and Bachman, 1965; Wilson and others, 1969; Tweto, 1979; and Hintze, 1981

— BOUNDARY OF STUDY AREA

● 5,310 -150 WATER WELL--Upper number is altitude of potentiometric surface in Dakota aquifer, in feet above sea level. Lower number is difference between altitude of potentiometric surfaces in the Dakota and Morrison aquifers

○ 5,410 -110 WATER WELL--Upper number is altitude of potentiometric surface in Entrada Sandstone, in feet above sea level. Lower number is difference between altitude of potentiometric surfaces in the Entrada Sandstone and Morrison aquifers

Figure 5.--Hydraulic heads in the Dakota aquifer and Entrada Sandstone relative to the Morrison aquifer, 1985-86.

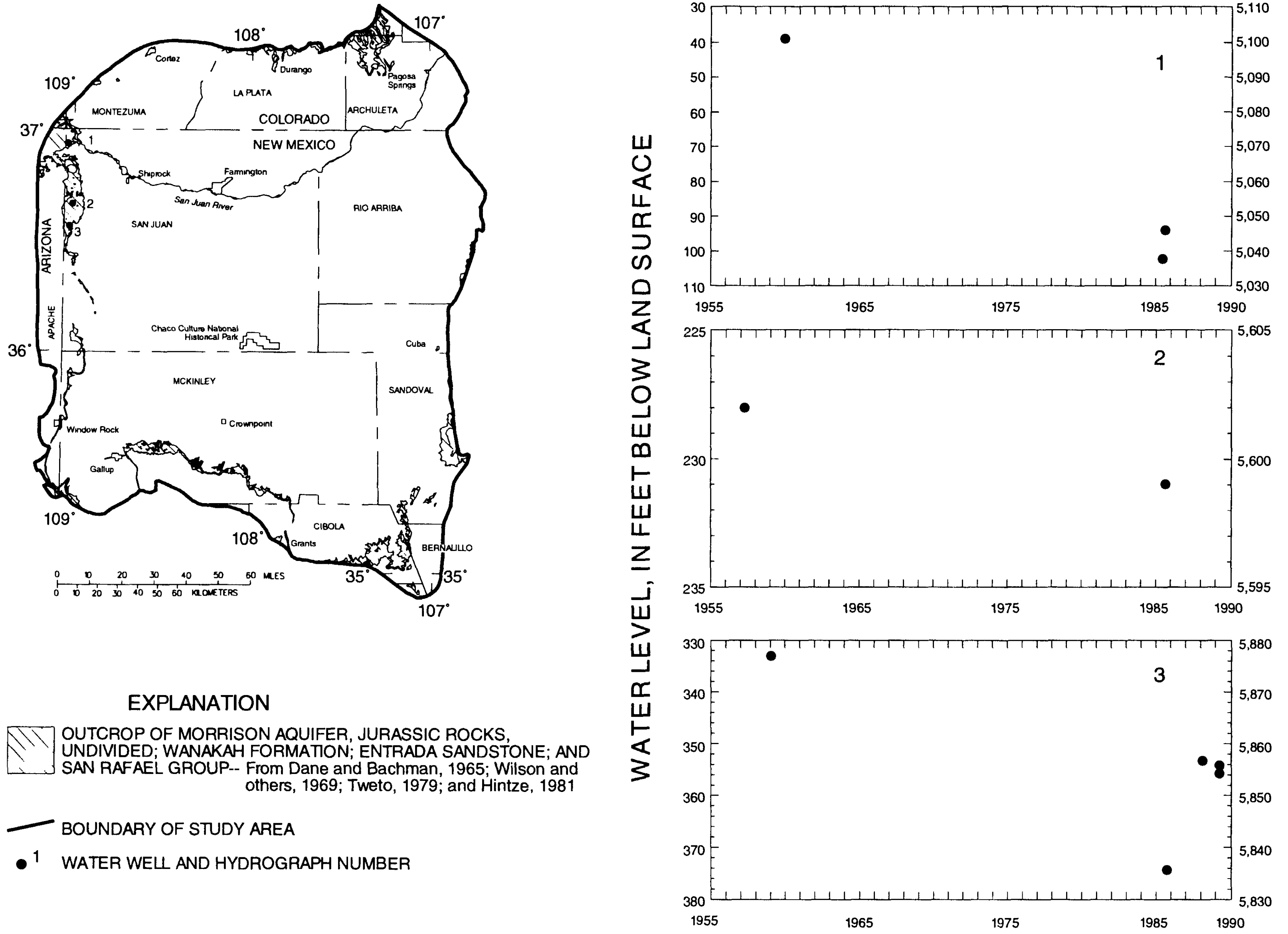
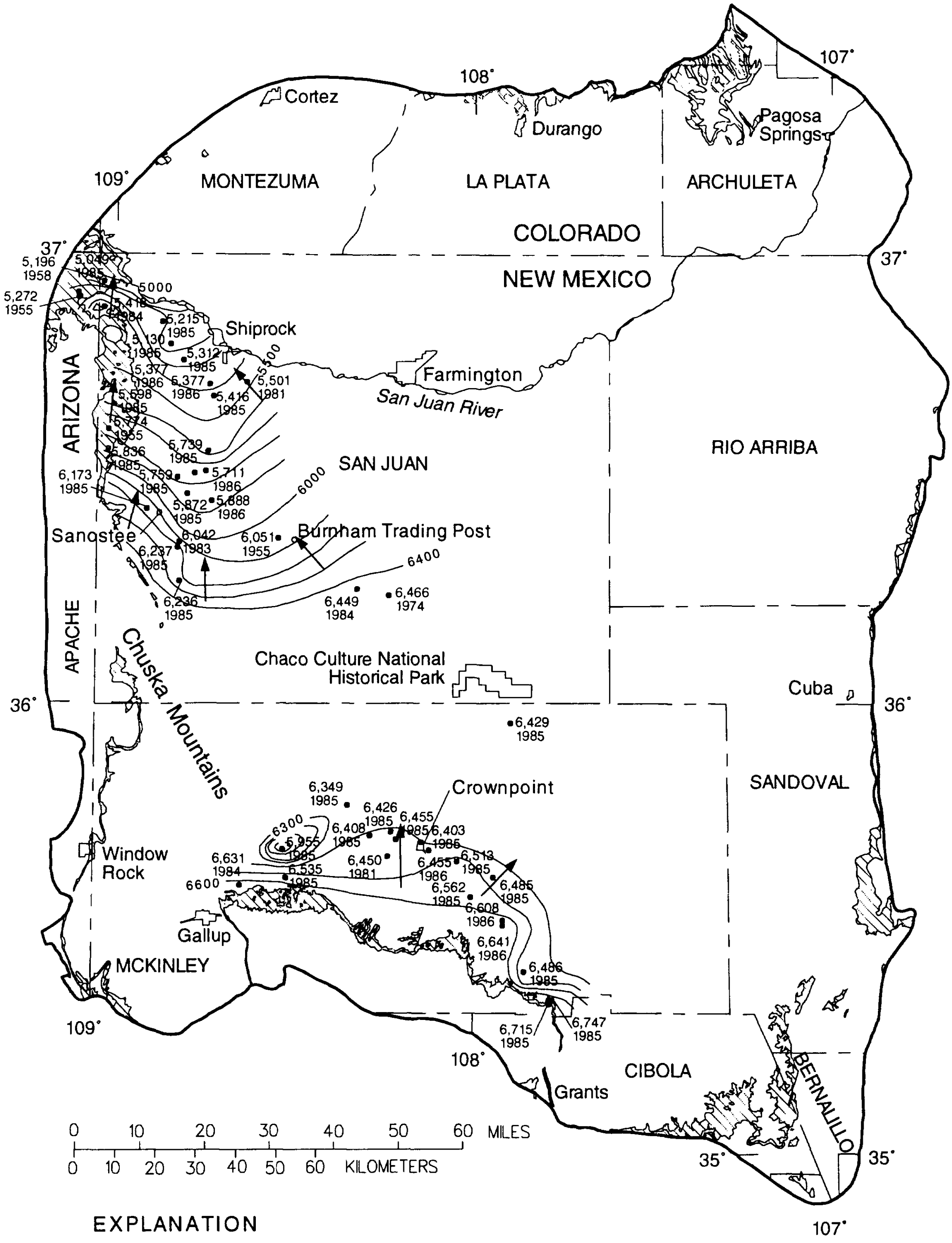


Figure 6.--Water-level hydrographs for three wells completed in the Morrison aquifer, 1957-87.



EXPLANATION

▨ OUTCROP OF MORRISON AQUIFER, JURASSIC ROCKS, UNDIVIDED; WANAKAH FORMATION; ENTRADA SANDSTONE; AND SAN RAFAEL GROUP--From Dane and Bachman, 1965; Wilson and others, 1969; Tweto, 1979; and Hintze, 1981

━ BOUNDARY OF STUDY AREA

⌒ 6400 POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval 100 feet. Datum is sea level

→ DIRECTION OF GROUND-WATER FLOW

•6,466
1974 WATER WELL--Upper number is altitude of water level, in feet above sea level. Lower number is year water level was measured or reported

Figure 7.--Potentiometric surface of the Morrison aquifer, 1985-86.

GEOCHEMISTRY OF GALLUP, DAKOTA, AND MORRISON AQUIFERS

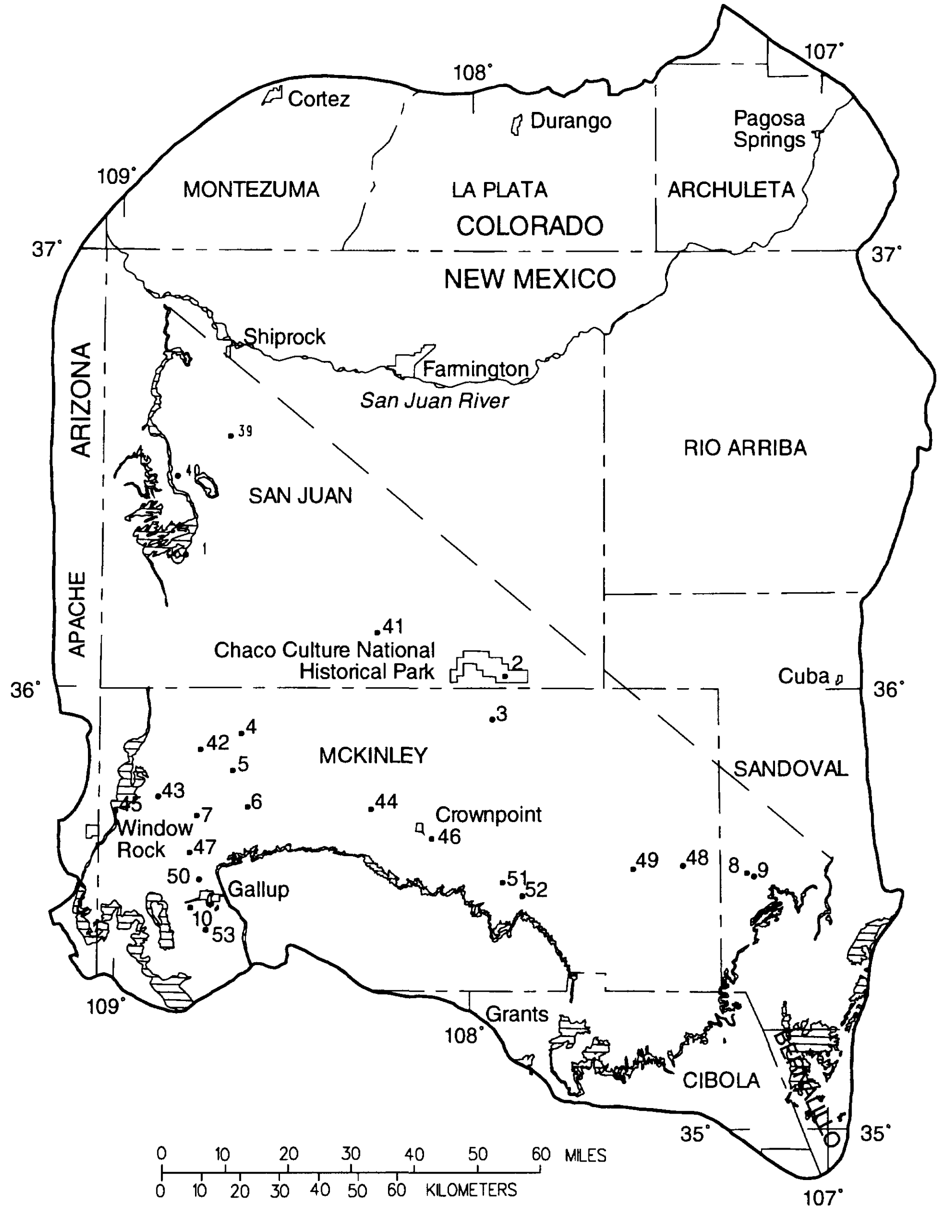
This section describes the methods used to collect the data including essential water well information. Geochemical data are discussed by type of constituent including major, minor, and trace elements; gases; and isotopes. Physical and geochemical processes controlling solute concentrations then are evaluated.

Methods

The field sampling methods used to collect the geochemical data are detailed in Dam (1988) and follow standard USGS procedures (Claassen, 1982; Knapton, 1985). Nonflowing wells were pumped for a sufficient duration to remove at least three borehole volumes of water. Field techniques were used to measure specific conductance, pH, temperature, DO, alkalinity, and sulfide. Alkalinity was used to calculate HCO_3^- and CO_3. Samples were collected and preserved for analysis of major, minor, and trace elements; stable and radioactive isotopes; and dissolved-organic carbon. Dissolved gases were collected in the field using double-chamber glass tubes under a vacuum. Carbon-14 samples were collected onsite by precipitation of strontium carbonate in a stainless-steel tank as described in Dam (1988). Chloride-36 samples were treated with nitric acid and silver nitrate to precipitate silver chloride and stored in light-proof brown bottles. An anion-exchange resin was used to concentrate chloride when chloride concentration was less than 10 mg/L. Preparation of the ^{36}Cl samples for analysis (primarily to remove interfering sulfur-36) is described in Jones and Phillips (1990).

All samples collected for laboratory analysis of major, minor, and trace elements were analyzed at the USGS National Water Quality Laboratory (NWQL) in Denver, Colorado. Gas samples were kept on ice and sent to the USGS laboratory in Reston, Virginia, for analysis. These samples were analyzed for N, oxygen, Ar, CO_2, methane, and ethane. Rapid analysis was necessary to ensure that loss of vacuum did not result in sample contamination from the air. Stable isotopes of oxygen and hydrogen and the radioisotope ^3H were analyzed at the USGS laboratory in Reston, Virginia. Carbon-13/carbon-12 and sulfur-34/sulfur-32 stable isotopes were analyzed by Global Geochemistry, and ^{14}C isotopes were analyzed by Kruger, Inc. These laboratories are under contract to the NWQL. The University of Rochester, in Rochester, New York, analyzed ^{36}Cl isotopes using a tandem accelerator mass spectrometer.

Geochemical data for analysis and interpretation were obtained by sampling 38 wells and using analyses from the USGS NWIS (National Water Information System) data base for 21 wells (figs. 8-10). Locations of water wells sampled for geochemical data are shown in figure 8 for the Gallup aquifer (wells 1-10), in figure 9 for the Dakota aquifer (wells 11-13), and in figure 10 for the Morrison aquifer (wells 14-38). The abundance of wells completed in the Morrison aquifer is a result of uranium exploration (without development or mining) in the early 1980's. Additional chemical analyses obtained from the NWIS data base augmented the geochemical data for the Gallup (15 wells) and Dakota (6 wells) aquifers.



EXPLANATION

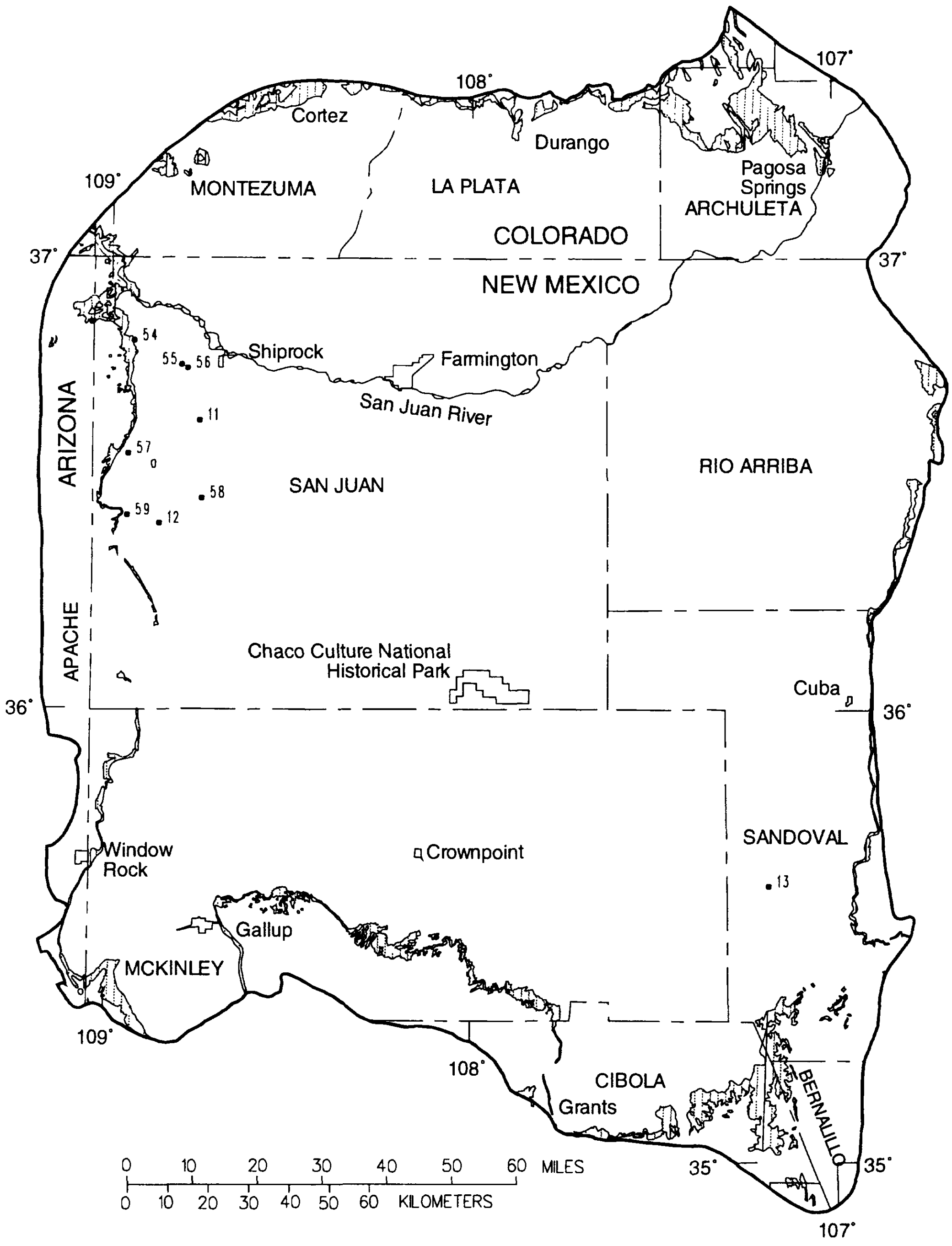
▤ OUTCROP OF GALLUP AQUIFER--In Arizona includes Pescado Tongue of Mancos Shale. In southeastern part of the study area mapped as part of the Mesaverde Group, undivided. From Dane and Bachman, 1965, and Hackman and Olson, 1977

— — APPROXIMATE SUBSURFACE EXTENT OF GALLUP AQUIFER--From Molenaar, 1973

—— BOUNDARY OF STUDY AREA

• 1 WATER WELL--Wells 1-10 were sampled from 1986 to 1989; wells 39-53 were sampled prior to 1986 and the analyses are from the National Water Information System data base

Figure 8.--Location of sampled water wells completed in the Gallup aquifer.



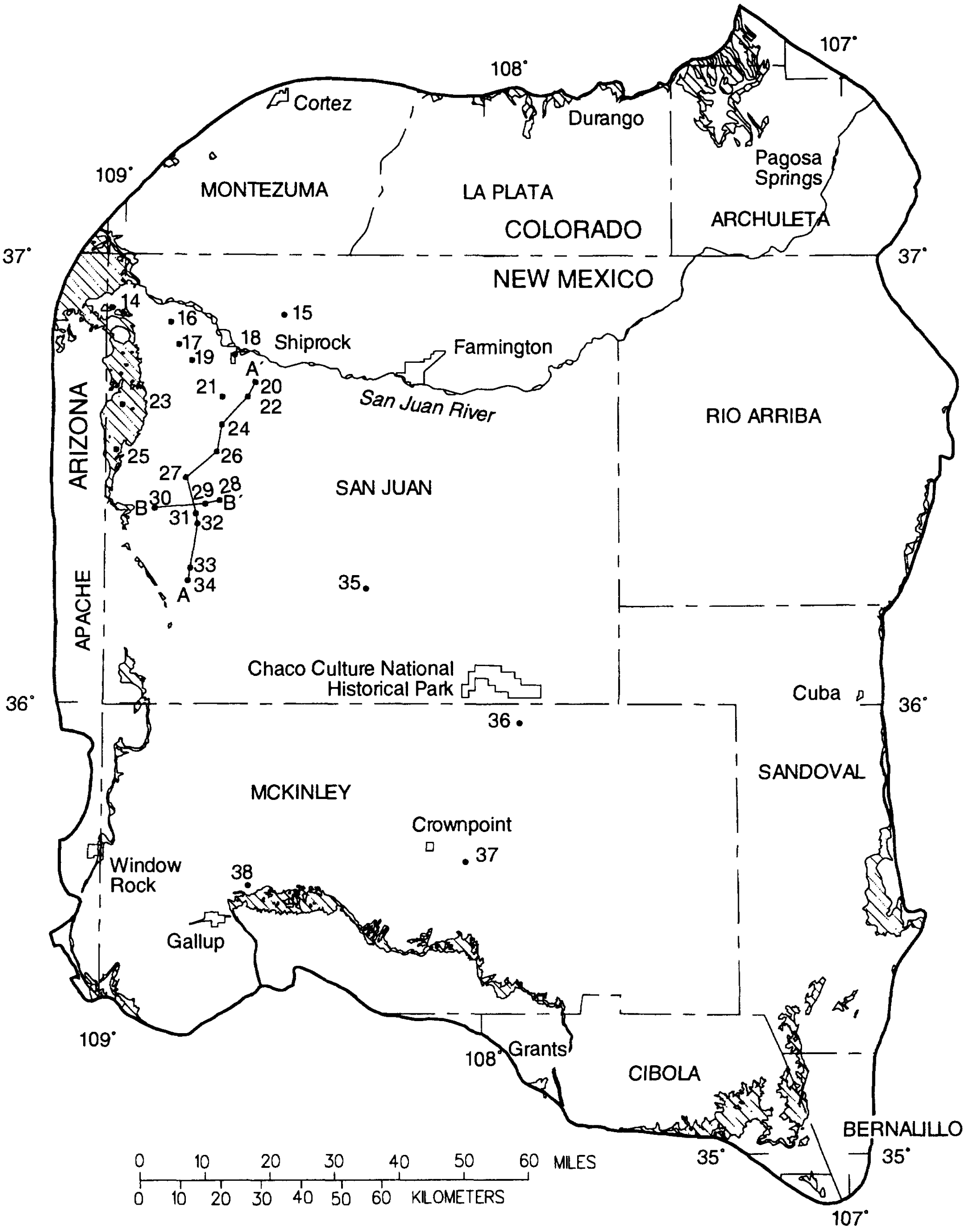
EXPLANATION

▥ OUTCROP OF DAKOTA AQUIFER, MANCOS SHALE, AND BURRO CANYON FORMATION--From Dane and Bachman, 1965; Wilson and others, 1969; and Tweto, 1979

— BOUNDARY OF STUDY AREA

●11 WATER WELL--Wells 11-13 were sampled from 1986 to 1989; wells 54-59 were sampled prior to 1986 and the analyses are from the National Water Information System data base

Figure 9.--Location of sampled water wells completed in the Dakota aquifer.



EXPLANATION

▨ OUTCROP OF MORRISON AQUIFER, JURASSIC ROCKS, UNDIVIDED; WANAKAH FORMATION; ENTRADA SANDSTONE; AND SAN RAFAEL GROUP--From Dane and Bachman, 1965; Wilson and others, 1969; Tweto, 1979; and Hintze, 1981

—— BOUNDARY OF STUDY AREA

A —— A' LINE OF GEOHYDROLOGIC SECTION--See figure 11

● 14 WATER WELL--Wells 14-38 were sampled from 1986 to 1989

Figure 10.--Locations of sampled water wells completed in the Morrison aquifer and of geohydrologic sections.

Table 1 provides data pertaining to the 38 wells sampled from 1986 to 1989. Well depths range from 150 to 5,250 ft. The part of the Gallup, Dakota, or Morrison aquifer that was sampled, as shown in table 1, is the thickness of the interval open to the aquifer; the interval thickness ranges from 31 to 876 ft. Most wells sampled were completed as open holes, so water was obtained from the entire open interval as opposed to one or more perforated intervals in the casing. Eight wells were completed with multiple perforated intervals so the well was open to selected zones; the perforated intervals were summed to determine the total thickness of the interval open to the aquifer that was sampled (table 1). Two geohydrologic sections for 12 wells completed in the Morrison aquifer are shown in figure 11. Section A-A' depicts nine wells in a north-trending line. Well 32 is the only well open solely to the Westwater Canyon Member; the other wells are open to varying combinations of the Westwater Canyon, Recapture, or Salt Wash Members of the Morrison Formation. Several wells are completed below the Morrison aquifer and open to the Wanakah Formation. Section B-B' depicts three wells in an east-trending line. Wells 29 and 30 are completed solely in the Morrison aquifer, whereas well 28 extends 155 feet into the Wanakah Formation. Flowing, artesian conditions occurred at most wells, facilitating sample collection. Most of these wells (22 of 29) (table 1) had the capacity to be shut in for a head measurement and therefore could be turned off after sampling was completed. However, seven wells (7, 11, 18, 20, 21, 32, and 33) could not be shut in for a head measurement or turned off to prevent continuous discharge. Six wells were equipped with windmills with positive-displacement piston pumps and three wells were equipped with submersible pumps. These data are listed in table 1.

Table 1.--Data for wells sampled from 1986 to 1989

[See figures 8-10 for location of wells. Type of lift: F, natural flow; P, piston; S, submersible. --, not reported]

Well number	Aquifer	Altitude of land surface (feet above sea level)	Depth of well (feet below land surface)	Thickness of interval open to aquifer (feet)	Type of lift	Shut-in capacity for flowing wells
1	Gallup	5,890	150	--	F	Yes
2	Gallup	6,195	3,090	60	F	Yes
3	Gallup	6,401	--	--	F	Yes
4	Gallup	5,990	1,239	80	F	Yes
5	Gallup	6,048	1,743	160	F	Yes
6	Gallup	6,379	1,082	502	P	--
7	Gallup	6,365	1,850	225	F	No
8	Gallup	6,430	969	64	F	Yes
9	Gallup	6,165	602	120	F	Yes
10	Gallup	6,515	667	64	S	--
11	Dakota	5,342	1,464	555	F	No
12	Dakota	6,035	521	147	P	--
13	Dakota	6,130	1,840	55	F	Yes
14	Morrison	5,545	604	342	P	--
15	Morrison	5,440	2,736	430	S	--
16	Morrison	5,120	2,000	782	F	Yes
17	Morrison	5,100	2,035	691	F	Yes
18	Morrison	4,941	1,777	295	F	No
19	Morrison	5,270	2,013	280	F	Yes
20	Morrison	5,060	2,300	788	F	No
21	Morrison	5,290	2,597	770	F	No
22	Morrison	5,139	2,520	747	F	Yes
23	Morrison	5,831	555	60	P	--
24	Morrison	5,270	2,682	876	F	Yes
25	Morrison	6,206	702	149	P	--
26	Morrison	5,522	1,992	247	F	Yes
27	Morrison	5,735	1,912	526	F	Yes
28	Morrison	5,595	2,034	834	F	Yes
29	Morrison	5,670	1,912	505	F	Yes
30	Morrison	6,090	1,751	275	F	Yes
31	Morrison	5,840	2,125	613	F	Yes
32	Morrison	5,830	1,691	410	F	No
33	Morrison	5,905	2,349	858	F	No
34	Morrison	6,010	2,518	768	F	Yes
35	Morrison	5,750	5,250	250	F	Yes
36	Morrison	6,330	3,988	31	F	Yes
37	Morrison	6,795	2,605	400	S	--
38	Morrison	6,825	410	110	P	--

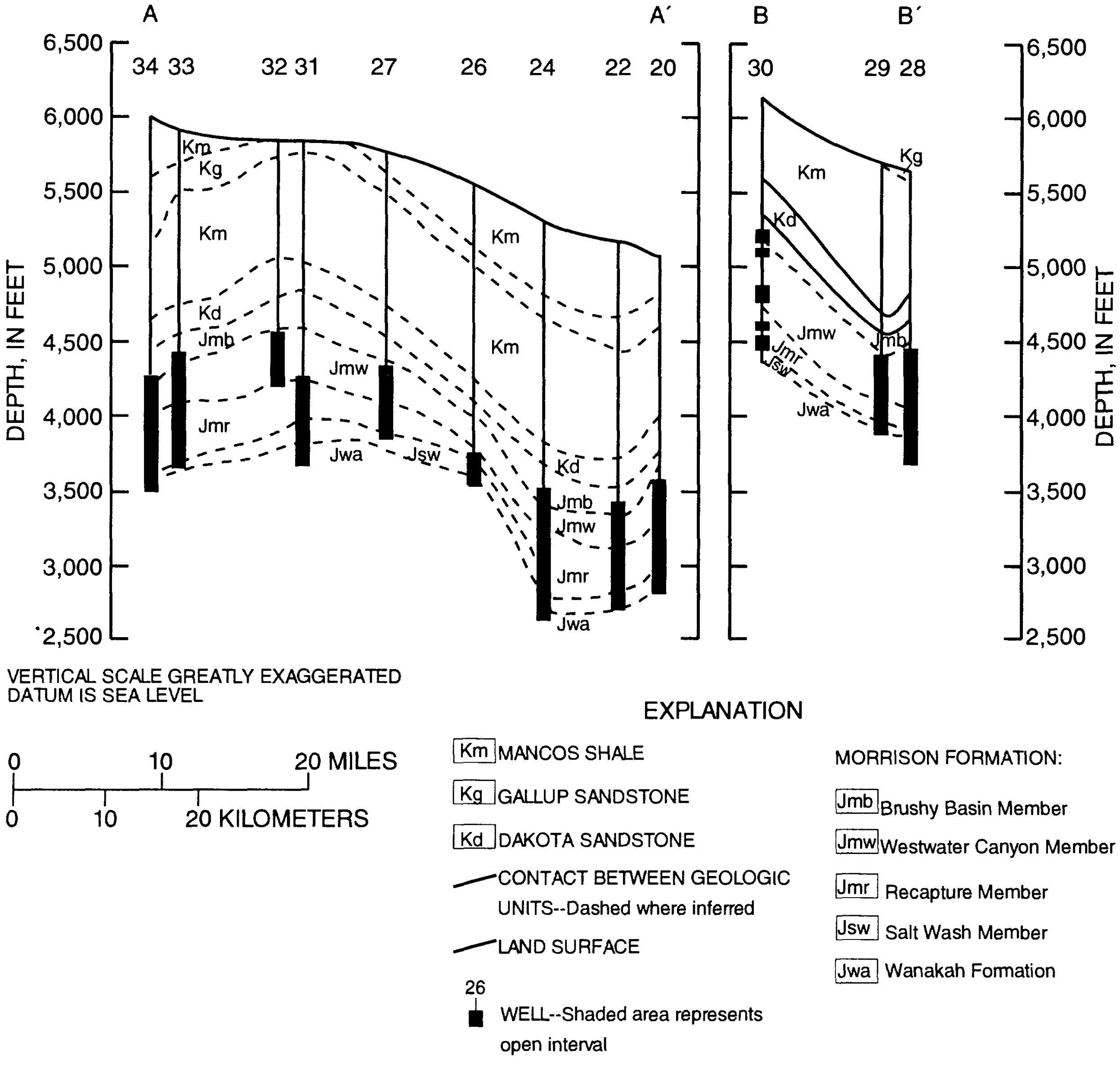


Figure 11.--Geohydrologic sections showing well completion in the Morrison aquifer. Lines of section are shown in figure 10 (modified from Dam, 1988).

Major Constituents and pH

Chemical analyses are shown for 61 water samples collected during 1986 through 1989 from 38 wells completed in the Gallup (table 2), Dakota (table 3), and Morrison aquifers (table 4). In addition, data from NWIS are presented for the Gallup aquifer (15 wells) and the Dakota aquifer (6 wells). Several wells, particularly wells completed in the Morrison aquifer, were sampled more than once during 1986 through 1989 to supplement the initial suite of constituents collected and to identify a possible change of constituent concentrations with time.

Concentrations of major ions (Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, CO_3^{2-}, SO_4^{2-}, and Cl^-) generally were found to be reproducible in samples collected from the Gallup and Dakota aquifers. Concentrations of major ions were found to change over time for samples collected from several wells completed in the Morrison aquifer.

Three of 10 wells in the Gallup aquifer were sampled twice between 1986 and 1987. Major ion concentrations differed by less than 10 percent for Na^+, alkalinity, and SiO_2^0 (table 2). Only one of three wells completed in the Dakota aquifer that were sampled during the investigation was sampled twice (table 3). Differences greater than 10 percent were detected between Ca^{2+}, Mg^{2+}, Na^+, and K^+ concentrations from two analyses for well 13. However, SO_4^{2-}, Cl^-, and several other properties and constituents differed by less than 10 percent between the two analyses. Three of six chemical analyses obtained from the NWIS data base for the Dakota aquifer indicated that major ion concentrations were within 10 percent (table 3).

Fifteen of 25 wells completed in the Morrison aquifer were sampled more than once between 1986 and 1989 (table 4). Concentrations of major ions in water samples collected from 9 of the 15 wells were reproducible within 10 percent. Thus, concentrations of several major ions in samples collected from 6 of 15 wells differed by more than 10 percent. Concentrations of Ca^{2+}, HCO_3^-, and Cl^- varied between sampling periods for wells 18, 20, 22, 25, 28, and 33, and Mg^{2+}, Na^+, and SO_4^{2-} concentrations varied by more than 10 percent in samples from wells 20 and 28. Because major ion concentrations in water from well 30 were nearly identical except for Cl^-, which changed from 4.7 to 2.7 mg/L, and for K^+, which changed from 2.3 to 1.9 (table 4), well 30 was not included with the six wells.

Several factors may contribute to the non-reproducibility of the samples with time. These include discharge of large volumes of water between sampling periods, a large open interval, and pump type--such as piston, which can introduce oxygen into the water resulting in chemical reactions. The range in discharge at wells 18, 20, 22, and 33 was 16 to 65 gal/min. At a discharge rate of only 20 gal/min over the minimum duration of 354 days between the 1986 and 1987 sampling dates, more than 10 million gal of water would have been discharged at each of these four wells. However, well 32 flowed continuously for the 3 years of sample collection, 1986-88, yet analytical results were reproducible within 10 percent. A smaller open interval for well 32 (410 ft) compared with well 33 (858 ft) may account for the difference in analytical results. Well 28 was constructed with a large open interval (834 ft) (table 1). Well 25 was constructed with a relatively small open interval (149 ft) (table 1); however, a windmill piston pump was used to obtain the water sample.

Table 2.--Selected properties of and constituents in water from the Gallup aquifer

[See figure 8 for location of wells; pH, standard units; °C, degrees Celsius; concentrations in milligrams per liter; <, less than; --, not reported]

Well number	Date of sample	Field pH	Temperature (°C)	Dissolved oxygen	Sulfide (H_2S+HS^-)	Calcium (Ca^{2+})	Magnesium (Mg^{2+})	Sodium (Na^+)	Sodium plus potassium (Na^++K^+)	Potassium (K^+)	Bicarbonate (HCO_3^-)	Carbonate (CO_3^{2-})	Alkalinity (as $CaCO_3$)	Sulfate (SO_4^{2-})	Chloride (Cl^-)	Fluoride (F^-)	Bromide (Br^-)	Iodide (I^-)	Silica (SiO_2^0)	Dissolved solids
1	07-01-88	7.90	16.7	1.2	<0.05	42	17	96	--	6.4	310	0	254	120	7.8	0.30	0.074	0.006	14	455
2	04-22-86	8.20	32.8	--	--	10	2.1	630	--	3.3	380	0	307	910	46	1.6	.18	.004	17	1,799
	10-21-87	8.33	32.9	--	.14	7.4	2.4	670	--	3.2	334	10	290	1,100	49	1.6	.066	.005	16	2,000
3	04-21-86	8.60	32.7	--	--	7.0	1.2	669	--	2.3	240	10	213	1,000	81	.70	.16	.004	17	1,900
4	07-15-88	8.57	24.4	--	.15	1.2	.28	220	--	1.1	451	14	394	84	4.1	1.2	.034	.005	12	559
5	06-30-87	8.81	26.0	--	--	3.8	.18	400	--	1.0	295	22	277	530	44	1.2	.15	.006	12	1,200
	06-28-88	8.81	25.0	--	.14	3.6	.15	400	--	.90	288	17	264	550	45	1.1	--	--	12	--
6	06-30-88	8.99	19.9	--	--	1.7	.62	230	--	.70	336	22	311	180	5.0	.70	.054	.005	11	639
7	06-28-88	9.00	20.7	--	.11	2.3	.29	140	--	.70	222	14	206	84	9.5	.30	.056	.005	13	374
8	12-03-87	8.73	18.4	--	.05	5.2	2.0	630	--	2.4	252	10	224	1,200	23	.60	.11	.004	12	2,000
9	04-29-86	9.10	18.0	--	--	1.4	.03	129	--	.80	259	20	244	31	4.3	.50	.044	.008	12	330
	08-11-87	8.83	18.0	--	.12	1.3	.31	130	--	.70	293	26	244	35	3.3	.70	--	--	13	330
10	06-30-88	9.20	16.9	--	--	.28	.06	170	--	.70	290	17	266	85	20	.80	.068	.005	9.9	444
39	05-26-64	7.8	18.5	--	--	33	6.7	--	1,000	--	410	0	336	1,700	180	3.5	--	--	12	3,200
40	07-03-74	8.0	--	--	--	400	120	150	--	2.0	170	13	161	1,500	20	.4	--	--	--	2,700
41	10-29-74	8.5	--	--	--	4.2	.7	580	--	3.6	520	19	457	480	240	3.0	--	--	16	1,600
42	10-14-64	7.8	--	--	--	37	11	--	25	--	200	0	167	19	2.8	.4	--	--	14	210
43	09-08-69	8.2	--	--	--	74	15	37	--	2.0	240	7	209	95	9.9	.3	--	--	--	390
44	01-28-72	8.2	--	--	--	12	4.8	120	--	2.0	190	0	156	140	4.6	.6	--	--	--	430
45	01-20-71	8.0	--	--	--	92	17	36	--	2.0	260	0	213	140	7.1	.5	--	--	--	450
46	03-10-70	7.8	--	--	--	80	26	87	--	5.0	270	0	221	260	8.9	.4	--	--	--	650
47	07-31-70	8.4	32.0	--	--	11	3.0	270	--	2.7	280	6	243	310	50	.8	--	--	16	810
48	09-19-62	8.2	24.5	--	--	9.5	2.1	720	--	3.0	310	0	254	1,200	42	.8	--	--	13	2,190
49	10-02-62	7.9	24.0	--	--	9.4	5.0	360	--	3.0	280	0	230	560	12	.8	--	--	14	1,100
50	10-14-64	8.5	--	--	--	12	3.6	--	220	--	250	7	205	270	21	.5	--	--	16	680
51	07-18-73	8.1	--	--	--	100	36	180	--	3.1	210	10	189	580	7.1	.7	--	--	--	1,100
52	09-18-62	8.8	20.0	--	--	3.1	.9	400	--	1.8	350	18	315	440	73	1.2	--	--	15	1,100
53	08-30-57	8.4	15.5	--	--	11	3.3	--	440	--	610	8	500	200	180	4.4	--	--	10	1,200

Table 3.--Selected properties of and constituents in water from the Dakota aquifer

[See figure 9 for location of wells; pH, standard units; °C, degrees Celsius; concentrations in milligrams per liter; --, not reported; >, greater than]

Well number	Date of sample	Field pH	Temperature (°C)	Sulfide (H_2S+HS^-)	Calcium (Ca^{2+})	Magnesium (Mg^{2+})	Sodium (Na^+)	Sodium plus potassium (Na^++K^+)	Potassium (K^+)	Bicarbonate (HCO_3^-)	Carbonate (CO_3^{2-})	Alkalinity (as $CaCO_3$)	Sulfate (SO_4^{2-})	Chloride (Cl^-)	Fluoride (F^-)	Bromide (Br^-)	Iodide (I^-)	Silica (SiO_2^0)	Dissolved solids
11	07-23-87	8.47	18.1	0.05	21	11	390	--	3.8	277	10	241	640	57	0.90	0.16	0.006	8.6	1,300
12	06-29-88	8.78	18.1	--	2.0	.16	100	--	1.1	215	10	192	25	2.6	.30	.038	.005	12	262
13	04-29-86	8.90	19.5	--	2.3	1.1	700	--	1.7	390	30	376	910	85	1.5	.24	.005	10	1,900
	12-03-87	8.91	19.5	>1.5	170	95	270	--	2.2	--	--	--	980	78	1.6	--	--	11	--
54	04-27-60	7.6	15.5	--	24	.5	780	--	3	280	0	230	1,100	260	2.2	--	--	8.5	2,320
55	09-21-66	8.0	--	--	53	10	1,300	--	11	360	12	315	1,600	720	8.2	--	--	--	3,780
56	06-27-52	--	--	--	19	3.1	--	690	--	170	6	149	980	280	1.3	--	--	13	2,080
	09-21-66	8.4	--	--	19	2.4	690	--	9	140	12	135	1,000	290	2.0	--	--	--	2,060
57	07-22-70	8.6	--	--	7.0	--	320	--	--	260	12	233	480	15	.3	--	--	--	961
	09-24-74	8.6	--	--	6.0	1.2	360		2	250	23	243	470	18	.4	--	--	8.7	1,040
58	06-08-67	9.4	--	--	2.0	1.2	120		--	160	26	175	70	15	.3	--	--	--	302
	01-08-70	9.4	--	--	1.0	--	130		2	180	34	204	68	12	.3	--	--	--	310
59	07-03-74	8.2	--	--	54	7.3	120		2	300	13	268	130	11	.2	--	--	9.8	512

Table 4.--Selected properties of and constituents in water from the Morrison aquifer

[See figure 10 for location of wells; pH, standard units; °C, degrees Celsius; concentrations in milligrams per liter; --, not reported; <, less than detection limit]

Well number	Date of sample	Field pH	Temperature (°C)	Dissolved oxygen	Sulfide ($H_2S + HS^-$)	Calcium (Ca^{2+})	Magnesium (Mg^{2+})	Sodium (Na^+)	Potassium (K^+)	Bicarbonate (HCO_3^-)	Carbonate (CO_3^{2-})	Alkalinity (as $CaCO_3$)	Sulfate (SO_4^{2-})	Chloride (Cl^-)	Fluoride (F^-)	Bromide (Br^-)	Iodide (I^-)	Silica (SiO_2^0)	Dissolved solids
14	06-10-88	7.56	17.0	--	--		13	42	1.3	286	0	234	79	11	0.60	0.135	0.008	28	361
15	07-21-87	7.52	39.9	--	35	50	28	1,700	18	305	0	250	3,800	210	1.6	.38	.033	33	6,000
16	06-24-86	9.20	19.9	--	--	1.1	.08	130	1.0	244	29	247	33	10	2.0	.050	.006	17	350
	06-08-88	9.37	20.1	--	.07	1.2	.06	140	.90	273	14	248	33	11	2.8	--	--	17	350
17	07-02-86	8.50	23.0	--	--	40	3.4	810	3.6	124	4	110	1,700	61	1.6	.13	.015	13	2,700
18	06-16-86	8.00	31.0	--	--	58	14	800	7.7	58	0	49	1,600	110	2.0	.13	.015	14	2,600
	06-09-87	8.03	31.1	--	<.05	110	14	810	7.2	71	0	60	2,100	57	1.9	--	--	14	3,200
19	07-14-87	7.74	29.1	--	.24	33	12	1,300	9.0	383	0	310	1,500	750	8.0	.05	.073	18	3,800
20	06-19-86	7.60	33.0	--	--	78	31	1,400	19	158	0	130	3,200	190	2.1	.20	.035	16	5,000
	06-10-87	7.80	31.0	--	.18	160	15	890	10	81	0	68	2,500	120	2.1	--	--	14	3,800
21	06-18-86	8.30	--	--	--	39	3	770	4.6	128	0	105	1,600	67	1.1	.15	.021	14	2,600
22	06-19-86	8.00	28.8	--	--	98	25	740	8.2	51	0	48	1,900	60	1.9	.12	.016	16	2,900
	06-10-87	8.03	30.5	--	.07	160	23	690	8.2	57	0	45	2,000	83	2.0	--	--	16	3,000
23	06-10-88	9.65	17.1	--	--	1.3	.06	120	.70	176	26	188	37	23	.80	.235	.018	11	308
24	07-01-86	8.10	18.0	--	--	14	8.1	290	2.7	327	0	265	390	38	1.3	.12	.005	12	920
25	06-09-88	8.87	16.9	5.0	--	14	5.9	54	2.1	156	7	140	21	10	.50	.074	.004	16	213
	04-25-89	9.12	16.0	--	--	5.0	1.6	60	1.0	117	10	112	23	8.3	.40	--	--	10	167
26	06-17-86	9.30	27.2	--	--	1.0	.04	110	.40	143	30	166	52	4.2	.40	.019	.002	19	300
	07-22-87	9.39	27.6	--	.16	2.6	.16	110	.60	176	34	200	35	4.1	.40	--	--	18	290
	07-01-88	9.33	27.1	--	.19	.98	.09	120	.40	159	43	202	48	3.9	.30	--	--	18	310
27	06-18-86	9.40	23.9	--	--	.80	.04	81	.30	156	34	182	9.8	1.1	.30	.014	.002	17	220
	06-11-88	9.65	23.9	--	--	.90	<.01	88	.30	166	29	184	10	.80	.30	--	--	18	230
28	06-30-86	9.33	22.0	--	--	1.8	.20	130	.90	170	36	199	71	28	.40	.032	.006	19	370
	07-17-87	9.45	21.3	--	<.05	3.1	.46	190	1.2	164	38	197	170	64	.90	--	--	17	570
	07-01-88	9.26	21.3	--	--	2.1	.37	160	.90	171	34	196	90	37	.60	--	--	18	430
29	06-29-88	9.51	23.3	--	--	.73	.03	110	.40	200	36	224	24	2.5	.80	.030	.003	16	290
	11-22-88	9.41	20.9	--	--	.86	<.01	120	.50	193	38	222	22	3.0	.70	--	--	17	297
30	07-23-87	8.37	24.0	1.0	<.05	11	.89	68	2.3	200	0	163	13	4.7	2.0	.010	<.001	18	220
	01-05-89	8.58	16.1	--	--	11	.89	70	1.9	200	0	164	13	2.7	.80	--	--	18	216
31	01-05-89	9.06	22.0	--	--	1.3	.06	66	.70	134	22	146	3.0	1.6	.20	--	--	16	174
32	06-24-86	9.05	21.9	--	--	1.0	.07	71	.60	151	14	147	5.6	1.6	.20	.018	.001	19	190
	07-15-87	9.31	22.4	<1.0	.10	.93	.05	72	.60	144	19	148	4.8	1.5	.30	--	--	19	190
	06-11-88	9.42	23.6	--	--	.95	.06	71	.50	149	19	154	5.2	1.1	.30	--	--	18	190
33	07-15-87	9.52	26.6	<	--	.85	.04	120	.50	168	34	194	38	12	.60	--	--	18	290
	06-29-88	9.53	--	--	--	.66	.01	110	.60	164	34	190	36	8.4	.50	--	--	19	290
	11-23-88	9.25	21.3	--															
34	07-16-87	8.96	25.5	<1.0	.71	1.8	.17	190	1.2	301	17	270	130	7.1	1.7	--	--	15	509
	11-22-88	8.88	23.9	--	--	1.9	.19	190	1.0	295	19	274	130	7.8	1.9	.062	.005	14	510
35	06-11-87	7.88	51.8	--	<.05	27	.42	240	2.3	173	0	142	430	19	1.2	.10	.009	35	840
36	04-24-86	8.20	42.2	--	--	12	.09	359	2.1	190	6	165	560	14	1.5	.16	.009	25	1,099
	10-22-87	8.31	37.4	--	.12	13	.15	340	2.0	188	5	162	580	17	1.6	.081	.012	25	1,100
37	10-02-87	9.05	30.5	--	.07	1.4	.32	200	.90	308	22	288	150	6.5	.40	.035	.006	14	550
38	07-01-87	7.64	15.0	4.3-5.0	--	49	17	180	2.6	344	0	282	290	7.9	.30	.10	.006	--	720
	07-14-88	7.64	15.4	--	--	51	17	180	2.4	344	0	282	310	7.2	.20	--	--	17	750

Values of pH were reproducible at most wells, and all samples were alkaline (above 7.0). Values of pH in water samples from the Gallup and Dakota aquifers were typically below 9.0 (figs. 12 and 13). Values of pH in water samples from the Morrison aquifer ranged from 7.52 to 9.65; water from 10 wells exceeded a pH of 9.0, indicating highly alkaline conditions. The areal distribution of pH in water from the Morrison aquifer indicates that highly alkaline water in the northwestern part of the basin generally is neutralized as it moves in a northerly direction (fig. 14). The pH in water along Morrison outcrop areas was typically below 9.0 except for one sample that had the highest pH value measured at 9.65. The pH of samples from wells located near Shiprock was typically below 8.0.

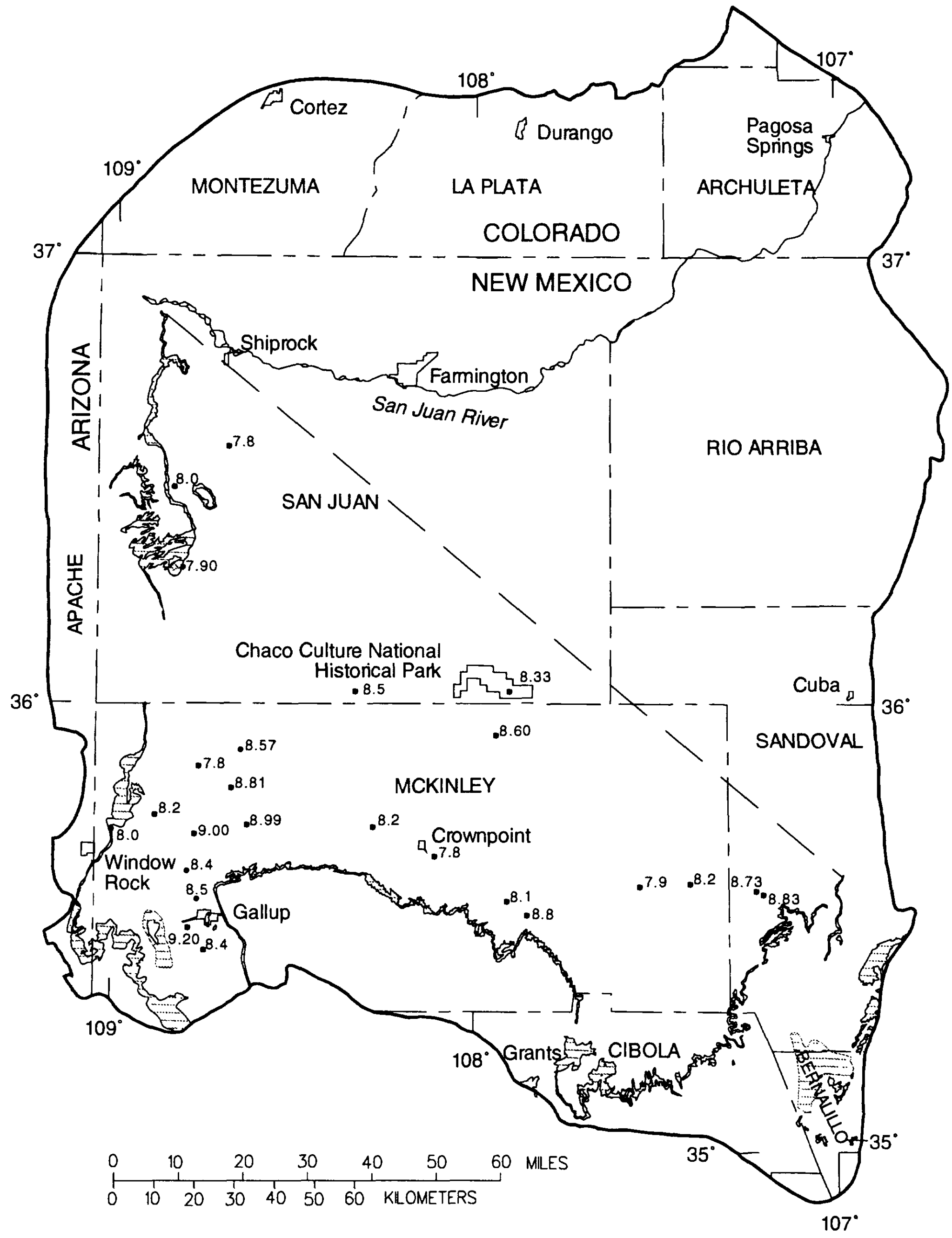
The distribution of major cations and anions found in water from the three aquifers is shown in figures 15 through 20. Two types of diagrams were used to depict ion concentrations: (1) chemical-constituent diagrams modified from Stiff (1951) to indicate spatial variations in ion concentrations, and (2) trilinear diagrams developed by Piper (1944) to relate variations in the relative percentage of ion concentrations.

Predominant ions in water from the three aquifers generally were Ca^{2+}, Na^{+}, HCO_3^-, and SO_4^{2-}, as shown in figures 15-17. Bicarbonate represents part of the alkalinity value in these figures. Major ions in water from the Gallup aquifer were predominantly Ca^{2+}-HCO_3^- in the southwestern outcrop area and Na^{+}-HCO_3^- in the northwestern outcrop area. The majority of samples were predominantly Na^{+}-HCO_3^- in the southwestern area of the basin and Na^{+}-SO_4^{2-} in the southeastern and central parts of the basin (fig. 15).

Predominant ions in water in the Dakota aquifer were Na^{+}-HCO_3^- for three samples located farthest south in the northwestern part of the basin. Predominant ions were Na^{+}-SO_4^{2-}, with minor HCO_3^-, for samples to the north and one sample in the southeastern part of the basin (fig. 16).

Distinct chemical groups of major ion distribution were observed in samples from wells completed in the Morrison aquifer (fig. 17). Chemical changes were observed in well samples from south to north in the general direction of flow. For one sample near the outcrop located near Gallup, New Mexico, Na^{+}-HCO_3^--SO_4^{2-} were predominant ions. Predominant ions near Crownpoint consisted of Na^{+}-HCO_3^- and predominant ions south and northwest of Chaco Culture National Historical Park consisted of Na^{+}-SO_4^{2-}. In the northwestern part of the basin, the predominant ions in 10 samples from the southern and outcrop areas were Na^{+}-HCO_3^- and in 8 samples from the northern area were Na^{+}-SO_4^{2-}. Predominant ions in two samples near Four Corners consisted of Ca^{2+}-HCO_3^- and Na^{+}-HCO_3^-. In the western part of the basin, water is dilute and ion concentrations progressively increased northward toward Shiprock.

Points in figures 18-20 represent the percentage of a cation, in meq/L, relative to the total sum of cations and the percentage of an anion, in meq/L, relative to the total sum of anions. The intersection of the two percentages is depicted in the quadrangular portion of the trilinear diagram. Calcium concentrations constitute approximately 0 to 35 percent of the total cations in the Gallup, Dakota, and Morrison aquifers (figs. 18-20).



EXPLANATION

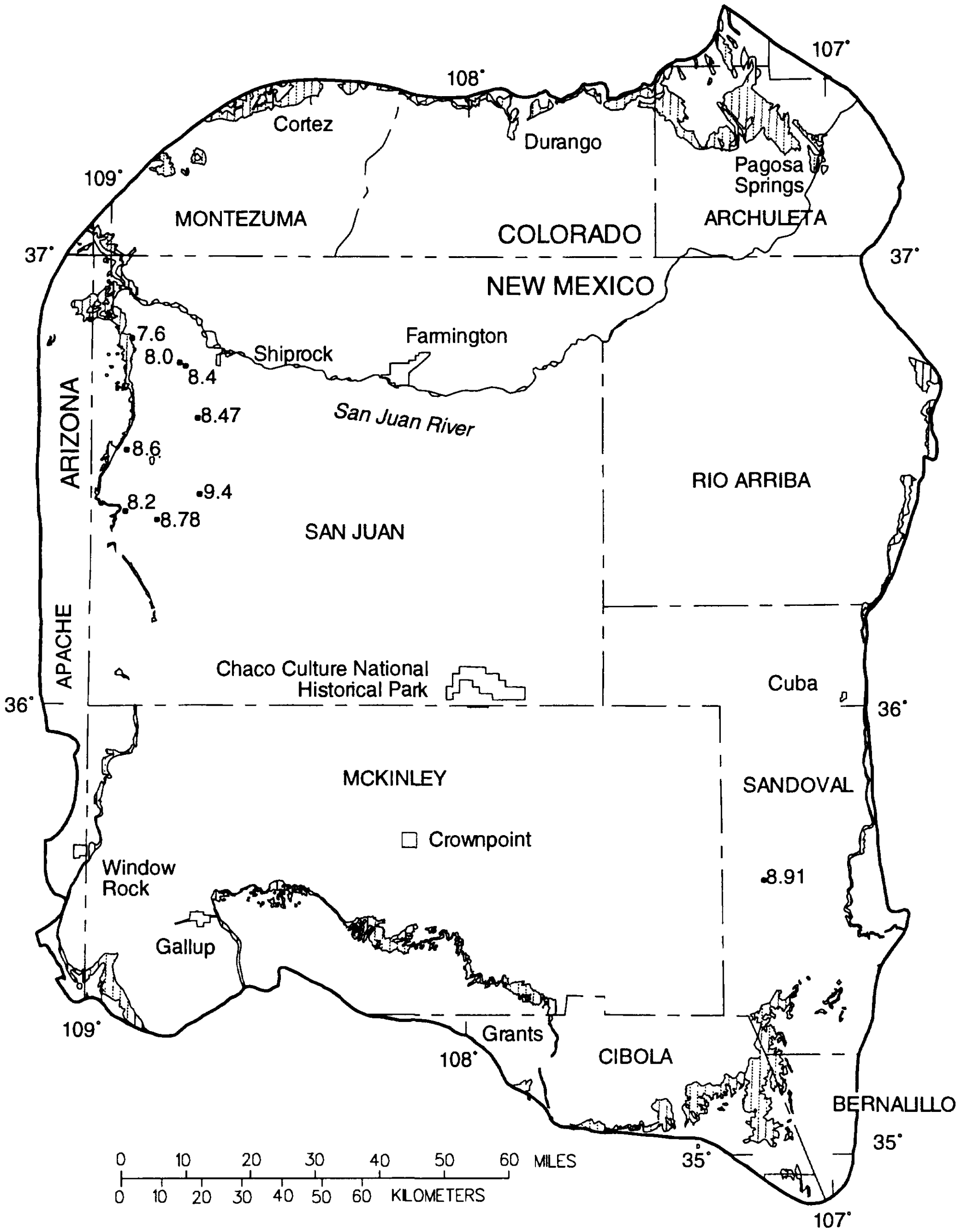
▤ OUTCROP OF GALLUP AQUIFER--In Arizona includes Pescado Tongue of Mancos Shale. In the southeastern part of the study area mapped as part of the Mesaverde Group, undivided. From Dane and Bachman, 1965; and Hackman and Olson, 1977

— — APPROXIMATE SUBSURFACE EXTENT OF GALLUP AQUIFER--From Molenaar, 1973

━ BOUNDARY OF STUDY AREA

• 7.8 WATER WELL--Number is pH, in standard units

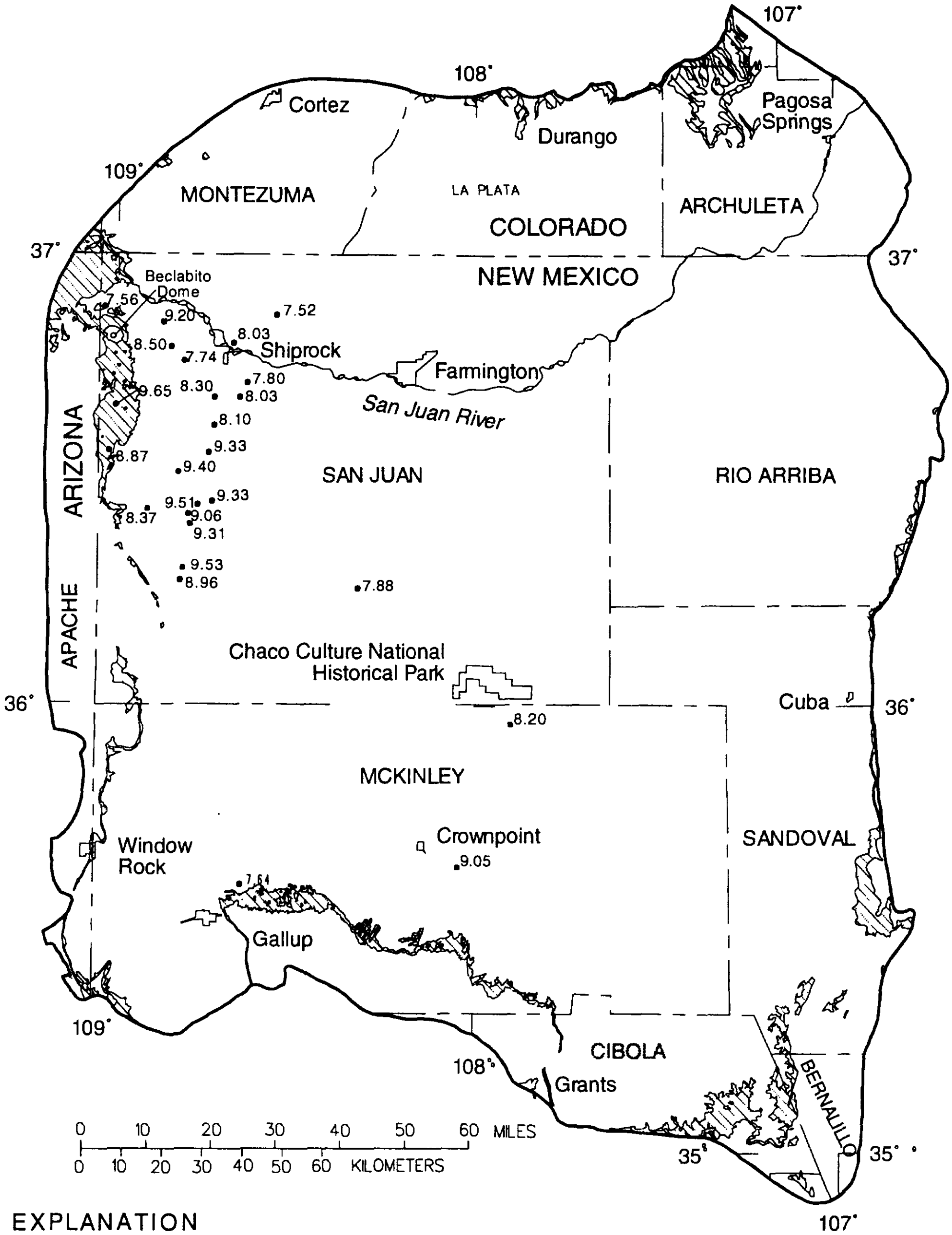
Figure 12.--Values of pH for water from water wells completed in the Gallup aquifer.



EXPLANATION

▥	OUTCROP OF DAKOTA AQUIFER, MANCOS SHALE, AND BURRO CANYON FORMATION--From Dane and Bachman, 1965; Wilson and others, 1969; and Tweto, 1979
———	BOUNDARY OF STUDY AREA
• 9.4	WATER WELL--Number is pH, in standard units

Figure 13.--Values of pH for water from water wells completed in the Dakota aquifer.



EXPLANATION

▨ OUTCROP OF MORRISON AQUIFER, JURASSIC ROCKS, UNDIVIDED; WANAKAH FORMATION; ENTRADA SANDSTONE; AND SAN RAFAEL GROUP--From Dane and Bachman, 1965; Wilson and others, 1969; Tweto, 1979; and Hintze, 1981

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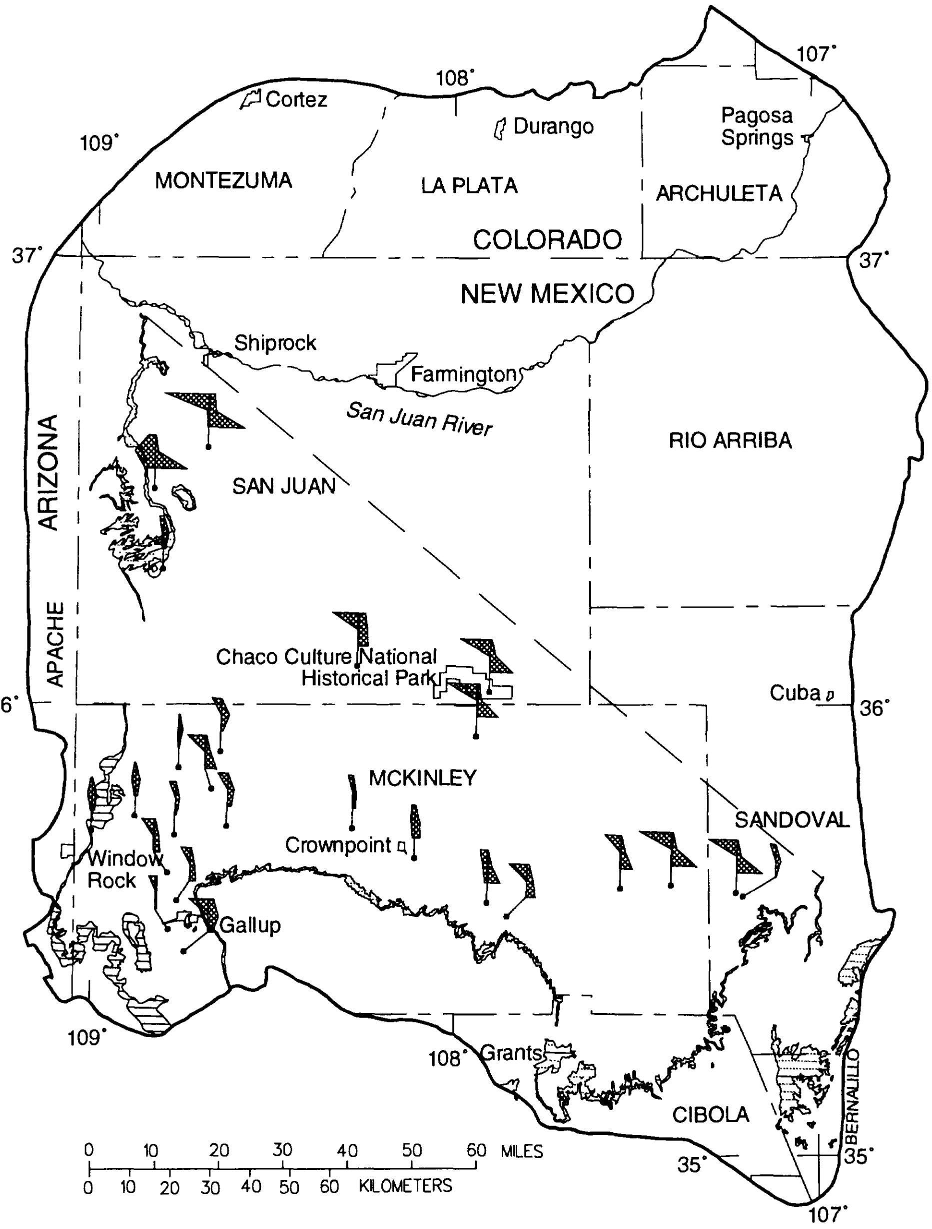
● 9.05 WATER WELL--Number is pH, in standard units

Figure 14.--Values of pH for water from water wells completed in the Morrison aquifer.



EXPLANATION

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— — APPROXIMATE SUBSURFACE EXTENT OF GALLUP AQUIFER--From Molenaar, 1973

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● WATER WELL

CHEMICAL-CONSTITUENT DIAGRAM (modified from Stiff, 1951)

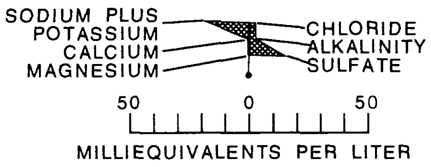
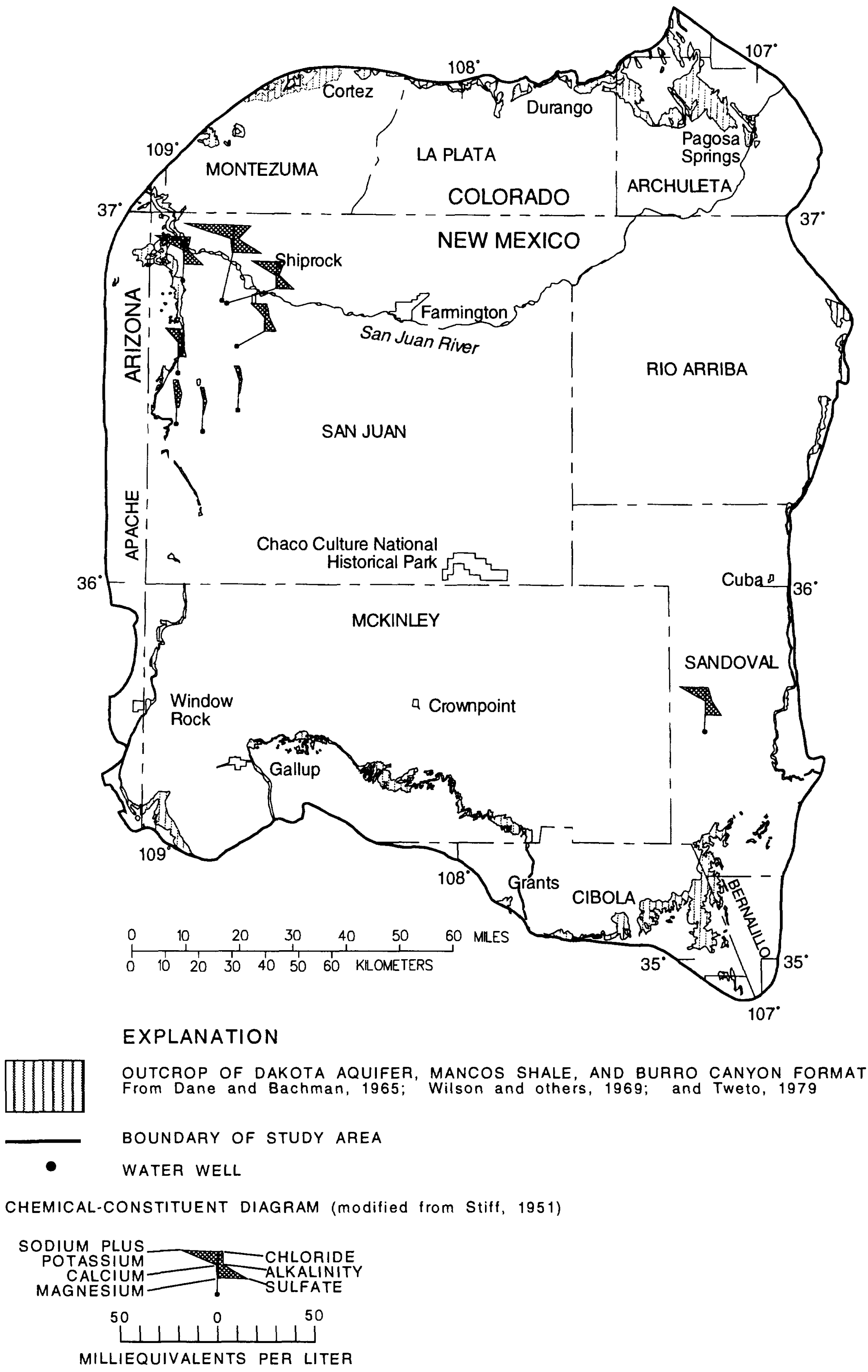


Figure 15.--Chemical-constituent diagrams of water from water wells completed in the Gallup aquifer.



EXPLANATION

▥ OUTCROP OF DAKOTA AQUIFER, MANCOS SHALE, AND BURRO CANYON FORMATION--From Dane and Bachman, 1965; Wilson and others, 1969; and Tweto, 1979

— BOUNDARY OF STUDY AREA

● WATER WELL

CHEMICAL-CONSTITUENT DIAGRAM (modified from Stiff, 1951)

Figure 16.--Chemical-constituent diagrams of water from water wells completed in the Dakota aquifer.

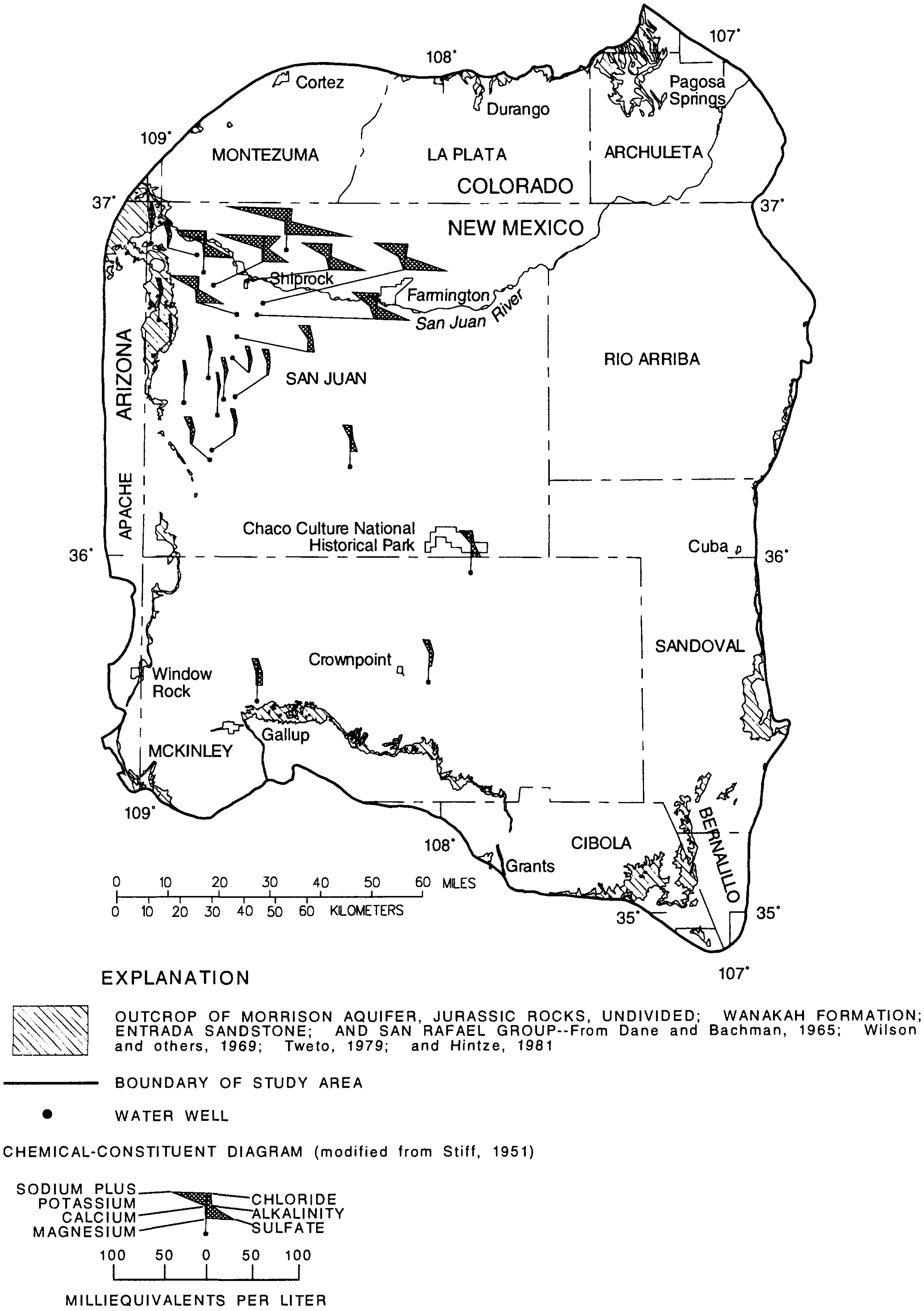


Figure 17.--Chemical-constituent diagrams of water from water wells completed in the Morrison aquifer.

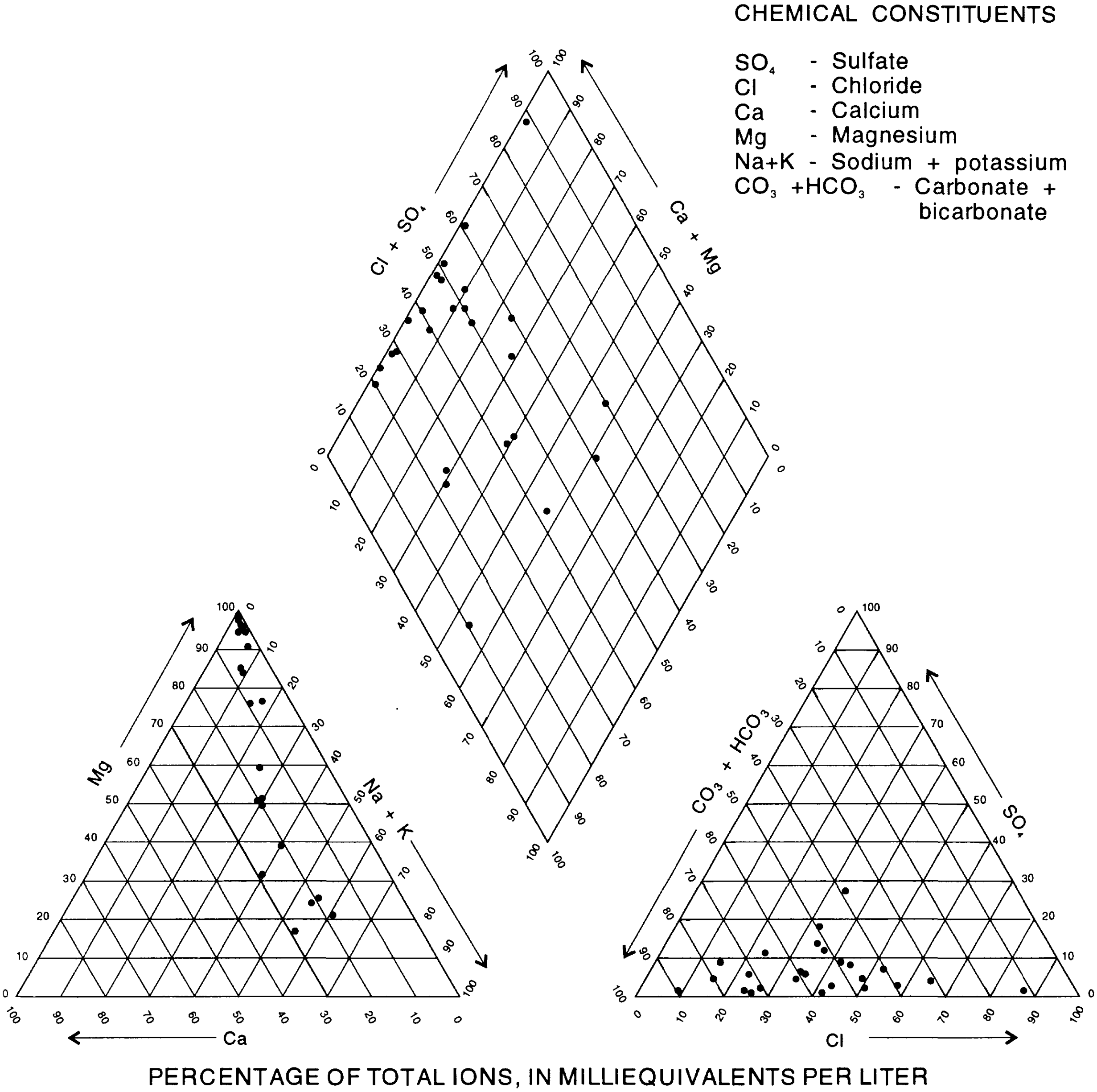


Figure 18.--Trilinear diagram of major ion chemistry from water wells completed in the Gallup aquifer.

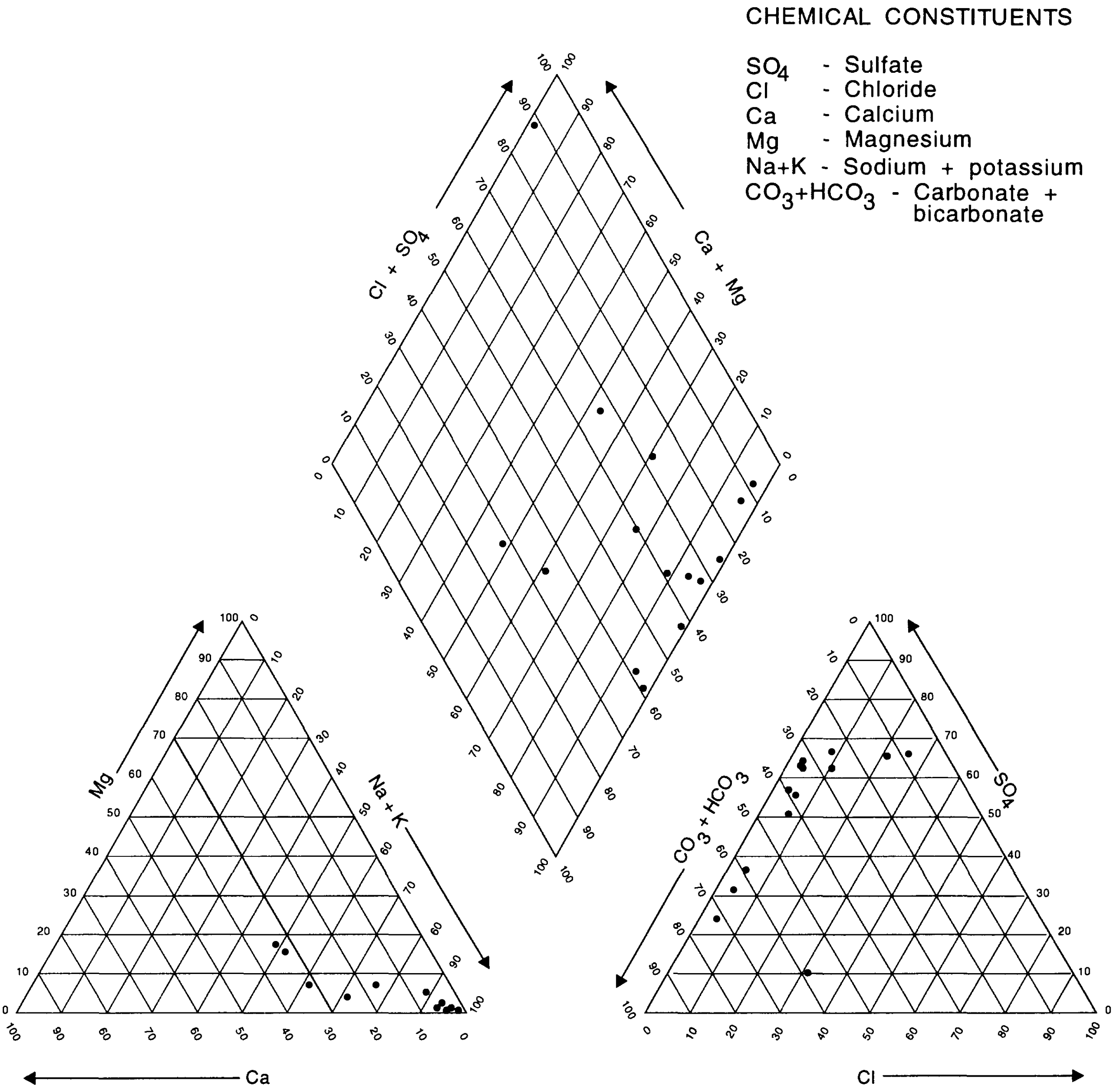


Figure 19.--Trilinear diagram of major ion chemistry from water wells completed in the Dakota aquifer.

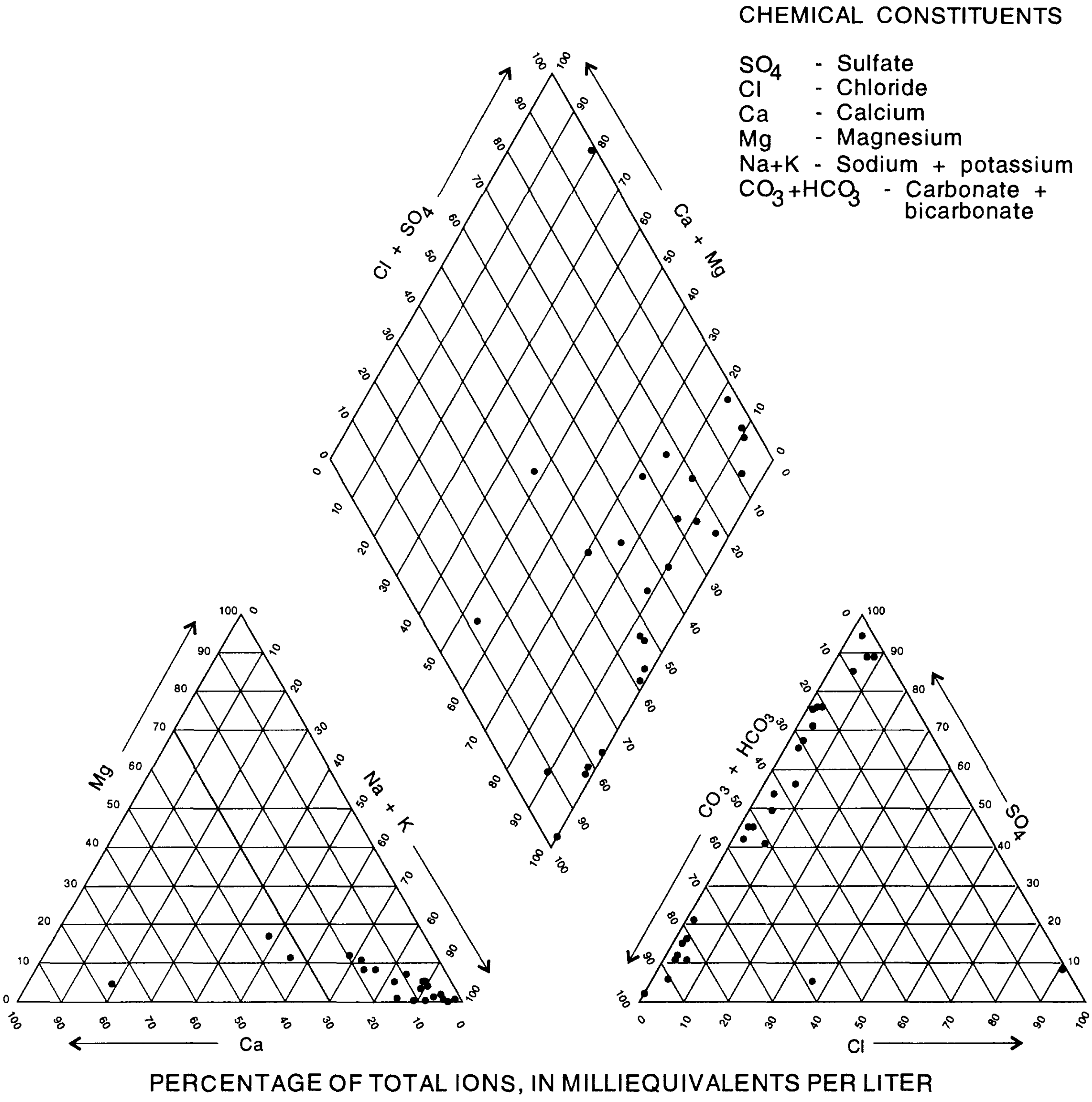


Figure 20.--Trilinear diagram of major ion chemistry from water wells completed in the Morrison aquifer.

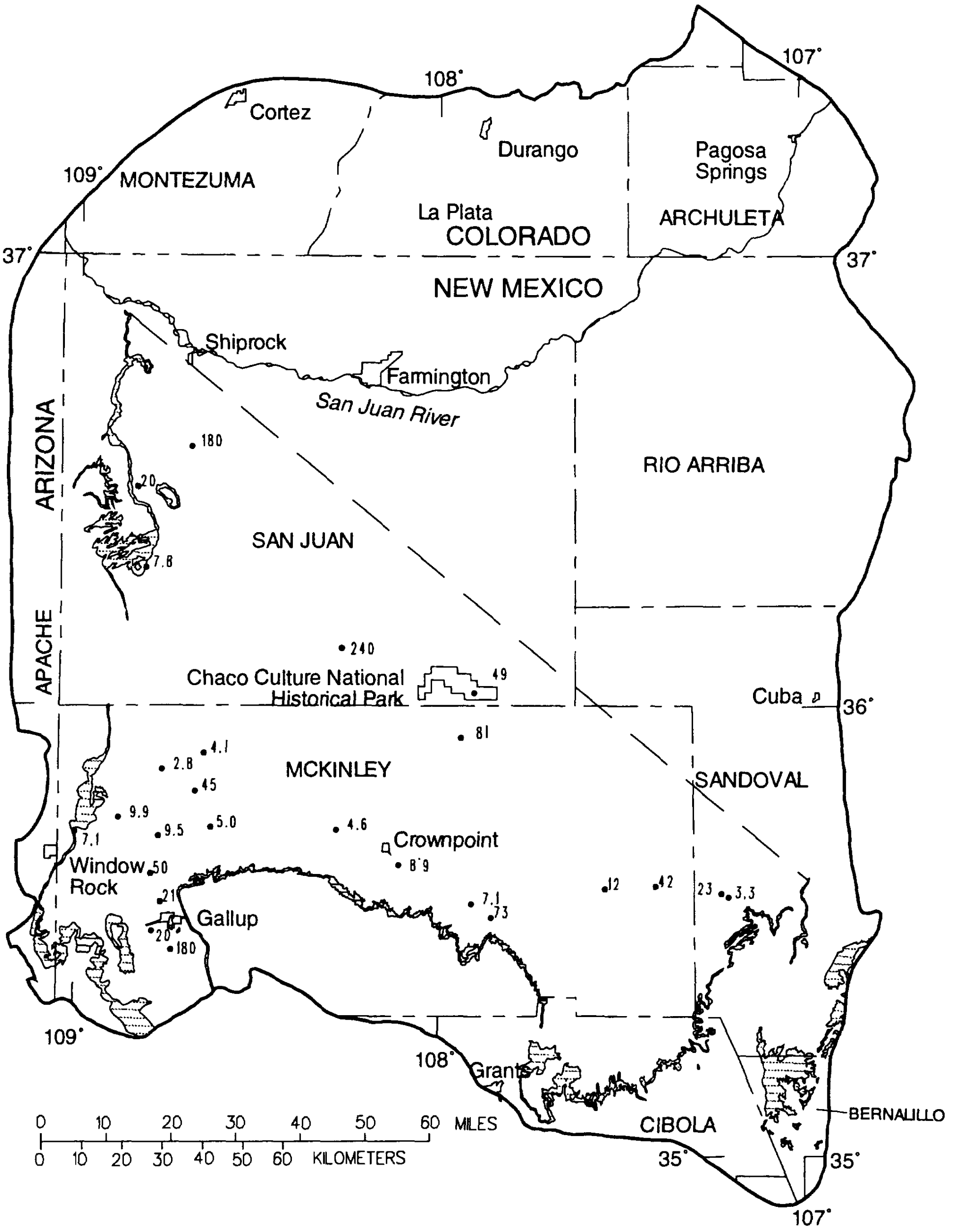
Chloride concentrations were small (less than 25 mg/L) in samples on or near recharge areas for the three aquifers (figs. 21-23). Downgradient, chloride concentrations generally increased by one to two orders of magnitude. Two samples from wells completed in the outcrop area of the Gallup aquifer contained less than 8 mg/L of Cl^- (fig. 21). Chloride concentrations ranged from 2.8 to 180 mg/L in samples downgradient from the western outcrop areas. For three water samples from the Gallup aquifer in the northwestern area, chloride concentrations ranged from 7.8 to 180 mg/L, increasing to the north in the general direction of ground-water flow (fig. 21). Similar trends were observed for the Dakota aquifer (fig. 22). Chloride concentrations were less than 20 mg/L for four samples and increased to the north toward Shiprock to a maximum of 720 mg/L. In outcrop areas of the Morrison aquifer, small chloride concentrations (less than 25 mg/L) as well as large increases (750 mg/L) toward Shiprock were observed (fig. 23). However, six samples at and downgradient from Sanostee contained extremely low chloride values ranging from 0.80 to 3.9 mg/L.

Minor and Trace Constituents

Concentrations of selected minor and trace constituents are shown for the Gallup, Dakota, and Morrison aquifers (tables 2-4, respectively). Dissolved oxygen and sulfide data were used to establish the redox (oxidation-reduction) potential of the water samples. The occurrence of DO in water along outcrop areas generally is anticipated although difficult to measure precisely. Wells sampled on or near outcrops were equipped with piston pumps that can transfer oxygen from the air to the water. For example, at well 38 the DO concentration in water ranged from 4.3 to 5.0 mg/L (table 4), increasing as the rate of pumping decreased. Therefore, values of DO shown in tables 2 and 4 are very approximate. Sulfide was detected in water from several wells downgradient from the outcrop area; this indicates reducing conditions. However, sulfide did not consistently increase to the north toward Shiprock, suggesting that localized conditions, such as the presence of organic matter or availability of reactive iron, may have affected sulfate reduction reactions. Sulfide consists largely of hydrogen sulfide gas (H_2S) and the bisulfide (HS^-) ion. Above a pH of 7.0, sulfide will occur predominantly as HS^- (Stumm and Morgan, 1981, p. 443). Therefore, the alkaline water found in the three aquifers indicates that HS^- was the predominant sulfide species.

Fluoride concentrations generally are small in water samples from the three aquifers (tables 2-4); however, a larger percentage of F^- concentrations were greater than 2 mg/L in samples from wells completed in the Dakota aquifer. The F^- concentration exceeded 2 mg/L for samples from 3 of 25 wells completed in the Gallup aquifer, 2 of 9 wells completed in the Dakota aquifer, and 3 of 25 wells completed in the Morrison aquifer. The 2-mg/L value is the recommended maximum contaminant level set by the U.S. Environmental Protection Agency (1986). The Dakota aquifer commonly contains elevated concentrations of F^- in the San Juan Basin (Craigg and others, 1989) and in other parts of the Western United States (Lawton and others, 1984, p. 227).

To further define geochemical and hydrologic processes within the aquifers, samples were analyzed for Br^- and I^- concentrations (tables 2-4). Bromide solid phases are highly soluble, and concentrations of bromide in most natural water are not affected by redox reactions, sorption, or precipitation reactions (Whittemore, 1988). Bromide concentrations ranged from 0.010 mg/L in water from well 30 to 0.38 mg/L in water from well 15. Both wells were completed in the Morrison aquifer, and bromide concentrations for the Gallup and Dakota aquifers were within this range (tables 2-4). For water from downgradient wells northeast of well 30 where chloride decreased in concentration, Br^- concentrations increased only slightly (as much as three times higher) relative to the Br^- concentration at well 30.



EXPLANATION

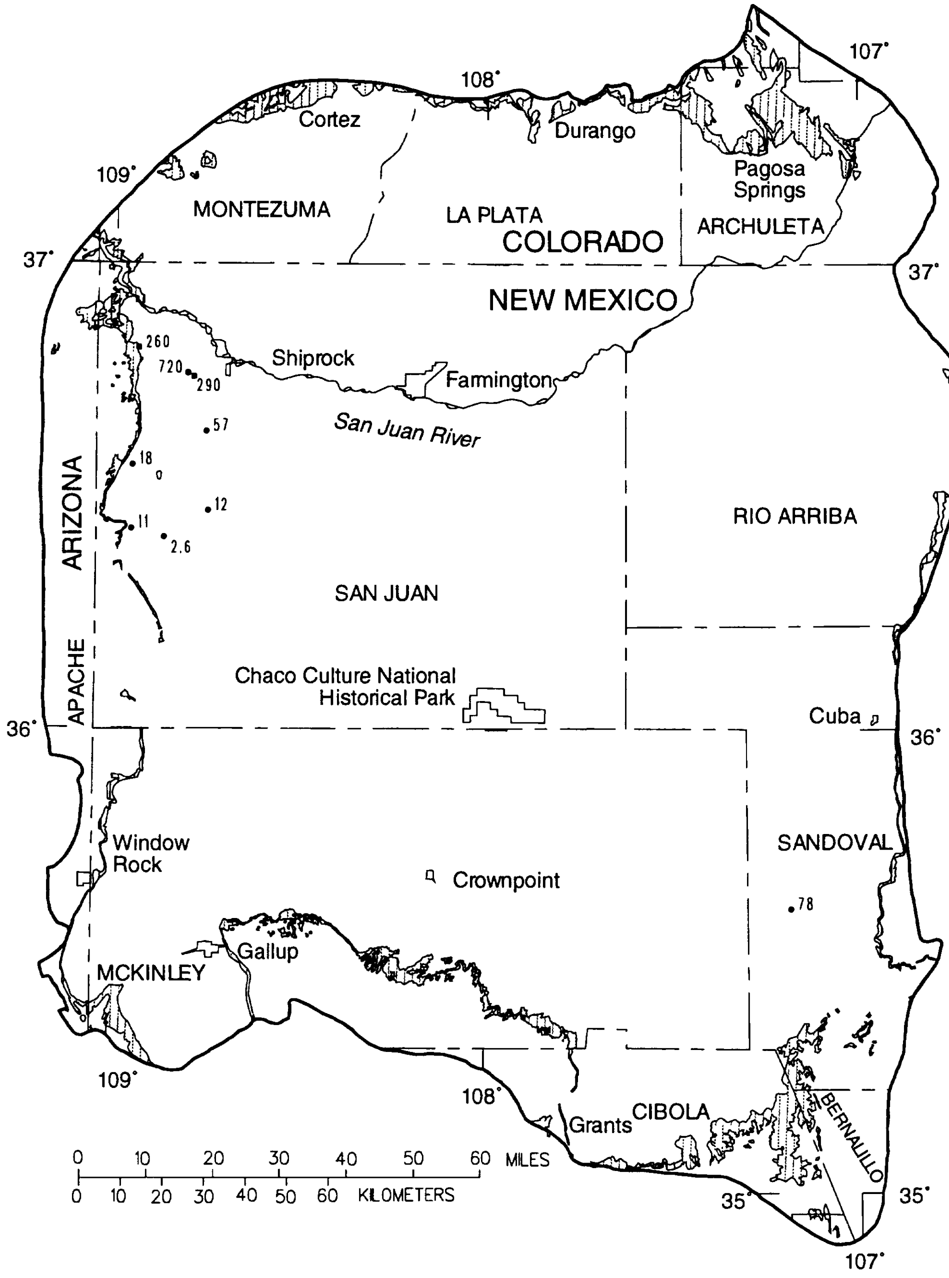
▤ OUTCROP OF GALLUP AQUIFER--In Arizona includes Pescado Tongue of Mancos Shale. In the southeastern part of the study area mapped as part of the Mesaverde Group, undivided. From Dane and Bachman, 1965; and Hackman and Olson, 1977

— — APPROXIMATE SUBSURFACE EXTENT OF GALLUP AQUIFER--From Molenaar, 1973

—— BOUNDARY OF STUDY AREA

• 81 WATER WELL--Number is concentration of chloride, in milligrams per liter

Figure 21.--Concentration of chloride in water from water wells completed in the Gallup aquifer.



EXPLANATION

▥	OUTCROP OF DAKOTA AQUIFER, MANCOS SHALE, AND BURRO CANYON FORMATION--From Dane and Bachman, 1965; Wilson and others, 1969; and Tweto, 1979
—	BOUNDARY OF STUDY AREA
•78	WATER WELL--Number is concentration of chloride, in milligrams per liter

Figure 22.--Concentration of chloride in water from water wells completed in the Dakota aquifer.

EXPLANATION

☐	OUTCROP OF MORRISON AQUIFER, JURASSIC ROCKS, UNDIVIDED; WANAKAH FORMATION; ENTRADA SANDSTONE; AND SAN RAFAEL GROUP--From Dane and Bachman, 1965; Wilson and others, 1969; Tweto, 1979; and Hintze, 1981
———	BOUNDARY OF STUDY AREA
• 6.5	WATER WELL--Number is concentration of chloride, in milligrams per liter

Figure 23.--Concentration of chloride in water from water wells completed in the Morrison aquifer.

Concentrations of silica ranged from 8.5 to 35 mg/L in the three aquifers (tables 2-4). Median SiO_2^0 concentrations in samples from the Gallup, Dakota, and Morrison aquifers were 13, 9.8, and 17 mg/L, respectively.

Data for dissolved nutrients and dissolved organic carbon in the three aquifers are shown in table 5. Nitrate was detected in samples from only four wells. Two wells located in the outcrop area of the Morrison aquifer contained NO_3^- concentrations greater than 0.2 mg/L. Ammonium was not detected in samples near outcrops, but a concentration of 0.520 mg/L was measured in well 20 in the Morrison aquifer south of Shiprock.

Trace-constituent data for samples collected from the three aquifers are presented in table 6. Constituent concentrations generally found to be below the minimum reporting level were Al, Be, Cd, Cr, Co, Cu, Pb, Hg, Mo, Ni, Se, Ag, and V. Trace-element concentrations generally found to be above the minimum reporting level included As, Ba, B, Fe, Li, Mn, and Sr. The minimum reporting levels differ for some elements due to the requested level of detection.

Twenty-three samples were filtered with both a 0.10-µm filter and a 0.45-µm filter (table 6). Of these 23 samples, 11 in which the 0.45-µm filter was used were larger or equal in concentration to the samples in which the 0.10-µm filter was used. This suggests that some Fe colloids passing through a 0.45-µm filter are removed with a 0.10-µm filter as described by Kennedy and others (1974). Iron concentrations in the 0.10-µm filtered samples that were greater than concentrations in the 0.45-µm filtered samples (12 of 23) may be caused by analytical uncertainties or field-collection techniques. There are no apparent systematic areal patterns of Fe concentrations in the Gallup aquifer. Iron concentrations in samples from the Dakota aquifer indicate a general increase in the direction of ground-water flow to the north. Iron concentrations in the Morrison aquifer were generally less than 12 µg/L in the recharge area and increased to a maximum value of 980 µg/L in a sample from a well near the San Juan River discharge area.

Arsenic concentration was less than 1 µg/L in 12 of 14 samples collected from the Gallup and Dakota aquifers, but was less than 1 µg/L in only 4 of 23 samples from the Morrison aquifer (table 6).

Concentrations of Li generally were larger in the Morrison aquifer than in the other two aquifers and increased in the direction of ground-water flow. Lithium concentrations in the Morrison aquifer increased from less than 50 µg/L in samples collected from wells in the recharge area to 540 µg/L in a sample collected from well 20 near the San Juan River.

Strontium concentrations in samples generally increased in the direction of ground-water flow in the three aquifers. In the Gallup aquifer, Sr^{2+} concentrations were 360 µg/L or less except for one concentration that was 920 µg/L (table 6). In the Dakota aquifer, Sr^{2+} concentrations were variable both spatially and in samples from the same well. Strontium concentrations ranged from 140 to 3,300 µg/L in four samples from three wells completed in the Dakota aquifer. Water from well 13 on two different dates contained Sr^{2+} concentrations of 350 and 3,300 µg/L, suggesting a problem in reproducibility and a need for additional sampling to verify Sr^{2+} concentrations. Strontium concentrations in the Morrison aquifer ranged from 38 to 12,000 µg/L and were substantially larger than in the other two aquifers.

Table 5.--Concentrations of dissolved nutrients and dissolved organic carbon in water from the Gallup, Dakota, and Morrison aquifers

[See figures 8-10 for location of wells. Wells 1-10 are completed in the Gallup aquifer, wells 11 and 13 in the Dakota aquifer, and wells 14-38 in the Morrison aquifer. Concentrations in milligrams per liter; --, not reported; <, less than detection limit]

Well number	Date of sample	Nitrite, as N	Nitrite plus nitrate, as N	Nitrogen ammonia, as N	Nitrogen ammonia plus organic, as N	Phosphorus, as P	Phosphorus ortho-phosphate, as P	Organic carbon
1	07-01-88	<0.010	<0.100	0.220	0.40	0.010	<0.010	--
2	04-22-86	--	--	--	--	--	--	1.3
	10-21-87	<0.010	<.100	.460	2.2	<.010	.021	.6
3	04-21-86	--	--	--	--	--	--	1.1
4	07-15-88	--	--	--	--	--	--	1.6
5	06-30-87	<.010	<.100	.041	1.9	.010	.010	.9
6	06-30-88	<.010	<.100	.180	.50	.021	.021	--
7	06-28-88	.021	.130	.041	.20	.021	.030	--
8	12-03-87	<.010	<.100	.060	<.20	.010	<.010	.8
9	04-29-86	--	--	--	--	--	--	1.1
	08-11-87	<.010	<.100	.030	<.20	.021	.010	--
10	06-30-88	<.010	<.100	.070	.30	.120	.120	.8
11	07-23-87	<.010	<.100	.120	.40	.010	<.010	--
13	04-29-86	--	--	--	--	--	--	1.0
	12-03-87	<.010	<.100	.730	.80	.010	<.010	--
14	06-10-88	.010	<.100	.041	<.20	<.010	<.010	--
15	06-24-86	--	--	--	--	--	--	.4
	07-21-87	<.010	<.100	.760	1.0	.010	<.010	1.8
17	07-02-86	--	--	--	--	--	--	.1
18	06-16-86	--	--	--	--	--	--	.2
	06-09-87	<.010	<.100	.540	1.3	.010	<.010	--
19	06-19-86	--	--	--	--	--	--	.2
	07-14-87	<.010	<.100	.140	.80	.010	<.010	1.8
20	06-10-87	<.010	<.100	.520	1.1	.010	<0.010	--
21	06-18-86	--	--	--	--	--	--	0.1
22	06-19-86	--	--	--	--	--	--	.2
	06-10-87	<.010	<.100	.450	1.3	.010	<.010	--
23	06-10-88	.021	.230	.010	<.20	.010	<.010	--
24	07-01-86	--	--	--	--	--	--	.6
25	06-09-88	<.010	.220	.010	<.20	<.010	<.010	.6
26	07-22-87	<.010	<.100	<.010	.90	<.010	<.010	--
	06-17-86	--	--	--	--	--	--	.2
27	06-18-86	--	--	--	--	--	--	.2
28	06-30-86	--	--	--	--	--	--	.2
	07-17-87	<.100	<.100	.021	.60	.010	<.010	--
30	07-23-87	<.010	<.100	<.010	.50	<.010	<.010	1.7
32	06-24-86	--	--	--	--	--	--	.2
	07-15-87	.021	.110	<.010	.20	.041	.021	--
33	07-15-87	<.010	<.100	<.010	.40	.030	.030	1.9
34	07-16-87	<.010	<.100	<.010	.30	.010	<.010	1.7
35	06-11-87	<.010	<.100	.110	.50	.010	<.010	4.1
36	04-24-86	--	--	--	--	--	--	.5
	10-22-87	<.010	<.100	.021	<.20	<.010	.021	.3
37	10-02-87	<.010	<.100	.090	.30	.010	.021	--
	07-01-87	<.010	<.100	.110	.30	.010	<.010	1.1
38	07-01-87	<.010	<.100	.110	.30	.010	<.010	1.1

Table 6.--Concentration of dissolved trace constituents in water from the Gallup, Dakota, and Morrison aquifers

[See figure 8-10 for location of wells; wells 1-10 are completed in the Gallup aquifer, wells 11-13 in the Dakota aquifer, and wells 14-38 in the Morrison aquifer; concentrations in micrograms per liter; --, not reported; <, concentration less than detection limit; samples filtered with a 0.45-micron filter except Al.1, Fe.1, and Mn.1 where a 0.10-micron filter was used]

Well number	Date of sample	Aluminum		Arsenic	Barium	Beryllium	Boron	Cadmium	Chromium	Cobalt	Copper	Iron	
		(Al)	(Al.1)	(As)	(Ba)	(Be)	B	(Cd)	(Cr)	(Co)	(Cu)	(Fe)	(Fe.1)
1	07-01-88	<10	--	2	33	<.05	--	<1	<1	<3	<1	330	--
2	04-22-86	<10	<10	<1	17	<17	--	<3	<1	<1	2	309	160
	10-21-87	<10	--	<1	<100	<10	--	<1	<1	2	1	250	--
3	04-21-86	10	10	<1	100	<10	--	<1	<1	<1	1	40	50
4	07-15-88	<10	--	<1	26	<.5	--	<1	<1	<3	2	22	--
5	06-30-87	<10	<20	<1	<34	<.5	--	<1	<1	<10	<10	<21	40
	06-28-88	<10	--	--	--	--	110	--	--	--	--	30	--
6	06-30-88	<10	--	<1	31	<.5	--	<1	2	<3	1	17	--
7	06-28-88	<10	--	<1	38	<.5	--	<1	1	<3	5	16	--
8	12-03-87	<10	--	<1	<100	<10	--	<1	<1	<1	<1	430	--
9	04-29-86	<10	<10	<1	7	<5	--	<1	<1	<3	1	10	10
	08-11-87	<10	--	--	--	--	90	--	--	--	--	<3	--
10	06-30-88	<10	--	<1	14	<.5	--	<1	<1	<3	44	640	--
11	07-23-87	<10	--	<1	10	<.5	--	<1	<1	<3	<1	680	--
12	06-29-88	<10	--	1	24	<.5	--	<1	<1	<3	1	53	--
13	04-29-86	<10	<10	<1	<100	<10	--	<1	<1	1	2	70	30
	12-03-87	<10	--	--	--	--	200	--	--	--	--	17	--
14	06-10-88	<10	--	1	19	<.5	--	<1	3	<3	6	440	--
15	07-21-87	20	10	1	<100	<10	--	<1	<1	<1	<1	300	230
16	06-24-86	<10	20	21	17	<.5	--	<1	<1	<3	<1	7	10
	06-08-88	<10	--	--	--	--	180	--	--	--	--	12	--
17	07-02-86	<10	--	12	<100	<10	--	<1	<1	<1	<1	30	--
18	06-16-86	<10	<10	<1	100	<10	--	<1	<1	<1	<1	170	160
	06-09-87	<10	--	--	--	--	150	--	--	--	--	170	--
19	07-14-87	--	<10	--	--	--	1,600	--	--	--	--	980	1,000
20	06-19-86	<10	--	13	100	<10	--	<1	<1	<1	<1	990	--
	06-10-87	<10	--	--	--	--	300	--	--	--	--	470	--
21	06-18-86	<10	10	1	100	<10	--	<1	<1	<1	1	540	540
22	06-19-86	<10	10	2	100	<10	--	<1	<1	<1	<1	140	150
	06-10-87	<10	--	--	--	--	150	--	--	--	--	240	--
23	06-10-88	<10	--	3	26	<0.5	--	<1	1	<3	<1	140	--
24	07-01-86	<10	<10	<1	10	<.5	--	<1	<1	<3	2	159	180
25	06-09-88	<10	--	2	120	<.5	--	<1	1	<3	1	85	--
	04-25-89	<10	--	--	--	--	30	--	--	--	--	180	--
26	06-17-86	20	20	4	36	<.5	--	<1	<1	<3	<1	6	<10
	07-22-87	20	--	--	--	--	30	--	8	--	--	15	--
	07-01-88	10	--	--	--	--	30	--	--	--	--	3	--
27	06-18-86	20	10	3	25	<.5	--	<1	<1	<3	1	<3	<10
	06-11-88	20	--	--	--	--	20	--	--	--	--	7	--
28	06-30-89	10	10	3	15	<.5	--	<1	<1	<3	1	3	<10
	07-17-87	10	6	--	--	--	--	--	--	--	--	--	--
	07-01-88	<10	--	--	--	--	100	--	--	--	--	>3	--
29	06-29-88	20	--	2	9	<.5	--	<1	1	<3	<1	8	--
	11-22-88	20	--	--	--	--	--	--	--	--	--	--	<3
30	07-23-87	<10	<10	11	61	<.5	--	<1	<1	<3	3	11	<10
	01-05-89	<10	--	--	--	--	--	--	--	--	--	--	11
31	01-05-89	10	--	--	--	--	--	--	--	--	--	--	8
32	06-24-86	20	20	2	24	<.5	--	<1	1	<3	1	7	<10
	07-15-87	30	--	--	--	--	10	--	--	--	--	34	--
	06-11-88	30	--	--	--	--	20	--	--	--	--	--	19
33	07-15-87	--	20	--	--	--	--	--	--	--	--	<10	--
	06-29-88	20	--	--	--	--	110	--	--	--	--	6	--
	11-23-88	<10	--	--	--	--	70	--	--	--	--	<3	--
34	07-16-87	<10	10	4	43	.5	--	1	<1	<3	<1	14	<10
	11-22-88	<10	--	--	--	--	--	--	--	--	--	8	--
35	06-11-87	20	20	5	46	<.5	--	<1	<1	<3	<1	140	120
36	04-24-86	<10	<10	6	30	<.5	--	<1	<1	<3	1	159	250
	10-22-87	<10	10	6	42	<.5	--	<1	<1	<3	<1	100	70
37	10-02-87	<10	<10	<1	34	<.5	--	<1	<1	<3	1	14	<10
38	07-01-87	<10	<10	<1	12	<.5	--	<1	<1	<3	<1	680	1,900
	07-14-88	<10	--	--	--	--	120	--	--	--	--	620	--

Table 6.– Concentration of dissolved trace constituents in water from the Gallup, Dakota, and Morrison aquifers–Concluded

Well number	Date of sample	Lead (Pb)	Lithium (Li)	Manganese		Mercury (Hg)	Molybdenum (Mo)	Nickel (Ni)	Selenium (Se)	Silver (Ag)	Strontium (Sr)	Vanadium (V)	Zinc (Zn)
				(Mn)	(Mn.1)								
1	07-01-88	<5	46	150	--	<0.1	<10	<1	<1	<1	920	<6	31
2	04-22-86	1	98	8	10	<.1	<1	<1	<1	<1	350	1	<9
	10-21-87	<5	120	<10	--	<.1	<1	5	<1	<1	350	<1	<10
3	04-21-86	<1	70	20	20	<.1	<1	1	<1	<1	280	<1	<10
4	07-15-88	<5	14	4	--	<.1	<10	<1	<1	1	97	<6	5
5	06-30-87	<10	<4	<5	<10	.1	<10	1	<1	1	89	<6	<100
	06-28-88	--	--	5	--	—	--	--	--	--	85	--	--
6	06-30-88	<5	12	6	--	.1	<10	1	<1	<1	89	<6	19
7	06-28-88	5	<4	4	--	<.1	<10	4	<1	<1	52	<6	<3
8	12-03-87	<5	100	20	--	.1	3	<1	<1	<1	360	<1	<10
9	04-29-86	<1	23	2	<10	<.1	<10	1	<1	<1	26	<6	<3
	08-11-87	--	--	2	--	—	--	--	--	--	26	--	--
10	06-30-88	<5	10	20	--	<.1	<10	<1	10	<1	18	<6	590
11	07-23-87	<5	140	30	--	.1	<10	<1	<1	<1	930	<6	4
12	06-29-88	<5	24	7	--	<.1	<10	<1	<1	1	140	<6	34
13	04-29-86	1	100	60	10	<.1	<1	<1	<1	<1	350	2	<10
	12-03-87	--	--	<3	--	—	--	--	--	--	3,300	--	--
14	06-10-88	<5	15	61	--	<.1	<10	5	<1	<1	1,100	<6	150
15	07-21-87	<5	840	130	140	<.1	<1	<1	<1	<1	6,700	3	40
16	06-24-86	<5	61	<1	<10	<.1	<10	<1	<1	<1	62	<6	6
	06-08-88	--	--	<1	--	—	--	--	--	--	66	--	--
17	07-02-86	<5	270	70	--	.1	1	<1	<1	<1	7,500	<1	<10
18	06-16-86	<5	300	100	90	<.1	1	<1	<1	<1	12,000	<1	10
	06-09-87	--	--	87	--	—	--	--	--	--	11,000	--	--
19	07-14-87	--	--	30	30	—	--	--	--	--	--	--	--
20	06-19-86	<5	540	110	16	<.1	13	<1	<1	<1	10,000	2	10
	06-10-87	--	--	87	--	—	--	--	--	--	9,000	--	--
21	06-18-86	<5	270	70	70	<.1	2	1	<1	<1	7,500	<1	<10
22	06-19-86	<5	220	160	160	<.1	3	<1	<1	<1	11,000	<1	<10
	06-10-87	--	--	9	--	—	--	--	--	--	9,800	--	--
23	06-10-88	<5	33	3	--	<0.1	<10	6	3	<1	100	<6	27
24	07-01-86	<5	88	3	<10	<.1	<10	1	<1	<1	469	<6	8
25	06-09-88	<1	37	2	--	<.1	<10	5	27	<1	1,100	6	94
	04-25-89	--	--	3	--	—	--	--	--	--	380	--	--
26	06-17-86	<5	20	3	<10	.3	<10	<1	<1	<1	70	<6	9
	07-22-87	--	--	4	--	—	--	--	--	--	63	--	--
	07-01-88	--	--	<1	--	—	--	--	--	--	71	--	--
27	06-18-86	<5	40	<1	<10	<.1	<10	<1	<1	<1	67	<6	7
	06-11-88	--	--	<1	--	—	--	--	--	--	76	--	--
28	06-30-89	<5	38	<1	<10	<.1	<10	<1	<1	<1	260	<6	10
	07-17-87	--	--	2	--	—	--	--	--	--	650	--	--
	07-01-88	--	--	<1	--	—	--	--	--	--	380	--	--
29	06-29-88	<1	15	2	--	<.1	<10	<1	5	<1	47	<6	<3
	11-22-88	--	--	1	--	—	--	--	--	--	56	--	--
30	07-23-87	<5	35	<1	<10	<.1	<10	<1	2	<1	810	14	51
	01-05-89	--	--	2	--	—	--	--	--	--	780	--	--
31	01-05-89	--	--	<1	--	—	--	--	--	--	47	--	--
32	06-24-86	<5	41	3	<10	<.1	<10	<1	2	<1	42	14	10
	07-15-87	--	--	2	--	—	--	--	--	--	39	--	--
	06-11-88	--	--	<1	--	—	--	--	--	--	41	--	--
33	07-15-87	--	--	--	<10	—	--	--	--	--	--	--	--
	06-29-88	--	--	3	--	—	--	--	--	--	45	--	--
	11-23-88	--	--	3	--	—	--	--	--	--	38	--	--
34	07-16-87	<5	42	13	10	.1	<10	<1	<1	<1	130	--	--
	11-22-88	--	--	12	--	—	--	--	--	--	140	--	--
35	06-11-87	6	70	19	20	.1	<10	<1	<1	1	1,100	<6	6
36	04-24-86	1	109	8	20	.1	30	<1	<1	<1	2,400	<6	<3
	10-22-87	<5	110	10	<10	<.1	30	1	<1	<1	2,200	<6	<3
37	10-02-87	<5	33	7	<10	<.1	<10	1	<1	<1	100	<6	5
38	07-01-87	<5	60	140	150	<.1	<10	3	<1	<1	2,000	6	200
	07-14-88	--	--	130	--	—	--	--	--	--	2,100	--	--

Dissolved Gases

Direct measurement of gas composition is useful for correcting pH values of water that loses carbon dioxide gas (Pearson and others, 1978). Results of four gas analyses for the Morrison aquifer are shown in table 7. The samples appear to be representative of dissolved-gas compositions expected from the aquifer.

Table 7.--Concentrations of dissolved gases in water from the Morrison aquifer [See figures 8-10 for location of wells; concentration in milligrams per liter; nd, not detected]

Well number	Date of sample	Nitrogen (N_2)	Oxygen (O_2)	Argon (Ar)	Carbon dioxide (CO_2)	Methane (CH_4)	Ethane (C_2H_6)
18	06-09-87	1.48	0.004	0.015	0.0007	0.008	nd
20	06-10-87	1.34	.007	.014	.001	.051	0.002
22	06-10-87	1.42	.010	.015	.0007	.018	nd
35	06-11-87	1.08	.009	.014	.003	.001	nd

Stable Isotopes

To evaluate hydrologic and geochemical processes, the stable isotopes of $\delta^{18}O$, δD, $\delta^{13}C$, and $\delta^{34}S$ were determined. Data for the first three isotopes are presented in the text. Stable-isotopic ratios are expressed in units of parts per thousand (per mil, $^0/_{00}$) relative to a standard:

$$\delta_x = \left[\frac{R_x}{R_s} - 1\right] \times 1,000 \tag{1}$$

where δ is delta;
R is the ratio of heavier to lighter isotope;
x is the sample; and
s is the standard.

For an example of deriving the delta (δ) notation, hydrogen isotopes are the ratio of deuterium (D = ^2H) to hydrogen (H):

$$\delta D = \left[\frac{\frac{D}{H_x}}{\frac{D}{H_{V-SMOW}}} - 1\right] \times 1,000 \tag{2}$$

where V-SMOW is Vienna-Standard Mean Ocean Water.

Oxygen and hydrogen isotopes can be ideal tracers of water movement because they compose the water. Isotopic variations in precipitation (atmospheric deposition) result from changes in temperature, altitude, and other factors. For example, winter precipitation is depleted in heavy isotopes (D, ^{18}O) relative to summer precipitation. Because high-latitude precipitation is depleted, the isotopic ratio is lighter than low-latitude precipitation. The mixing of recharge water tends to average the isotopic variations of precipitation. At low temperatures (as compared to geothermal regimes) associated with most aquifers, no hydrogen isotopes are exchanged between water and solid phases. Thus, the isotopic composition of water changes only as a function of physical and chemical processes in the aquifer such as evaporation or mineral dissolution.

Isotopic ratios are shown in table 8, and a plot of the δD and $\delta^{18}O$ ratios for 36 samples collected from the Gallup, Dakota, and Morrison aquifers is shown in figure 24. A line defined by Craig (1961) as $\delta D = 8\delta^{18}O + 10$ represents samples collected from various localities in the world. Vuataz and Goff (1986) defined a local meteoric water line for northern New Mexico as $\delta D = 8\delta^{18}O + 12$, which is parallel to and slightly left of the world meteoric line. This local meteoric line was applied to the San Juan Basin study area by Phillips and others (1986b) in their report on the Ojo Alamo aquifer. However, most of the isotopic ratios plot to the right of the world meteoric line in figure 24. This suggests a different local meteoric water line for these samples or evaporation during infiltration of precipitation, which is common in semiarid environments (Phillips and others, 1986b, p. 181).

Phillips and others (1986b, p. 181) calculated the mean isotopic ratio for modern precipitation in the central San Juan Basin as $-12.8\ ^{0}/_{00}$ for $\delta^{18}O$ and as $-90\ ^{0}/_{00}$ for δD. Recharge water of Pleistocene age averaged $3.0\ ^{0}/_{00}$ lighter in $\delta^{18}O$ and $25\ ^{0}/_{00}$ lighter in δD than modern recharge water. During the Pleistocene, climatic changes such as a decrease in mean annual temperature and an increase in winter precipitation may have accounted for the shift to lighter isotopic ratios (Phillips and others, 1986b, p. 183).

The areal distribution of δD is shown for the Morrison aquifer in figure 25. Heavier isotopic ratios ($\delta^{18}O = -14.2\ ^{0}/_{00}$ and $\delta D = -103.5\ ^{0}/_{00}$) were found in samples at well 30 in the recharge area near Sanostee than in samples collected from wells 10 mi downgradient to the east and northeast. Water in an area encompassing four wells in the Morrison aquifer had light values of $\delta^{18}O$ ($-15.0\ ^{0}/_{00}$ to $-15.6\ ^{0}/_{00}$) and δD ($-114\ ^{0}/_{00}$ to $-116\ ^{0}/_{00}$). Comparing data for these four wells to modern precipitation calculated by Phillips and others (1986a) indicates a depletion of $2.8\ ^{0}/_{00}$ in $\delta^{18}O$ and $26\ ^{0}/_{00}$ in δD, which is similar to Pleistocene samples. The data imply that ground water 10 mi from the outcrop area was recharged during the Pleistocene.

Carbon-13/carbon-12 ratio data were collected to examine sources and sinks of carbon as an aid in determining chemical reactions that control the carbon distribution in the aquifers. In general, soil gas CO_2 contains a $\delta^{13}C$ value of $-20\ ^{0}/_{00}$ to $-25\ ^{0}/_{00}$, and carbonate minerals have $\delta^{13}C$ values close to $0\ ^{0}/_{00}$ (Drever, 1982, p. 345). Stable carbon isotopic values typically range from $-10\ ^{0}/_{00}$ to $-12.5\ ^{0}/_{00}$ in samples, as a result of soil gas CO_2 reacting with carbonate minerals. Chemical reactions will affect $\delta^{13}C$ values in water in different ways: calcite dissolution adds carbon so $\delta^{13}C$ values become heavier; calcite precipitation removes carbon so $\delta^{13}C$ values become lighter; feldspar dissolution does not change $\delta^{13}C$ values in a system closed to CO_2. The oxidation of organic matter adds light carbon ($\delta^{13}C$) to the system.

Table 8.--Isotopic ratios of stable isotopes in water from the Gallup, Dakota, and Morrison aquifers

[See figures 8-10 for location of wells; wells 1-10 are completed in the Gallup aquifer, wells 12-13 in the Dakota aquifer, and wells 14-38 in the Morrison aquifer; values are in per mil ($^0/_{00}$); --, not reported]

Well number	Date of sample	Oxygen ($\delta^{18}O$)	Hydrogen (δD)	Carbon ($\delta^{13}C$)	Sulphur, SO_4^{2-} ($\delta^{34}S$)
1	07-01-88	-13.6	-101	-12.3	-14.0
2	04-22-86	-13.5	-113	--	--
	10-21-87	--	--	-9.8	-6.0
3	04-21-86	-14.3	-110	--	--
4	07-15-88	-14.2	-105	-8.0	15.4
5	06-30-87	-13.9	-98	-26.1	--
	06-28-88	--	--	--	-5.4
6	06-30-88	-14.0	-104	-8.6	-6.1
7	06-28-88	-15.0	-111	-11.2	1.6
8	12-03-87	-13.0	-97	--	--
9	04-29-86	-11.8	-87	--	--
	08-11-87	-11.9	-90	-7.6	-10.4
10	06-30-88	-14.3	-106	-12.2	-1.6
12	06-29-88	-14.4	-106	-13.1	-1.3
13	04-29-86	-13.0	-96	--	--
14	06-10-88	-13.0	-96	-8.6	.5
15	07-21-87	-13.6	-101	-19.0	--
16	06-24-86	-14.6	-107	--	9.4
	06-08-88	--	--	-6.5	--
17	07-02-86	-14.1	-103	--	11.7
18	06-16-86	-14.1	-103	-8.8	10.2
	06-09-87	--	-104	--	--
19	07-14-87	-12.7	-97	-3.7	8.6
20	06-19-86	-13.9	-103	--	10.1
21	06-18-86	-14.1	-103	--	9.0
22	06-19-86	-14.0	-104	-9.2	10.1
23	06-10-88	-15.9	-120	-9.1	3.0
24	07-01-86	-12.5	-94	-10.9	-6.1
25	06-09-88	-13.2	-98	-10.3	3.7
26	06-17-86	-15.6	-114	-10.8	10.1
	07-01-88	--	--	-10.5	11.2

Table 8.--Isotopic ratios of stable isotopes in water from the Gallup, Dakota, and Morrison aquifers--Concluded

Well number	Date of sample	Oxygen ($\delta^{18}O$)	Hydrogen (δD)	Carbon ($\delta^{13}C$)	Sulphur, SO_4^{2-} ($\delta^{34}S$)
27	06-18-86	-15.9	-115	-10.0	10.9
28	06-30-86	-15.7	-114	--	--
	07-01-88	--	--	-10.0	14.0
29	06-29-88	-15.6	-116	-10.5	14.9
30	07-23-87	-14.2	-104	-10.9	--
32	06-24-86	-14.6	-107	-13.4	5.0
	07-15-87	--	--	-12.7	--
33	07-15-87	-15.3	-113	-11.7	--
34	07-16-87	-14.1	-104	-10.7	--
35	06-11-87	-14.0	-104	-11.9	--
36	04-24-86	-14.3	-114	--	--
	10-22-87	-14.4	-108	-11.7	12.8
37	10-02-87	-14.5	-108	-12.2	-18.7
38	07-01-87	-11.0	-82	-13.5	-13.0
	07-14-88	--	--	-13.1	-10.3

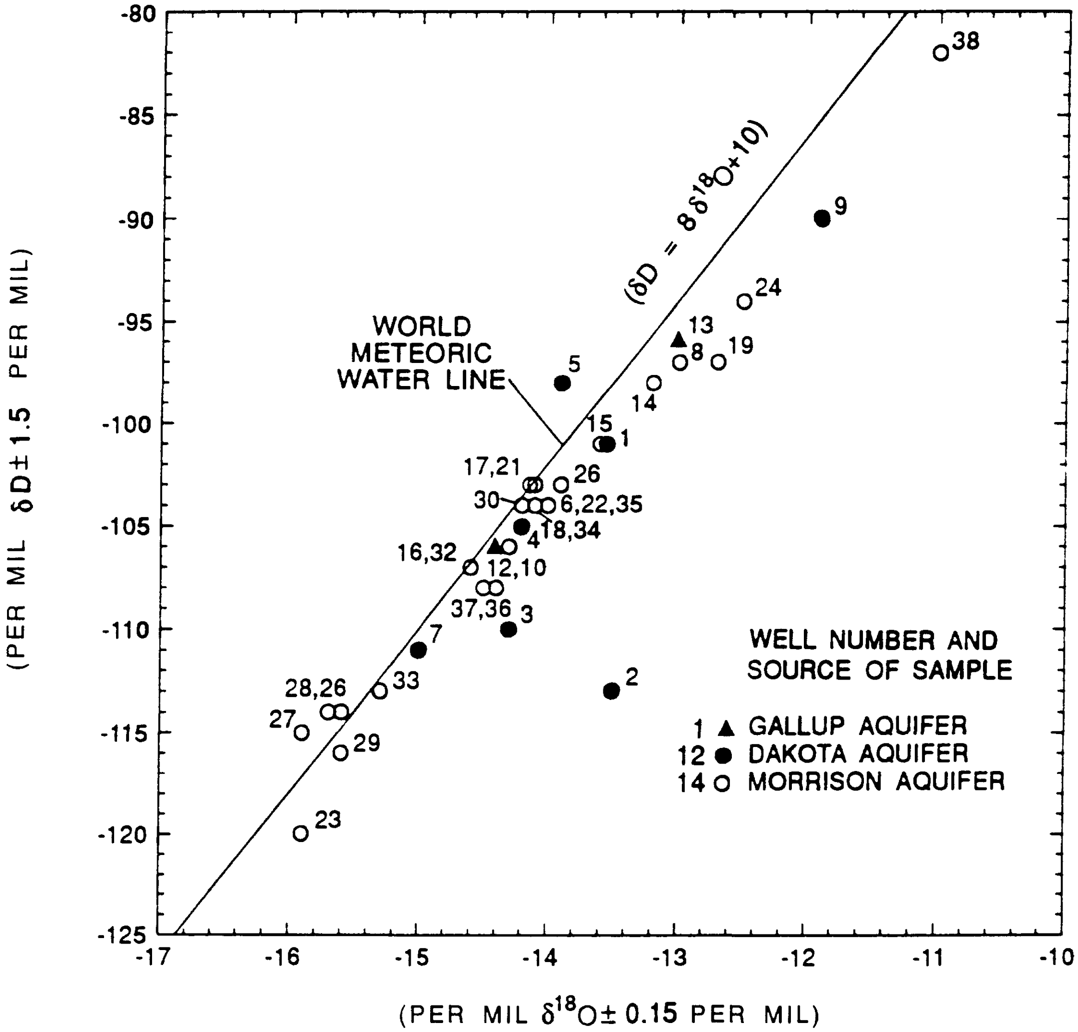
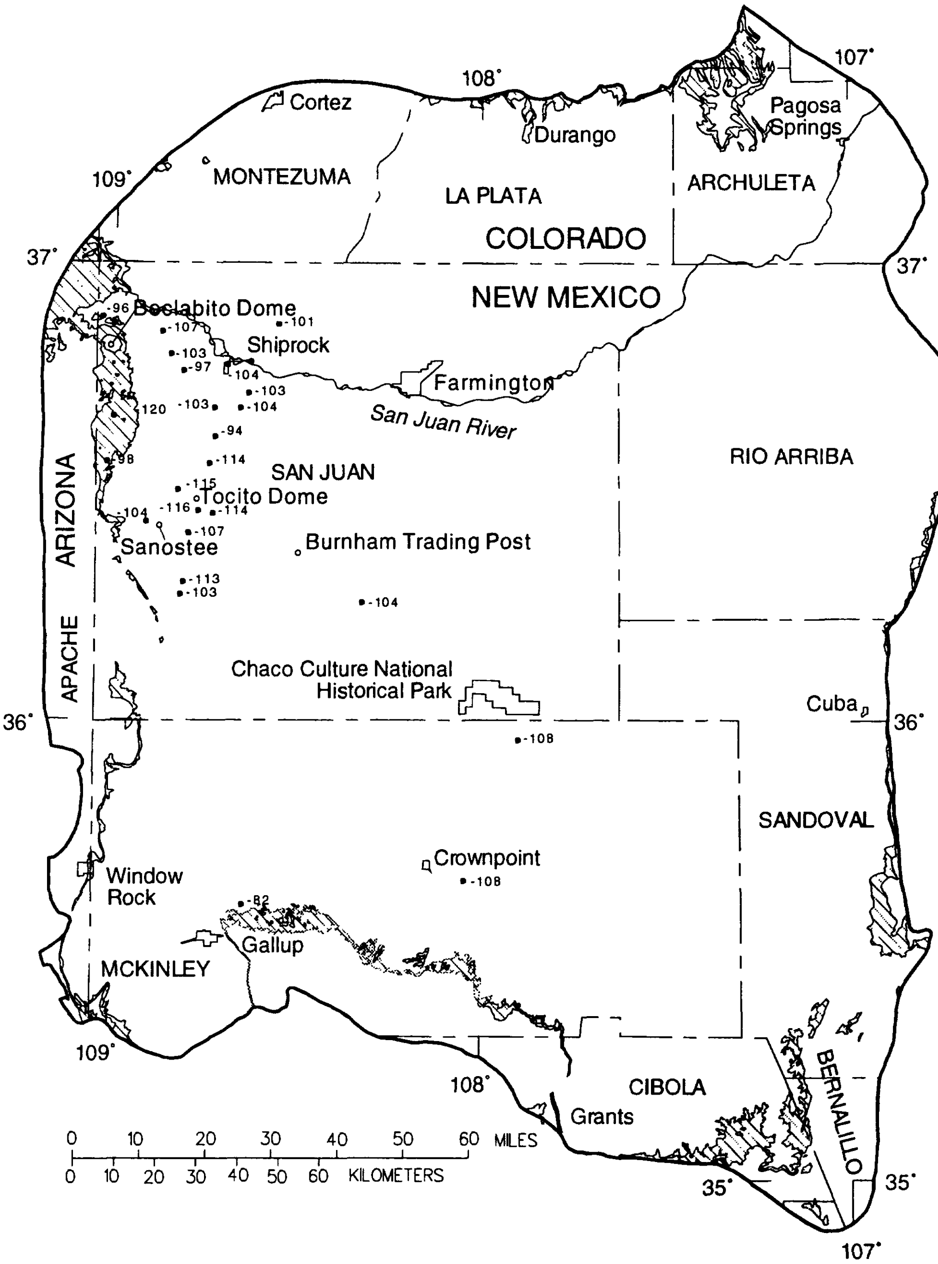


Figure 24.--Oxygen and deuterium isotopic ratios in water from water wells completed in the Gallup, Dakota, and Morrison aquifers. Well locations are shown in figures 8, 9, and 10.



EXPLANATION

▨ OUTCROP OF MORRISON AQUIFER, JURASSIC ROCKS, UNDIVIDED; WANAKAH FORMATION; ENTRADA SANDSTONE; AND SAN RAFAEL GROUP--From Dane and Bachman, 1965; Wilson and others, 1969; Tweto, 1979; and Hintze, 1981

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• -104 WATER WELL--Number is deuterium isotopic ratio, in per mil relative to Standard Mean Ocean Water (SMOW)

Figure 25.--Deuterium isotopic ratio in water from water wells completed in the Morrison aquifer.

Stable carbon isotopic data ($\delta^{13}C$) are shown in table 8 and in figure 26 for the Gallup aquifer and figure 27 for the Morrison aquifer. Values of $\delta^{13}C$ for the Gallup aquifer generally were consistent with carbonate minerals reacting with soil gas (-7.6 $^{0}/_{00}$ to -12.3 $^{0}/_{00}$) except for one sample that contained very light $\delta^{13}C$ of -26.1 $^{0}/_{00}$ (fig. 26), suggesting an organic carbon source.

Carbon-13/carbon-12 ratio values for samples from the Morrison aquifer ranged from -3.7 $^{0}/_{00}$ to -19.0 $^{0}/_{00}$ (fig. 27). However, 16 of 20 samples had a smaller range of -9.1 $^{0}/_{00}$ to -13.1 $^{0}/_{00}$, which coincides with well locations that are more than 10 mi from the San Juan River (fig. 26). The analytical accuracy of the $\delta^{13}C$ analysis was generally ± 0.3 $^{0}/_{00}$ (Carol Kendall, U.S. Geological Survey, oral commun., 1989). Thus, the minor variability of the $\delta^{13}C$ values in the samples may be due to chemical reactions involving carbon or may be due to analytical accuracy. For example, a value of -10.5 $^{0}/_{00}$ ±0.3 $^{0}/_{00}$ includes three samples (wells 26 and 29) in the northwestern part of the basin (table 8).

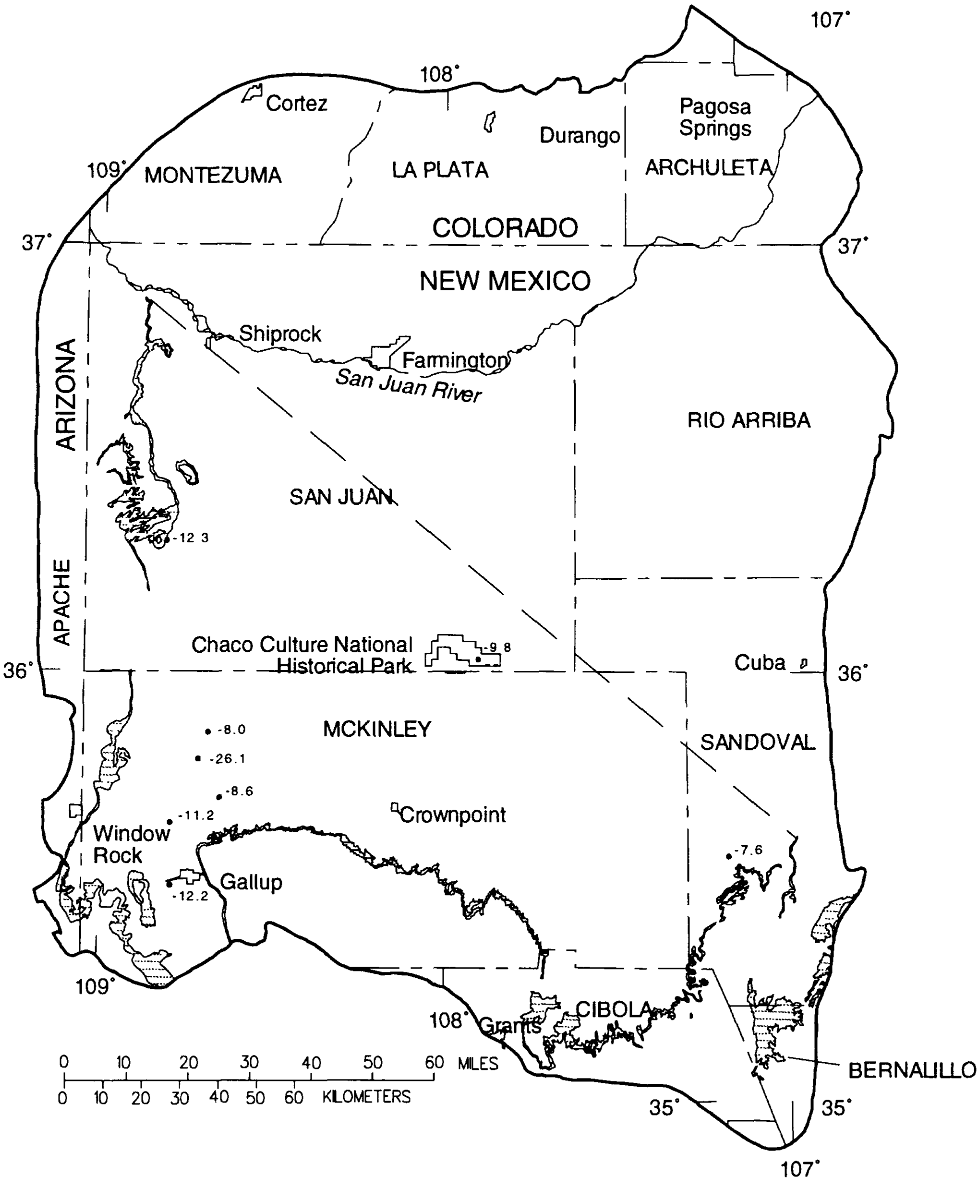
Radioactive Isotopes

The radioactive isotopes ^{3}H, ^{14}C, and ^{36}Cl were used to determine the residence time that water has been isolated from the atmosphere. Residence times are useful for determination of aquifer characteristics and for geochemical analysis of flow paths. The half-lives of the three radioisotopes are: ^{3}H = 12.26 years, ^{14}C = 5,730 years, and ^{36}Cl = 301,000 years. Therefore, applications of age dating with the three radioisotopes are significantly different. Tritium is applicable in detecting modern (post-1952) water in the sample. The isotope ^{14}C is applicable in determining ages to approximately 50,000 years (Durrance, 1986). Because of its slow decay, ^{36}Cl is applicable in age determinations of 100,000 to approximately 1 million years (Bentley and others, 1986). Processes that include mixing and ion filtration can be determined using ^{36}Cl radioisotopes as shown by Phillips and others (1986a).

Activities of ^{3}H in samples from 26 wells generally were less than 1 tritium unit (3.2 pCi/L) as shown in table 9. This indicates that the sampled ground water has not mixed with modern water and has been isolated from the atmosphere at least since 1952.

During the initial collection of radioisotope samples in 1986, samples for ^{14}C analysis were collected from four wells completed in the Morrison aquifer. Of water from wells 18, 22, 26, and 27, only water from well 27, closest to the recharge area, contained measurable ^{14}C (table 9). Therefore, the ^{14}C dating technique could be applied practicably only to water samples near recharge areas in the Morrison aquifer in this part of the study area. Twenty-four ^{14}C samples were analyzed between 1986 and 1989, 12 of which contained detectable ^{14}C.

The ^{14}C technique revealed that samples collected from the Morrison aquifer rapidly increased in apparent age; ^{14}C was not detected downgradient from the recharge areas. Slow flow rates or mixing of modern and ancient waters may have resulted in nondetectable ^{14}C activities. Therefore, in view of the limited application of the ^{14}C data to samples from the Morrison aquifer, Dr. Fred Phillips at New Mexico Institute of Mining and Technology prepared, analyzed, and interpreted results of ^{36}Cl samples. The atmosphere produces ^{36}Cl by cosmic ray spallation of ^{36}Ar and neutron activation of ^{36}Ar (Bentley and others, 1986). Meteroic water contains ^{36}Cl; as precipitation becomes recharge water moving into the subsurface, ^{36}Cl decays exponentially. Chlorine-36 can be added from subsurface sources derived from rock weathering and production of neutrons in uranium radionuclide decay. The application of ^{36}Cl to ground-water hydrology has been demonstrated in two regional aquifers: the Great Artesian Basin in Australia (Bentley and others, 1986) and the Milk River aquifer in Alberta, Canada (Phillips and others, 1986a). Age-dating techniques using ^{36}Cl were substantiated with independent modeling results and provided new insights into hydrochemical processes in the two aquifer systems.



EXPLANATION

▤ OUTCROP OF GALLUP AQUIFER--In Arizona includes Pescado Tongue of Mancos Shale. In the southeastern part of the study area mapped as part of the Mesaverde Group, undivided. From Dane and Bachman, 1965; and Hackman and Olson, 1977

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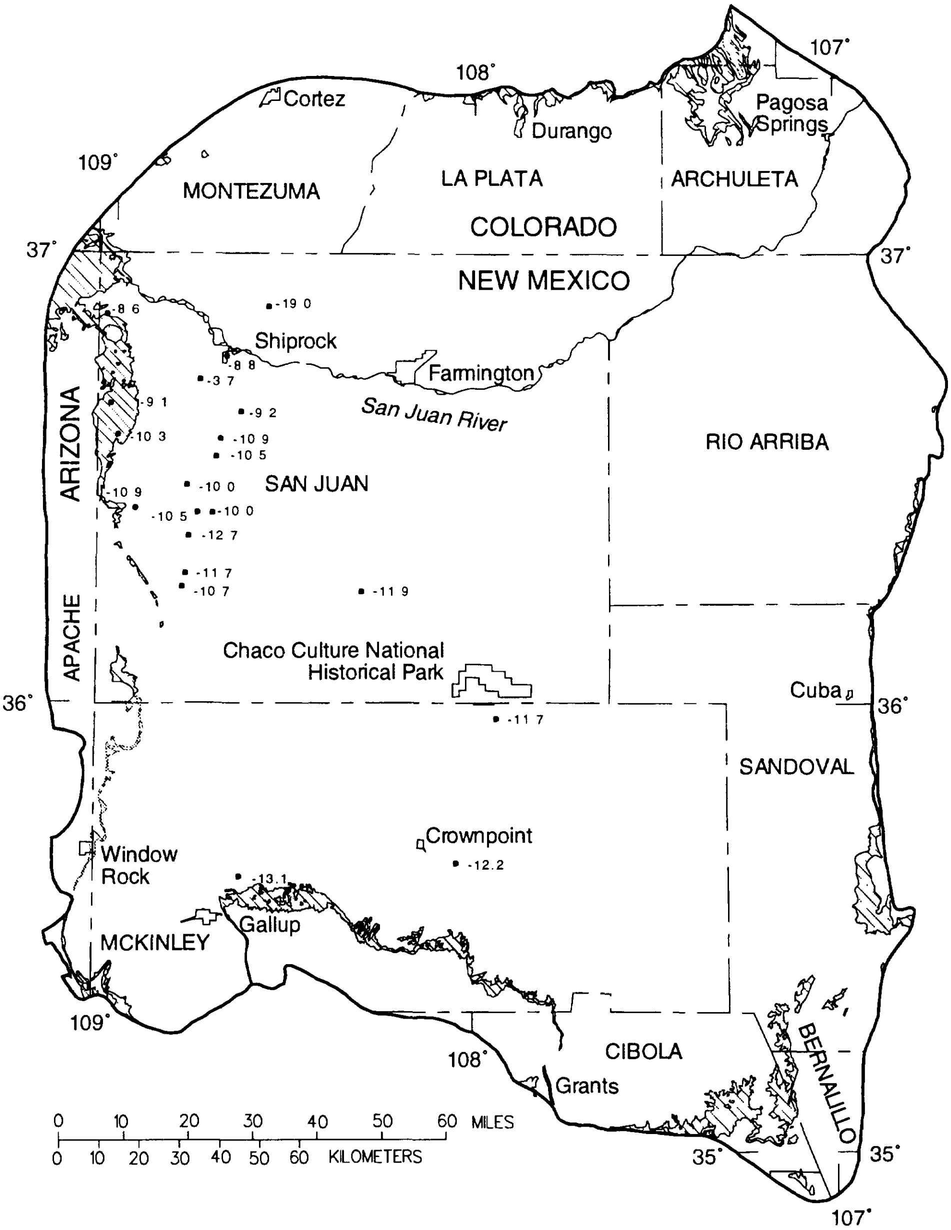
— — APPROXIMATE SUBSURFACE EXTENT OF GALLUP AQUIFER--From Molenaar, 1973

• -8.0 WATER WELL--Number is carbon-13 isotopic ratio, in per mil relative to Peedee belemnite (PDB)

Figure 26.--Carbon-13 isotopic ratio in water from water wells completed in the Gallup aquifer.



EXPLANATION

▨	OUTCROP OF MORRISON AQUIFER, JURASSIC ROCKS, UNDIVIDED; WANAKAH FORMATION; ENTRADA SANDSTONE; AND SAN RAFAEL GROUP--From Dane and Bachman, 1965; Wilson and others, 1969; Tweto, 1979; and Hintze, 1981
———	BOUNDARY OF STUDY AREA
• -11.9	WATER WELL--Number is carbon-13 isotopic ratio, in per mil relative to Peedee belemnite (PDB)

Figure 27.--Carbon-13 isotopic ratio in water from water wells completed in the Morrison aquifer.

Water samples from 34 wells were collected to measure ^{36}Cl, as shown in table 9. Analytical error was less than 10 percent. The primary focus of the ^{36}Cl investigation was a detailed examination of the Morrison aquifer. The ^{36}Cl/10^{15}Cl values (unitless atomic ratios of ^{36}Cl atoms per 10^{15} chlorine atoms where chloride is the atomic sum of the stable isotopes ^{35}Cl and ^{37}Cl) ranged from 4 to 2,201. Figure 28 displays the areal distribution of ^{36}Cl/10^{15}Cl data for the Morrison aquifer. Multiple samples for the same well location are shown where available. The expected recharge input value for the San Juan Basin area was 700 (Jones and Phillips, 1990). Samples obtained near the southern outcrop (well 38) and western outcrop (well 30) contained ratios of 630 and 573, respectively. The simple interpretation of data shown in figure 28 is that values greater than 700 are a result of buildup of ^{36}Cl and values less than 700 are due to radioactive decay of ^{36}Cl. Repeat sampling for ^{36}Cl at four of five wells indicated that ^{36}Cl/10^{15}Cl ratios were not reproducible within 10 percent (fig. 28; table 9). Well construction and open-hole completion opposite multiple sandstones within the Morrison aquifer have a similar effect on the ^{36}Cl data as on the previously discussed water-chemistry data.

Comparison of the ^{14}C data with the ^{36}Cl data was not reliable due to collection of the data on different sampling dates. Chemical concentrations and isotope contents varied in several wells over time as previously described.

Collection and analysis of ^{36}Cl radioisotopes, as well as other constituents, clearly indicated that the original assumptions of the ground-water flow system were inadequate. The flow system was re-evaluated to provide a conceptual model, consistent with the chemical data, with which to interpret the sources of solutes.

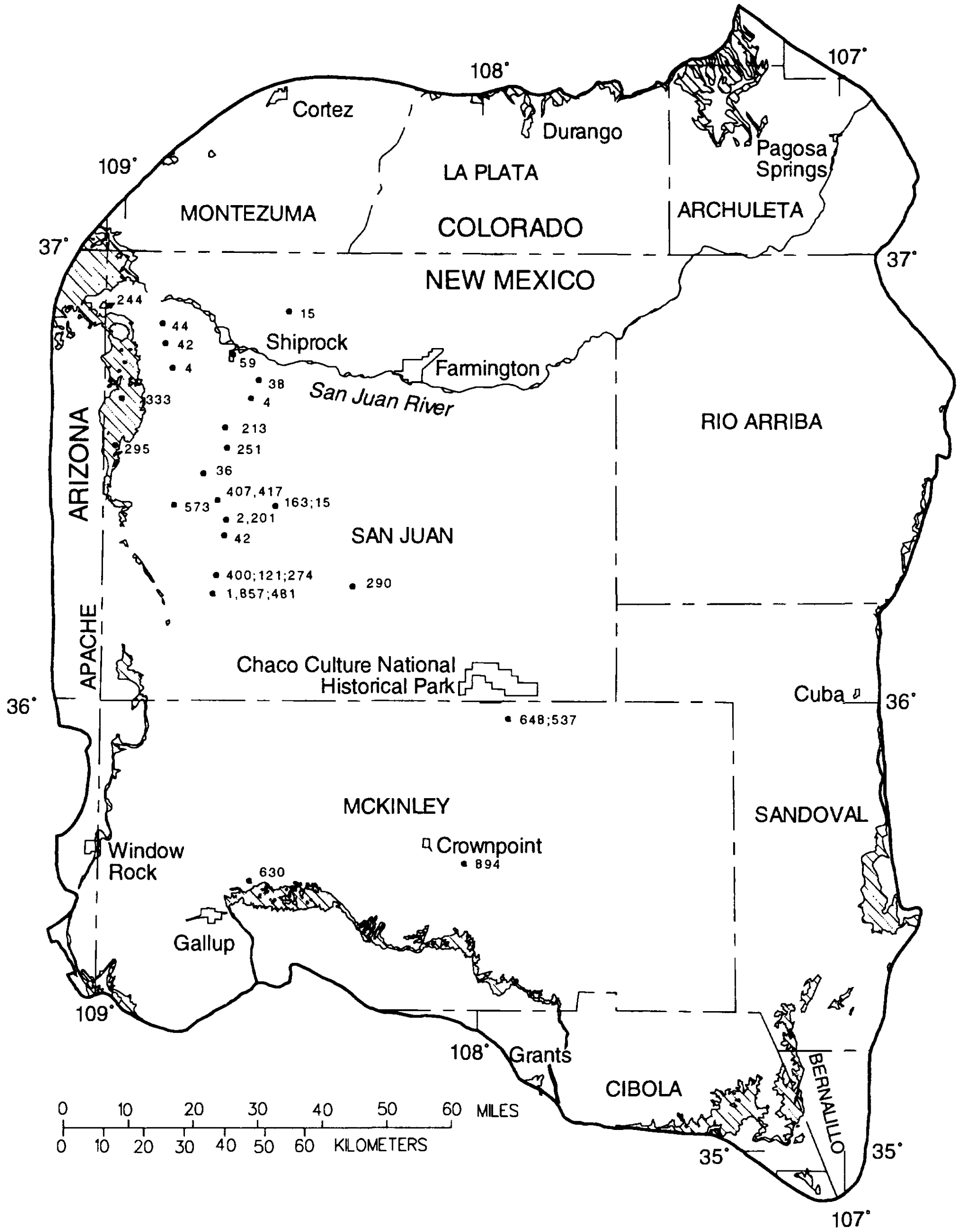
Table 9.--Activities of tritium, carbon-14, and chlorine-36 isotopes in water from the Gallup, Dakota, and Morrison aquifers

[See figures 8-10 for location of wells; wells 1-2 and 4-10 are completed in the Gallup aquifer, wells 11-13 in the Dakota aquifer, and wells 14-38 in the Morrison aquifer; pCi/L, picocuries per liter; <, less than detection limit; --, no data. A, B, and C refer to repeat sampling of wells as shown in figures 31-33]

			Carbon-14 (^{14}C) (percent modern)	Chlorine-36	
Well number	Date of sample	Tritium (^{3}H) (pCi/L)		(^{36}Cl/10^{15}Cl) (ratio)	(^{36}Cl) (atoms/liter)
1	07-01-88	<0.3	--	676	9.0
2	10-21-87	<.3	<0.4	198	16.5
4	07-15-88	<.3	2.2	122	.9
5	06-30-87	<.3	<.4	--	--
	06-28-88	--	--	153	11.7
6	06-30-88	1.5	6.4	22	.2
7	06-28-88	<.3	2.6	569	9.2
8	12-03-87	--	--	537	21.0
9	08-11-87	.4	4.5	--	--
10	06-30-88	<.3	2.8	--	--
11	07-23-87	--	--	169	16.4
12	06-29-88	--	--	730	3.2

Table 9.--Activities of tritium, carbon-14, and chlorine-36 isotopes in water from the Gallup, Dakota, and Morrison aquifers--Concluded

Well number	Date of sample	Tritium (^{3}H) (pCi/L)	Carbon-14 (^{14}C) (percent modern)	Chlorine-36	
				(^{36}Cl/10^{15}Cl) (ratio)	(^{36}Cl) (atoms/liter)
13	12-03-87	--	--	149	19.7
14	06-10-88	--	--	244	4.6
15	07-21-87	<0.3	<1.0	15	5.5
16	06-24-86	4.0	--	--	--
	06-08-88	--	<1.1	44	.8
17	07-02-86	--	--	42	4.4
18	06-16-86	--	<1.2	--	--
	06-09-87	<.4	--	59	5.7
19	07-14-87	<.3	<.4	4	5.1
20	06-10-87	1.2	--	38	7.7
22	06-19-86	3.0	<1.2	--	--
	06-10-87	--	--	42	5.9
23	06-10-88	<.3	10.5	333	13.0
24	07-01-86	<.3	--	213	13.8
25	06-09-88	<.3	31.5	295	5.0
26	06-17-86	2.0	<.8	--	--
	07-01-88	--	--	251	1.7
27	06-18-86	1.0	3.1	--	--
	06-11-88	--	--	36	.1
28	06-30-86A	--	--	163	7.8
	07-17-87B	--	--	15	1.6
29	06-29-88B	--	--	417	2.1
30	07-23-87	<.3	15.6	--	--
	01-05-89	--	--	573	2.6
31	01-05-89	<26	--	2,201	6.0
32	06-24-86	3.0	--	--	--
	07-15-87	<.3	11.2	--	--
	06-11-88	--	--	42	.1
33	07-15-87A	<.3	<1.0	400	29.2
	06-29-88B	--	--	121	2.5
	11-23-88C	--	--	274	3.9
34	07-16-87B	<.3	<1.0	1,857	22.4
	11-22-88A	<26	--	481	6.4
35	06-11-87	<1.0	<.4	290	9.4
36	04-24-86A	--	--	648	15.4
	10-22-87B	<.3	<.4	537	15.5
37	10-02-87	<.3	.8	894	9.9
38	07-01-87	.3	14.4	--	--
	07-14-88	--	--	630	7.7



EXPLANATION

▨ OUTCROP OF MORRISON AQUIFER, JURASSIC ROCKS, UNDIVIDED; WANAKAH FORMATION; ENTRADA SANDSTONE; AND SAN RAFAEL GROUP--From Dane and Bachman, 1965; Wilson and others, 1969; Tweto, 1979; and Hintze, 1981

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● 333 WATER WELL--Number represents ratio of chlorine-36 to stable chlorine isotopes. Multiple ratios for a well are listed in chronological order

Figure 28.--Ratio of chlorine-36 to stable chlorine isotopes in water from water wells completed in the Morrison aquifer.

Physical and Geochemical Processes

Physical processes of the flow system and geochemical processes controlling rock/water/gas interactions affect the observed chemical concentrations and isotopic contents. Physical processes that are examined include ground-water flow, mixing, evaporation, dilution, and ion filtration. Geochemical processes examined include mineral solubility, ion exchange, and oxidation/reduction. The geochemical data were used to examine these physical and geochemical processes.

The fluctuation in ion concentration among water analyses, particularly for wells containing large open intervals, may be due to the lithology of the Morrison aquifer, which is a sequence of sandstones and shales. Heterogeneity in sandstone properties, such as hydraulic conductivity, may result in variability of ion concentrations contained in the individual sandstone layer if the sandstones are confined between shale layers and no mixing occurs within the Morrison aquifer. Thus, a water sample from a well completed in multiple lithologies in the Morrison aquifer may be a mix of different water chemistries. Changes in ion chemistry in samples collected at a well at different times may be due to changes in hydraulic head. A change in hydraulic head may cause the sandstone layers in the aquifer to contribute different amounts of water to the well bore, which would change the mix of different water chemistries. Wells completed in the Morrison aquifer that flowed continuously during the duration of the field sampling caused a lowering of the hydraulic head, resulting in changes in ion chemistry for samples collected at different times. In large regional aquifer systems such as the San Juan Basin, the water chemistry at a particular location commonly has been assumed to have changed little, if any, over short time periods of a few years. The results determined for six wells completed in the Morrison aquifer and one well in the Dakota aquifer suggest that repeated sampling over time is needed to verify reproducibility of ion chemistry.

Decreases in chloride concentrations 10 mi downgradient from the recharge area may be due to factors including mixing of recharge water with more dilute water within the Morrison aquifer; leakage of more dilute water from above or below the Morrison aquifer; or ion filtration. Another potential cause of low chloride concentrations may be changing rates of recharge in the Morrison aquifer. Large rates of recharge during times of high precipitation would dilute chloride concentrations. Conversely, small rates of recharge during dry periods would likely concentrate chloride in the recharge area by evaporation in the vadose zone.

Ion filtration is a process previously proposed as being active in the San Juan Basin (Berry, 1959) and other basins (such as Phillips and others, 1986b). The ion-filtration hypothesis assumes a semipermeable membrane such as a clay layer or shale separating two zones of higher hydraulic conductivity. Electrochemical and pressure factors can result in exclusion of negatively charged ions, such as chloride, and a decrease in salinity on the low-pressure side of the membrane. Dilute water passes through the membrane to increase the pressure on the "filtrate" side. By applying this hypothesis to the Morrison aquifer, saline water from either the Dakota above the Morrison or the Entrada below the Morrison would be filtered by clay or shale layers and result in the observed low chloride concentrations. Clays or shales of the Brushy Basin and Recapture Members within the Morrison aquifer are the most likely semipermeable membranes within the Dakota-Entrada sequence.

As previously described, δD values in samples from four wells completed in the Morrison aquifer were depleted by $26^0/_{00}$ relative to modern precipitation. These lighter isotopic values may indicate that recharge for these four wells occurred during a time period of cooler mean temperature and wetter conditions than exist today. This would be consistent with average Pleistocene values found for the Ojo Alamo aquifer by Phillips and others (1986b). A second hypothesis explaining the existence of depleted $\delta^{18}O$ and δD values is membrane filtration. The ion filtration process would enrich the heavy isotopes in the residual solution and deplete the heavy isotopes in the solution passing through the shale (Coplen and Hanshaw, 1973).

Increases in chloride concentrations in wells near the San Juan River relative to chloride concentrations in recharge areas may be due to factors including dissolution of halite (NaCl) within the Morrison aquifer; leakage of saline water from above or below the Morrison aquifer; mixing of dilute recharge water with saline, deep-basin water near the discharge area in the Morrison aquifer; or oil-field brine contamination. The large solubility of halite, lack of observed halite, and deposition in a freshwater (nonmarine) environment suggest that NaCl dissolution is an unlikely source of increased chloride concentration. Leakage of saline water into the Morrison aquifer and mixing of dilute and saline water within the aquifer are likely processes controlling chloride concentrations.

Figure 29 compares the ratio for concentrations of Br^-/Cl^- to the concentration of chloride. The log-log plot was developed by Whittemore (1988) to evaluate mixing of brines with dilute water and to differentiate between natural brines and oil-field brines. In general, dilute recharge water has Br^-/Cl^- ratios as low as 10×10^{-4} (concentration ratio). Saline solutions from natural brines increase in chloride and the Br^-/Cl^- ratio decreases. The points plotted in figure 29 represent analyses of water from the three aquifers. The lowest Br^-/Cl^- ratio was for well 19, which contained 750 mg/L Cl^- and 0.05 mg/L Br^-, resulting in a ratio of 0.67×10^{-4} Br^-/Cl^-. By comparison, the lowest Br^-/Cl^- ratio found in a natural salt water was 0.57×10^{-4} (Whittemore, 1988, p. 345). Samples from wells completed in the Morrison aquifer near the San Juan River contain Br^-/Cl^- ratios between values found for recharge-type water and halite brine. This suggests mixing of dilute recharge water with saline water.

To aid in identifying physical processes, sampled wells completed in the Morrison aquifer were grouped by location and sample type by Jones and Phillips (1990). Five groups of wells are shown in figure 30 and were designated as follows: group 1 is wells near the San Juan River with elevated chloride concentrations; group 2 is wells located near the Morrison Formation outcrop; group 3 is wells downgradient from the recharge area; group 4 is wells 33 and 34; and group 5 is wells in the central and southern parts of the basin.

Graphical representation of ^{36}Cl data is useful in delineating processes such as dissolution of radioactively "dead" Cl^-, ion filtration, dilution, evaporation, and decay or buildup of ^{36}Cl from uranium deposits (Bentley and others, 1986; Phillips and others, 1986a; Jones and Phillips, 1990). Figure 31 is a plot of the $^{36}Cl/10^{15}Cl$ ratio data and ^{36}Cl concentrations (in atoms/liter x 10^{-7}) for each sample using the group symbol defined in figure 30. As described in Phillips and others (1986a, p. 2012), the addition of "dead" Cl^- will decrease the $^{36}Cl/10^{15}Cl$ ratio (addition of ^{35}Cl and ^{37}Cl) without changing the ^{36}Cl concentration, resulting in a downward shift of the data points as shown by the diagram in figure 31. Dilution, evaporation, or ion filtration will affect the ^{35}Cl, ^{36}Cl, and ^{37}Cl concentrations; therefore, the $^{36}Cl/10^{15}Cl$ ratio will not change, and points in figure 31 would shift horizontally if these processes occurred. Radioactive decay decreases and buildup increases ^{36}Cl concentrations; these processes are represented by sloped lines in figure 31.

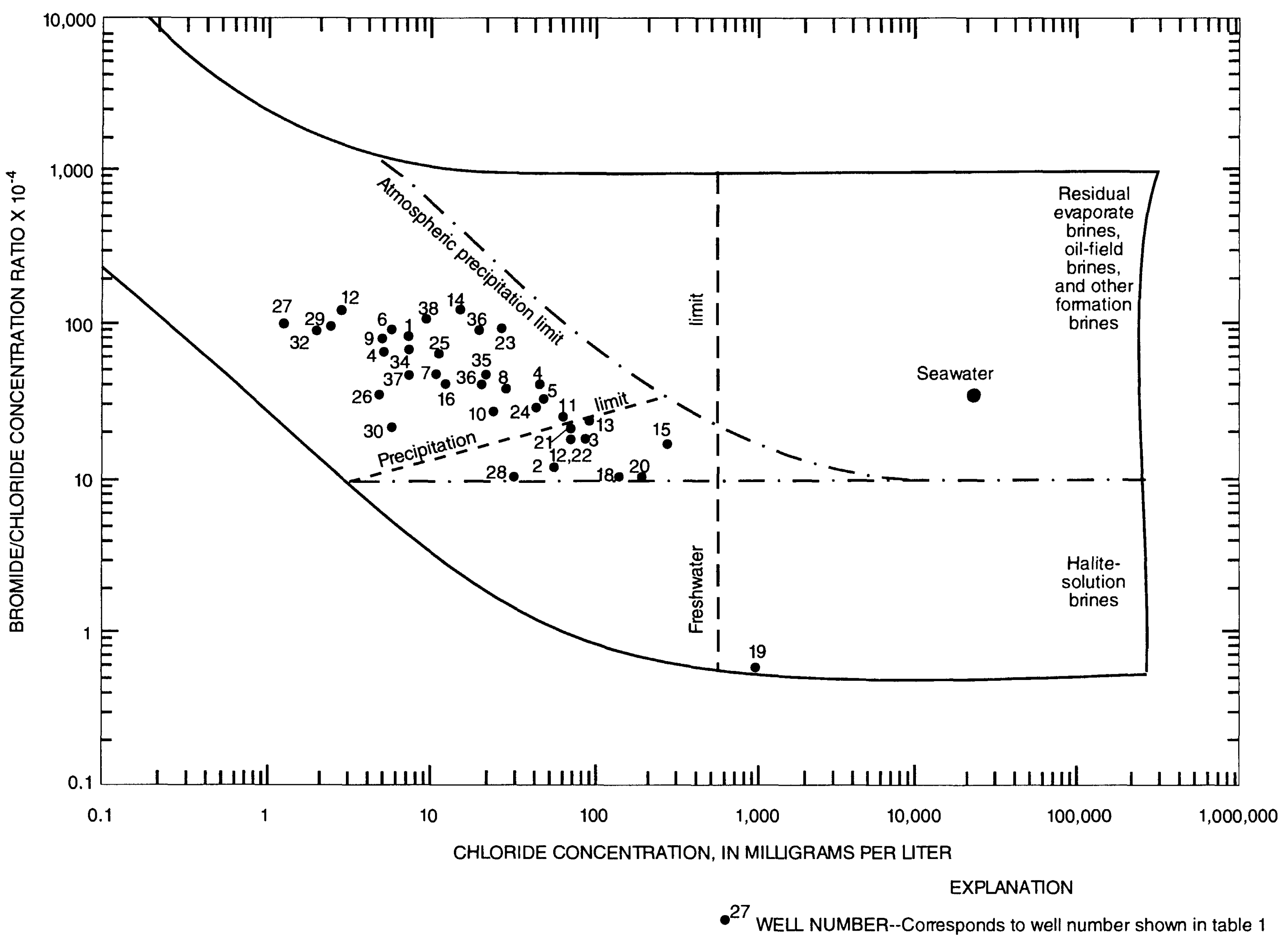
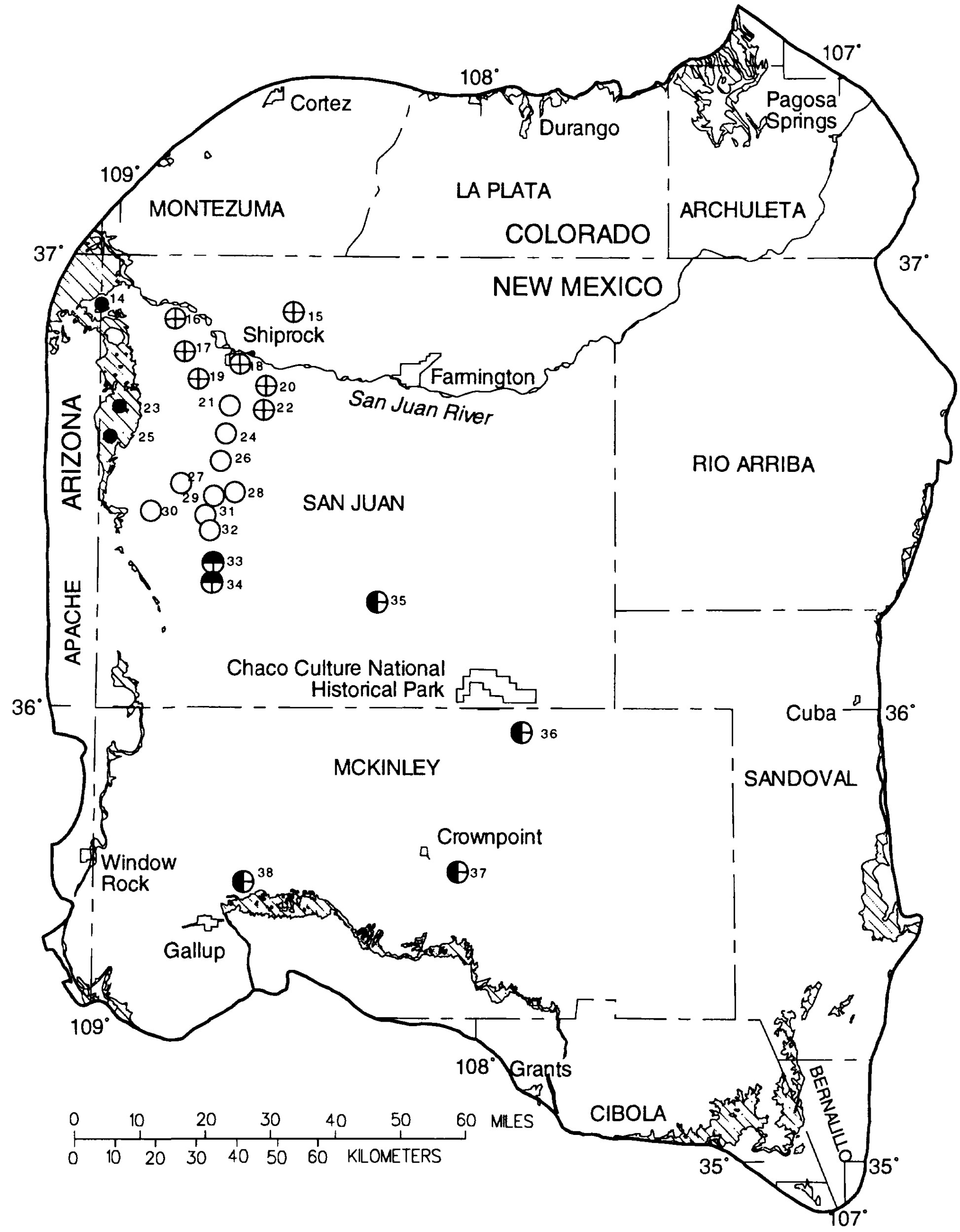


Figure 29.--Ratio of bromide/chloride versus chloride concentrations for water samples from the Gallup, Dakota, and Morrison aquifers.



EXPLANATION

☐ OUTCROP OF GALLUP AQUIFER, JURASSIC ROCKS, UNDIVIDED; WANAKAH FORMATION; ENTRADA SANDSTONE; AND SAN RAFAEL GROUP--From Dane and Bachman, 1965; Wilson and others, 1969; Tweto, 1979; and Hintze, 1981

— BOUNDARY OF STUDY AREA

⊕ 15 WATER WELL--Symbol represents group 1 wells located near the San Juan River with elevated Cl⁻ concentrations. Number corresponds to well number shown in table 1

● 23 WATER WELL--Symbol represents group 2 wells located near the outcrop of Morrison Formation. Number corresponds to well number shown in table 1

○ 24 WATER WELL--Symbol represents group 3 wells located downgradient from the recharge area. Number corresponds to well number shown in table 1

◓ 33 WATER WELL--Symbol represents group 4 wells, wells 33 and 34. Number corresponds to well number shown in table 1

◐ 38 WATER WELL--Symbol represents group 5 wells located in the central and southern parts of the basin. Number corresponds to well number shown in table 1

Figure 30.--Location, well number, and group for water wells completed in the Morrison aquifer used in analysis of chlorine-36 data shown in figures 31-33.

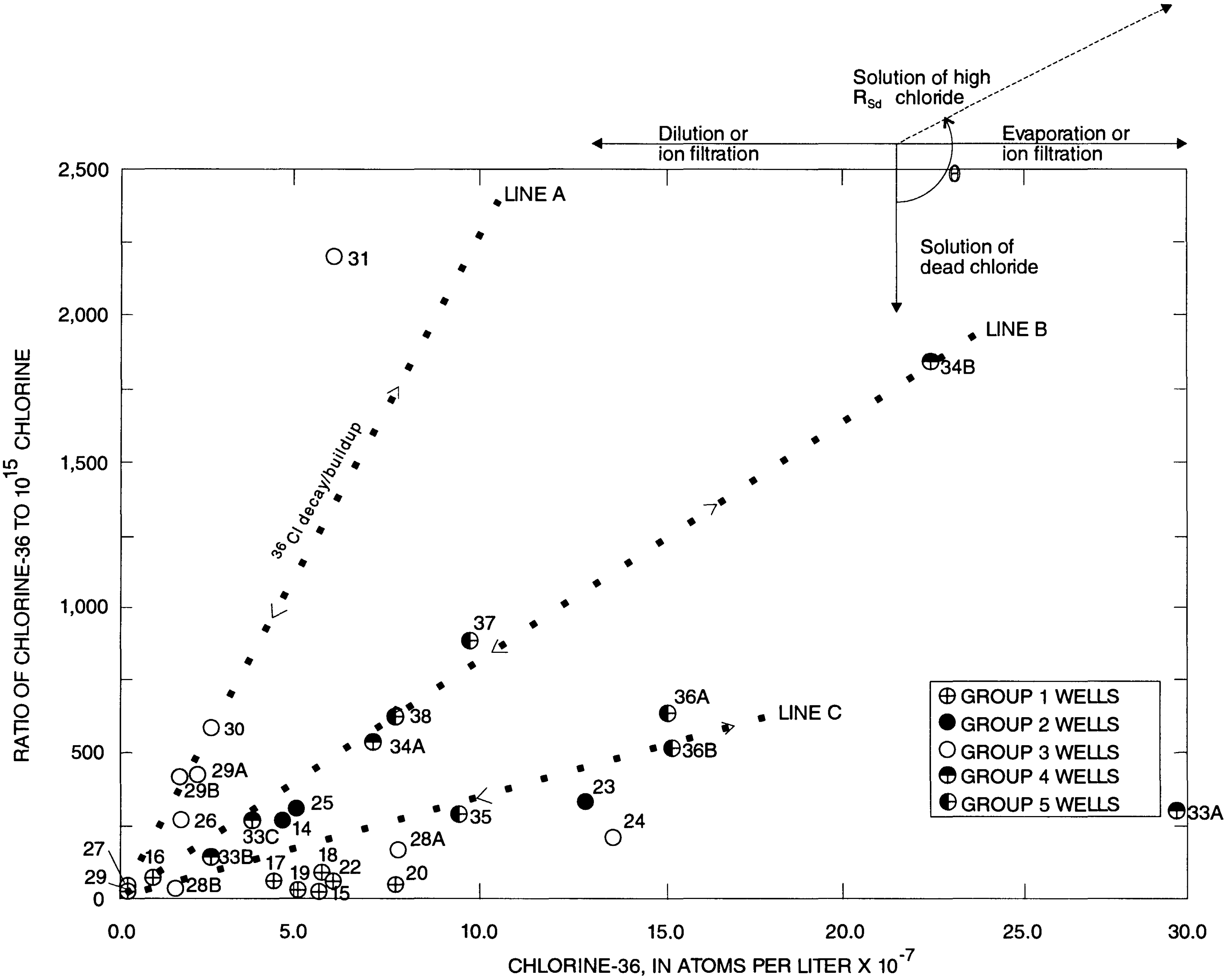


Figure 31.--Chlorine-36/chlorine versus chlorine-36 for water from the Morrison aquifer. The displacement caused by various processes is illustrated (modified from Jones and Phillips, 1990).

Three decay (or buildup) lines were plotted in figure 31 to show samples containing different salinities: line (A) was drawn through sample 30 and the origin for dilute samples; line (B) was drawn through sample 34B and the origin for slightly saline samples; and line (C) was drawn through sample 36B and the origin for saline samples. In general, data points assigned to the well groups defined in figure 30 are described by these three lines. Dilute samples generally followed line A and consisted primarily of group 3 wells: 30, 29, 26, 27, and 31. Samples containing slightly saline values plotted along line B and generally belonged to groups 2 and 5 (outcrop samples and southern San Juan Basin samples). Samples containing saline values plotted along line C and generally consisted of group 5 wells. Wells located near Shiprock and the San Juan River plotted below line C. The buildup of ^{36}Cl due to uranium deposits may have affected samples 31 and 34B (fig. 31).

Chloride mass-balance equations derived by Jones and Phillips (1990) indicate that mixing of waters could be evaluated by plotting the $^{36}\mathrm{Cl}/10^{15}\mathrm{Cl}$ ratio against the inverse of the chloride concentration in milligrams per liter (figs. 32 and 33). The three lines A, B, and C in figure 31 are shown in figures 32 and 33. Compared to figure 31, lines A, B, and C plot in reverse order in figures 32 and 33 because the chloride concentration decreases away from the origin in figures 32 and 33. Line A represents the ^{36}Cl decay curve and is not affected by other processes such as dilution or ion exchange. Samples that fall on the ^{36}Cl decay curve are 30, 29B, and 26. A decrease in chloride concentration for samples 29A, 32, and 27 results in plots to the right of line A as shown by line D in figure 32. These samples may be the result of dilution or ion filtration of chloride in the Morrison aquifer. Likewise, samples that plotted to the left of line A were concentrated in chloride, possibly due to evaporation or ion filtration on the opposite side of the membrane, as represented by line E.

Dr. Fred Phillips (New Mexico Institute of Mining and Technology, written commun., 1991) compared the ^{36}Cl/Cl ratios with $\mathrm{Br^-/Cl^-}$ ratio data. The mixing of three end-member sources explains the observed data. The first end member is recharge water having a large ^{36}Cl/Cl ratio and large $\mathrm{Br^-/Cl^-}$ ratio; chloride concentrations range from 7 to 14 mg/L. The second end member is likely either ion filtrate or very ancient ground water recharged under a more humid climate. This second end member is characterized by a small ^{36}Cl/Cl ratio, large $\mathrm{Br^-/Cl^-}$ ratio, and is very dilute with chloride concentration less than 5 mg/L. The third end member is upward-leaking deep-basin brine containing small ratios of ^{36}Cl/Cl and $\mathrm{Br^-/Cl^-}$; $\mathrm{Cl^-}$ concentrations exceed 100 mg/L. Therefore, the mixing of recharge water and an ion filtrate or ancient dilute recharge water with upward-leaking brine dominates the flow regime in the northwestern part of the San Juan Basin. This mixing of ground water affects ion constituent concentrations and precluded quantitative mass-balance calculations of geochemical reactions affecting water chemistry.

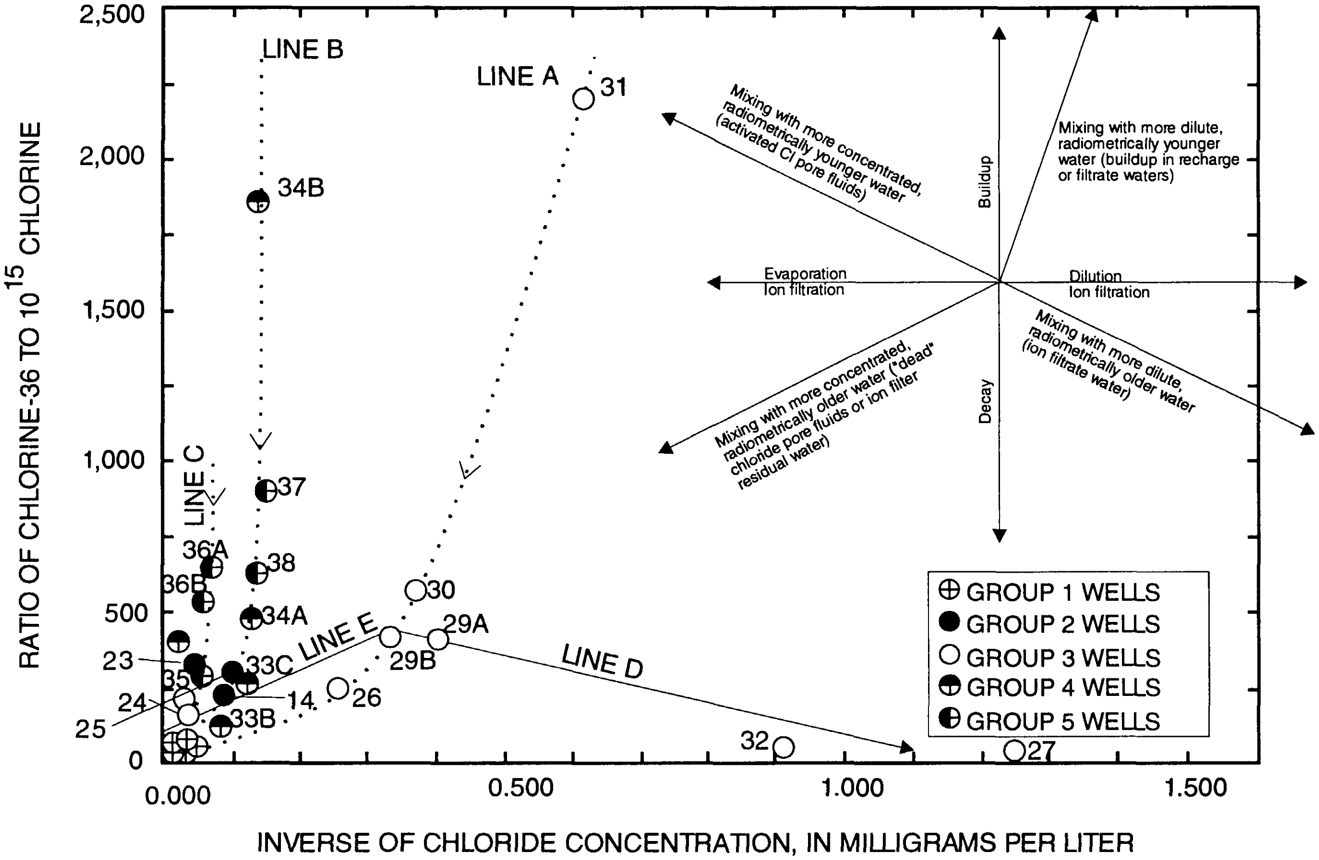


Figure 32.--Chlorine-36/chlorine versus inverse of chloride concentration for water from the Morrison aquifer. Figure 33 provides additional details (modified from Jones and Phillips, 1990).

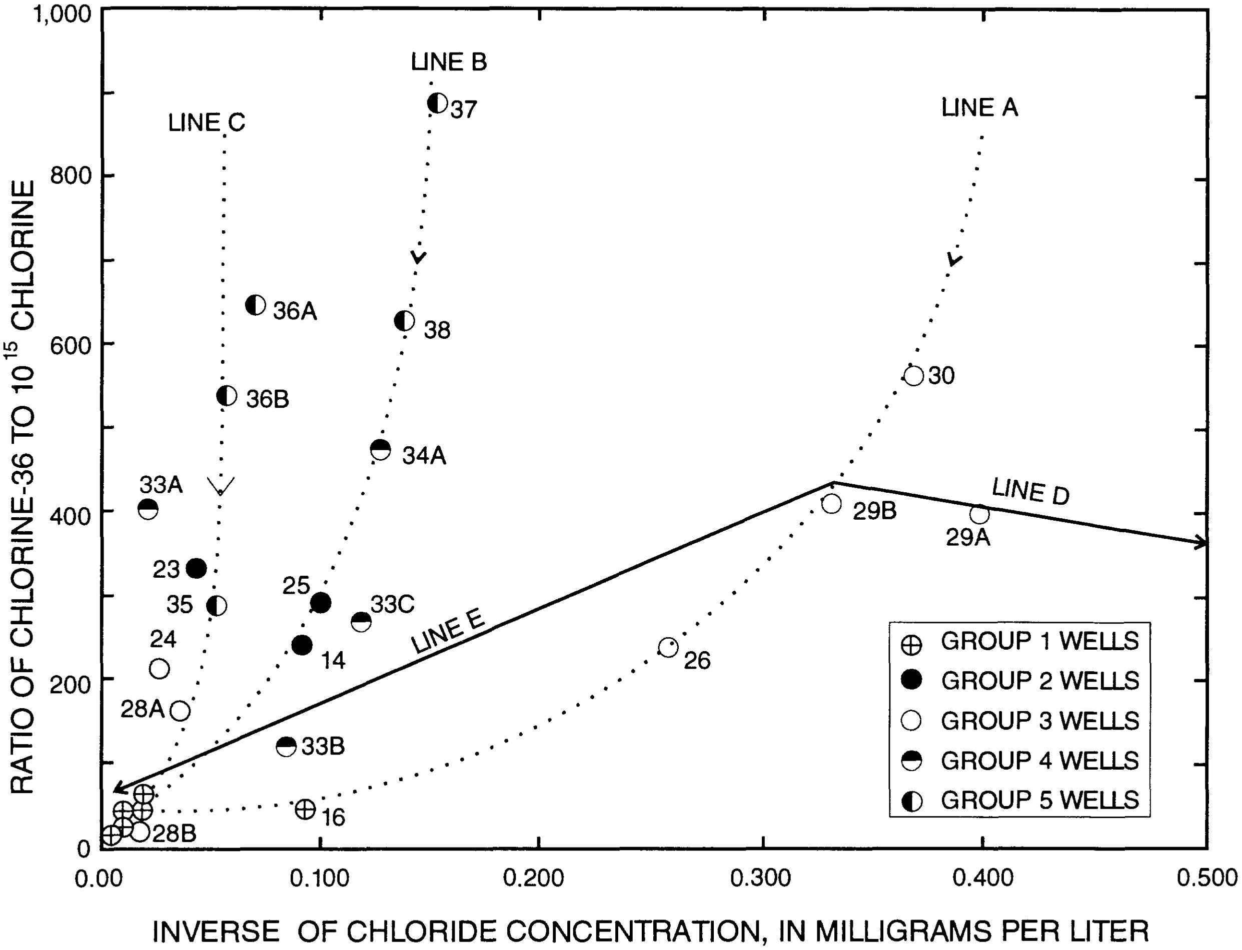


Figure 33.--Chlorine-36/chlorine versus inverse of chloride concentration for water from the Morrison aquifer--expanded scale. Expanded scale shows part of figure 32 in more detail (modified from Jones and Phillips, 1990).

To examine further the possibility of upward leakage into the Morrison aquifer, water-quality analyses were retrieved from the NWIS data base. Single-completion wells in the Wanakah Formation were not available. Chemical analyses for two samples from wells completed in the Entrada Sandstone are shown in table 10. Well Je1 is located on the northwest side of the basin approximately 8 mi west of Morrison well 21, and well Je2 is located approximately 8 mi east of Morrison well 36 (table 10). Sodium, sulfate, and chloride are the predominant major ions in both samples from the Entrada Sandstone. Chloride concentrations are significantly larger in water from the Entrada than in water from the Morrison aquifer. The chloride concentration is 1,100 mg/L in water from well Je1 compared with a chloride concentration of 67 mg/L (table 4) in well 21 from the Morrison aquifer. The chloride concentration is 810 mg/L in water from Entrada well Je2 compared with a chloride concentration of 17 mg/L (table 4) in well 36 from the Morrison. Vertical leakage of water into the Morrison through fractures or other areas of large permeability would increase chloride concentrations in the Morrison aquifer. This finding is generally consistent for samples from wells that have multiple completions in the Morrison and Wanakah Formations. Water from two wells, 26 and 24, completed in the Morrison aquifer, contain chloride concentrations of 3.9 and 38 mg/L (table 4). Well 26 is completed in the Recapture Member and well 24 is completed in the Recapture and Salt Wash Members and in the Wanakah Formation.

Table 10.--Two chemical analyses of water from the Entrada Sandstone
[Concentration in milligrams per liter except where otherwise indicated. --, no data]

	Well identification	
	Je1	Je2
Latitude	364838	360344
Longitude	1085154	1075156
Sample date	09-17-69	03-28-78
Specific conductance (microsiemens per centimeter at 25 degrees Celsius)	9,320	10,000
pH (standard units)	8.20	8.30
Alkalinity (as $CaCO_3$)	410	470
Bicarbonate	570	--
Carbonate	10	2
Calcium	72	70
Manganese	28	8.3
Sodium	2,200	2,800
Potassium	9.0	15
Chloride	1,100	810
Sulfate	2,800	4,300
Fluoride	3.6	5.3
Dissolved solids	6,600	8,300

Physical processes, predominantly leakage and mixing, account for some of the sources and distribution of solutes and isotopes in the three aquifers. Other sources and mechanisms for addition and removal of solutes are controlled by geochemical processes.

Magnesium concentrations were larger in water samples from the Gallup aquifer than from the other two aquifers. This suggests a mineral source of Mg^{2+} in the Gallup aquifer that was not present in the other two aquifers or a sink for Mg^{2+} in the other two aquifers. Dissolution of calcite would contribute Ca^{2+} ions and dissolution of dolomite contributes Ca^{2+} and Mg^{2+} ions as shown in reactions 3 and 4:

$$CaCO_{3(c)} + H^+ = Ca^{2+} + HCO_3^- \tag{3}$$

$$CaMg(CO_3)_{2\,(c)} + 2H^+ = Ca^{2+} + Mg^{2+} + 2HCO_3^- \tag{4}$$

Dolomite, but not calcite, was observed in the Gallup aquifer by Kaharoeddin (1971), suggesting that the source of Ca^{2+} and Mg^{2+} is likely dolomite dissolution reactions.

The small Ca^{2+} and Mg^{2+} concentrations in the Dakota aquifer indicate that either dolomite dissolution is not a major process, cation exchange occurs, or the available data were not representative of the Dakota aquifer. Calcium and magnesium concentrations were also small in the Morrison aquifer. Dolomite minerals have not been observed in the Morrison, and calcite minerals are present but in small amounts (less than 10 percent calcite from two outcrop locations in the northwestern part of the basin according to Hansley, 1990).

The removal of Ca^{2+} and Mg^{2+} and the increase in Na^+ in the Gallup aquifer in the direction of ground-water flow are indicative of ion-exchange reactions with clay minerals (reaction 5):

$$Ca^{2+} + Na_2X = 2Na^+ + CaX; \tag{5}$$

where X = ion-exchange site.

Chlorite and glauconite clay minerals were observed by Kaharoeddin (1971) in the Gallup aquifer. Chlorite has a very low cation-exchange capacity of less than 10 meq/100 g (Drever, 1982, p. 82). Glauconite, an iron-rich variety of illite, has a higher cation-exchange capacity of 10 to 40 meq/100 g (Drever, 1982, p. 74 and 82). This suggests that glauconite rather than chlorite would be more effective in the exchange of the divalent cations (Ca^{2+}, Mg^{2+}) for the monovalent Na^+ cation in the Gallup aquifer.

The presence of small concentrations of Ca^{2+} and Mg^{2+} in samples from the Dakota and Morrison aquifers may be a result of sampling where dissolution of carbonates and cation exchange both occur in the recharge area, possibly in the soil zone or unsaturated zone, prior to reaching the location of the sampled wells. Another possible explanation is that dissolution of carbonates was not a significant process and that silicate hydrolysis was the major process resulting in Na^+ concentrations. The dissolution of albite ($NaAlSi_3O_8$) releases Na^+ as shown in reactions 6 and 7. Albite altering to kaolinite ($Al_2Si_2O_5(OH)_4$) has been observed in core and outcrop samples from the Morrison aquifer (Hansley, 1990).

$$NaAlSi_3O_{8\,(c)} + 8H_2O = Na^+ + Al(OH)_4^- + 3H_4SiO_4^0 \tag{6}$$

$$2NaAlSi_3O_8 + 2CO_2 + 11H_2O = 2Na^+ + Al_2Si_2O_5(OH)_{4\,(c)} + 4H_4SiO_4^0 + 2HCO_3^- \tag{7}$$

Sources of bicarbonate include carbonate dissolution (reactions 3 and 4) and silicate hydrolysis (reaction 7). Dissolution of the carbonate mineral dolomite is a likely source of HCO_3^- in the Gallup aquifer (reaction 6). Silicates hydrolyzing in the presence of CO_2 gas contribute HCO_3^- (reaction 7). Silicate minerals observed in all three aquifers include potassium feldspar, plagioclase feldspar (such as albite), and several clay minerals.

Sources of sulfate include dissolution of sulfate-bearing minerals and oxidation of sulfide minerals. However, for the Gallup aquifer, no sulfate or sulfide minerals were observed by Williams (1956) or Kaharoeddin (1971). The large concentrations of SO_4^{2-} in water analyses shown in table 2 suggest that there is a source of SO_4^{2-} and that the mineralogical data may not be complete for the Gallup aquifer. The Mancos Shale confines the Gallup aquifer and may be a source of SO_4^{2-}.

Sulfate concentrations in the Dakota aquifer do not increase uniformly but rather form two groups of small and large concentrations. No sources of SO_4^{2-} were studied by Walters and others (1987), who were concerned primarily with trace-element concentrations.

Sulfate concentrations increase downgradient in the Morrison aquifer toward Shiprock. Sources of SO_4^{2-} in water from the Morrison aquifer include dissolution of sulfate minerals or oxidation of sulfide minerals. Anhydrite ($CaSO_4$) and pyrite (FeS_2) have been observed in the Morrison aquifer (Hansley, 1990). A dissolution reaction for anhydrite producing SO_4^{2-} is shown in reaction 8. Oxidation of 1 mole of pyrite can release 2 moles of SO_4^{2-} (reaction 9).

$$CaSO_{4(c)} = Ca^{2+} + SO_4^{2-} \qquad (8)$$

$$FeS_{2(c)} + 4O_{2\,(g)} + 2H_2O = FeO(OH) + 2SO_4^{2-} + 4H^+ \qquad (9)$$

$(Silica)_T$ is the total sum of three ions: $H_4SiO_4^0$, $H_3SiO_4^-$, and $H_2SiO_4^{2-}$. Below a pH of 9, most dissolved $(SiO_2)_T$ exists as $H_4SiO_4^0$. As pH rises above 9, $H_3SiO_4^-$ becomes an important species (Drever, 1982, p. 91-92), followed by $H_2SiO_4^{2-}$ above a pH of 12. Dissolved $(SiO_2)_T$ concentrations would be expected to increase with increasing pH above 9 because both $H_2SiO_4^{2-}$ and $H_3SiO_4^-$ would be in solution. Dissolved $(SiO_2)_T$ is plotted against field pH in figure 34 for water from the Morrison aquifer. No correlation exists for all points; however, a cluster of $(SiO_2)_T$ samples plot in the range of 18 to 20 mg/L with pH values between 9.2 and 9.5. Another control on $(SiO_2)_T$ concentration is temperature (Krauskopf, 1979, p. 169-170). The effects of water temperature on dissolved $(SiO_2)_T$ appear to be significant for values greater than 25 °C (fig. 34). The maximum $(SiO_2)_T$ concentration of 35 mg/L was associated with the warmest water of 51.8 °C.

An oxidation-reduction (redox) reaction controls nitrogen speciation. The denitrification process (reaction10) is shown below:

$$NO_3^- + 2CH_2O + 2H^+ = NH_4^+ + 2CO_{2(g)} + H_2O; \qquad (10)$$

where CH_2O = organic matter.

Microbes use the oxygen in nitrate ions to oxidize organic matter to CO_2. The denitrification process in the aquifer probably occurs after oxygen is consumed by the oxygen-reducing microbes.

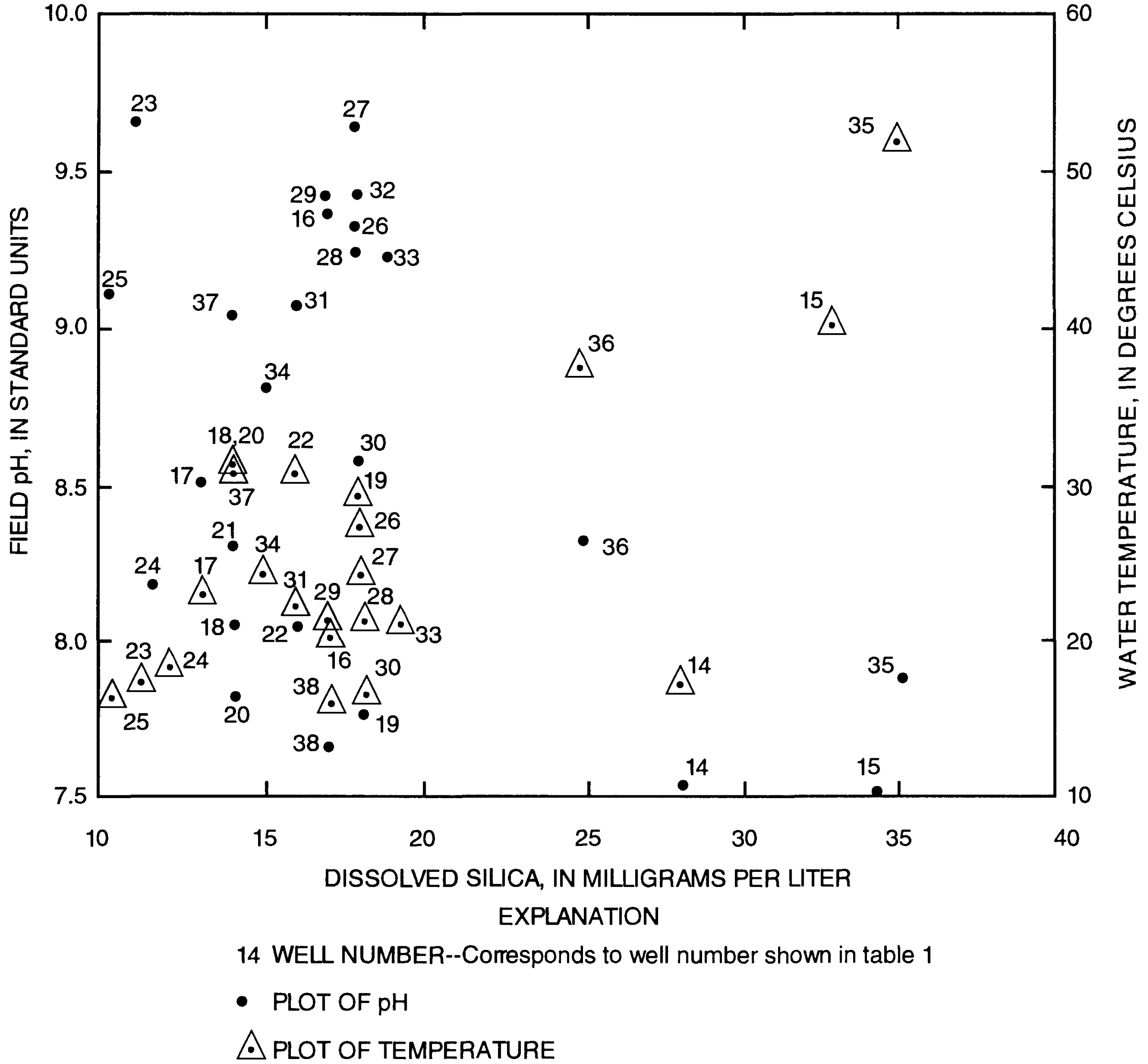


Figure 34.--Concentration of dissolved silica versus field pH and temperature of water samples from the Morrison aquifer.

Degrees of mineral saturation were computed with the computer code WATEQF (Plummer and others, 1976) to identify areas where minerals are likely to dissolve, precipitate, or be in thermodynamic equilibrium with the water. Requirements for input into the code include data on the major ions, pH, temperature, SiO_2, Fe, PO_4, Sr, and F. Analytical data for Al and $(SiO_2)_T$ are required for calculating states of saturation for aluminosilicate minerals. A value of 10 µg/L for Al was assumed for values less than the detection limit of 10 µg/L. Redox calculations were made using dissolved oxygen (where detected) or the SO_4/H_2S ratio (H_2S was converted from total sulfide data).

WATEQF modeling provides an estimate of the mineral saturation index (SI) for a suite of minerals for each sample. The definition of SI is:

$$SI = \log \frac{IAP}{K_T} \qquad (11)$$

where IAP is ion activity product; and
K is equilibrium constant at temperature T, in degrees Kelvin.

If SI is negative, the solution is undersaturated with respect to the mineral. Conversely, a positive SI indicates supersaturation with respect to the mineral. Where IAP equals K_T, thermodynamic equilibrium is indicated.

Results from WATEQF modeling indicate various states of saturation for minerals in the three sandstone aquifers. Albite, amorphous silica, and gypsum were found to be undersaturated in all samples collected from the three aquifers, suggesting that these minerals would dissolve in ground water where they are present in the aquifer. Values of SI for calcite in the Gallup and Dakota aquifers generally are positive, suggesting conditions suitable for calcite precipitation.

Values of SI for calcite in samples from the Morrison aquifer ranged from positive to negative, indicating both precipitation and dissolution of calcite minerals in some parts of the aquifer. Most samples were supersaturated with respect to calcite, indicating that calcite would precipitate. Several samples, particularly near the San Juan River in the vicinity of Shiprock, were undersaturated with respect to calcite, indicating that calcite would dissolve where present.

Values of SI calculated for dolomite ($CaMg(CO_3)_2$) for samples in the three aquifers have similar patterns to the SI data for calcite. Notable exceptions are three samples from the Gallup aquifer in the central part of the basin that are supersaturated with respect to calcite and undersaturated with respect to dolomite. The difference in SI values for dolomite relative to calcite may be the presence of small Mg^{2+} concentrations detected in several samples from the Gallup aquifer.

SI values were computed for clay minerals including chlorite, kaolinite, illite, and the smectite group of montmorillonite minerals. SI values for chlorite samples from the Gallup aquifer ranged from highly positive (5.0) to highly negative (-4.3). Highly positive SI values indicate that precipitation of chlorite may consume 0.5 mole/liter of Mg from the water. SI values for chlorite in the Morrison aquifer ranged from 3.7 to -6.2. No discernible trends in SI values for chlorite were evident.

Kaolinite minerals were observed in the Dakota and Morrison aquifers. Values of SI for both aquifers show general trends of undersaturation (suggesting dissolution) with respect to kaolinite near the recharge areas and supersaturation (suggesting precipitation) downgradient.

WATEQF calculations for illite minerals indicate predominant undersaturation of the minerals in samples collected from the three aquifers. Exceptions were two samples obtained from wells located in the outcrop area of the Morrison aquifer. Illite has been observed in the Dakota and Morrison aquifers, suggesting the potential for dissolution reactions that would release Mg^{2+}, Al hydroxides, and silicic acid.

Smectite minerals were observed in the Dakota and Morrison aquifers. The thermodynamic data for smectite minerals are not well constrained, creating large uncertainties in the SI calculations. Smectite was found to be supersaturated for all samples from the two aquifers.

SUMMARY AND CONCLUSIONS

Geochemical data were obtained for 38 wells completed in the Gallup, Dakota, and Morrison aquifers to examine sources of solutes and hydrologic controls that affect the concentration and distribution of solutes in the San Juan Basin. The scope was constrained primarily to the northwestern part of the basin because of well availability and disturbances to the natural ground-water system by uranium mining in the southern part of the basin. Although the Gallup, Dakota, and Morrison aquifers were examined, 25 of the 38 wells were completed in the Morrison aquifer, which had the most available wells completed in single aquifers.

Based on a series of samples collected along ground-water flow paths, chemical concentrations were variable depending on vertical sampling interval, well location, and sampling date. Several sandstone units contributed water to wells completed in the Morrison aquifer, suggesting that the Morrison aquifer is not a simple two-dimensional flow system. The data presented in this report indicate an upward component of flow into the Morrison aquifer. The entire section above and below the Morrison aquifer appears to be controlled by a three-dimensional flow regime where saline brine leaks upward near the San Juan River discharge area. Temporal changes in ion constituent concentrations may be a result of changes in hydraulic head in individual sandstone layers that contributed water to the well. The assumption that water chemistry in wells does not change over short periods in a large regional aquifer cannot be made as has been done commonly in previous investigations.

Predominant ions found in the three aquifers were generally Ca^{2+}, Na^{+}, HCO_3^{-}, and SO_4^{2-}. The Gallup aquifer contained Ca^{2+}-HCO_3^{-} in recharge areas and Na^{+}-SO_4^{2-} downgradient. The Dakota Sandstone contained Na^{+}-HCO_3^{-} in recharge areas with the addition of SO_4^{2-} downgradient. Predominant ions in the Morrison aquifer were Na^{+}-HCO_3^{-} in recharge areas and Na^{+}-SO_4^{2-} downgradient.

Maximum chloride concentrations found in the Gallup, Dakota, and Morrison aquifers were 240, 720, and 750 mg/L, respectively. Median chloride concentrations were 20, 57, and 11 mg/L, respectively. Detectable trace-element concentrations included As, Ba, B, Fe, Li, Mn, and Sr.

Radioactive isotopes were useful in distinguishing sources of water to the Morrison aquifer. The absence of ^3H activities confirmed that ground water from all wells sampled has not mixed with modern water and has been isolated from the atmosphere since at least 1952. Of 24 samples analyzed, ^{14}C activities were detected in 12. Age dating with ^{14}C was not meaningful given the different sources of water in the aquifer. The ^{36}Cl radioisotopic data proved most useful in differentiating the sources of water in the Morrison aquifer. Comparing Br^-/Cl^- concentration ratios to $^{36}Cl/Cl$ ratios indicates three major end members of water resulting from different sources. Recharge water had a large $^{36}Cl/Cl$ ratio and small Br^-/Cl^- ratio. Chloride concentrations were between 7 and 14 mg/L. A second end member of water contained small ^{36}Cl ratios, large Br^-/Cl^- ratios, was very dilute, and contained chloride concentrations below 5 mg/L. These results suggest that water may have filtered into the Morrison through zones that trap dissolved solids by the ion-filtration process. A second hypothesis is that this water is very ancient water that was recharged during a humid climatic period. The third end member of water is characterized by upward-leaking, deep-basin brine containing small ratios of $^{36}Cl/Cl$ and Br^-/Cl^- and large chloride concentrations exceeding 100 mg/L.

Chemical and radioisotopic data indicate that water from overlying and underlying units mixes with recharge water in the Morrison aquifer. Recharge water contained a large $^{36}Cl/Cl$ ratio and a small Br^-/Cl^- ratio. Approximately 10 mi downgradient, however, samples from four wells completed in the Morrison aquifer were considerably different in composition compared to recharge samples. Oxygen stable isotopes decreased by 2.8 $^0/_{00}$ and deuterium decreased 26 $^0/_{00}$, relative to recharge. Carbon-14 radioisotope activities were not detectable. Chlorine-36/Cl ratios were small and Br^-/Cl^- ratios were large. These results suggest two potentially viable processes: ion filtration or trapping of ancient dilute water recharged under a humid climate. For water samples near the San Juan River, pH decreased to about 8.0, Cl^- concentrations increased to more than 100 mg/L, and $^{36}Cl/Cl$ ratios and Br^-/Cl^- ratios were small. Leakage of deep basin brine into the fresher water of the Morrison aquifer appears to control ion constituent concentrations.

The mixing of recharge water and an ion filtrate or ancient dilute recharge water with upward-leaking brine dominates the flow regime in the northwestern part of the San Juan Basin. This mixing of ground water controls ion constituent concentrations and precluded quantitative mass-balance calculations of geochemical reactions controlling water chemistry. Geochemical reactions involve dissolution of carbonate, silicate, and sulfate minerals present in the three aquifers, ion-exchange reactions, and oxidation reduction.

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