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BASE OF MODERATELY SALINE GROUND WATER

IN SAN JUAN COUNTY, UTAH

By Lewis Howells

Prepared by the
United States Geological Survey
in cooperation with the
Utah Department of Natural Resources
Division of Oil, Gas and Mining
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[Plate is in pocket]

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CONVERSION FACTORS

For readers who prefer to use metric (International System) units rather than the inch-pound units used in this report, the following conversion factors may be used:

Multiply inch-pound unit	By	To obtain metric unit
acre	0.4047	hectare
barrel (42 gallons)	158.99	liter
foot	0.3048	meter
foot per day	0.3048	meter per day
mile	1.609	kilometer
square mile	2.590	square kilometer

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

$$°C = 5/9\ (°F - 32)$$

Permeability, in millidarcies, can be converted to hydraulic conductivity in feet per day by multiplying by 0.002725, or in meters per day by multiplying by 0.000831.

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

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ABSTRACT

The base of moderately saline ground water (water that contains from 3,000 to 10,000 milligrams per liter of dissolved solids) was delineated for San Juan County, Utah, based on water-quality data and on formation-water resistivities determined from geophysical well logs using the resistivity-porosity, spontaneous-potential, and resistivity-ratio methods. These data and the contour map developed from them show that a thick layer of very saline to briny ground water (water that contains more than 10,000 milligrams per liter of dissolved solids) underlies the eastern two-thirds of San Juan County. The upper surface of this layer is affected by the geologic structure of the area, but it may be modified locally by recharge mounds of less saline water and by vertical leakage of water through transmissive faults and fractures. The highest altitude of the base of moderately saline water is west of the Abajo Mountains where it is more than 6,500 feet above sea level. The lowest altitude is in the western part of the county and is below sea level; depressions in the base of moderately saline water in recharge areas in the La Sal and Abajo Mountains also may be that low. The base of moderately saline water commonly is in the Permian Cutler Formation or the Pennsylvanian Honaker Trail Formation of the Hermosa Group, but locally may be as high stratigraphically as the Triassic (?) and Jurassic Navajo Sandstone north of the Abajo Mountains and in the Jurassic Morrison Formation south of the mountains.

INTRODUCTION

Real or potential contamination of domestic, livestock, and irrigation water supplies by disposal of saline water produced from oil and gas wells ("production water") in San Juan County is a matter of public concern. The concentration of dissolved solids in production water usually exceeds 10,000 mg/L (milligrams per liter) and can exceed 400,000 mg/L. Historically, production water was disposed of on the land surface. However, as the volume of production water increased, so did awareness that surface disposal ponds may leak into streams or shallow aquifers. To reduce the threat of increased salinity and sodium hazards to agricultural land and of saline contamination of both surface- and ground-water supplies of potable and irrigation water, many oil- and gas-well operators began to dispose of saline production water by injecting it into permeable strata that already contained saline water. In 1985 in San Juan County, about 95 percent of production water was disposed of by injection; much of it was used in secondary recovery operations, but at least 2,382,000 bbls (barrels) of production water was injected through disposal wells (G.L. Hunt, Utah Division of Oil, Gas and Mining, oral commun., 1987). At least 1,145,000 bbls (and possibly more than 1,871,000 bbls) of production water was disposed of in surface pits.

Purpose and Scope

The Utah Division of Oil, Gas and Mining, the principal State agency responsible for regulating the disposal of production water to prevent the contamination of water supplies, is concerned not only about possible leakage from surface disposal ponds, but also about migration of saline water disposed of by injection into usable water supplies. To better define intervals into which saline production water could be injected without contaminating possible underground sources of domestic and agricultural water, the U.S. Geological Survey and the Utah Division of Oil, Gas and Mining jointly did a study during 1985-87 to delineate the base of moderately saline water[1] in San Juan County. This report summarizes that study.

San Juan County, in southeastern Utah, has an area of 7,707 square miles (fig. 1). It contains the northern part of the Navajo Indian Reservation. The county is bounded on the south by the Arizona State line, on the east by the Colorado State line, on the north by Grand County, and on the west by the Colorado and Green Rivers. The county has been the site of extensive exploration for gas, oil, and uranium since the late 1940's. Many oil and gas fields have been found, as have some commercial-grade deposits of uranium ore.

Data-Site Numbering System

In this report, data sites are identified by numbers based on the Federal cadastral land-surveying system. Under this system, Utah is divided into two regions, each of which has its own meridian and base line. Most of the State, including all of San Juan County, lies within the survey region of the Salt Lake Meridian and Base Line.

The numbering system is described below and is shown in figure 2. Within a survey region, the area is divided into quadrants by the principal meridian and base line; these quadrants are designated by the letters A through D, assigned in a counterclockwise direction beginning in the northeastern quadrant. This letter is followed by the township number and then the range number. The quadrant designation and the township and range numbers are enclosed by parentheses that, in turn, are followed by the number identifying the section. As many as three lowercase letters are used after the section number to indicate the location of the site within the section. The first letter indicates the quarter section (160-acre tract); the second letter indicates the quarter-quarter (40-acre tract); and the third letter, the quarter-quarter-quarter (10-acre tract). The letters "a" through "d" are assigned to the tracts in a counterclockwise direction beginning in the northeastern corner of each tract. To identify wells and springs, this site

[1]In this report, water salinity is classified as follows:

Class	Concentration of dissolved solids (mg/L)
Fresh	0 to 1,000
Slightly saline	1,000 to 3,000
Moderately saline	3,000 to 10,000
Very saline	10,000 to 35,000
Briny	more than 35,000

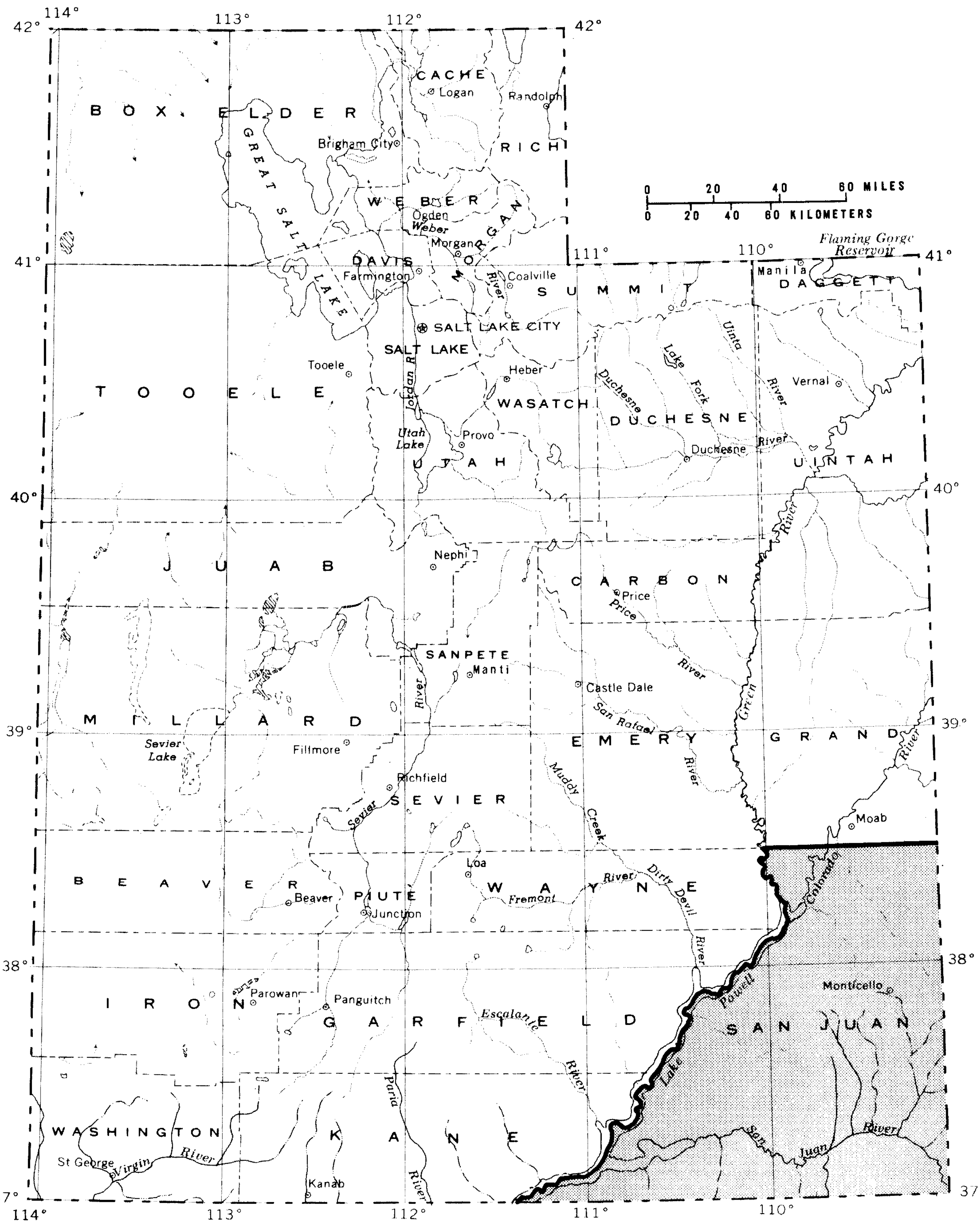

Figure 1.--Location of San Juan County, Utah.

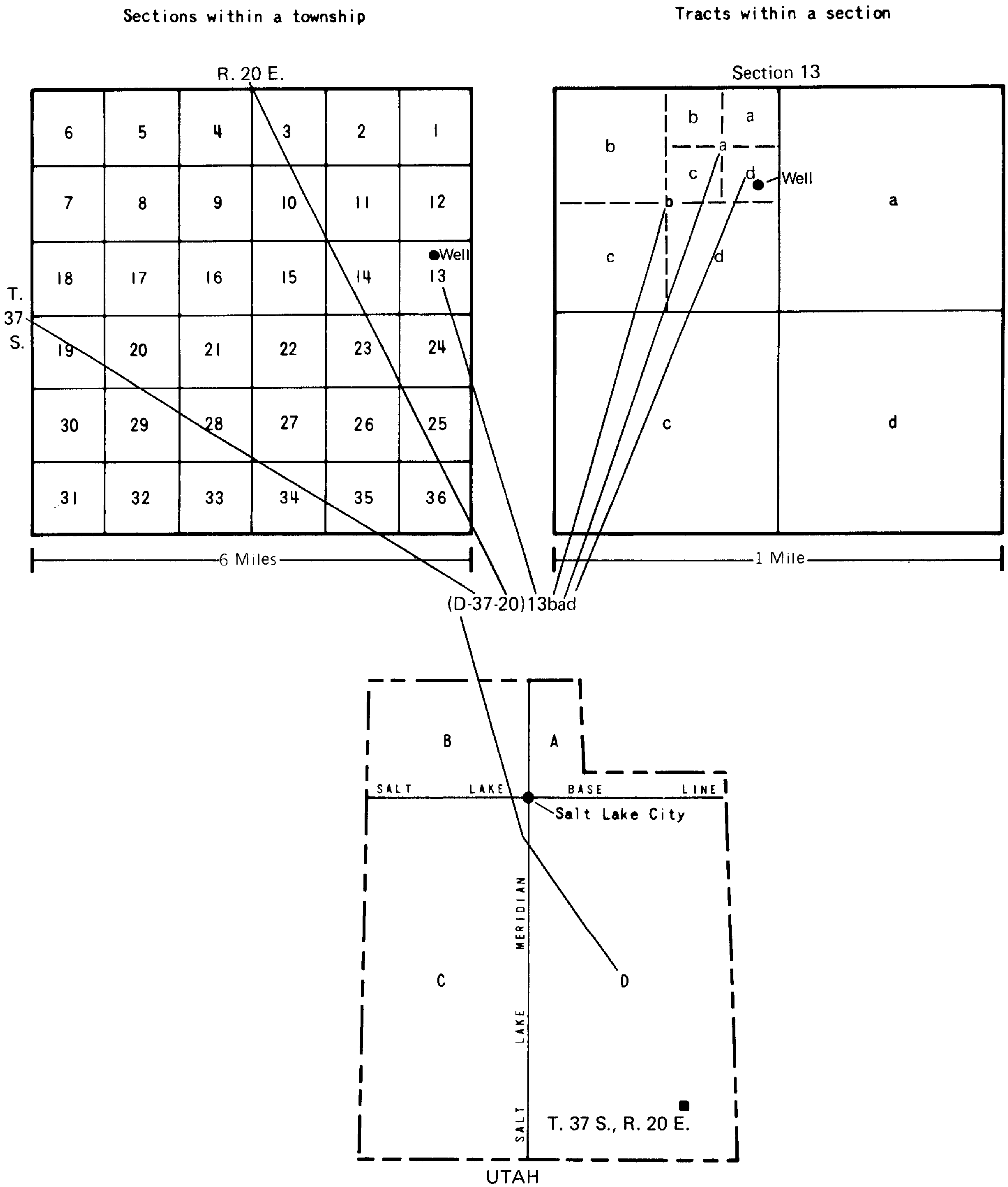

Figure 2.--Data-site numbering system used in this report.

location is followed by a serial number that identifies each well within the tract or by the letter "S" and a serial number to identify each spring within the tract. Thus, (D-37-20)13bad may be used to specify the location of a data-collection site or a feature of interest in the SE¼NE¼NW¼ of section 13, T. 37 S., R. 20 E., in the area covered by the Salt Lake Meridian and Base-Line survey, but (D-37-20)13bad-1 identifies the first well constructed (or visited by U.S. Geological Survey personnel) in the same 10-acre tract, and (D-37-20)13bad-S1 identifies the first spring visited in the same 10-acre tract.

Acknowledgments

The author wishes to express his appreciation to John N. Daum, consulting geologist, Denver, Colo., and Charles T. Thompson, Schlumberger Well Services, Denver, Colo., for suggestions, constructive criticism, and discussions of methodology used in this study.

METHODS OF ANALYSIS

The base of moderately saline ground water defines an isoconcentration surface (surface of constant dissolved-solids concentration) of 10,000 mg/L. To prepare a map of an isoconcentration surface ideally requires measurement of changes in salinity with increasing depth at many places throughout the area of interest. Because such measurements apparently have not been made at any sites in San Juan County, and the total number of individual salinity measurements available was inadequate to define the 10,000 mg/L isoconcentration surface, it was necessary to use indirect methods of determining water salinity. Three methods generally suitable for use in the area were available, all utilizing geophysical well logs. For this study, the preferred method was the resistivity-porosity method first proposed by Archie (1942) and subsequently extended and refined by many others. A formation-compaction correction of 1.3 was used when calculating porosity from sonic logs. The SP (spontaneous potential) method developed by Alger (1966) was used as a check on the resistivity-porosity method, and was used for logged wells for which a porosity log was not available. The least reliable of the three methods, the resistivity-ratio method, is the ratio of the resistivity of the flushed zone to the resistivity of the uninvaded zone of the bore hole. It requires a microresistivity log and was used if there was neither a porosity log nor an SP log, or if these logs were not suitable for analysis. All of these methods yield calculated water resistivities that have to be converted to dissolved-solids concentrations. Water salinities calculated by such indirect methods should be checked by comparing them with measured salinities wherever possible.

More extensive explanations of the methods used in this study are available in a report by Howells and others (1987), in texts such as those by Asquith and Gibson (1982) or Hilchie (1982a,b), or in manuals published by well-log service companies such as Schlumberger (1972, 1974, 1984) or Dresser Atlas (1982, 1983).

The several hundred geophysical logs used in this study either were copied from the microfilm archive of the Utah Division of Oil, Gas and Mining, or were purchased from the Petroleum Information Corporation.[1] Formation tops used in interpretation were those listed in the files of the Petroleum Information Corporation. Identification of particular formations as sources of water samples analyzed or tested for resistivity either were listed as such on the analyses or were determined from information in the files of the Petroleum Information Corporation.

Water-quality data for San Juan County were collected from oil- and gas-well operators and from public agencies and their consultants. The data included chemical analyses and specific conductance or resistivity of water from springs, public- and domestic-supply wells, livestock and irrigation wells, observation wells and test holes of public agencies, and oil and gas wells and test holes. A water-quality data base was developed from this information. This data base is available on the computer system of the U.S. Geological Survey, Water Resources Division, Utah District office in Salt Lake City under the filename "ARCHIVE>SANJUAN.UT.QW.1987".

GEOLOGIC AND HYDROLOGIC SETTING

The discussion of geology and hydrology that follows, as well as the information in figure 3 and table 1, is summarized primarily from Avery (1986), Blanchard (1986), Cooley and others (1969), Feltis (1966), Freeman and Visher (1975), Hackman and Wyant (1973), Hanshaw and Hill (1969), Haynes and others (1972), Hill (1976), Newman and Goode (1979), Petersen (1956), Ritzma and Doelling (1969), the Rocky Mountain Association of Geologists (1972), Sanborn (1958), Stanley and others (1971), Thomas (1989), Wengerd and Matheny (1958), Wiegand (1981), Williams (1964), and Williams and Hackman (1971). Where applicable, the aquifer classification and nomenclature used follow that of Thomas (1989, table 1), and generally correspond to that of Avery (1986) and of Cooley and others (1969).

The stratigraphic nomenclature and age relations of the major bedrock formations in San Juan County are shown in figure 3, geographic features of the area are shown in figure 4, major older (pre-Laramide) tectonic elements are shown in figure 5, and major modern tectonic elements are shown in figure 6. No consolidated rocks of Cenozoic age have been reported in San Juan County except for intrusive and volcanic rocks found mostly in the La Sal and Abajo Mountains and Navajo Mountain (fig. 4, pl. 1). Brief descriptions of the major bedrock formations and an outline of their hydrologic significance are given in table 1.

Geologic History and Structure

Geologic structures in San Juan County that have the most important effect on ground-water movement are salt anticlines and three domes of Tertiary intrusive rock; of lesser, but significant, importance are tectonic flexures, such as the Monument Upwarp (fig. 6). The widespread faulting and fracturing of rocks commonly permit vertical movement of water between aquifers.

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[1]The use of company names in this report is for identification only and does not constitute endorsement by the U.S. Geological Survey.

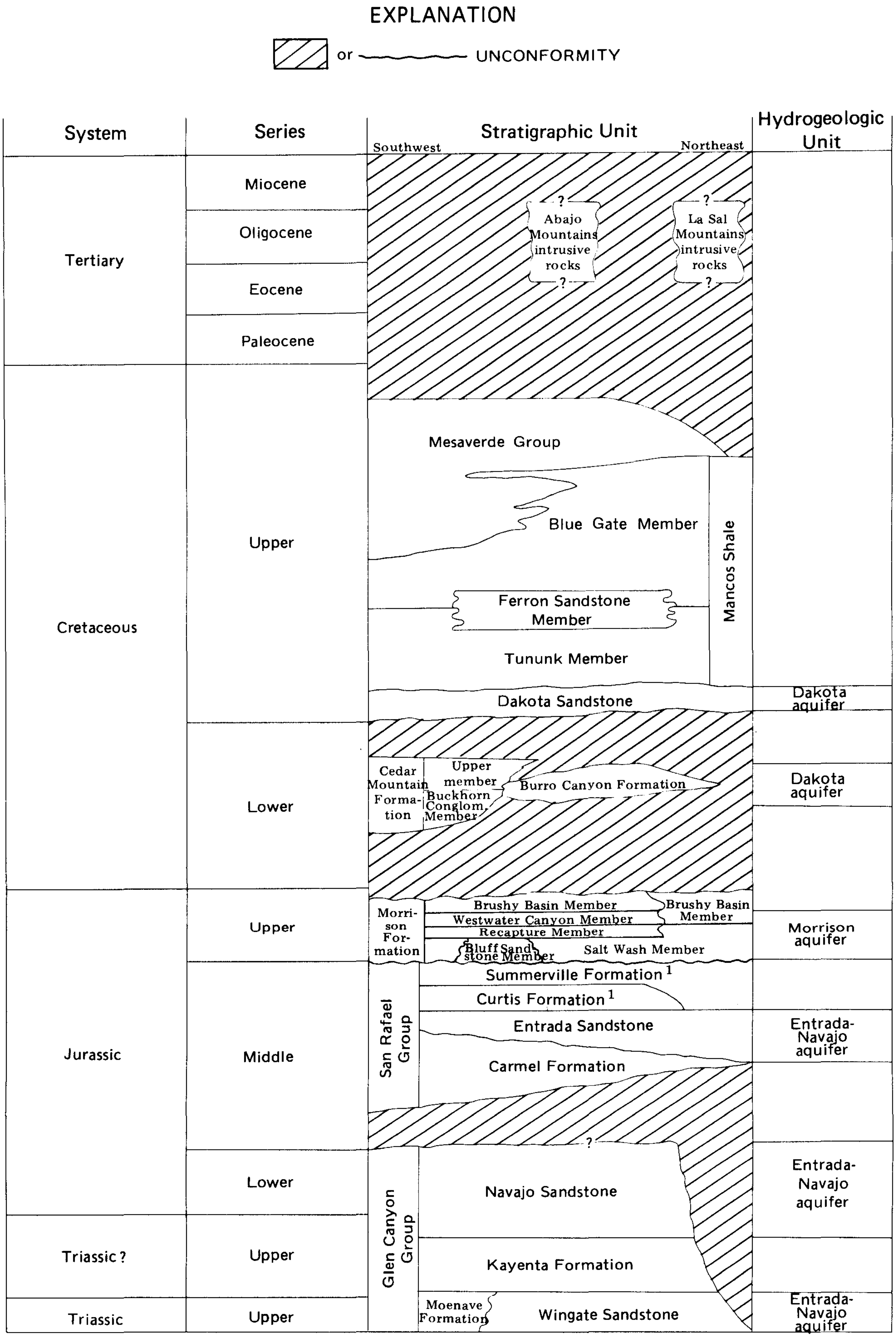


Figure 3.--Major bedrock stratigraphic units of San Juan County.

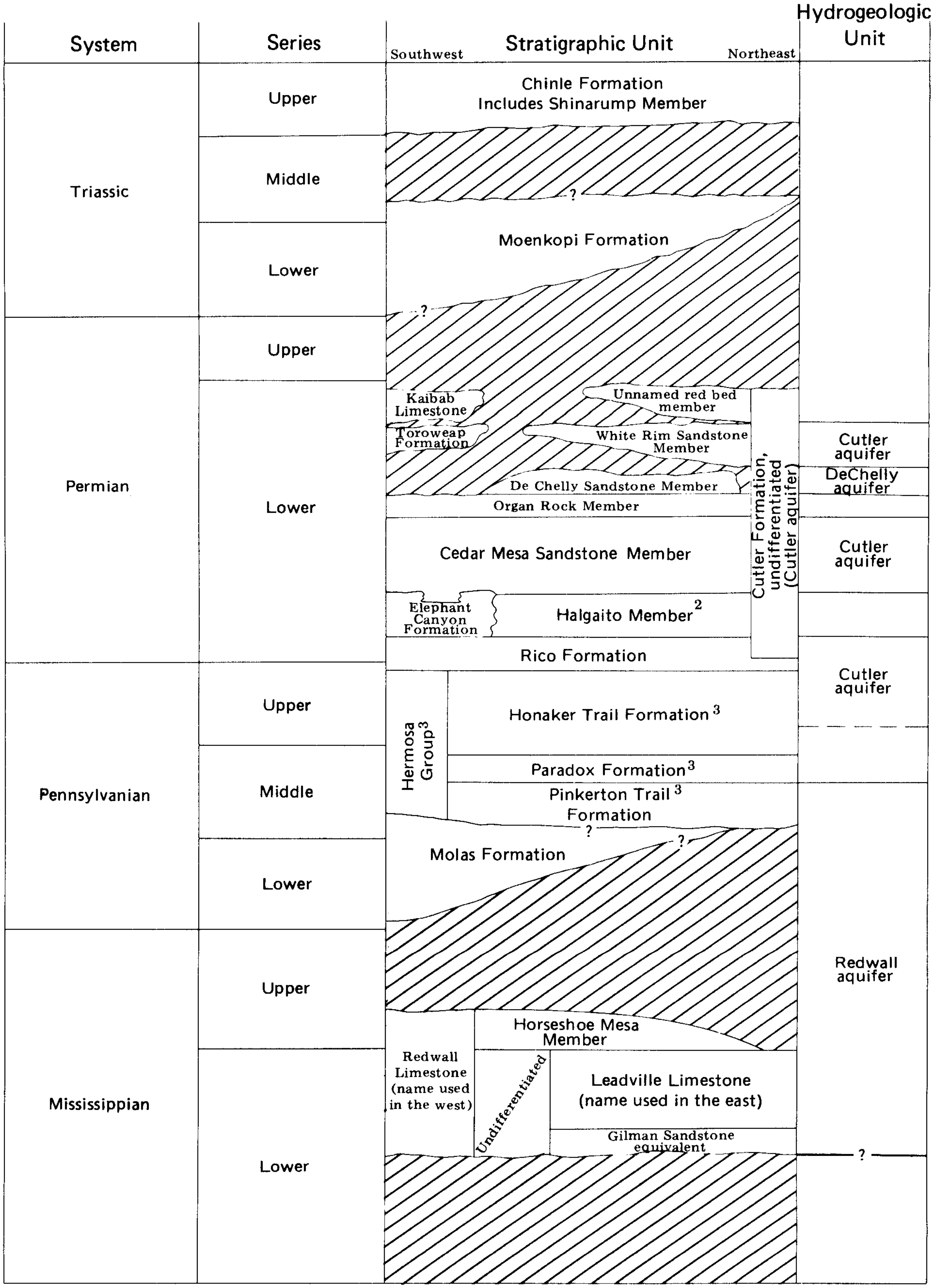
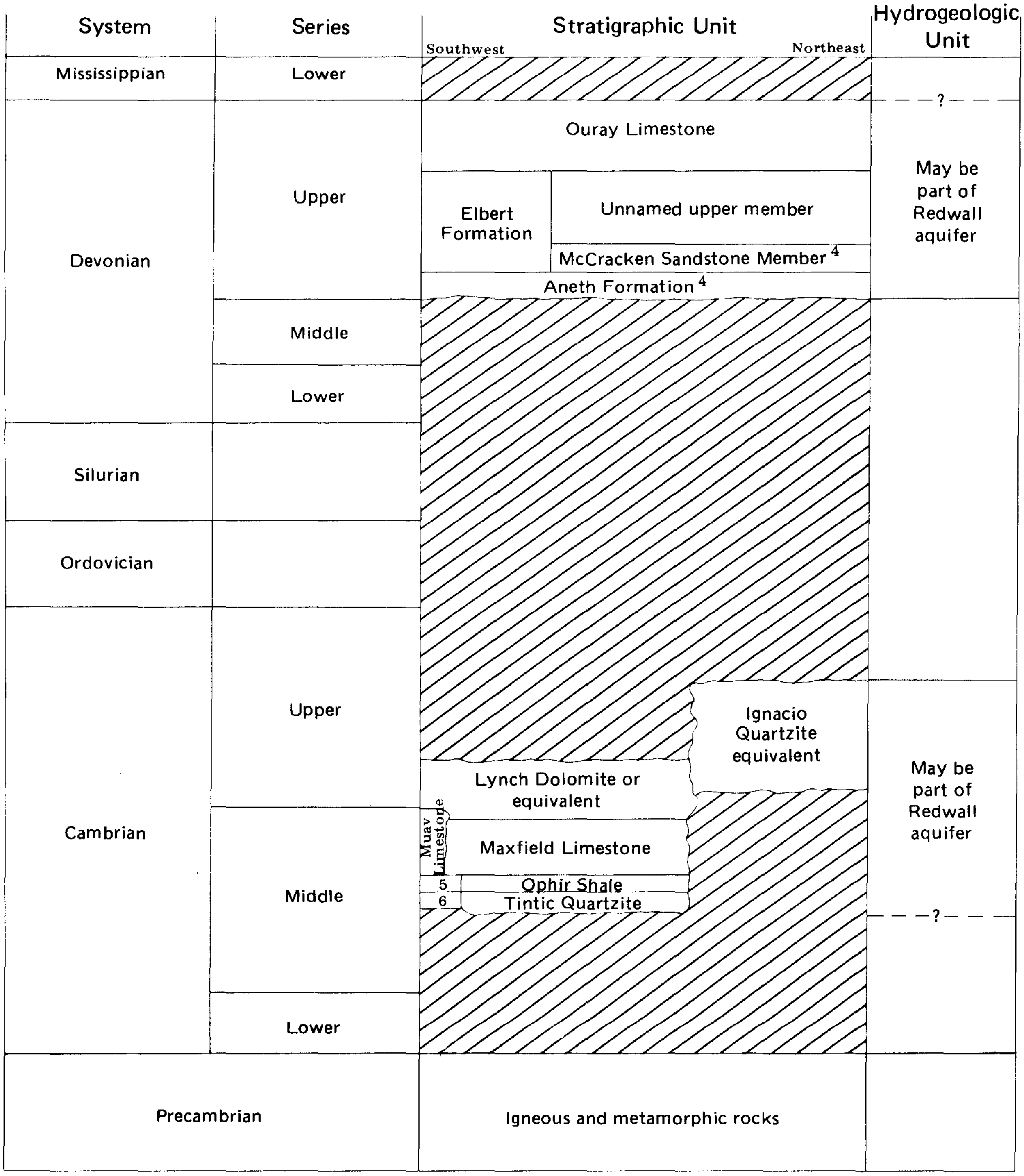


Figure 3.--Major bedrock stratigraphic units of San Juan County--Continued.



[1] Stratigraphic nomenclature has been revised for the Curtis and Summerville Formations. The Wanakah Formation is now considered the stratigraphic equivalent of the Curtis and Summerville Formations in San Juan County (O'Sullivan, 1980).
[2] Baars (1962)
[3] Wengerd and Matheny (1958)
[4] Knight and Cooper (1955)
[5] Bright Angel Shale
[6] Tapeats Sandstone

Figure 3.--Major bedrock stratigraphic units of San Juan County--Continued.

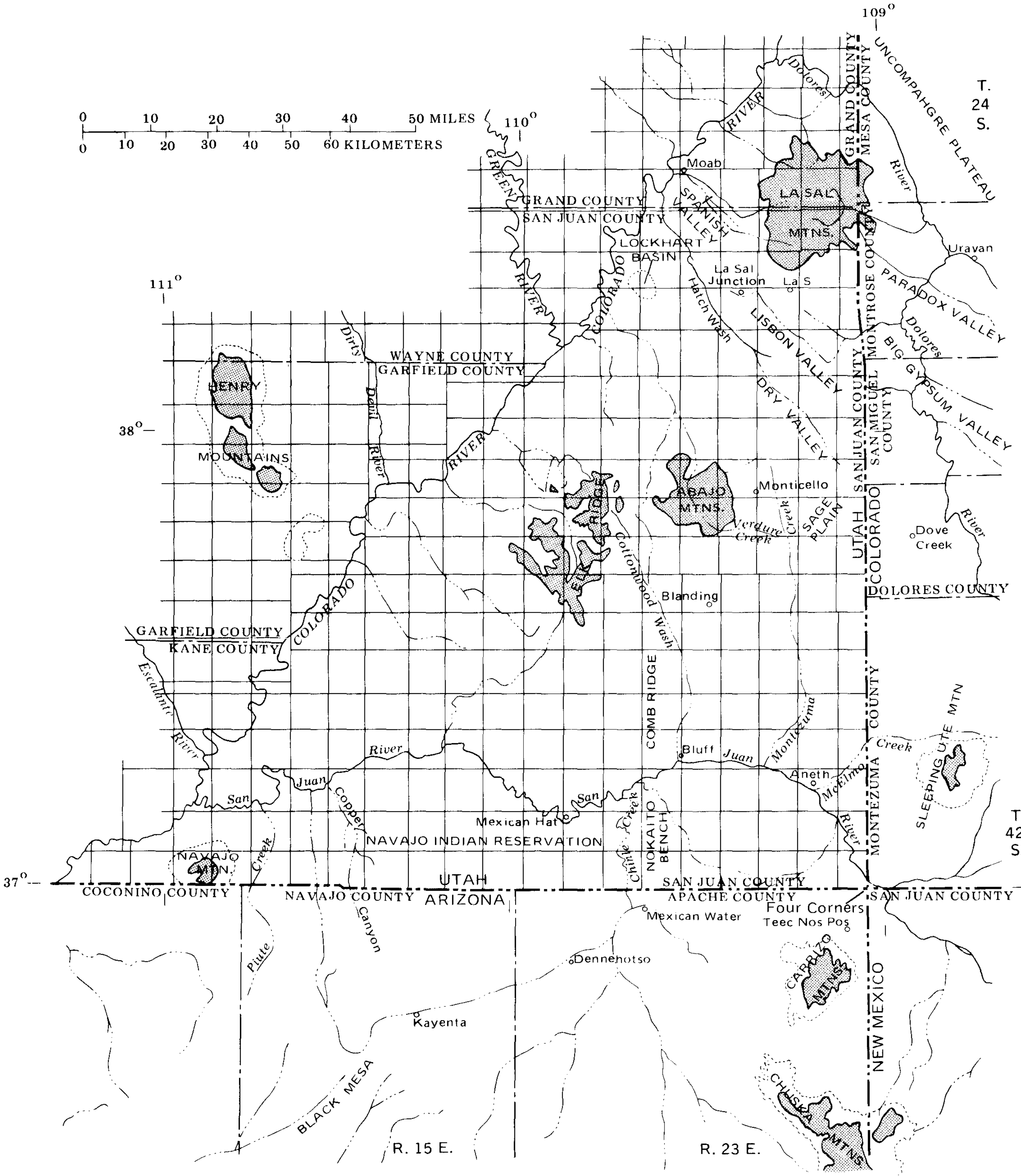


Figure 4.--Geographic features in and adjacent to San Juan County. Shaded areas are more than 8,000 feet above sea level and are probable recharge areas.

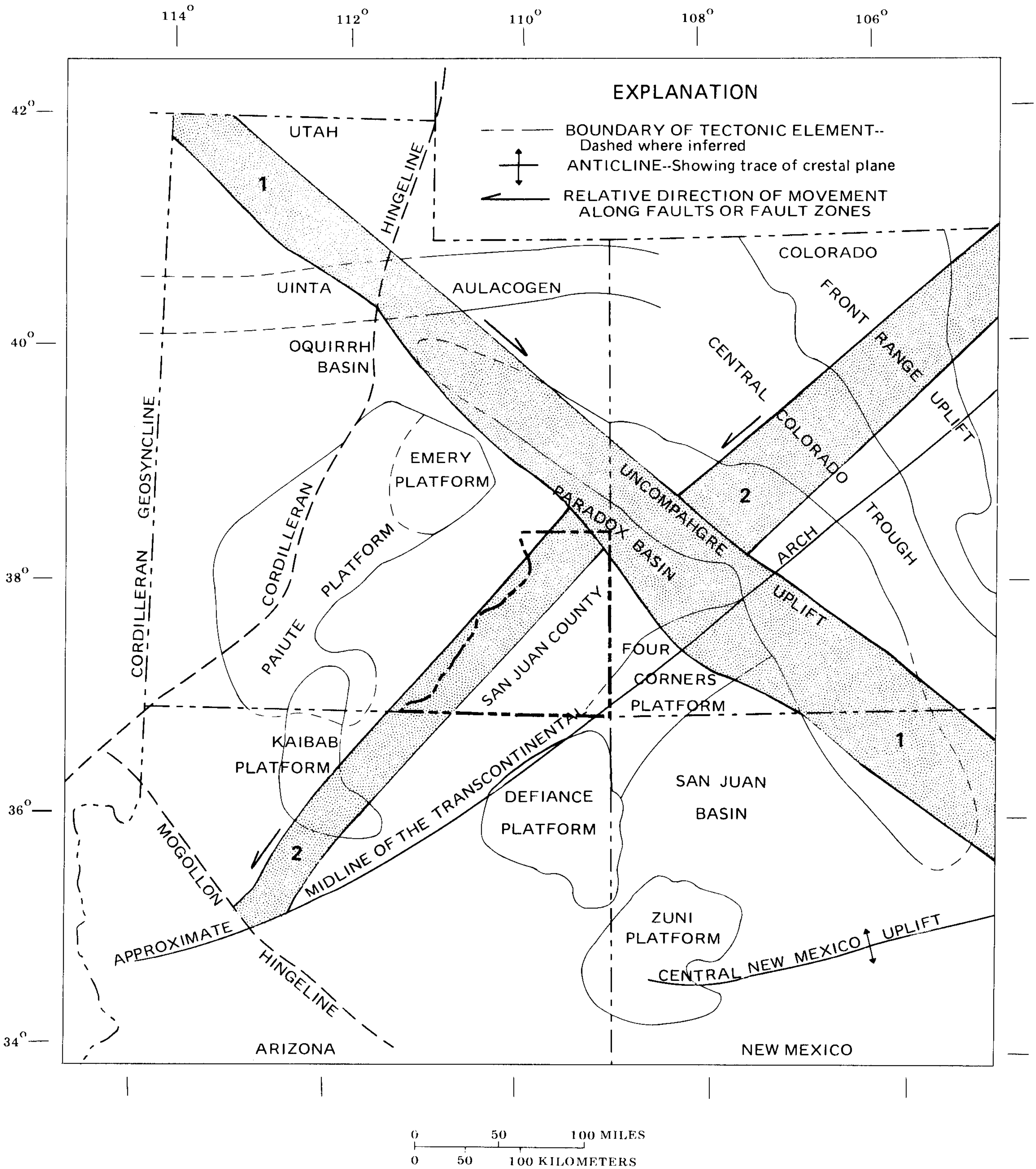


Figure 5.--Pre-Laramide major regional tectonic elements. Shaded elements are from Baars and Stevenson (1981, fig. 2): (1) Olympic-Wichita lineament and (2) Colorado lineament.

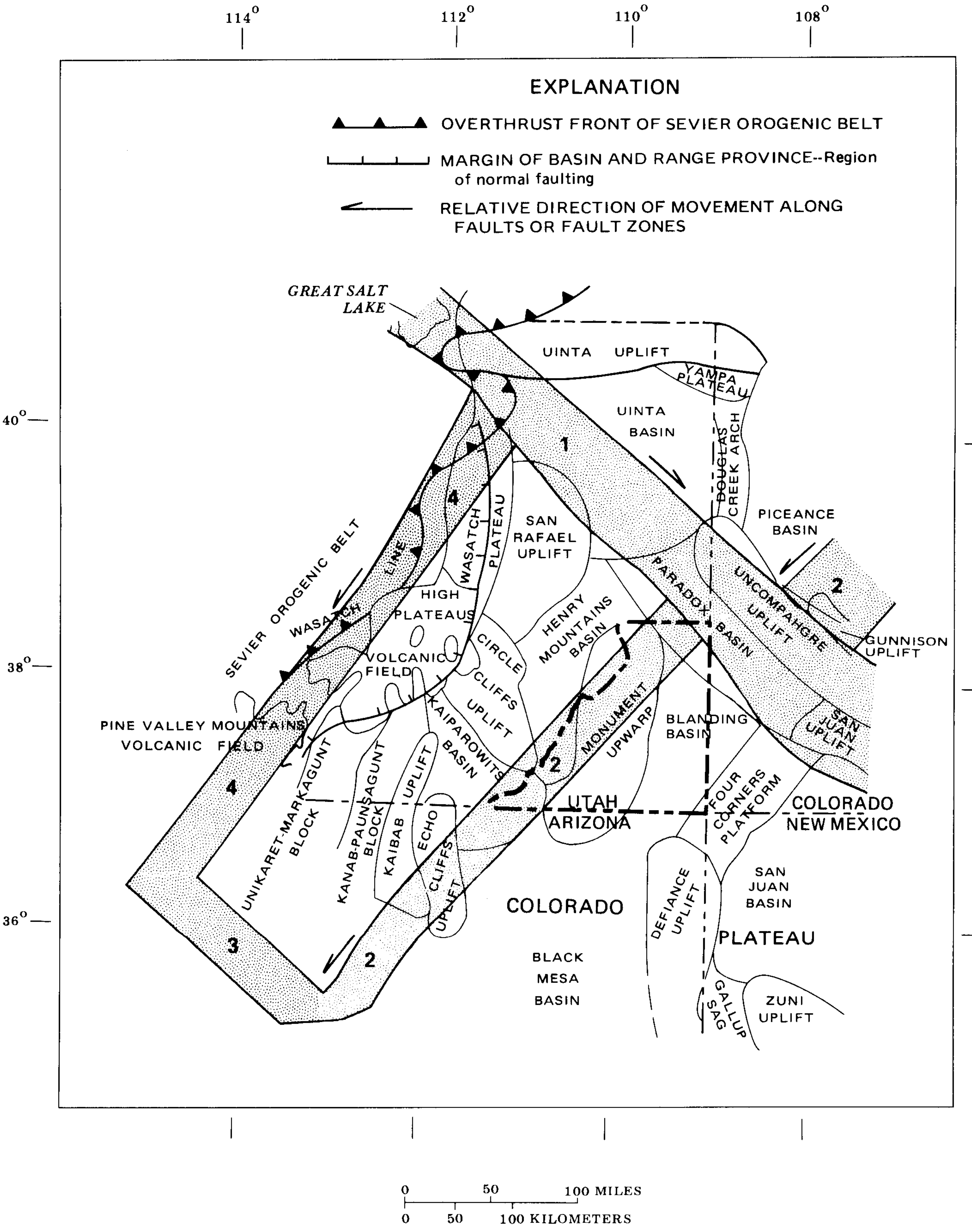


Figure 6.--Modern major regional tectonic elements (modified from Grose, 1972, fig. 1). Shaded elements are from Baars and Stevenson (1981, fig. 2): (1) Olympic-Wichita lineament, (2) Colorado lineament, (3) Mogollon hingeline (Walker Lane-Texas lineament), and (4) the Cordilleran hingeline.

Table 1.--*Generalized stratigraphic column for San Juan County describing the major bedrock units and their hydrologic characteristics and significance*

Erathem	System	Series	Group, formation, or rock unit	Maximum reported thickness (feet)	Description	Hydrologic characteristics and significance
CENOZOIC	TERTIARY	Eocene and Oligocene	Intrusive igneous rocks	5,000+	Intrusions are domal, each consisting of a central stock surrounded by a radial cluster of laccoliths and subordinate dikes and sills. The intrusives of the Abajo Mountains are mostly quartz diorite to diorite porphyry, but include granodiorite and quartz monzonite; also, diorite porphyry breccia is found in the stocks. Most of the laccoliths were emplaced in the Mancos Shale, but others were emplaced in the Cutler, Chinle, and Summerville Formations, and the Entrada Sandstone. The intrusives of the La Sal Mountains are mostly diorite porphyry, but include soda syenite, syenite, monzonite porphyry, and some vent breccia. The large sodium content of these rocks probably is the result of assimilation of salt from the intruded salt anticline. Navajo Mountain is believed to be a stock and laccolith dome similar to the Abajo and La Sal Mountains. The only igneous rock found thus far at Navajo Mountain is a small exposure of syenite porphyry.	Very low permeability[1]. Known to yield water only where jointed, fractured, or faulted. Water yielded is fresh. Fractures, particularly in sedimentary rock adjacent to an intrusion, may be the major path by which recharge of infiltrating precipitation reaches depths of several thousand feet to create thick recharge mounds of fresh to moderately saline water in the Abajo and La Sal Mountains, and, probably, at Navajo Mountain.
MESOZOIC	CRETACEOUS	Upper Cretaceous	Mesaverde Group	30(?)	A regressive sequence of continental fluvial, deltaic, and swamp deposits of shale, siltstone, sandstone, and coal beds that interfinger with the upper part of the Mancos Shale. Although the Mesaverde Group probably exceeded 1,000 feet in thickness throughout the county when deposited, subsequent erosion has removed all but a small, thin bed of basal sandstone in the La Sal Mountains.	Insignificant; too small in areal extent.
			Mancos Shale	800(?)	Soft, fissile, blue-gray to black, marine shale that contains a few thin beds of sandstone or limestone. The Mancos Shale has three members: The Blue Gate Member at the top, a bluish-gray shale that contains thin beds of bentonite or shaly sandstone and limestone; the Ferron Sandstone Member in the middle, a fine-grained, thin-bedded sandstone and sandy shale; and the Tununk Member at the base, a dark-gray to black mudstone and shale that contains some thin bentonite beds. The Mancos Shale is gradational with and laterally interfingers with the overlying Mesaverde Group. Although the Mancos Shale probably exceeded 3,000 feet in thickness throughout the county when deposited, erosion has removed all but small remnants in the Abajo and La Sal Mountains, in the deeper synclines in the northeastern part of the county, in scattered areas underlying some hills and ridges on the Sage Plain east of Monticello, and a small area on the Colorado State line near the southeastern corner of the county.	Very low permeability; a barrier to the movement of water unless fractured. Water in the Mancos Shale, or in alluvium or colluvium derived from it, is saline. The Ferron Sandstone Member is too thin and too small in areal extent to have any hydrologic significance.

Table 1.--*Generalized stratigraphic column for San Juan County describing the major bedrock units and their hydrologic characteristics and significance*--Continued

Erathem	System	Series	Group, formation, or rock unit	Maximum reported thickness (feet)	Description	Hydrologic characteristics and significance
MESOZOIC	CRETACEOUS	Upper Cretaceous	Dakota Sandstone	250	Deposited ahead of the westward advancing Mancos sea, the Dakota Sandstone includes continental deposits at the base and marine sediment at the top. The Dakota is yellowish-brown to gray, quartzitic, sometimes conglomeratic, fluvial to nearshore marine sandstone that contains interbedded gray to black non-marine shale and thin beds of low-grade coal. The formation locally contains a coarse conglomerate at the base. Most of the Dakota has been removed by post-Cretaceous erosion, but scattered remnants are in the Abajo and La Sal Mountains, in the deeper synclines in the northeastern part of the county, and capping some ridges and mesas on the Sage Plain and the area east of Comb Ridge and Nokaito Bench.	Generally very low to low permeability except where faulted or fractured. Ground water in the Dakota Sandstone usually is under water-table conditions, although in some areas, particularly where the Dakota is overlain by Mancos Shale or by clayey alluvium or colluvium, ground water may may be under artesian conditions. Because the areal distribution of the formation is fragmented, flow systems are local. The Dakota Sandstone and Burro Canyon Formation make up the Dakota aquifer (Thomas, 1989, table 1). Water in the Dakota aquifer ranges from fresh to moderately saline. The Dakota Sandstone yields fresh to slightly saline water in most areas, but water may be more saline where recharge has been in contact with Mancos Shale or with alluvium or colluvium derived from Mancos Shale. The Dakota Sandstone is a major source of potable water near Monticello and La Sal.
		Lower Cretaceous	Cedar Mountain Formation / Burro Canyon Formation	200	These formations, believed to be contemporaneous, were deposited on an erosional surface developed on the Morrison formation, by stream systems that drained to a distant northeastern sea. The Cedar Mountain Formation is a fluvial deposit that consists of two members. The upper member is composed of pastel-colored swelling clay and mudstone that contain many limestone nodules and a few scour-fill sandstone beds. The lower member, the Buckhorn Conglomerate Member, is a yellowish-gray, scour-and-fill sandstone that contains granule- to cobble-sized conglomeratic material. Where the formation has not been subjected to post-Cretaceous erosion, it seldom contains more than 30 percent sandstone and conglomerate. The Cedar Mountain Formation was deposited by streams that flowed from the west and southwest (present-day Nevada, California, and the northwestern corner of Arizona). The Cedar Mountain interfingers laterally with and grades into the Burro Canyon Formation at about the present location of the Colorado River. The Burro Canyon is a fluvial deposit of white, gray, and light-brown, quartzose sandstone and conglomerate interbedded with greenish and purplish, generally nonbentonic siltstone, shale, and silty and sandy mudstone, that contain a few thin beds of limestone. Where the formation has not been subjected to post-Cretaceous erosion, it usually is more than 50 percent sandstone and conglomerate. The proportion of sandstone and conglomerate is larger in the lower part, and the formation may be mostly shale in	Generally very low to low permeability except where faulted or fractured. The Cedar Mountain Formation is limited in areal extent; and thus, is hydrologically insignificant. Where the Burro Canyon Formation is water-bearing, ground water usually is under water-table conditions, though in some areas it is under artesian conditions. Because the areal distribution of the formation is fragmented, flow systems are local, and water quality is variable. The Burro Canyon Formation and the overlying Dakota Sandstone make up the Dakota aquifer. The Burro Canyon Formation is a major source of potable water around Blanding and on the Sage Plain, east of Monticello.

Table 1.—*Generalized stratigraphic column for San Juan County describing the major bedrock units and their hydrologic characteristics and significance*—Continued

Erathem	System	Series	Group, formation, or rock unit	Maximum reported thickness (feet)	Description	Hydrologic characteristics and significance
MESOZOIC	CRETACEOUS	Lower Cretaceous	Cedar Mountain Formation / Burro Canyon Formation		the upper part. The Burro Canyon was deposited by streams that flowed north and northwest from what are now Arizona and New Mexico. Both formations have been removed from most of the county by erosion, except for remnants in the Abajo and La Sal Mountains, in the deeper synclines in the northeastern part of the county, and capping mesas or underlying the Dakota Sandstone from the Sage Plain southward in the area east of Comb Ridge and Nokaito Bench.	
MESOZOIC	JURASSIC	Upper Jurassic	Morrison Formation	1,350+	Continental deposits of mostly fluvial (some lacustrine) shale, siltstone, mudstone, and sandstone that contain a few beds of fresh-water limestone. In the northern half of the county, the Morrison Formation is composed of two members. The upper member, the Brushy Basin Member, is laminated, variegated, gray, pale-green, red-brown, and purple bentonitic mudstone and siltstone that contain a few lenses of distinctive red and green chert-pebble conglomerate and sandstone that are locally uraniferous. The basal member is the Salt Wash Member, which is correlative with the Bluff Sandstone Member in the southern part of the county. The Salt Wash Member is a pale-gray, grayish-orange, and reddish-brown, fine- to medium-grained, sometimes conglomeratic sandstone interbedded with brown and greenish- or reddish-gray mudstone. The Salt Wash contains thin beds of calcareous gypsiferous shale and has thin beds of limestone near the base of the member. In some areas, the Salt Wash carries subcommerical to commercial concentrations of vanadium and uranium minerals. The Bluff Sandstone Member, an eolian deposit that contains minor interbeds of fluvial material, is a gray to buff, massive, mostly fine- to medium-grained sandstone deposited by westerly to southwesterly winds. The Bluff Sandstone Member is 350 ft thick near the town of Bluff, thins northward to zero thickness near Blanding, and thins southward to about 20 feet near the Arizona State line. In the southern half of the county the Morrison Formation thickens and is further divided; the Recapture and Westwater Canyon Members separate the Salt Wash and correlative Bluff Sandstone Members from the Brushy Basin Member. The Westwater Canyon Member is a yellowish- and greenish-gray to pinkish-gray, lenticular, fine- to coarse-grained, arkosic sandstone and conglomerate that contains some interbedded greenish-gray to grayish-red, sandy shale and mudstone. The Westwater Canyon Member interfingers with and grades into the lower part of the Brushy	The Brushy Basin Member has very low permeability and is a barrier to the movement of water except where faulted or fractured. A sample of the Brushy Basin Member from the canyon of McElmo Creek, just east of the Colorado State line, had a permeability of less than 10 millidarcies[2]. The average permeability of the Brushy Basin has been estimated as less than 5 millidarcies[3]. Permeability of samples of the Salt Wash, Recapture, and Westwater Canyon Members ranged from 263 to 813 millidarcies[3], with a general trend of decreasing permeability to the northeast. The Bluff Sandstone Member has low to moderate permeability. Samples of the Bluff ranged in permeability from 430 to 3,240 millidarcies, with a slight trend of increasing permeability to the southeast. The Salt Wash, Recapture, Westwater Canyon, and Bluff Sandstone Members make up the Morrison aquifer (Thomas, 1989, table 1). Water in the aquifer is usually under water-table conditions where the units that make up the Morrison aquifer crop out, but where the units are overlain by the Brushy Basin Member or by relatively impermeable beds within the Morrison Formation below the Brushy Basin, the water may be under artesian conditions. Water in the Bluff Sandstone Member is under artesian conditions southeast of the Abajo Mountains; wells near Montezuma Creek and near the town of Bluff may flow. Water from the Morrison Formation ranges from fresh to moderately saline in most of the area, but south of T. 35 S., water may be very saline locally.

Table 1.--*Generalized stratigraphic column for San Juan County describing the major bedrock units and their hydrologic characteristics and significance*--Continued

Erathem	System	Series	Group, formation, or rock unit	Maximum reported thickness (feet)	Description	Hydrologic characteristics and significance
MESOZOIC	JURASSIC	Upper Jurassic	Morrison Formation		Basin Member between Monticello and Blanding. The Recapture Member is a reddish-gray, white, and brown, fine- to medium-grained, calcareous and gypsiferous sandstone and interbedded reddish-gray siltstone and mudstone, locally uraniferous, that thins and grades into the underlying Salt Wash Member to the northeast. The stream system that deposited the Salt Wash Member flowed from the southwest, whereas the streams that deposited the other members flowed from the south or southeast. All streams apparently flowed out of the county to the northeast. The Morrison Formation is the oldest major stratigraphic unit for which the source area of the sediment was to the west in the former Cordilleran geosyncline. The Morrison Formation is thickest in the southern part of the county and thins to the north and east. This formation has been eroded from most of the county west of Comb Ridge and Nokaito Bench, but is found in most of the county east of these areas. North of the Abajo Mountains, it is found east of R. 23 E.; it also is found in a small area west of Navajo Mountain.	
		Middle Jurassic	Summerville Formation Curtis Formation	300 (Summerville) 200 (Curtis)	The Summerville Formation[4], found throughout the county, is the marginal-marine, tidal-flat, and fluvial facies, and the Curtis Formation[4], found in the northwestern part of the county, is the marine facies of a sedimentary deposit that resulted from the final episode of marine invasion from the western Cordilleran sea. The Summerville is calcareous and gypsiferous, laminated, dark reddish-brown or gray shale, siltstone, and very fine to fine-grained sandstone. The formation contains an irregular zone of chert (and, locally, limestone) concretions near its top. Ripple marks and mud cracks are common. The Curtis Formation is greenish-gray to brown, glauconitic, fine- to coarse-grained sandstone and siltstone that contain thin beds of shale and locally contain thin lenses of conglomerate. The Curtis grades southward, eastward, and upward into the Summerville Formation. Both the Curtis and Summerville Formations thicken toward the northwest. Both formations have been removed from the county by erosion west of Comb Ridge. Small, scattered remnants of the Curtis are found near the Colorado River. The Summerville is found east of Comb Ridge and Nokaito Bench, in the area	Very low to low permeability; a barrier to the movement of water except where faulted or fractured.

Table 1.--*Generalized stratigraphic column for San Juan County describing the major bedrock units and their hydrologic characteristics and significance*--Continued

Erathem	System	Series	Group, formation, or rock unit	Maximum reported thickness (feet)	Description	Hydrologic characteristics and significance
MESOZOIC	JURASSIC	Middle Jurassic	Summerville Formation Curtis Formation		east of R. 22 E. and north of the Abajo Mountains, and in a small area west of Navajo Mountain.	
MESOZOIC	JURASSIC	Middle Jurassic	Entrada Formation Carmel Formation	550 (Entrada) 164 (Carmel)	The Entrada Sandstone is the shoreward, shallow-marine, coastal-dune, and continental-eolian facies, and the Carmel Formation is the marine facies formed by a cycle of advance and retreat of the western Cordilleran sea. The Entrada Sandstone contains a topmost unit of white or light-colored, medium-grained, well-sorted sandstone believed to have been a coastal-dune complex; a middle unit of light buff to light reddish-brown, yellowish-orange to salmon, very fine to medium-grained, massive sandstone of eolian and, possibly, shallow-marine origin; and a basal unit of reddish-brown, poorly bedded, sandy siltstone and silty sandstone that had been deposited in a shallow-marine environment. The Carmel is a greenish-gray to red, silty shale, siltstone, and sandstone that contains gypsum and thin beds of limestone. The Carmel Formation thickens westward. The Carmel and Entrada underlie much of the area east of Comb Ridge and Nokaito Bench and east of R. 23 E., north of the Abajo Mountains; but to the west, most of these formations have been removed by erosion except for scattered remnants near the Colorado River and west of Navajo Mountain.	Very low to low permeability. Both the lower unit of the Entrada Sandstone and the Carmel Formation are barriers to the movement of water except where faulted or fractured. Permeability of samples from the Entrada ranged from 26 to 1,445 millidarcies[3], but generally was about 250 millidarcies. Where the Entrada Sandstone is overlain by other formations, water in the Entrada commonly is under artesian conditions. Wells flow in the Blanding Basin. Water from the Entrada Sandstone is fresh to moderately saline, but south of T. 35 S., it may be very saline locally. Permeability of samples from the Carmel ranged from 1 to as much as 54 millidarcies[3], though most samples were less than 10 millidarcies. The largest permeability was found where the Carmel locally contained relatively clean sandstone beds. The Entrada, Navajo, and Wingate Sandstones and the Carmel and Kayenta Formations make up the Entrada-Navajo aquifer (Thomas, 1989, table 1)
MESOZOIC	TRIASSIC (?) AND JURASSIC	Upper Triassic (?) and Lower Jurassic	Navajo Sandstone	1,250	White and gray to very pale-orange, well-rounded, well-sorted, massive, fine- to medium-grained eolian sandstone deposited by northwesterly winds. The Navajo Sandstone thins eastward and northward and intertongues with the underlying Kayenta Formation in southwestern Utah. The Navajo Sandstone locally contains beds of blue-gray, cherty, dolomitic, freshwater limestone that probably were deposited in playa lakes. Some geologists believe that the Navajo is a nearshore, shallow-marine, and coastal-dune complex deposit or a tidal-dominated shallow-marine shelf deposit. The Navajo Sandstone is thickest south of the San Juan River. The formation underlies most of the area east of Comb Ridge and east of R. 20 E., north of the Abajo Mountains; west of there, it has been removed by erosion except in areas west of Piute Creek and within a band 10 to 17 miles wide near the Colorado River, south of T. 35 S.	Low permeability. Permeability of samples of the Navajo Sandstone ranged from about 200 to 665 millidarcies[2] and generally increased from east to west, commonly increasing as the thickness of the formation increases. Wherever the Navajo is overlain by other formations, particularly the Carmel, Curtis, or Summerville Formations, water in the Navajo usually is under artesian conditions. In the Blanding Basin, wells flow. The Navajo Sandstone is the major unit making up the Entrada-Navajo aquifer. The Navajo is the major source of potable ground water in the county. Water from the formation generally is fresh to moderately saline, but south of T. 35 S., it may be very saline to briny locally.

Table 1.--*Generalized stratigraphic column for San Juan County describing the major bedrock units and their hydrologic characteristics and significance*--Continued

Erathem	System	Series	Group, formation, or rock unit	Maximum reported thickness (feet)	Description	Hydrologic characteristics and significance
MESOZOIC	TRIASSIC	Upper Triassic	Kayenta Formation	339	Red, gray, purplish-gray, reddish-purple, and lavender, very fine to coarse-grained, irregularly bedded, locally conglomeratic, fluvial sandstone, siltstone, and shale, that contain beds of red and green mudstone or lacustrine limestone. The proportion of silt is greatest north of the San Juan River, and the proportion of sand is greatest south of the river. The Kayenta Formation thins southeastward to a thickness of about zero in the southeastern corner of the county. The Kayenta intertongues with the overlying Navajo Sandstone in southwestern Utah. The Kayenta was deposited by westward-flowing streams. The formation underlies most of the area east of Comb Ridge and east of R. 20 E., north of the Abajo Mountains. It also is found west of Copper Canyon and in scattered areas near the Colorado River.	Very low to low permeability; somewhat of a barrier to the movement of water except where faulted or fractured. Permeability of samples of the Kayenta Formation ranged from 30 to 295 millidarcies[2]. Permeability values seem to be lowest in the northeastern part of the county. The Kayenta is a semipermeable, leaky confining bed within the Entrada-Navajo aquifer. Water from the Kayenta generally is fresh to moderately saline, but south of T. 35 S., it may be very saline to briny locally.
			Moenave Formation Wingate Sandstone	650	The Moenave Formation has a basal member of reddish-orange, fine- to coarse-grained, friable sandstone, siltstone, and mudstone, and an upper member of pale reddish-brown, medium-grained, micaceous sandstone that contains some siltstone. The Wingate Sandstone is very pale-orange, reddish- to grayish-orange, light-brown, and buff, well-sorted, very fine to medium-grained, calcareous, massively bedded, well-cemented, eolian sandstone that was deposited by northwesterly winds. In the southwestern part of the county, the fluvial Moenave Formation interfingers with the Wingate Sandstone. The Moenave thickens to the southwest, whereas the Wingate is thickest south of the San Juan River and thins northward. The Moenave Formation is present west of Copper Canyon. The Wingate Sandstone underlies most of the county east of Comb Ridge and east of R. 20 E., north of the Abajo Mountains. It also is found in scattered areas near the Colorado River and west of Copper Canyon.	Very low to low permeability except where faulted or fractured. Permeability of samples of Wingate Sandstone ranged from 65 to 340 millidarcies[2] and was fairly uniform throughout the county. The lowest permeability values were measured in samples from just east of the Colorado State line. This formation is the lowest part of the Entrada-Navajo aquifer. Water from the Wingate is fresh to moderately saline, but locally it may be very saline to briny.
			Chinle Formation	2,000	Varicolored, red, reddish-brown, and orange-red fluvial and lacustrine deposits laid down by northward- and northwestward-flowing streams. The Chinle Formation usually has siltstone and conglomeratic sandstone near the top, flood-plain or lacustrine, bentonitic mudstone and marly mudstone in the middle, and fluvial, conglomeratic sandstone and mudstone in the lower part. The Chinle Formation underlies most of the area east of Comb Ridge and east of R. 20 E., north of the Abajo Mountains. It also occurs in scattered	Very low to low permeability; a barrier to the movement of water except where jointed, faulted, or fractured. Uranium ore bodies in the La Sal Mountains yield large quantities of water to the mines. Permeability of samples of sandstone beds in the lower part of the Chinle ranged from 3 to 1,000 millidarcies[2]. Permeability of the sandstone beds increases from northeast to southwest and reaches a maximum near the center of the county. The Chinle Formation is a confining bed between the Entrada-Navajo and Cutler or DeChelley

Table 1.--*Generalized stratigraphic column for San Juan County describing the major bedrock units and their hydrologic characteristics and significance*--Continued

Erathem	System	Series	Group, formation, or rock unit	Maximum reported thickness (feet)	Description	Hydrologic characteristics and significance
MESOZOIC	TRIASSIC	Upper Triassic	Chinle Formation		areas near the Colorado River and along the Arizona State line, and west of Copper Canyon. Uraniferous in some areas, particularly the La Sal Mountains.	aquifers. Water from the basal sandstone of the Chinle ranges from fresh to briny.
MESOZOIC	TRIASSIC	Lower and Middle Triassic	Moenkopi Formation	2,500+	A marginal marine deposit that grades from tidal-flat, deltaic, and fluvial beds in the eastern part of the county to a shallow-water, marine limestone facies in the western part of the county. The Moenkopi Formation has an upper unit of brown to reddish-brown, shaly siltstone, thin, flaggy sandstone, and thick, massive sandstone that, in the northwest, contains a thin marine limestone bed. The lower unit is interbedded thin, commonly contorted, beds of reddish-brown to reddish-orange, fine- to medium-grained, micaceous, silty sandstone and shaly siltstone that locally contain gypsum beds. Ripple marks and mudcracks are common. In the northeastern part of the county, the formation may contain arkosic conglomerate. The Moenkopi Formation is thickest adjacent to the major salt anticlines in the northeastern part of the county because the salt diapirs were rising and their anticlinal crests were being eroded as the Moenkopi was being deposited. The Moenkopi is found throughout the county except where it has been eroded from the Monument Upwarp and from the crests of the salt anticlines.	Commonly very low permeability; a barrier to the movement of water except where faulted or fractured. The average permeability of the Moenkopi Formation has been estimated as less than 5 millidarcies[3].
PALEOZOIC	PERMIAN	Lower Permian	Kaibab Limestone / Toroweap Formation / Cutler Formation	10,000+	The Cutler Formation is mostly red to purple, fluvial arkose and arkosic fanglomerate, conglomerate, and finer grained continental and nearshore marine clastics derived from the ancestral Rocky Mountains. In the eastern and central parts of the county, fluvial deposition prevailed through most of the Permian, but in the southwestern and western parts of the county, marine, eolian, and fluvial deposition from meandering streams occurred. The coarsest beds are adjacent to the Uncompahgre Plateau. Many geologists place any arkosic conglomerate or fanglomerate of Pennsylvanian or Permian age in the undifferentiated Cutler Formation. Within 40 miles of the Uncompahgre Plateau, grain size decreases enough and bedding is prominant enough so that members of the Cutler can be distinguished. The topmost member commonly is an unnamed sequence of fluvial red beds--reddish-brown, red, and purple siltstone, mudstone, and shale that contain some interbedded sandstone. This unit is the fluvial and nearshore marine equivalent of the Kaibab Limestone. The Kaibab is a light-gray to	Very low to low permeability except where faulted or fractured. Shaly beds are barriers to the movement of water except where faulted or fractured. The permeability of sandstone beds in the Cutler Formation ranges from less than 2 to more than 900 millidarcies[2]. The undifferentiated Cutler Formation and the White Rim and Cedar Mesa Sandstone Members, where water bearing and permeable, are part of the Cutler aquifer; the DeChelly Sandstone Member, where water bearing and permeable, is defined as the DeChelly aquifer. The Organ Rock and Halgaito Members are confining beds within the Cutler aquifer. West of Comb Ridge, flow systems in the Cutler Formation probably are local. Water in the Cutler Formation ranges from fresh to briny.

Table 1.--*Generalized stratigraphic column for San Juan County describing the major bedrock units and their hydrologic characteristics and significance*--Continued

Erathem	System	Series	Group, formation, or rock unit	Maximum reported thickness (feet)	Description	Hydrologic characteristics and significance
PALEOZOIC	PERMIAN	Lower Permian	Cutler Formation		light-brown, cherty, dolomitic marine limestone. The next lower member of the Cutler is the White Rim Sandstone Member, a white, gray, and buff, fine- to coarse-grained, well-sorted sandstone that is the nearshore and sandbar-complex facies of the Toroweap Formation. Some geologists believe that the White Rim Sandstone Member is an eolian deposit. The Toroweap is a massive, marine, limey sandstone and, farther west, it is largely carbonate. Some geologists report Coconino Sandstone underlying the White Rim Sandstone Member in the northwestern part of the county and adjacent areas. These "Coconino Sandstone" beds interfinger with and laterally grade into the White Rim Sandstone Member and the underlying Organ Rock Member of the Cutler Formation. These "Coconino Sandstone" beds are not part of the true Coconino Sandstone of northwestern Arizona and southwestern Utah, but are local sandstone beds derived from erosion of an emergent Emery platform. They are considered here as part of the White Rim Sandstone Member. The next lower member, present south of Blanding, is the DeChelly Sandstone Member, a light colored to light-brown, reddish-orange or pale reddish-brown, fine-grained, mostly eolian sandstone deposited by northeasterly winds. The Organ Rock Member, the eastern extension of the Hermit Shale of the Grand Canyon, is red to reddish-brown shale, siltstone, and fine-grained sandstone that laterally grade into the coarser arkosic facies of the Cutler to the northeast. As far east as the eastern edge of the Monument Upwarp, the Organ Rock Member is underlain by the Cedar Mesa Sandstone Member, a white to light-gray, yellowish-gray, reddish-orange, and reddish-brown, fine- to coarse-grained sandstone that had been deposited in a shallow-marine foreshore environment. The Cedar Mesa Sandstone Member is underlain by the marine Elephant Canyon Formation of Baars (1962) in the west and by the Halgaito Member of the Cutler Formation in the east. The Elephant Canyon Formation is limestone and dolomite beds that contain red to brown or purple sandstone, siltstone, and shale beds in the middle and red siltstone and light-colored sandstone near the top. The Halgaito Member of the Cutler Formation is a fluvial red bed sequence of dark red-brown to chocolate-brown, fine- to medium-grained, thin-bedded, arkosic sandstone, siltstone, and mudstone. The Halgaito Member contains a few thin, lenticular beds of purplish-	

Table 1.--*Generalized stratigraphic column for San Juan County describing the major bedrock units and their hydrologic characteristics and significance*--Continued

Erathem	System	Series	Group, formation, or rock unit	Maximum reported thickness (feet)	Description	Hydrologic characteristics and significance
PALEOZOIC	PERMIAN	Lower Permian	Cutler Formation		gray limestone near the base. The Cutler Formation underlies all of the county except where removed by erosion on the crests of the salt anticlines and in the deeper canyons.	
	PENNSYLVANIAN and PERMIAN	Upper Pennsylvanian and Lower Permian	Rico Formation	900	Deposited in a retreating sea, the Rico Formation includes normal marine carbonate deposits, associated nearshore and shoreline deposits, and coastal-plain fluvial deposits of reddish-brown and greenish-gray, fine- to medium-grained, calcareous sandstone, reddish-brown, grayish-green, or pale red-purple, partly gypsiferous, micaceous siltstone and sandy shale, and gray, thin- to thick-bedded, cherty limestone. The formation underlies the entire county except where eroded on the crests of salt anticlines and in the deeper canyons.	Very low permeability; probably a barrier to the movement of water except where faulted or fractured. Except at outcrops, water from the Rico Formation is moderately saline to briny. Permeable units in the Rico Formation are considered part of the Cutler aquifer.
	PENNSYLVANIAN	Middle and Upper Pennsylvanian	Hermosa Group of Wengerd and Matheny (1958)	15,000+	Deposited in an environment that ranged from normal marine shoal and shelf to hypersaline evaporite basin, the Hermosa Group has been divided into three formations. The top and bottom formations, the Honaker Trail and Pinkerton Trail Formations, are similar in lithology. They commonly are blue to gray, thin- to thick-bedded limestone and dolomite that contain beds of gray, fine-grained micaceous sandstone and siltstone, lavender sandy shale, and occasional thin interbeds of black shale and anhydrite; reefs and algal bioherms are common. The middle formation, the Paradox Formation, contains a thick sequence of evaporite deposits interbedded with black shale, carbonate, and fine-grained sandstone and siltstone in what was the deepest part of the Paradox Basin, and limestone and dolomite interbedded with shale and fine-grained sandstone to the west and south of the evaporite sequence. Toward the Uncompahgre Plateau, all three members interfinger with coarse arkosic sediments eroded from the ancestral Rocky Mountains. The Hermosa Group is thickest in the salt anticlines in the northeastern part of the county.	Very low to high permeability. Evaporites are a barrier to the movement of water. Carbonate rocks, except reefs and bioherms, usually are barriers to the movement of water except where faulted or fractured or where solution channels have developed. Reef and biohermal deposits may be highly permeable and can have porosities of as much as 30 percent. Except at outcrops, water from the Hermosa Group usually is moderately saline to briny. Dissolved-solids concentrations can exceed 400,000 milligrams per liter. Permeable intervals in the upper two-thirds of the Honaker Trail Formation are considered part of the Cutler aquifer. Permeable intervals and facies in the Pinkerton Trail Formation of the Hermosa Group are part of the Redwall aquifer.
		Lower and Middle Pennsylvanian	Molas Formation	290	A continental deposit, the Molas Formation commonly is a regolith that developed on the karst surface of the Mississippian carbonate beds. The formation is variegated from reddish-brown to maroon siltstone; red, silty shale; and calcareous sandstone and contains some gray to reddish-brown, thin-bedded limestone. Locally the Molas is conglomeratic, particularly near the base.	Very low to low permeability; probably a barrier to the movement of water except where faulted or fractured. Permeable intervals and facies are part of the Redwall aquifer.

Table 1.--*Generalized stratigraphic column for San Juan County describing the major bedrock units and their hydrologic characteristics and significance*--Continued

Erathem	System	Series	Group, formation, or rock unit	Maximum reported thickness (feet)	Description	Hydrologic characteristics and significance
PALEOZOIC	MISSISSIPPIAN	Lower and Upper Mississippian	Redwall (Leadville) Limestone	828	Deposited on a broad, relatively flat, shallow-water, marine shelf, this formation is called the Redwall Limestone by some geologists, the Leadville Limestone by others. Many geologists call it the Redwall in the western part of the area and the Leadville in the eastern part of the area. The upper part of the formation is light-colored, dense, thin-bedded, sometimes oolitic, limestone; the lower part is tan, brown, gray, and pink, massive, cherty dolomite that locally contains thin beds of limestone near the top and also may contain thin beds of shale. In the eastern part of the county, the formation may contain a sandstone facies equivalent to the Gilman Sandstone of Colorado. Throughout much of the county, particularly in the western half, the upper part of the Redwall Limestone is a thin-bedded silty and clayey carbonate rock that is named the Horseshoe Mesa Member.	Very low to low permeability except where faulted or fractured or where solution channels have developed. Caverns and solution channels have been penetrated in several oil- or gas-test wells. Water from the Redwall (Leadville) Limestone probably is moderately saline to briny. This unit is the major part of the Redwall aquifer.
	DEVONIAN	Upper Devonian	Ouray Limestone	300	Deposited in a quiet-water, shallow-marine environment, the Ouray Limestone is a light-gray to tan, dense, commonly oolitic limestone that locally contains partings of green shale. Contact with the underlying Elbert Formation is gradational.	Very low to low permeability except where faulted or fractured or where solution channels have developed. Water in the formation probably is moderately saline to briny.
			Elbert Formation	420	Deposited in a shallow-water, in part intertidal, marine-shelf environment, the Elbert Formation is a gray-brown, thin-bedded, sandy dolomite that contains streaks of gray-green and red sandy shale. In the southeastern part of the county, the basal Elbert Formation contains a shoal and offshore bar facies, the McCracken Sandstone Member of Knight and Cooper (1955). The McCracken Sandstone Member is white and light-gray to red, fine- to medium-grained, poorly sorted, tightly cemented sandstone, commonly glauconitic and contains streaks of sandy dolomite.	Very low to low permeability except where faulted or fractured or where solution channels have developed. Water in the formation is moderately saline to briny.
			Aneth Formation of Knight and Cooper (1955)	249	Dark-brown to black, argillaceous, marine limestone and dolomite, commonly anhydritic and slightly glauconitic, and gray-green, brown, and black calcareous shale.	Very low permeability except where faulted or fractured or where solution channels have developed. Water in the formation probably is moderately saline to briny.
	CAMBRIAN	Upper Cambrian	Ignacio Quartzite equivalent	730	A basal transgressive marine deposit of light-red, thin-bedded, slightly friable sandstone.	Very low permeability except where faulted or fractured. Water in the formation probably is moderately saline to briny.

Table 1.--*Generalized stratigraphic column for San Juan County describing the major bedrock units and their hydrologic characteristics and significance*--Continued

Erathem	System	Series	Group, formation, or rock unit	Maximum reported thickness (feet)	Description	Hydrologic characteristics and significance
PALEOZOIC	CAMBRIAN	Upper Cambrian	Lynch Dolomite	1,300	Massive marine dolomite and interbedded shale.	Probably very low in permeability except where faulted or fractured or where there are solution channels. Water in the formation is very saline or briny.
		Middle Cambrian	Muav Limestone or Maxfield Limestone	650	Massive marine limestone that locally contains partings of green shale. Called the Muav Limestone in the southwestern part of the county and the Maxfield Limestone in the rest of the county.	Probably very low in permeability except where faulted or fractured or where there are solution channels. Water in the formation probably is very saline or briny.
			Bright Angel Shale or Ophir Shale	450	The offshore shale facies of a transgressive sea, the formation is red, green, and gray shale interbedded with fine-grained sandstone, siltstone, dolomite, and limestone. The formation grades from carbonate to shale to siltstone and sandstone from west to east. Known as the Bright Angel Shale in the southwestern part of the county and as the Ophir Shale in the rest of the county.	Probably very low permeability; a barrier to the movement of water except where faulted or fractured.
			Tapeats Sandstone or Tintic Quartzite	400	A basal transgressive marine deposit of red, brown, and white, fine- to coarse-grained, tightly cemented sandstone that is silty and shaly at the top. The formation thickens eastward from the southwestern corner of the county. Called the Tapeats Sandstone in the southwestern part of the county and the Tintic Quartzite in the rest the county.	Probably very low permeability except where faulted or fractured. Water in the formation probably is very saline or briny.
PRECAMBRIAN			Igneous and metamorphic rocks		Undifferentiated igneous and metamorphic rocks.	Very low permeability; a barrier to the movement of water except where jointed, faulted, or fractured.

[1]Ranges of permeability are defined as follows:

Range	Permeability, in millidarcies
Very low	Less than 185
Low	185 to 1,850
Moderate	1,850 to 18,500
High	18,500 to 185,000
Very high	More than 185,000

[2]Jobin, 1962.

[3]Ritzma and Doelling, 1969.

[4]Stratigraphic nomenclature has been revised for the Curtis and Summerville Formations. The Wanakah Formation is now considered the stratigraphic equivalent of the Curtis and Summerville Formations in San Juan County (O'Sullivan, 1980).

The salt anticlines had their origin in depositional and structural events that occurred from early Middle Pennsylvanian to middle Permian. Prior to Middle Pennsylvanian, the region was a fairly stable shelf that alternately was the site of erosion and deposition as it slowly oscillated above and below sea level. By early Middle Pennsylvanian, the ancestral Rocky Mountains (Uncompahgre uplift, fig. 5) were developing and had reached a height of at least 10,000 feet by Early Permian. The rise of the mountains was accompanied on the southwest by a parallel downwarping that formed the Paradox Basin (figs. 5 and 6). This basin developed as a series of northwest-southeast trending, southwest-tilted half grabens that stepped down into the basin from the southwest.

Deposition on the surface thus created was in the form of "synclines" and "anticlines". A greater thickness of sediment was deposited in the syncline over the southwestern down-tilted part of each half graben and a lesser thickness of sediment was deposited over the anticline of the northeastern uptilted part of each half graben.

As the Uncompahgre uplift rose throughout the Middle and Late Pennsylvanian, it shed increasing quantities of clastics into the northeastern margin of the Paradox Basin. The uplift continued as an area of high relief until the middle or early Late Permian. During this period, sediments deposited on the flanks of, and adjacent to, the uplift were coarse arkosic clastics, commonly fanglomerates and associated finer grained materials. The thickness of the Cutler Formation decreased from as much as 15,000 to 20,000 feet immediately adjacent to the ancestral Rocky Mountains to only 2,000 feet within 50 miles to the southwest; within the same distance, grain size decreased from boulder and cobble to sand and finer particles.

During the middle of the Middle Pennsylvanian, the Paradox Basin developed a restricted-circulation hypersaline environment punctuated by periodic influxes of normal marine water that resulted in cyclic deposition of a black shale-dolomite-evaporite sequence. The deepest part of the basin contains at least 29 evaporite cycles that had an aggregate maximum thickness of 5,000 to 7,000 feet at the time of deposition. By, or shortly after, the end of deposition of the evaporite sequence, the evaporite beds were mobilized and were beginning to develop anticlinal diapirs. Mobilization of the evaporite beds probably was due to tectonic stress because overburden pressure would have been too small to cause evaporite flow—depth of burial was less than 2,000 feet when the salt anticlines began to form. The location of the sites of formation of the diapirs, and their form as parallel northwest-southeast-trending anticlines, were controlled by the regional stress field and by the structure of the basin floor. Most diapiric movement had occurred by the end of the Permian; however, some general movement continued until the Jurassic, by which time most of the evaporites that had been over the uptilted parts of the half grabens had been squeezed out into the diapirs (local diapiric movement occurred as recently as the Cretaceous).

During the latest Cretaceous and early Tertiary, the crests of the salt anticlines collapsed in two stages. The first stage followed Late Cretaceous arching, when the crests of the salt anticlines dropped, as grabens, by as much as several hundred feet, possibly due to stress relaxation of the arches at a time when the evaporite cores of the arch crests were buried by about 5,000 feet of other sediments. The second stage of anticlinal crest collapse followed uplift and erosional breaching of the sedimentary cover of the evaporite cores of the anticlines. Removal of evaporite by solution led to the final collapse of the anticlinal crests. The maximum known thickness of evaporite in the anticlines is more than 14,000 feet. The maximum thickness of evaporite removed from the anticlinal crests by solution has been estimated to be more than 5,700 feet (Shoemaker and others, 1958).

Arching of the Monument Upwarp (fig. 6) in Late Cretaceous to mid-Tertiary time (Grose, 1972, p. 36) affects ground-water movement in the area because it resulted in removal, by erosion, of all strata younger than the Permian Cedar Mesa Sandstone Member of the Cutler Formation from the crest of the upwarp. Locally, all beds younger than the Pennsylvanian Honaker Trail Formation of the Hermosa Group (Wengerd and Matheny, 1958) have been removed by erosion.

During the mid-Tertiary, large domal uplifts developed at several places in the region. Three of these large domes are in San Juan County. All three domes, now known as the La Sal Mountains, Abajo Mountains, and Navajo Mountain (fig. 4), are believed to be igneous intrusions, each consisting of one or more central stocks surrounded by a radial cluster of laccoliths and subordinate dikes. In figure 7, the approximate outline of the Navajo Dome at Navajo Mountain is shown; the outlines of the domes at the La Sal and Abajo Mountains are approximately the extents of the La Sal and Abajo intrusives (fig. 7).

Description of Aquifers

The Redwall (Leadville) Limestone and permeable intervals and facies in the overlying Molas Formation and Pinkerton Trail Formation of the Hermosa Group (Wengerd and Matheny, 1958) probably make up the most widespread, continuous aquifer in San Juan County, which is defined in this report as the Redwall aquifer. Oil- and gas-test holes reportedly have penetrated solution channels and caverns in the carbonate beds in some places. Diagenesis of Cambrian and Devonian strata generally has reduced the porosity and permeability of these rocks so that they are relatively impermeable and can yield water only where they are faulted or fractured or where systems of solution channels have developed. Whether permeable intervals in Cambrian and Devonian strata are part of the Redwall aquifer or are of sufficient areal extent and continuity to make up one or more other aquifers is not known, but so little information is available that these formations are discussed in this report as part of the Redwall aquifer.

Although the Paradox Formation and the lowest one-third of the Honaker Trail Formation of the Hermosa Group usually are barriers to the movement of water, and are not defined as an aquifer in this report, this interval locally contains permeable deposits, many of which had been reefs or bioherms. In the Paradox Formation, biohermal deposits are more common west of the area of evaporite deposition. Water in these permeable deposits is thought to be connate, or to be leakage through faults and fractures from overlying or underlying aquifers.

Avery (1986) defined the "P aquifer" to include the permeable beds in the undifferentiated Cutler Formation and the Cedar Mesa Sandstone Member of the Cutler. Thackston and others (1981) believed that the permeable intervals

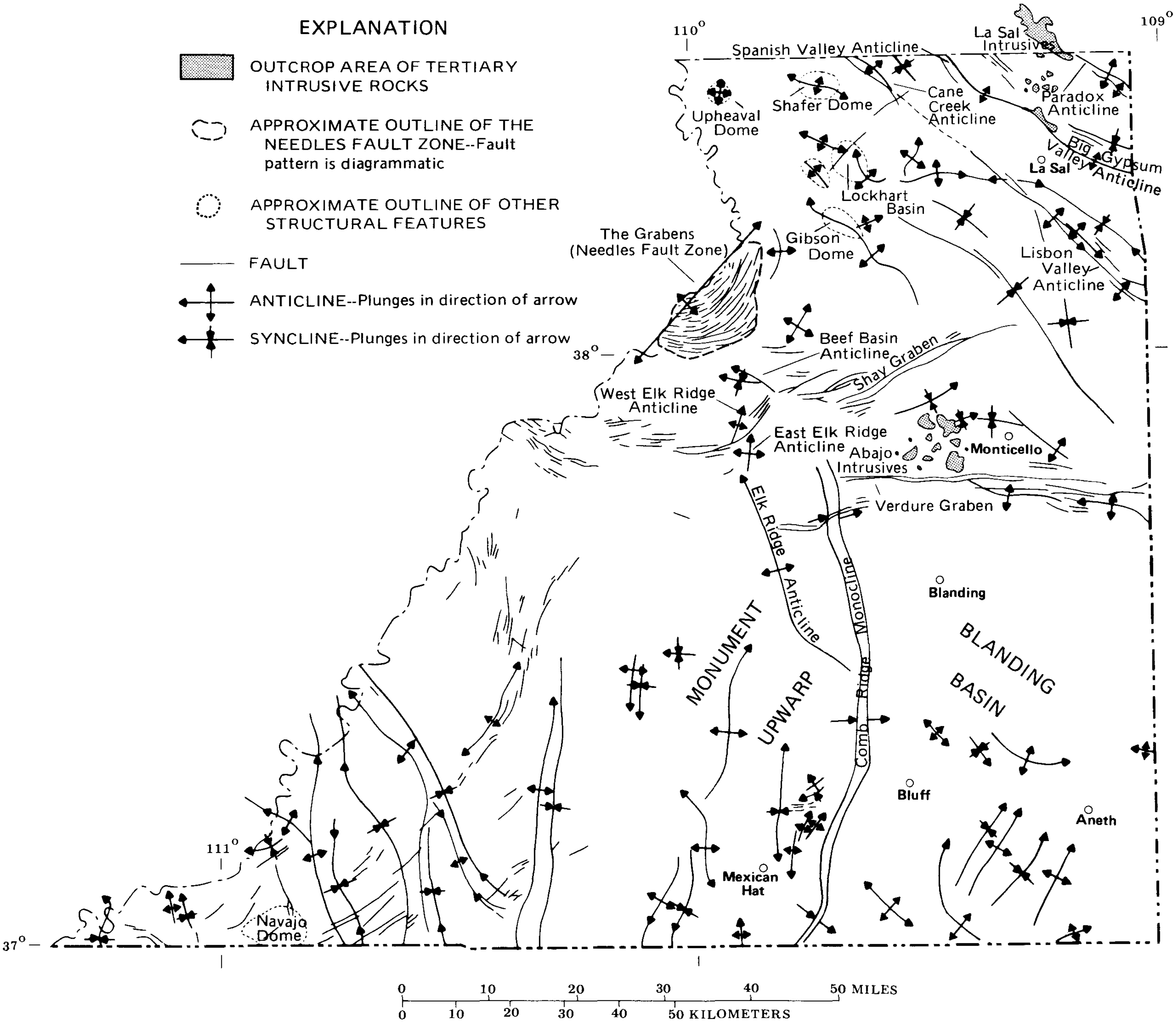


Figure 7.--Major tectonic and structural elements in San Juan County.

in the Rico Formation and in the upper two-thirds of the Honaker Trail Formation of the Hermosa Group was also part of the "P aquifer". In this report, the above units and the White Rim Sandstone Member of the Cutler Formation, where they are water bearing, are defined as the Cutler aquifer. Avery (1986) considered the DeChelly Sandstone Member of the Cutler Formation to be a separate aquifer. This unit occurs in a different geographic area than most of the Cutler aquifer, generally south of the San Juan River (Avery, 1986, table 1), and Avery defined it as the "C aquifer". In this report, the DeChelly Sandstone Member is defined as the DeChelly aquifer.

The Wingate, Navajo, and Entrada Sandstones, and any permeable intervals in the Kayenta and Carmel Formations, are defined in this report as the Entrada-Navajo aquifer, following the usage of Thomas (1989, table 1). This aquifer correlates with the "N aquifer" of Avery (1986) and of Cooley and others (1969). The Entrada-Navajo aquifer is the main source of domestic and livestock water in San Juan County. The Curtis and Summerville Formations are barriers to the movement of water except where they contain transmissive faults or fractures.

The Bluff Sandstone, Salt Wash, Recapture, and Westwater Canyon Members of the Morrison Formation are defined as the Morrison aquifer (Thomas, 1989, table 1), which correlates with the "M aquifer" of Avery (1986). The Burro Canyon Formation and overlying Dakota Sandstone form the Dakota aquifer (Thomas, 1989, table 1), which correlates with the "D aquifer" of Avery (1986).

Geologic Controls on Recharge, Movement, and Discharge of Ground Water

Ground-water hydrology in San Juan County seems to be controlled about equally by geologic structure (fig. 7) and by stratigraphy. An important secondary control of ground-water movement is the widespread faulting and fracturing of the rocks, which often permit vertical movement of water between aquifers. The location and orientation of most faults and fracture systems in the area were determined by the structural framework that had been established before the end of the Precambrian, including the faults and the fracture systems caused by the rise and partial dissolution of the salt diapirs, and by the Laramide Orogeny. Another possible conduit for vertical movement of water is collapse breccia, which is the result of removal of evaporite or carbonate by solution in ground water. Such collapse features range in size from breccia pipes or chimneys less than 50 feet in diameter to the Lockhart Basin (figs. 4, 7), more than 3 miles in diameter. Known collapse features in San Juan County are near the Colorado River north of T. 33 S.

Mississippian and older beds were fractured and fragmented by the vertical movement on faults that resulted in the formation of the half grabens in the Paradox Basin. Hydrologic continuity was maintained, however, through transmissive faults and fractures. Deformation subsequent to deposition of the Paradox Formation of the Hermosa Group, that accompanied formation of the salt diapirs, resulted, at least locally, in incorporation of sizeable blocks of older strata, such as the Redwall (Leadville) Limestone, within the salt diapirs.

All areally extensive major bedrock aquifers receive recharge by infiltration of precipitation in one or more of the following recharge areas: (1) In or adjacent to the Tertiary intrusions of the La Sal and Abajo Mountains, and, probably, Navajo Mountain, where faults, fractures, and perhaps some porous rocks in the intrusives themselves provide paths for the downward movement of water to buried aquifers; (2) along the southwestern flank of the Uncompahgre Plateau (fig. 4) through permeable or faulted strata; (3) in the San Juan Mountains of Colorado (about 90 miles east of the Colorado-Utah State line near Dove Creek) and the Carrizo Mountains and Black Mesa of Arizona (fig. 4); (4) in the Henry Mountains of Garfield County, Utah (fig. 4), for aquifers below the Wingate Sandstone where those aquifers either crop out or can receive recharge through faults and fractures; and (5) for aquifers above the Paradox Formation of the Hermosa Group at the topographically highest outcrops of each aquifer within San Juan County. Most recharge occurs where the land surface is more than 8,000 feet above sea level because that is where most precipitation occurs. Throughout the area, faults and fractures may permit the vertical movement of water between aquifers.

The general regional pattern of ground-water movement to San Juan County is north from Arizona, west from Colorado, and southwest from the Uncompahgre Plateau. Within San Juan County, the direction of ground-water movement locally may differ greatly from this regional pattern. Major deviations from the regional flow pattern are caused by local recharge or discharge.

All major bedrock aquifers discharge water to other aquifers wherever the hydraulic head in the discharging aquifer is higher than that in the receiving aquifer and where there are transmissive faults or fractures. All aquifers that crop out in San Juan County discharge water to springs and seeps and may lose water by evapotranspiration from phreatophytes in areas where the water table is near the land surface.

The Redwall aquifer not only receives recharge from the sources previously mentioned, but probably also receives recharge in Spanish and Lisbon Valleys (fig. 4), where faults provide paths for the downward movement of water, and the hydraulic head in the Redwall aquifer is several hundred feet lower than that in overlying aquifers. Natural discharge, in addition to leakage to overlying aquifers through faults and fractures, probably includes some minor subsurface outflow to Arizona in southwestern San Juan County and to southwestern Utah.

Recharge to the Cutler aquifer, in addition to that mentioned above, is at areas of outcrop on the Monument Upwarp (fig. 7) and in Lisbon Valley, on the flanks of the salt anticlines, and, possibly, from the San Juan River east of Mexican Hat on the west side of the Raplee anticline (fig. 7). From the area of the La Sal and Abajo Mountains and the Sage Plain, water movement in the aquifer generally is northwest and northeast toward the Dolores and Colorado Rivers (fig. 4). South of the Abajo Mountains and Sage Plain, movement of water in the Cutler aquifer is south toward the San Juan River. On the western side of the Monument Upwarp, water movement generally is toward the Colorado River.

Natural discharge from the Cutler aquifer in San Juan County, in addition to that mentioned above, is to springs and seeps, mostly in the canyons of the Colorado, San Juan, and Green Rivers, and tributary canyons, particularly where the permeable beds that comprise the aquifer crop out less than 3,700 feet above sea level. Subsurface outflow to Colorado east of the La Sal Mountains and the Sage Plain also accounts for some discharge from the Cutler aquifer.

The DeChelly aquifer generally does not crop out in the recharge areas; thus, recharge to this aquifer mainly is from leakage from other aquifers and subsurface flow from Arizona and Colorado (Avery, 1986, p. 19). Sources of natural discharge from the DeChelly aquifer are similar to those of the Cutler aquifer.

Most recharge to the Entrada-Navajo aquifer occurs within the county in spring and early summer by infiltration of snowmelt, in spring by rain, and by streamflow. In addition to those mentioned on page 28, major areas of direct recharge are Navajo Mountain, Nokaito Bench, along Comb Ridge, west of Copper Canyon (fig. 4), the headwaters of Cottonwood Wash, Dry Valley and adjacent areas, upper Hatch Wash, upper Montezuma Creek, and the highlands separating the valleys that have developed on the crests of the salt anticlines in the northeastern part of the county. Subsurface inflow from Colorado occurs south of T. 37 S. South of the Abajo Mountains and Sage Plain, movement of water in the Entrada-Navajo aquifer is toward the San Juan River. North of the Abajo Mountains and the Sage Plain, the general direction of water movement is toward the Colorado and Dolores Rivers, including some subsurface outflow to Colorado southeast of the La Sal Mountains and in the highlands between the anticlinal valleys in the northeastern part of the county. Natural discharge from the Entrada-Navajo aquifer, in addition to that mentioned on page 28, is to the San Juan River and to sections of Montezuma Creek, Cottonwood Wash, Chinle Creek, and other streams, and by subsurface outflow to Grand County and to Colorado.

The Morrison aquifer is present only in the eastern part of the county: South of T. 31 S., it is east of Comb Ridge, and north of T. 31 S., it is east of R. 22 E. Recharge to the Morrison aquifer is mostly by infiltration of precipitation and streamflow in areas where the formations that comprise the aquifer crop out. Verdure and lower Montezuma Creeks are known to recharge the aquifer. Sources of recharge mentioned on page 28 are of lesser importance in furnishing recharge to the Morrison aquifer. Subsurface inflow from Colorado occurs south of T. 40 S. Movement of water in the aquifer generally reflects the gradient of the topography, but south of the Sage Plain, a general trend of flow also is toward the San Juan River. Natural discharge from the Morrison aquifer is to the San Juan River, McElmo and upper Montezuma Creeks, and to other streams that intersect the aquifer below the water table. Subsurface outflow to Colorado occurs north of T. 41 S.

The Dakota aquifer, found only east of R. 22 E., is highly fragmented and commonly caps the highest mesas in the area. Recharge, discharge, and flow systems are local because of the aquifer's fragmentation.

Quality of Ground Water

In areas of surface recharge, water in all permeable formations that crop out is fresh and is mostly of calcium bicarbonate or calcium magnesium bicarbonate type. With increasing depth and distance from outcrop areas, however, the water becomes increasingly saline, and the proportions of sodium, sulfate, and chloride in the dissolved solids increase.

The Redwall aquifer appears to contain very saline to briny, sodium chloride type water (dissolved-solids concentrations are as large as 350,000 mg/L) in and near the area where the Hermosa Group contains evaporite beds. To the west and southwest, water in the Redwall is less saline; dissolved-solids concentrations in the water may be less than 6,500 mg/L.

In or near the area underlain by evaporite beds in the Paradox Formation of the Hermosa Group, water from permeable intervals in the lower one-third of the Honaker Trail Formation and from the Paradox Formation commonly is very saline to briny and of sodium chloride type. The dissolved-solids concentration of the water may exceed 400,000 mg/L. Locally, at some areas of outcrop that receive recharge from precipitation, water from shallow depths may be fresh and of calcium bicarbonate or calcium magnesium bicarbonate type. West and southwest of the area containing evaporite deposits, water from the Honaker Trail and Paradox Formations may be only slightly to moderately saline.

Dissolved-solids concentration of water in the Cutler aquifer generally increases rapidly with increasing depth and distance from areas of surface recharge, and commonly exceeds 10,000 mg/L. Where the water is very saline or briny, the dominant ions are calcium, magnesium, and sulfate in water from permeable beds in the Cutler Formation, but sodium and chloride predominate in water from the Honaker Trail Formation of the Hermosa Group. In the Aneth area, where the DeChelly aquifer is about 2,500 feet below the land surface, water in the DeChelly aquifer is moderately saline to briny and is of sodium chloride type.

Water in the Entrada-Navajo aquifer commonly is fresh to moderately saline; however, in the Aneth area, where the Entrada-Navajo aquifer is most deeply buried, the water may be very saline to briny and of sodium chloride type. Water in the Morrison aquifer generally is fresh to moderately saline and, with increasing distance from areas of surface recharge, increases in salinity and changes from calcium magnesium bicarbonate to sodium bicarbonate type.

Water in the Dakota aquifer commonly is fresh and is of calcium bicarbonate or calcium magnesium bicarbonate type. However, in some areas it is slightly to moderately saline and of calcium magnesium sulfate or sodium bicarbonate type, particularly where recharge is by runoff from areas underlain by Mancos Shale or through alluvium or colluvium derived from Mancos Shale.

BASE OF MODERATELY SALINE WATER

The base of moderately saline water is defined as the top of the first identifiable permeable interval containing water that has a dissolved-solids concentration of more than 10,000 mg/L. The surface thus defined coincides with the top of very saline to briny water. However, to be classified as below the base of moderately saline water, the sequence of beds that contained very saline to briny water had to be more than 500 feet thick and include no permeable intervals more than 30 feet thick that contained fresh to moderately saline water.

The base of moderately saline water in San Juan County, as interpreted from geophysical logs and available water-quality information, is shown on plate 1. The configuration of the base of moderately saline water is greatly affected by geologic structure, but is substantially modified by the effects of faults and fractures. In most of the county, the base of moderately saline water is from 2,000 to 6,500 feet above sea level. However, on the western flank of the Monument Upwarp (figs. 6, 7) on the western edge of San Juan County, the base slopes downward to below sea level and drops stratigraphically from the lower part of the Permian Cutler Formation to below the Devonian Elbert Formation and, in at least some places, may be below the depths from which data are available. At the latitude of Bluff, Utah, this decline in the altitude of the base of moderately saline water may extend as far east as R. 20 E.

In the northeastern part of the county, where the salt anticlines are strongly developed, the base of moderately saline water is high on anticlinal crests, to within 300 feet or less of the land surface in some places, and low in the intervening synclines, to more than 3,000 feet below land surface in some places. Superimposed on this "ridge and valley" pattern is a recharge mound in the La Sal Mountains, which locally lowers the base, possibly to below sea level. Though information is sparse, the effect of recharge in the La Sal Mountains in lowering the base of moderately saline water may not extend to the southwest beyond the Cane Creek-Lisbon Valley anticline. The stratigraphic location of the base is within the Honaker Trail Formation of the Hermosa Group (Wengerd and Matheny, 1958) or the Cutler Formation except on the flanks of the salt anticlines, where it commonly rises in the stratigraphic section into the Moenkopi or Chinle Formations, and in some places into the Wingate Sandstone, and locally may be as high as the Navajo Sandstone. The most likely conduits for this stratigraphically higher saline water are transmissive faults and fractures associated with the salt anticlines.

In the northwestern part of the county, the base of moderately saline water generally is within the Honaker Trail Formation of the Hermosa Group or the Cutler Formation, and thus is structurally controlled. Locally, however, as in and near T. 27 S., R. 19 E., section 3, the base of moderately saline water may be in the upper part of the Chinle Formation or the overlying Wingate Sandstone. Such local variations probably are due to upward movement of more saline water through transmissive fractures or faults or, possibly, through breccia pipes or chimneys.

The general shape of the base of moderately saline water south of Gibson Dome and north of North Elk Ridge seems to be that of a dome whose apex, at an altitude of more than 6,500 feet above sea level, is over the Beef Basin anticline and the East and West Elk Ridge anticlines (fig. 7). From this high area, the base of moderately saline water slopes generally southeastward toward Colorado and southward toward Arizona to an altitude of about 4,500 feet above sea level, but slopes more steeply southwestward. Superimposed on the base is a depression caused by recharge in the Abajo Mountains; the depth of this depression is not known, but it may be below sea level. Radiating to the northeast, east, and south from the Abajo Mountains are "valleys" in the base of moderately saline water where fresh to moderately saline ground water is flowing away from the recharge area. Valleys in the base also exist in southern and southeastern San Juan County caused by inflow of less saline ground water from Black Mesa and the Carrizo Mountains in Arizona (fig. 4) and from Sleeping Ute Mountain (fig. 4), and possibly other areas in Colorado.

Between Gibson Dome and the Abajo Mountains, the base of moderately saline water, though generally in the Cutler Formation or the Honaker Trail Formation of the Hermosa Group, somewhat less commonly may be in the Moenkopi Formation or the Shinarump Member of the Chinle Formation. South of the Abajo Mountains and east of Comb Ridge (fig. 7) in an elongate area that extends north from the Arizona State line to T. 34 S., and east from about R. 20 E. to the Colorado State line, the shape of the base of moderately saline water appears to be much more complex than it is north of the Abajo Mountains, though this complexity may be due to lack of data and/or erroneous data in some areas.

South of the Abajo Mountains, the base of moderately saline water is stratigraphically higher where it is at a higher altitude and is stratigraphically lower where it is at a lower altitude. For example, near the town of Blanding, the base of moderately saline water is less than 2,000 feet above sea level and is in the Cutler Formation; but, to the east where the base is more than 4,500 feet above sea level, it is at least as high stratigraphically as the Wingate Sandstone, and may be as high as the Navajo Sandstone. South of T. 37 S., in those areas where the base is above an altitude of 4,000 feet above sea level, the base of moderately saline water may be stratigraphically as high as the Morrison Formation.

CONCLUSIONS

The stratigraphy and geologic structure of San Juan County are major factors controlling the occurrence and movement of ground water, the configuration of the base of moderately saline water, and the location and distribution of very saline to briny water in the area. A thick layer of very saline to briny ground water underlies the eastern two-thirds of the county. Very saline to briny water in the county generally is found in and near the area that contains evaporite deposits of Pennsylvanian age. The configuration of the upper surface of this layer of very saline to briny ground water generally is controlled by the geologic structure of the area, but locally may be substantially modified by recharge mounds of less saline water and by vertical leakage of water through transmissive faults and fractures.

The highest altitude of the base of moderately saline water is west of the Abajo Mountains and is more than 6,500 feet above sea level. The lowest altitude is in the western part of the county and is below sea level.

Depressions in the base of moderately saline water at recharge areas in the La Sal and Abajo Mountains also may be below sea level. The base of moderately saline water generally is in the Cutler Formation or the Honaker Trail Formation of the Hermosa Group, but locally may be as high stratigraphically as the Navajo Sandstone north of the Abajo Mountains and in the Morrison Formation south of the mountains.

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