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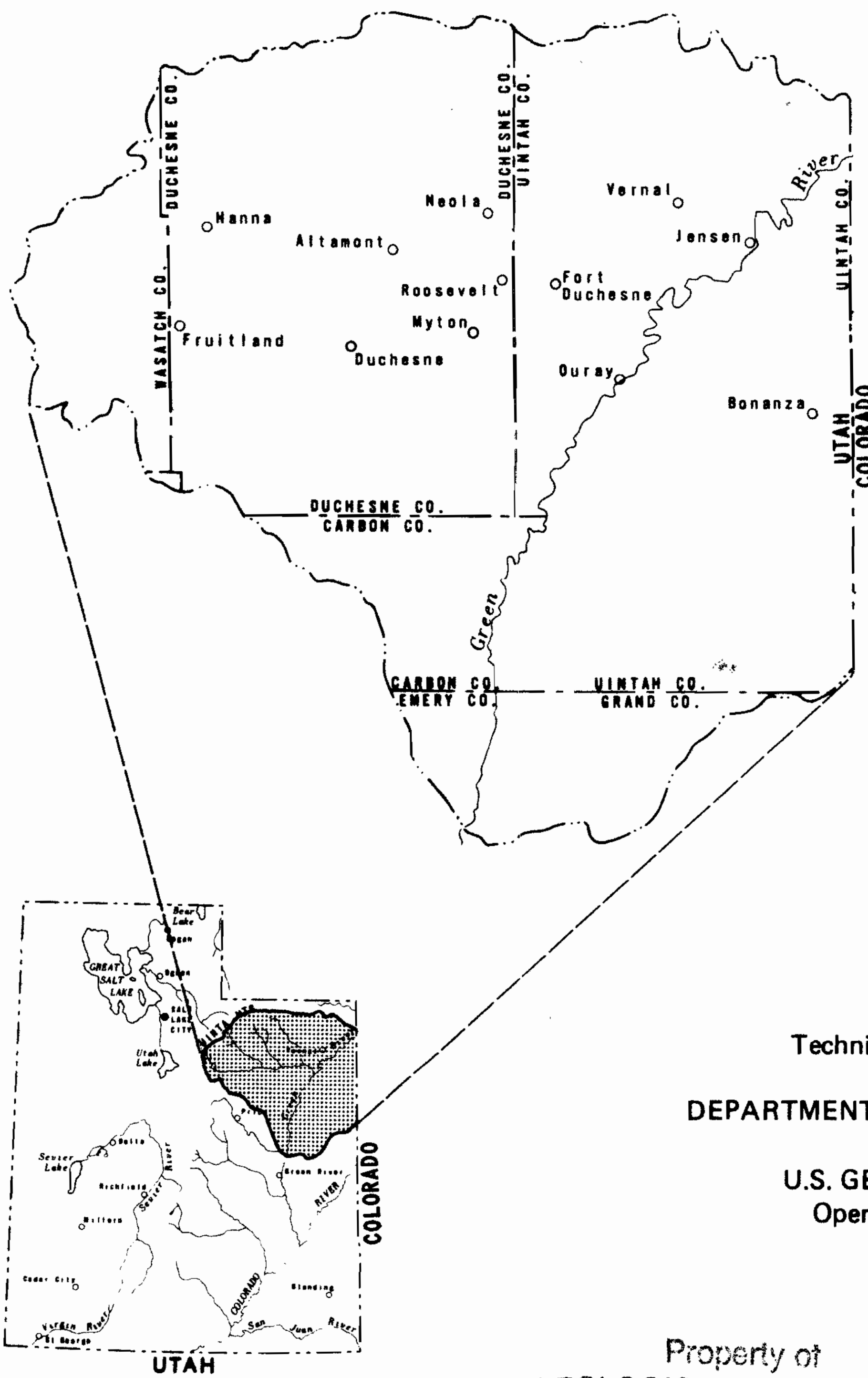

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By Lewis Howells, Mark S. Longson, and Gilbert L. Hunt

Prepared by the
United States Geological Survey
in Cooperation with the
Utah Department of Natural Resources
Division of Oil, Gas and Mining
1987

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[Plates are in pocket]

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CONVERSION FACTORS

For readers who prefer to use metric (SI) 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
inch	2.54	centimeter
	25.40	millimeters
cubic feet per second	0.02832	cubic meter per second
foot	0.3048	meter
foot per day	0.3048	meter per day
foot squared per day	0.0929	meter squared per day
gallon per minute	0.06308	liter per second
mile	1.609	kilometer
square mile	2.590	square kilometer

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

$$^{\circ}C = 5/9\ (^{\circ}F - 32)$$

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 "Mean Sea Level of 1929."

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and Gilbert L. Hunt, Utah Division of Oil, Gas, and Mining

ABSTRACT

The base of the moderately saline water (water that contains from 3,000 to 10,000 milligrams per liter of dissolved solids) was mapped by using available water-quality data and by determining formation-water resistivities from geophysical well logs based on the resistivity-porosity, spontaneous-potential, and resistivity-ratio methods. The contour map developed from these data showed a mound of very saline and briny water, mostly of sodium chloride and sodium bicarbonate type, in most of that part of the Uinta Basin that is underlain by either the Green River or Wasatch Formations. Along its northern edge, the mound rises steeply from below sea level to within 2,000 feet of the land surface and, locally, to land surface. Along its southern edge, the mound rises less steeply and is more complex in outline. This body of very saline to briny water may be a lens; many wells or test holes drilled within the area underlain by the mound re-entered fresh to moderately saline water at depths of 8,000 to 15,000 feet below land surface.

INTRODUCTION

Disposal of saline water produced by oil and gas wells ("production water") in the Uinta Basin is a problem of increasing concern (Fiske and Clyde, 1981). The concentration of dissolved solids in production water usually exceeds 10,000 mg/L (milligrams per liter) and exceeds 200,000 mg/L in some areas. Real and potential contamination of domestic, livestock, and irrigation water supplies is a matter of public concern. During 1984 in the Uinta Basin, legally-licensed evaporation pits for disposal of production water had a surface area much less than that needed to evaporate all of the disposed saline water. Many, possibly most, surface-disposal pits leak into surface streams or into shallow aquifers (Baker and Brendecke, 1983). 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-well operators dispose of saline production water by injecting it into permeable strata that already contain saline water. At present (1985) about 90 percent of saline production water in the Uinta Basin is disposed of by injection (some of the injected water is used in secondary-recovery operations). The Utah Division of Oil, Gas, and Mining is the principal agency responsible for regulating the disposal of production water to prevent contamination of water supplies.

Purpose and Scope

The purpose of this study was to define the base of moderately saline water in the Uinta Basin so that the Utah Division of Oil, Gas, and Mining can better regulate oil and gas drilling and production to minimize contamination of ground water that is fresh to moderately saline. This report summarizes a study of the base of moderately saline water in the Uinta Basin (fig. 1), with special emphasis on the greater Altamont-Bluebell oil field, made during 1984-86 by the U.S. Geological Survey and the Utah Division of Oil, Gas, and Mining. The report also describes the methods used to determine the altitude of the base of moderately saline water. The base of moderately saline water[1] was mapped to provide improved definition of zones into which saline production water could be injected without contaminating possible underground sources of drinking water.

The Uinta Basin is both a structural and a topographic basin located in northeastern Utah and northwestern Colorado. The topographic basin extends about 200 miles west to east and 173 miles north to south and has an area of about 10,000 square miles. In Utah, the Uinta Basin, as defined for this report, has an area of about 9,700 square miles and is bounded on the north by the crest of the Uinta Mountains, on the west by the limits of drainage of the Strawberry River in the Wasatch Range, and on the south by the escarpment of the Roan Cliffs. The northern part of this area contains most of the population centers, as well as the greater Altamont-Bluebell, Red Wash, and other oil and gas fields. The southern part of the area contains no major population centers but does include the Chapita Wells, Natural Buttes, and other oil and gas fields.

Data-Site Numbering System

Under the Federal land-survey system, Utah is divided into two regions, each of which has its own meridian and base line. Most of the State lies within the survey region based on the Salt Lake meridian and base line; part of the Uinta Basin, however, is within a separate survey region based on the Uinta meridian and base line.

The numbering system used for site identification in this report is described below and is shown in figure 2. Within each of the survey regions, 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 counter-clockwise 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 within parentheses that, in turn, are followed by the number identifying the section.

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[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

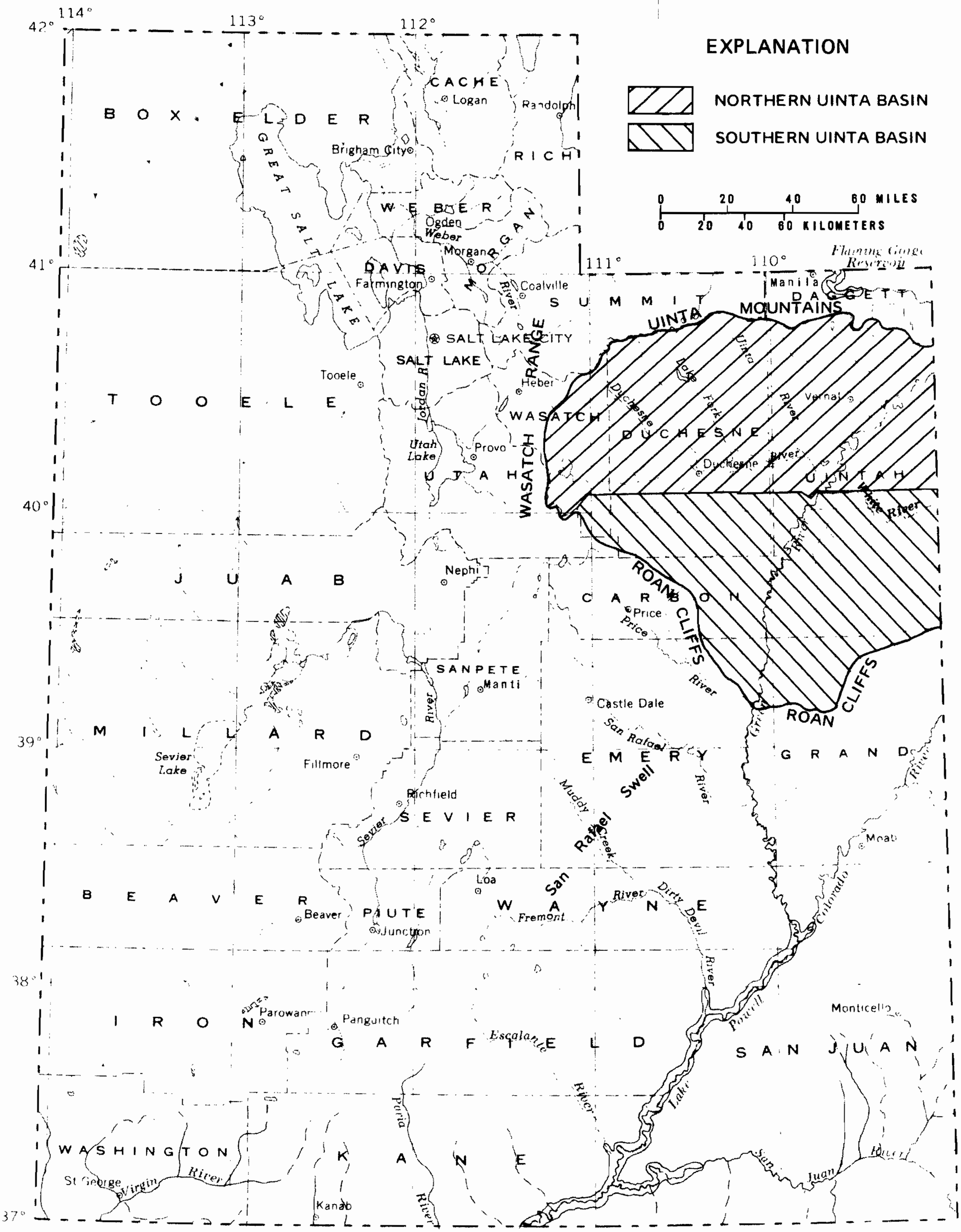

Figure 1.—Location of the Uinta Basin and selected topographic features mentioned in the report.

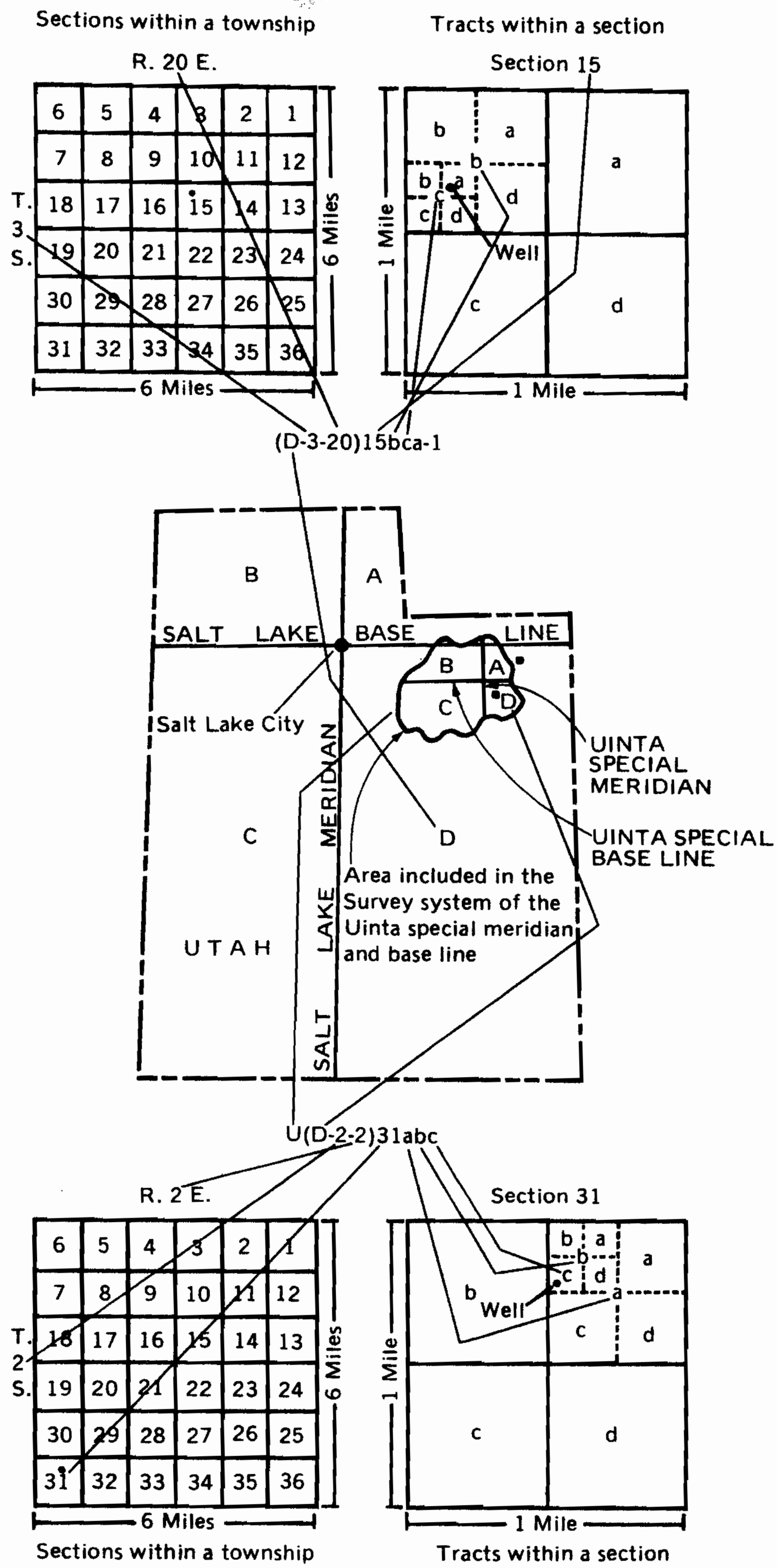

Figure 2.—Data-site numbering system used in this report.

As many as three lower case 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 counter-clockwise direction beginning in the northeastern corner of each tract. To identify wells and springs, this site 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-3-20)15bca may be used to specify the location of a data-collection site or a feature of interest in the NE1/4SW1/4NW1/4 of section 15, T. 3 S., R. 20 E. in the area covered by the Salt Lake meridian and base-line survey, but (D-3-20)15bca-1 identifies the first well constructed (or visited by U.S. Geological Survey personnel) in the same 10-acre tract, and (D-3-20)15bca-S1 identifies the first spring visited in the same 10-acre tract. Locations within the Uinta meridian and base-line system are distinguished from those within the Salt Lake system by preceding the location designation with a "U"; thus, U(D-2-2)31abc is a location within the Uinta meridian and base-line system, but (D-2-2)31abc is a location within the Salt Lake meridian and base-line system.

Acknowledgments

The authors wish to express their appreciation to John N. Daum, consulting geologist, Denver, Colorado, and Charles T. Thompson, Schlumberger Well Services, Denver, Colorado, for suggestions, constructive criticism, and discussions of methodology used in this study.

METHODS OF ANALYSIS

The base of the moderately saline 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 were not made at any sites in the Uinta Basin, 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 Uinta Basin, all utilizing geophysical well logs, have been developed by researchers. For this study, the preferred method was the resistivity-porosity method first proposed by Archie (1942) and subsequently extended and refined by many others. 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, here called 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 was used where a microresistivity log had been made, but not a porosity log, and the SP log either was not suitable for analysis or had not been made. All of these methods yield calculated water resistivities (R_w's) that have to be converted to dissolved-solids concentrations. Water salinities calculated by such indirect methods must be checked by comparing them with measured salinities wherever possible.

Water-quality data for the Uinta Basin were collected from oil- and gas-well operators, as well as 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.

The 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 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 Base

A water-quality data base was developed for this study from chemical analyses of ground water in the Uinta Basin. 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 file name "ARCHIVE>UINTA.BASIN.QW.1986." Initially, chemical data were omitted from the data base for three reasons: if there was any indication that the sample analyzed had been significantly contaminated by drilling fluid or was otherwise not representative of the formation water; if no location could be determined for the sampling site; or if the depth interval that had been sampled could not be determined.

The resistivity of water at a given dissolved-solids concentration varies with the proportions of the various dissolved constituents. Therefore, assumptions had to be made about the composition of dissolved mineral matter in each interval for which water resistivity was calculated so that the dissolved-solids concentration could be estimated. For water that contains 10,000 mg/L dissolved solids, the resistivity of a pure sodium chloride solution is 0.57 ohm-meter, of a pure sodium sulfate solution is 0.80 ohm-meter, and of a pure sodium bicarbonate solution is 0.82 ohm-meter. Naturally occurring moderately saline to briny water in the Uinta Basin seems to be mostly of sodium chloride type; much of the remainder is sodium bicarbonate type and, in a few areas, is sodium sulfate type in some intervals. Ninety-three percent of available analyses of ground water in the basin in which calcium, magnesium, or both, are the dominant cations had less than 3,000 mg/L dissolved solids and about eighty percent had less than 1,000 mg/L.

Naturally occurring water is not a pure solution of any one salt, so the the values of resistivity cited above served only as guides. For sodium chloride water, a resistivity of 0.60 ohm-meter was used to define the 10,000 mg/L dissolved-solids concentration from well-log analysis because measured values ranged from 0.57 to 0.65 ohm-meters. For sodium bicarbonate and sodium

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

sulfate waters a resistivity of 0.80 ohm-meter seemed to be a reasonable average for analyses of both types.

Borehole Geophysical Methods

Resistivity-Porosity Method

To assist those readers not fully familiar with the symbols and conventions commonly used in well-log interpretation, a diagram giving some symbols and their definitions is shown in figure 3. Many of the terms in the equations that follow are included in the explanation of figure 3.

In 100-percent water-saturated rock, the resistivity of water in the pore space is proportional to the resistivity of the water-saturated rock. This relation was defined by Archie (1942) in the equation:

$$R_w = \frac{1}{F} R_o = \frac{R_o}{a/\phi^m},$$

where R_w = resistivity of water in the pore space, in ohm-meters;
F = formation-resistivity factor;
R_o = resistivity of the water-saturated rock, in ohm-meters;
a = proportionality coefficient;
ϕ = porosity of the rock, in decimal format; and
m = cementation factor.

Although "a" supposedly is related to the tortuosity of the flow path of the electric current of the resistivity tool through the rock, both "a" and "m" seem to be related to such physical characteristics of rocks as grain size, type of pore system, permeability, degree of cementation, pattern of cementation, tortuosity of the interconnected pore space that constitutes the permeability of the rock, and, possibly, other factors. Extensive studies made of the formation factor (for example, Carothers, 1968, and Porter and Carothers, 1970) have shown that F usually does not change rapidly in rocks that have sufficient permeability to be of interest to hydrologists or to petroleum engineers. The factor "m" commonly has its larger values in rocks that are shale free and that have homogeneous porosities; very small or negative values of "m" may be possible in highly-complex fractured reservoirs (Sethi, 1979).

The ideal way to determine formation factor is by measurements of cores in the laboratory. Few laboratory determinations of F were available for this study, so "field" formation factors were calculated from available data.

Probably the best approach in determining R_w from geophysical well logs is to develop formation factors for the formations of interest in the area being studied. This determination is done empirically by using available R_w measurements (from drill-stem tests, production water, and so forth) to calculate F (see below) and then determine "a" and "m" to develop $F = a/\phi^m$ equation(s) for the target formations, facies, or basin. At best, more accurate or more rapid calculation of R_w becomes possible; at worst (assuming that sufficient measured R_w's from logged holes are available), some

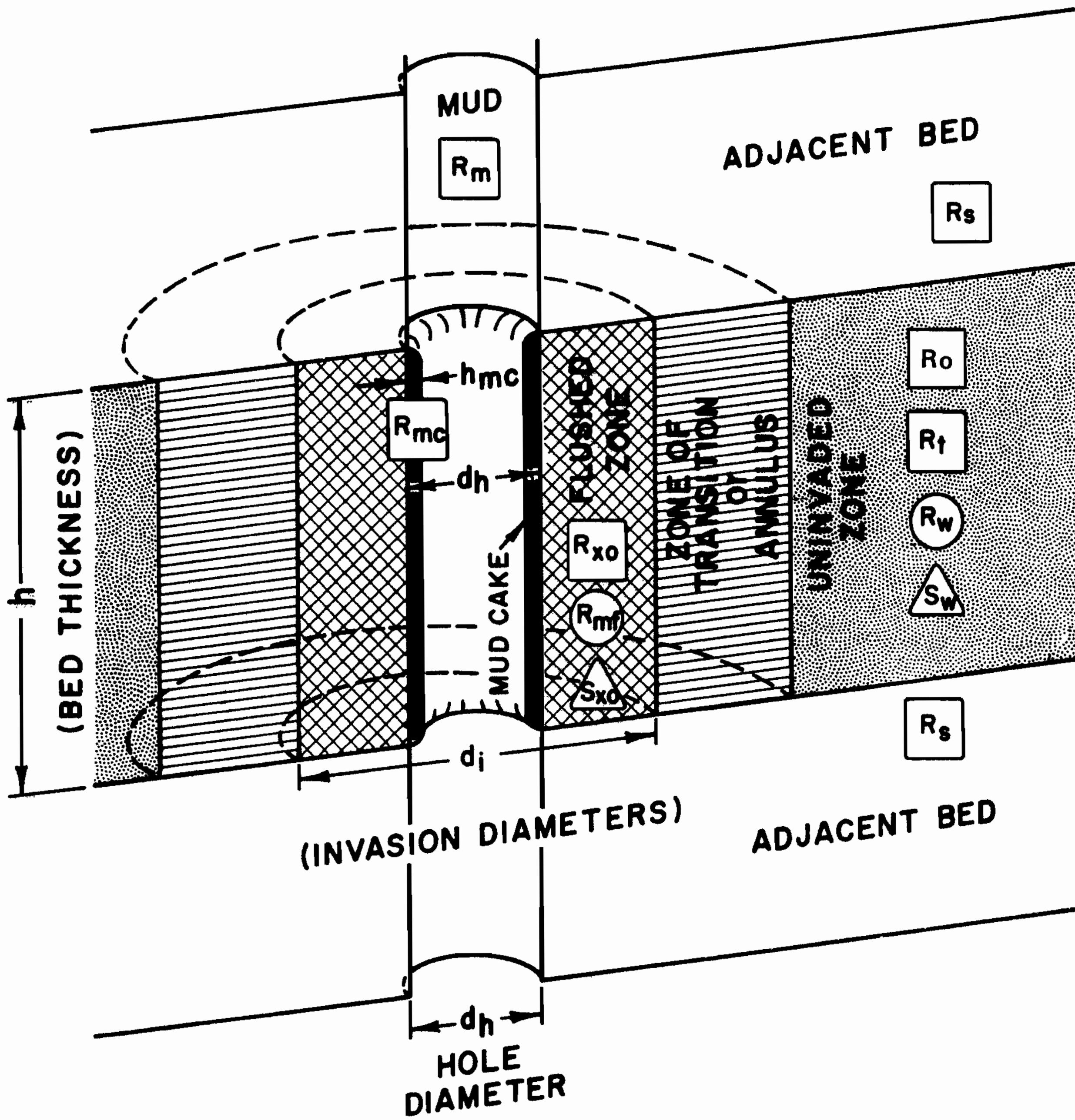

Figure 3.—Symbols used in the interpretation of well logs (modified from Schlumberger, 1984, chart Gen-3).

Explanation of figure 3

□ RESISTIVITY OF THE ZONE

○ RESISTIVITY OF THE WATER IN THE ZONE

△ WATER SATURATION IN THE ZONE

FLUSHED ZONE--That part of the formation adjacent to the bore hole that has been invaded sufficiently by fluid from the drilling mud (mud filtrate) so that all moveable formation water and moveable hydrocarbons have been flushed away by the mud filtrate

MUD (drilling mud)--A mixture of liquid (usually water, but may be oil, kerosene, or other fluids) and clay, gel, lime, salt, or other chemicals or materials used to support the wall of the drill hole to keep it from collapsing during drilling, testing, or other down-hole operations in an uncased hole, to reduce fluid (mud) loss from the hole, and to carry cuttings from the drilling operation to the surface

MUD CAKE--A coating or "cake" on the walls of the bore hole formed by the solid particles of the mud as they are filtered out of the mud by the formation being invaded by the drilling fluid. Mud cake can vary greatly in thickness, usually has a very low permeability, and can greatly reduce the permeability of the bore-hole wall

MUD FILTRATE--The fluid part of the drilling mud that invades formations adjacent to the bore hole. It is what remains after the solid particles (mud cake) are filtered out of the drilling mud by the invaded rocks

ZONE OF TRANSITION--That part of the formation surrounding the bore hole that lies immediately outside of, but adjacent to, the flushed zone and in which displacement of formation fluids by mud filtrate has begun but has not yet proceded to the degree reached in the flushed zone

Di--Diameter of the cylinder represented by the bore hole plus the flushed zone

R--Resistivity

R_m--Resistivity of the drilling mud

R_{mc}--Resistivity of the mud cake

R_{mf}--Resistivity of the mud filtrate

R_o--Resistivity of the uninvaded formation when pore space is 100-percent saturated with natural formation water of resistivity R_w

R_s--Resistivity of the bed adjacent (above, below, or both) to the interval of interest. This adjacent bed also is known as the "shoulder" bed

R_t--Resistivity of the uninvaded formation saturated with whatever fluids naturally and normally are present. These may include water, gas, oil, tar, and other organic materials. As water saturation approaches 100 percent, the value of R_t approaches R_o

R_w--Resistivity of the formation water

R_{xo}--Resistivity of the flushed zone

S_w--The water saturation of the uninvaded formation. Depending on context, it may be expressed either as a percentage or as the decimal equivalent of the percentage

S_{xo}--The water saturation of the flushed zone understanding of the variability and pattern of variability of F can be acquired.

To determine the formation factor from measured formation-water resistivities in 100-percent water-saturated rocks, first determine R_o for the sampled interval from resistivity logs. Then $F = R_o/R_w$. In actual practice, R_t, the resistivity of the fluid-saturated rock in the zone uninvaded by drilling fluid, is used, rather than R_o, because R_t is the quantity that is obtained by applying appropriate corrections to the resistivity value read from the log trace of a deep-reading resistivity tool. $R_t = R_o$ for 100-percent water-saturated rock. For rocks in which R_w is constant, or in which its value changes slowly, the values of F and of porosity (in percent, from porosity logs) for a series of permeable intervals are plotted as the ordinate and abscissa, respectively, on a log-log graph. Theoretically, if there is only a single $F = a/\phi^m$ relation involved, the data will plot in a straight line. On the plot, "a" is the intercept of the line when porosity is 100 percent; "m" is the slope of the line. Examples of the graphical determination of "a" and "m" are shown in figure 4.

Many petroleum geologists believe that setting a = 1 is adequate for almost any practical application. Thus, to determine "m", the porosity for target zones (in percent, from porosity logs) is plotted on the ordinate of a log-log graph and R_t (from logs) is plotted on the abscissa. Data points for clean, 100-percent water-saturated intervals will plot as a straight line, the slope of which is "m". The resistivity at 100-percent porosity is R_w (see figure 5).

For more extensive discussions of evaluating formation factor, see Carothers (1968), Porter and Carothers (1970), Pickett (1973), MacCary (1978, 1980), and Sethi (1979).

If the resistivity of the formation water is constant, then the formation factor generally decreases with permeability in brine-saturated rocks, increases with permeability in fresh water-saturated rocks and, in sand formations, decreases as grain size decreases (this is particularly noticeable for rocks that contain fresh water, because the surface conductivity of the grains then becomes an increasingly more important component of R_o as grain size decreases). F commonly is a constant for a given porosity, particularly if R_w is less than 1 ohm-meter [10,000 µS/cm (microsiemens per centimeter) or about 5,500 mg/L of dissolved solids for sodium chloride water]. If the resistivity of the formation water is more than 1 ohm-meter, the formation factor decreases as formation-water resistivity increases.

If the resistivity of the formation water is more than 2 ohm-meters, the formation factor can vary by 20 percent or more with differences in grain size. Formation factor also changes significantly (at constant grain size) as formation-water resistivity increases (Sarma and Rao, 1962, 1963). When R_w increases from:

1 to 2 ohm-meters, F decreases about 17 percent;
2 to 5 ohm-meters, F decreases about 15 percent;
5 to 10 ohm-meters, F decreases about 12 percent;
1 to 5 ohm-meters, F decreases about 29 percent;
1 to 10 ohm-meters, F decreases about 44 percent.

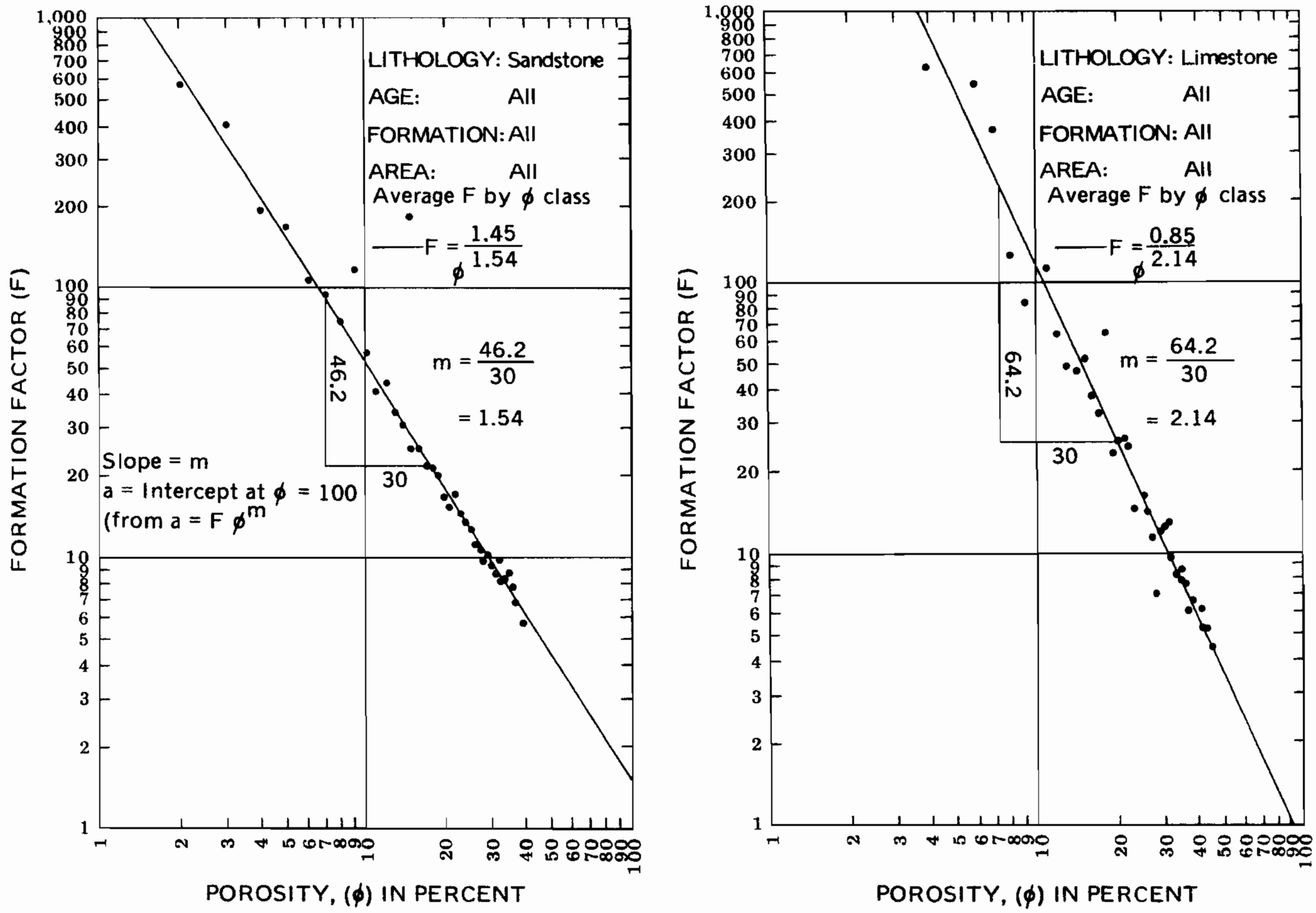

Figure 4.—Method for determining "a" and "m" in the formation-factor equation $F = \frac{a}{\phi^m}$ (modified from Carothers, 1968, figs. 2 and 9).

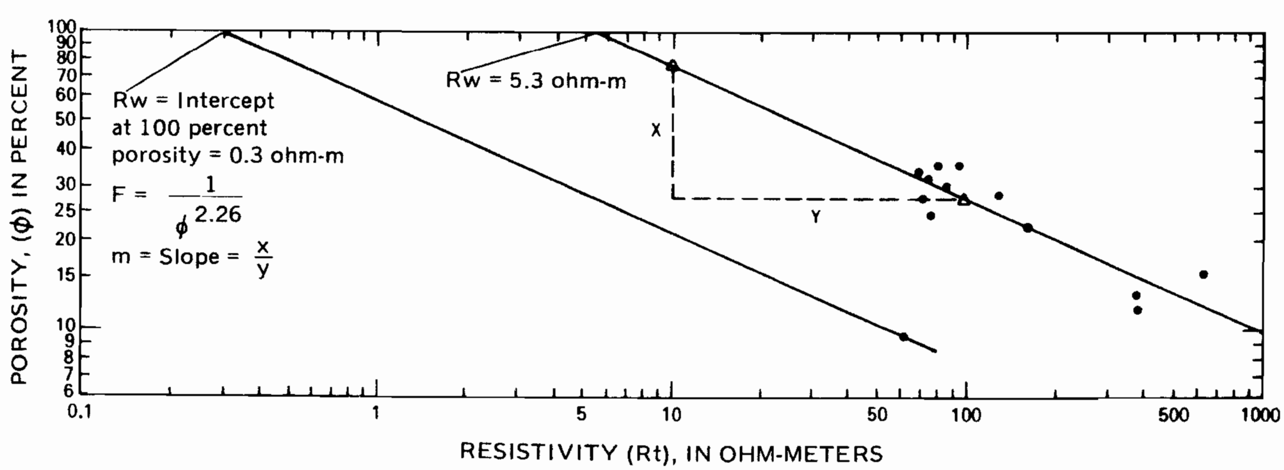

Figure 5.—Method for determining "m" in the formation-factor equation $F = \frac{a}{\phi^m}$ when "a" is set equal to 1 (modified from MacCary, 1978, fig. 8).

The Archie equation for 100-percent water-saturated rock can be generalized by defining a quantity, R_{wa}, such that

$$R_{wa} = \frac{R_{deep\text{-}reading\ tool}}{F} \approx \frac{R_t}{F} = \frac{R_o \phi^m}{a}.$$

where R_{wa} = apparent resistivity of the formation water at formation temperature, in ohm-meters;

$R_{deep\text{-}reading\ tool}$ = corrected resistivity, in ohm-meters, read from the log of a tool that has a deep nominal depth of investigation; and all other terms are as defined previously.

Then,

$$F = \frac{R_o}{R_w} = \frac{R_t}{R_{wa}} \text{ or } R_{wa} = \frac{R_t}{R_o}(R_w).$$

where all terms are as previously defined.

If the permeable interval of interest contains hydrocarbons, but all other factors are identical, the formation factor is the same as the value in hydrocarbon-free rocks, but R_t should be larger. Thus, for a series of permeable intervals that have the same formation factor, but some of which contain various amounts of hydrocarbons, R_{wa} has its lowest value in a hydrocarbon-free interval that is 100-percent saturated with water.

R_{wa}, both in concept and in interpretation, is based on the assumption that formation water is a sodium chloride solution. When "significant" quantities of other ions are present in solution, R_{wa} is the resistivity of a sodium chloride-equivalent solution. The extensive exposition by Desai and Moore (1969) or curves such as those by Schlumberger (1984, chart Gen-8), Dresser Atlas (1983, chart 1-3), Birdwell Division (1983, chart B-110), or Hilchie (1982a, figure 2-4) can be used either to calculate sodium chloride equivalent or to develop an understanding of the effects of other ions. MacCary (1980) suggested that the effects of other ions commonly become significant when R_{wa} is more than 1 ohm-meter.

Work by many investigators has led to the development of several widely applied empirical equations for the computation of the formation factor for 100-percent water-saturated rock. These equations are summarized in the following table:

Equation	Rock types where applied	Remarks
[1] $F = 1/\phi^2$	Carbonates and tightly cemented granular rocks	Archie (1942); used in Schlumberger (1984) and Dresser Atlas (1983) charts
[1] $F = 0.62/\phi^{2.15}$	Soft, granular (sucrosic), unconsolidated sandstone of medium to high permeability.	"Humble equation" (Winsauer and others, 1952); used in Schlumberger (1984), Dresser Atlas (1983), and Birdwell (1983) charts
[1] $F = 0.81/\phi^2$	Consolidated sandstones	"Tixier equation"
$F = 1/\phi^{(1.87+0.019/\phi)}$	Low porosity carbonates	"Shell equation"
$F = 1.45/\phi^{1.54}$	"Clean" sandstones	"Phillips equations" Carothers (1968)
$F = 1.65/\phi^{1.33}$	Shaly sandstones	"Phillips equations" Carothers (1968)
$F = 1.45/\phi^{1.70}$	Calcareous sandstones	"Phillips equations" Carothers (1968)
$F = 0.85/\phi^{2.14}$	Limestones	"Phillips equations" Carothers (1968)
$F = 1/\phi^{(2.05-\phi)}$	Clean granular formations	Sethi (1979)

[1]Most widely used equations according to Asquith and Gibson (1982)

A cursory examination of the literature shows that, for empirically developed equations "a" may vary from 0.62 to 2.45 and "m" may vary from a negative number (Sethi, 1979) in fractured complex reservoirs to as much as 7.0 in some rocks (Hilchie, 1982b).

Efforts to develop formation-factor equations for the various permeable lithologic facies found in the Uinta Basin were not successful. Large variability in the formation factor for what seemed to be the same lithologic facies occurred in short distances, both laterally and vertically. Results were no more accurate (at best) than using an appropriate equation from the above table.

The Humble equation was not used because strata in the basin are consolidated except for surficial deposits of alluvium and outwash. For this study, formation factors were calculated using the Tixier and Phillips sandstone equations, the Phillips shaly sandstone and calcareous sandstone equations, and the Archie and Phillips carbonate equations. Commonly, the salinity increase to more than 10,000 mg/L seemed abrupt; that is, for the lowest permeable interval that contained moderately saline water, the calculated salinity was less than 10,000 mg/L no matter which equation (for the appropriate lithology) was used, and for the next lower interval, the calculated salinity was greater than 10,000 mg/L regardless of the equation used. Where the 10,000 mg/L isoconcentration surface is in the Green River Formation or in the Mancos Shale, interpretation was complicated by the presence of as much as 2,500 feet of beds of relatively low permeability in the Green River or 1,500 to 5,000 feet of beds of very low permeability in the Mancos that may separate permeable beds that are thick enough to permit computation of formation-water resistivities. The current state of tool design and interpretive theory generally limit determination of R_t to beds more than 5 or 6 feet thick.

Resistivities read from the logs of both deep-reading tools (8- to 10-foot nominal depth of investigation) and medium-reading tools (4- to 6-foot nominal depth of investigation) need to be corrected for bed thickness, nominal bore-hole diameter, resistivity of adjacent beds (R_S), and invasion of the formation by drilling fluid. Additional corrections may be required, depending upon tool design; among these are: standoff of the tool from the wall of the bore hole, deviations from roundness of the bore hole, and displacement of bed boundaries and of resistivity maxima and minima on the log trace. Charts and diagrams for these corrections are given in the various well-log service-company manuals and chart books.

Resistivities measured with shallow-reading tools commonly need correction for nominal bore-hole diameter, mud resistivity, and tool standoff from the wall of the bore hole. Additional corrections usually are incorporated into the interpretive charts supplied by the various service companies for their tools.

Porosity is obtained from the sonic, neutron, or density (gamma-gamma) logs. For this study, sonic porosity ($\emptyset_S$) was calculated by using the Wyllie formula (Wyllie and others, 1958):

$$\emptyset_S = \frac{(\Delta t_a - \Delta t_{ma})}{(\Delta t_f - \Delta t_{ma})}$$

where Δt_a = transit time read from the sonic log, in μsec/ft (microseconds per foot);
Δt_{ma} = transit time of the rock matrix material, in μsec/ft; and
Δt_f = transit time of the fluid in the tested interval, in μsec/ft.

The Wyllie formula was used, rather than the empirical curves given by Schlumberger (1984, chart Por-3), because its use usually resulted in calculated formation-water resistivities that were in better agreement with measured values. Porosities determined from a sonic log are primary porosities and do not include fracture or vuggy secondary porosity. Compaction corrections were not used because most permeable rocks in the Uinta Basin are compacted; even permeable shaly units usually had transit times of less than 100 μsec/ft. Of the relatively few intervals that appeared to need compaction corrections, all seemed to contain gas, and most would have required corrections of 1.2 or less. However, correction of the sonic porosity was needed where the permeable target interval contained more than a small amount of shale. The nominal depth of investigation of sonic tools is about 8 to 12 inches.

Porosities determined from neutron logs (ϕ_N) are highly tool dependent, so neutron porosities must be read from charts developed by each service company for its particular tool. Neutron-logging tools actually measure the hydrogen concentration of the target-rock volume, including that in bound water in shale and water of crystallization in minerals such as non-porous gypsum. Corrections must be made for lithology. Density corrections commonly need be made only where some pore space is occupied by gas. Modern neutron logs, those recorded since about 1970, are made with an assumption of matrix lithology built into the raw-data-to-log-trace conversion program of the logging-truck computer. A limestone matrix usually is used, but logs sometimes are recorded with a dolomite or a quartz-sandstone matrix.

Depending upon tool design, corrections for nominal bore-hole diameter, mud salinity, mud-cake thickness or tool stand-off, temperature, pressure, and lateral tool position in the hole may be needed; the service companies supply correction tables or charts for their tools. The presence of gas in a formation causes the porosity measured by the neutron log to be anomalously low.

The depth of investigation of neutron tools varies with tool design and bore-hole and formation conditions, but for sidewall neutron tools it ranges from a maximum of 12 to 14 inches for zero-porosity rock to about 2 to 6 inches for 35-percent porosity rock, and for compensated neutron tools it ranges from as much as 16 inches for zero-porosity rock to about 4 to 9 inches for 35-percent porosity rock. Thus, the pore space of rock investigated by a neutron tool usually is filled with drilling fluid.

Recognition of shale beds on the neutron log requires some caution because the porosity of shale varies with its compaction. Relatively uncompacted shale, commonly at or near the surface, may have a porosity of 40 percent or more, whereas shale buried to a depth of more than 10,000 feet may have a porosity of 10 percent or less. Also, because of differences in tool design (possibly detector spacing), shale porosity shown for a particular shale bed may vary for a particular type of tool from service company to service company. The Schlumberger compensated-neutron log, for example, commonly yields shale porosities of from 50 to 70 percent for shallow shale beds, whereas the equivalent Dresser Atlas log yields shale porosities of from 30 to 40 percent for the same shale beds (Hilchie, 1982a, p. 9-4). Corrections to the neutron porosity are needed for shaly permeable target intervals.

The density-logging tool measures the electron density of the formation by use of the Compton-scattering effect. Electron density is related to the true bulk density (ρ_b) which is, in turn, dependent upon the density of the rock matrix (ρ_{ma}), formation porosity (ϕ), and the density of the fluids filling the pores of the rock (ρ_f). As the density-logging tool has a depth of investigation of about 6 inches, the pore fluid usually is mud filtrate.

Porosity is calculated from density logs by the relation:

$$\phi_D = \frac{(\rho_{ma}) - (\rho_b)}{(\rho_{ma}) - (\rho_f)}$$

where terms are as defined in the preceding paragraph. Bulk density usually is equivalent to the apparent density (ρ_a), the density read from the density log.

Corrections are needed if the tool is not in perfect contact with the bore-hole wall (usually due to mud cake or to wall roughness), for nominal hole diameter (commonly not needed for holes less than 10 inches in diameter), pore-fluid density, for some minerals such as sylvite, halite, gypsum, anhydrite, and coal, and for gas-bearing formations. Corrections may have to be made for shales or for shaly permeable zones because of variations in the bulk density of shale with compaction. Some "modern" density logs are made with tools that are designed to be self-compensating for some environmental (bore-hole) problems or may have correction routines built into the recording program of the logging-truck computer. Where such logs show a correction ($\Delta \rho$) greater than 0.20 gm/cc (grams per cubic centimeter), the bulk density and, thus, the porosity, read from the log is not valid.

Density-porosity logs, like neutron-porosity logs, are made with an assumption of matrix lithology built into the recording program of the logging-truck computer. A limestone matrix (ρ_{ma} = 2.710) usually is used, but some logs are recorded with a dolomite (ρ_{ma} = 2.876) or a quartz-sandstone (ρ_{ma} = 2.648) matrix. Calculated porosity values must be corrected for matrix lithology. The presence of gas in a formation causes the porosity measured by the density log to be anomalously high.

In this study, lithology and porosity were determined by crossplots of sonic-, neutron-, and density-log data wherever possible.

Corrections for shalyness were made where the data indicated that the target interval was shaly and if gamma-ray and caliper logs were available. Shale content was estimated by using the gamma-ray index (I_{gr}):

$$I_{gr} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}}$$

where GR_{log} = gamma-ray log value, in API units, for the interval of interest;

GR_{min} = gamma-ray log value, in API units, for a clean sandstone (or for the "sand line"); and

GR_{max} = gamma-ray log value, in API units, for a shale bed (or for the "shale line").

Shale content, as a percentage of total volume, was obtained by using the graph shown in figure 6; similar charts are found in many textbooks and in service-company chart books. The value of the gamma-ray index is plotted on the ordinate. A line then is projected horizontally to the curve for consolidated rock, and then vertically to the scale to obtain the percentage of shale. Like all other methods of estimating shale content that are based solely on geophysical well logs, the gamma-ray index method occasionally yields very incorrect results. However, because the cleanest (least shaly) permeable intervals were selected for computation of R_w, errors resulting from using the method probably are much smaller than the errors that would have resulted had no shale corrections been made. Service-company chart books and textbooks such as those by Hilchie (1982a, 1982b) and Asquith and Gibson (1982) contain nomographs or charts to correct porosity values for the known or estimated shale content of permeable beds.

The following was used to calculate R_w by the resistivity-porosity method:

1. Correlate the resisitivity and porosity logs.
2. Select a permeable zone for which formation-water resistivity is to be calculated.
3. Read the resistivities from the logs, apply appropriate corrections for bed thickness, bore-hole conditions, drilling-fluid invasion, and so forth, and determine R_t.
4. Determine porosity for exactly the same stratigraphic interval as that for which R_t was determined; make corrections, as appropriate, for fluid density, bore-hole conditions, shalyness, lithology, temperature, and so forth. If possible use crossplots to determine lithology and porosity.
5. Select the appropriate equation(s) and calculate formation factor.
6. Calculate R_{wa}.
7. Correct R_{wa} to R_w at 77 ^{o}F.

Spontaneous Potential Method

Spontaneous potential (SP) logs, which measure the natural electrical currents generated by interaction of drilling fluid, formation water, and formation rocks, can be used to calculate R_w from the relation:

$$SSP = -K \log R_{mf}/R_w$$

where: SSP = the static SP deflection, in millivolts;
R_{mf} = resistivity of the drilling-mud filtrate, in ohm-meters;
R_w = resistivity of the water in the formation, in ohm-meters;
K = a proportionality constant = 60 + 0.133 T; and
T = formation temperature, in degrees Fahrenheit.

This relation works best where the formation water is a sodium chloride solution that has a dissolved-solids concentration of more than 20,000 mg/L and the permeable zone is a clean sand or sandstone. The value calculated by the SP method is called R_{we}, the equivalent water resistivity. R_{we} is, by definition, the value obtained by assuming that the formation water is a 100-percent sodium chloride solution and that the inverse relationship between the logarithm of water resistivity, in ohm-meters, and the logarithm of sodium ion activity, in gram-ions per liter, is linear. However, the SP method can be used only if permeable zones are present, conductive muds were used, and the resistivity of the formation water is less than or more than (but not equal to) the resistivity of the drilling-mud filtrate.

Good SP logs that have large deflections can be obtained in formations that have only a small fraction of a millidarcy of permeability. There is no direct relationship between the magnitude of the SP-curve deflection and the hydraulic permeability or the porosity of a formation. The amplitudes of the SP deflections are related mostly to electrochemical reactions and electrokinetic effects taking place between the mud, the formation, and the adjacent beds (primarily the shale beds). For an SP deflection to occur,

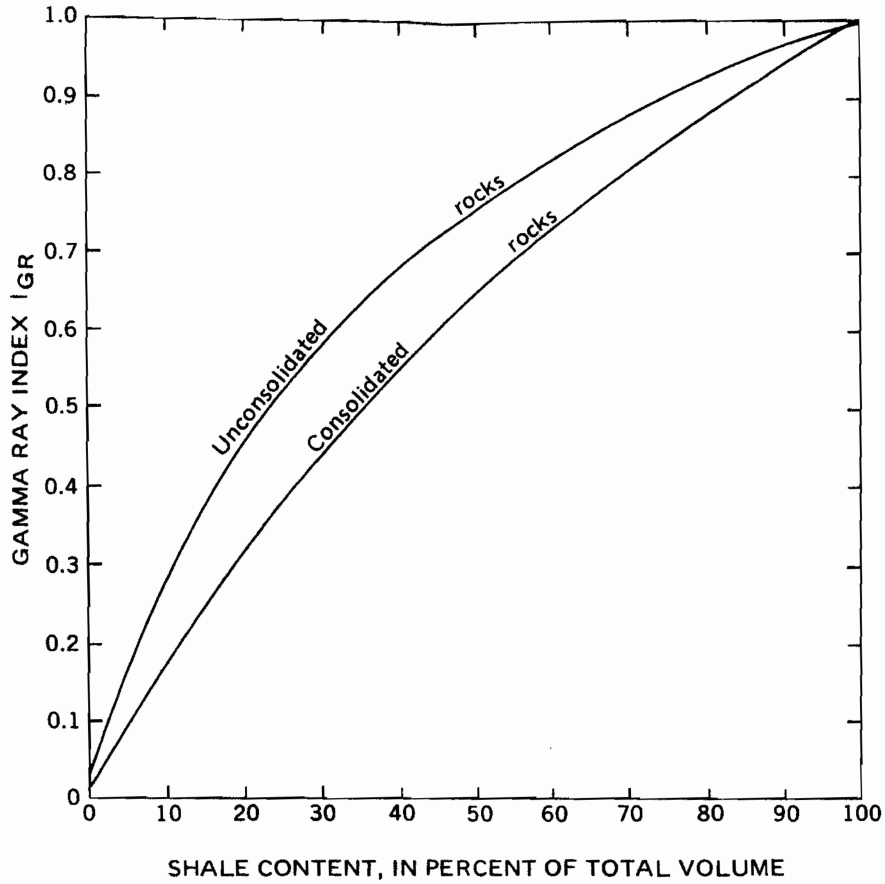

Figure 6.—Estimation of the shale content, in percent of total volume by the gamma-ray index method (modified from Dresser Atlas, 1982, fig. 10.1).

permeability need be only large enough to permit ion flow between the mud and the formation (Schlumberger, 1974, p. 19).

The SP method commonly is applicable if the formation water is predominantly of sodium chloride type and if R_w and R_{we} are more than 0.1 ohm-meter (100,000 µS/cm at 77° F or about 79,000 mg/L dissolved solids for a sodium chloride solution). Martin (1956) gives an R_w of 0.3 ohm-meter (33,000 µS/cm at 77° F or about 22,000 mg/L dissolved solids for a sodium chloride solution) as the upper limit of water resistivity for using the SP method and 0.08 ohm-meter (125,000 µS/cm at 77° F or 92,000 mg/L dissolved solids for a sodium chloride solution) as the lower limit.

Some general observations on using the SP method are:

1. The SP curve has a negative deflection when the resistivity of the formation water is less than the resistivity of the mud filtrate.
2. The SP curve has a positive deflection when the resistivity of the formation water is more than the resistivity of the mud filtrate.
3. A "base shift" of the shale line occurs in the SP log wherever:
   (a) Two beds that contain water of different salinities are separated by a shale bed that is not a "perfect" cationic membrane; and

(b) layers that contain water of different salinities are in contact (not separated by an impervious layer or shale bed). Then, the SP shift does not occur at the contact, but at the base of the permeable interval. The SP deflections at the upper and lower limits of the permeable interval will have different polarities if the mud-filtrate salinity is between the salinities of the two layers.

4. The magnitude of the SP deflection is affected by:
   (a) Bed thickness; a correction may be needed for beds less than 30 feet thick and usually is needed for beds less than 10 feet thick;
   (b) the SP deflection for a permeable interval decreases in direct proportion to the volume of "effective" shale in the interval. Effective shales are those having significant cation-exchange capacities (which means mostly montmorillonites, bentonites, and illites). Thus, if 25 percent of an interval is shale, the SP deflection is 25 percent less than it would have been if the interval had been shale-free. If hydrocarbons are present, they magnify the depressant affect of shale on the SP deflection. If no shale is present in the permeable interval, then hydrocarbons have no significant effect on the SP log;
   (c) nominal hole diameter (unless the tool was held against the bore-hole face);
   (d) the depth of invasion by drilling fluid;
   (e) the ratio R_{mf}/R_w (there is no SP deflection when R_{mf}/R_w 1);
   (f) bed resistivity (significant for highly-resistive beds);
   (g) drilling-mud resistivity (R_m); the amplitude of the SP deflection decreases with decreasing mud resistivity. For very low valuses of mud resistivity (saline muds), the SP deflection approaches zero; and
   (h) instrumentation.

If a shale correction was needed, the percentage of shale in the volume of the permeable bed was estimated by the gamma-ray index method (see page 16).

The procedure followed to calculate R_w by the spontaneous potential method is:

1. Select a permeable interval for which R_w is to be calculated.
2. Establish both sand and shale lines on the SP curve.
3. Calculate the difference between the sand and shale lines at the permeable interval; this is the static SP (SSP) unless corrections are needed. For corrections see step 4.
4. Correct the SP reading, if needed, to get the SSP:
   (a) Bed-thickness corrections usually can be made based on Dresser Atlas (1983) chart 2-1;
   (b) drilling-fluid invasion corrections beyond those incorporated into Dresser Atlas chart 2-1 seldom are needed but, if needed, can be obtained from the charts developed by Segesman (1962) (see also, Schlumberger, 1984, chart SP-3);
   (c) shale as previously discussed;
   (d) bore-hole-size corrections seldom are needed but, if necessary, can be obtained from the charts of Segesman (1962); and

(e) corrections for the resistivity of adjacent beds usually are not needed but, when made, can be obtained from the charts of Segesman (1962) (see also Schlumberger, 1984, chart SP-3).

5. Resistivities of the mud and the mud filtrate (from the log heading) are recalculated for the formation temperature using the Arps equation (see page 23). If the mud-filtrate resistivity is not given, but the mud resistivity is, then a useable value of mud-filtrate resistivity is calculated from Schlumberger (1984) chart Gen-7, Birdwell Divison (1983) chart Tfm-6, or Dresser Atlas (1983) chart 1-6.
6. The equivalent resistivity of the mud filtrate (R_{mfe}) is calculated:
   (a) If sodium chloride-based mud had been used, and the resistivity of the mud-filtrate was more than 0.1 ohm-meter at 77° F, then at formation temperature, R_{mfe} is assumed to be equal to 0.85 R_{mf};
   (b) if sodium chloride-based mud had been used, and the resistivity of the mud filtrate was less than 0.1 ohm-meter at 77° F, R_{mfe} is determined at formation temperature from Schlumberger (1984) chart SP-2;
   (c) lime-based mud is treated as "regular" mud;
   (d) if gypsum-based mud had been used, the "average" fresh-water curves on Schlumberger (1984) chart SP-2 are used; and
   (e) if the mud filtrate is known to have contained appreciable calcium or magnesium ions, the sodium chloride equivalent is calculated and the R_{mfe} of that value is determined (Desai and Moore, 1969).
7. R_{we} is determined from Schlumberger (1984) chart SP-1 or Birdwell Division (1983) chart SP-4.
8. R_{we} is corrected to R_w at 77° F.

Resistivity-Ratio Method

This method, used only if a porosity log was not available and the SP log either was uninterpretable or was not available, requires resistivity logs of the flushed zone and of the uninvaded zone. Archie's (1942) equation, generalized for rock that is not 100-percent water saturated, is the basis of the analysis:

$$S_w^n = FR_w/R_t,$$

where S_w = decimal-fraction water saturation of pore space in the interval of interest; and all other terms are as previously defined.

This equation is divided by a variation of Archie's equation written for the zone adjacent to the bore hole that was flushed by drilling fluid,

$$S_{xo}^n = FR_{mf}/R_{xo}$$

where all terms are as previously defined, to yield

$$(S_w/S_{xo})^n = R_{xo}/R_t \div R_{mf}/R_w$$

where all terms are as previously defined.

For 100-percent water-saturated rock, S_w/S_{xo} 1 and the equation reduces to

$$R_w = \frac{R_{mf}}{R_{xo}/R_t},$$

where all terms are as previously defined (Doll, 1950). R_{xo}, the resistivity of the zone flushed by drilling fluid, is read from a microresistivity log (corrected, where necessary); R_t is determined, as in the resistivity-porosity method, from the logs of deeper-reading tools such as the deep-induction log or, if invasion is slight, the long-normal log; R_{mf} is read from the log heading and is calculated for the appropriate formation temperature. The R_w thus determined is at formation temperature and is recalculated, using the Arps equation, to R_w at 77° F.

Factors Affecting the Calculation of Formation-Water Resistivity

Identification of permeable intervals

Permeable intervals usually are identified by using the SP log, resistivity log, or microresistivity log. Significant deflection of the trace of the SP curve from its base line commonly indicates a permeable interval, though the permeability of that interval may be too low to produce pore fluid (water or hydrocarbons) at an economically acceptable rate.

Resistivity logs that contain traces of two or more tools that have different nominal depths of investigation commonly delineate permeable beds by a separation of the traces of the curves. The curve separations are due to invasion of permeable intervals by mud filtrate, which commonly results in the resistivity of the invaded zone being larger or smaller than the resistivity of the uninvaded zone, depending on whether the resistivity of the mud filtrate is more than or less than the resistivity of the formation fluid. Curve separations on resistivity logs also can be caused by other factors, such as bore-hole size or bore-hole rugosity, which can strongly influence shallow-reading tools, and by shale beds adjacent to a thin, somewhat permeable bed, which may influence a deep-reading tool. Caliper and gamma-ray logs are useful in helping to recognize such situations and to evaluate the corrections needed. An additional problem sometimes occurs when using the dual-induction laterolog or dual-induction guard log: the design of some shallow-reading tools, such as the short normal and lateral or guard devices, commonly results in those tools yielding a different resistivity than do the deeper-reading medium- and deep-induction devices when no invasion has occurred because the resistivities measured by those shallow-reading tools usually includes a significant vertical component. Where this happens, separation of the medium- and deep-induction curves is used to identify permeable intervals; however, an increase in bore-hole size or the presence of gas in the formation can cause a separation of these two curves even if no permeable interval is present.

Microresistivity logs from tools that read resistivity at two depths of investigation commonly show a separation of the two log traces if mud cake is present. Mud cake forms at permeable intervals and usually is thick enough to significantly affect the resistivity recorded by the shallower-reading device but not that of the deeper-reading device.

If none of these methods seems to yield satisfactory determination of permeable intervals, the porosity, gamma-ray, and caliper logs can be used to identify such intervals. The caliper log shows bore-hole size, and thus permits evaluation of the validity of the other logs. One can assume that clean sandstone probably is productively permeable if porosity is more than 8 percent and that carbonate rocks probably are productively permeable if porosity is more than 3 or 4 percent (Hilchie, 1982a, p. 1-7). If all three types of porosity logs are available, the lithology and, hence, a fairly accurate value for porosity can be determined by cross-plots or by the MID plot or M-N plot methods (Schlumberger, 1972, p. 69-75, 1974, p. 22-29, 1979, p. 34 and 37-46, 1984, p. 26-41; Dresser Atlas, 1983, p. 45-57). If only two types of porosity logs are available, the lithology and porosity still may be estimated with some confidence. If only one porosity log is available, and no information is available about lithology (lithology often can be determined or inferred by correlation) assume sandstone lithology for a sonic or density log and dolomite lithology for a neutron log. These lithologic assumptions are conservative and assure that any error in identifying permeable intervals is failure to identify a permeable interval rather than to incorrectly identify an interval of very low permeability as having moderate to high permeability. The best procedure for identifying permeable intervals is to compare as many types of logs as possible so that the effects of problems that might cause any one method to yield questionable results are minimized.

Equilibrium bottom-hole temperature

To determine formation temperatures, the geothermal gradient at each well had to be estimated. Because of limitations of data and time, a linear gradient was assumed. Also, because equilibrium bottom-hole temperature measurements are not available, and bottom-hole temperatures recorded on logs may be as much as 50° F less than the equilibrium temperature, the equation developed by the American Association of Petroleum Geologists' Geothermal Survey of North America Committee (Wallace and others, 1979) was used to correct the recorded bottom-hole temperature for each well. The equation is:

$$T_E = T_L + (7.689 \times 10^{-14} D^3 - 3.888 \times 10^{-9} D^2 + 3.619 \times 10^{-5} D + 0.270245) \frac{D}{100}$$

where T_E = equilibrium bottom-hole temperature, in degrees Fahrenheit;
T_L = bottom-hole temperature given on the log, in degrees Fahrenheit; and
D = depth of the hole, in feet.

Then the geothermal gradient $= \frac{T_E - T_{ma}}{D}$, where T_{ma} = mean annual surface temperature, in degrees Fahrenheit. The mean annual surface temperature was obtained from National Oceanic and Atmospheric Administration records (1984).

Changes of resistivity with temperature

The resistivities of the mud, mud filtrate, and mud cake must be converted from their measured values (at the temperatures at which they were measured) to their values at the formation temperature of each interval for which R_w is to be determined. Also, R_{wa} and R_{we} must be converted from values at formation temperature to values at 77° F to get R_w. Formation temperatures were calculated for the midpoints of the intervals of interest. Resistivity was calculated for different temperatures using the Arps formula (Arps, 1953):

$$R_2 = R_1\left(\frac{T_1 + 6.77}{T_2 + 6.77}\right)$$

where R_1 = initial resistivity, in ohm-meters;
R_2 = final resistivity, in ohm-meters;
T_1 = initial temperature, in degrees Fahrenheit; and
T_2 = final temperature, in degrees Fahrenheit.

Hydrocarbons

Previous discussion of the determination of formation-water resistivity dealt solely with 100-percent water-saturated rocks. Hydrocarbons, however, are widely distributed throughout the sedimentary strata of the Uinta Basin as tar sand, oil shale, oil, gas, gilsonite, kerogen, and other organic materials. Organic materials can occupy some or most of the pore space in the rocks. Tar sand and oil shale, though porous, have very low permeability and thus do not cause problems in water-resistivity interpretation unless they are so severely fractured as to be aquifers. Oil is difficult, to impossible, to identify solely from available geophysical logs, so it can cause large errors in the calculated water resistivity. For intervals where oil was known to be present, from information given in drill-stem test or production-test reports, reported producing zones, and so forth, a correction of varying reliability was made to the calculated formation-water resistivity. Where possible, the water saturation of the flushed zone (S_{xo}) was determined from geophysical logs. From this, the water saturation of the uninvaded zone (S_w) was estimated using the relationship $S_w = (S_{xo})^5$ given by Schlumberger (1972, p. 85, and 1984, chart S_w-7) for commercially productive zones that produce little water. For commercially productive zones producing abundant water, the maximum probable water saturation was assumed to be 0.7 for carbonates and 0.6 for sandstones. For non-producing intervals that contained oil, the water saturation of the flushed zone was assumed to be the maximum possible saturation for that interval. The water resistivity that had been calculated for 100-percent water-saturated rock was corrected for oil content by using the equation that Archie (1942) developed for rocks that contain pore fluids other than water:

$$R_w = \frac{R_t}{F}\,(S_w)^n$$

where n can range from 1.8 to 2.5 but commonly is set equal to 2. Fortunately, accurate values for formation-water resistivity were not a necessity; what was required was a determination of whether water resistivity was more than or less than a value that corresponded to 10,000 mg/L dissolved solids.

Gas in the permeable zone often is easier to detect than oil if two or three different types of porosity logs have been made. Corrections to the calculated formation-water resistivity were made the same way as for oil. If the density- and neutron-porosity logs are available and examination of an overlay of the two logs discloses a crossover of the two porosity curves (when plotted for the correct lithology), gas is indicated (fig. 7). If the two log traces are mirror images of each other (fig. 7a), a "clean" gas-producing formation is indicated and invasion by drilling fluid either was almost nil or was deep enough to exceed the depth of investigation of the neutron tool. If crossover occurs but the two log traces do not mirror each other (fig. 7b), gas is present, the formation may be clean, but invasion by drilling fluid was intermediate. The density tool was investigating the flushed zone and the neutron tool was investigating both the flushed zone and the uninvaded zone.

The presence of shale in the interval under examination can confuse interpretation because the effect of shale on the two porosity logs is the opposite of the effect of gas. In a clean sand, the effect of gas on both the neutron and density log is proportional to the fraction of pore volume occupied by gas. Gas has no noticeable effect on the sonic log in consolidated-rock reservoirs. With combinations of the sonic and neutron or sonic and density logs, identification of gassy zones is more difficult than with the neutron-density log combination in the absence of other information, such as a good lithologic description. If lithology is known, then on crossplot charts such as those supplied by logging-service companies, data for a gassy zone plots to the left of the correct point for a non-gassy zone of identical lithology on a sonic-neutron crossplot chart, and below the non-gassy point on a sonic-density crossplot chart.

GEOLOGIC AND HYDROLOGIC SETTING

The discussion of geology and hydrology that follows is summarized from Crowley (1957), Goode and Feltis (1962), Hintze (1964), Osmond (1964), Feltis (1966), Ritzma (1969), Sales (1969), Untermann and Untermann (1969), Maxwell and others (1971), The Rocky Mountain Association of Geologists (1972), Miller (1975), Hood and others (1976), Price and Hood (1976, 1977a, b), Hood and Fields (1978), Holmes (1980, 1985), Lindskov and others (1983), Bryant (1985), Cole (1985), Picard (1985), and Smith and Cook (1985). Rocks that crop out in or are known to underlie the Uinta Basin range from Precambrian to Holocene in age. About 63,000 feet of sedimentary beds are exposed in composite section in the western part of the basin and about 53,000 feet in the eastern part. More than 24,000 feet of this thickness consists of Precambrian rocks. Along the axis of the basin, Cambrian and younger rocks reach a maximum thickness of more than 30,000 feet. The nomenclature and age relationships of the major bedrock formations are shown in figure 8. Along the southwestern edge of the Uinta Basin (southwestern limb of the Uncompahgre uplift) additional strata, more commonly associated with the Paradox or Oquirrh Basins, may be present or have been reported as penetrated in oil and gas test wells. Among these are

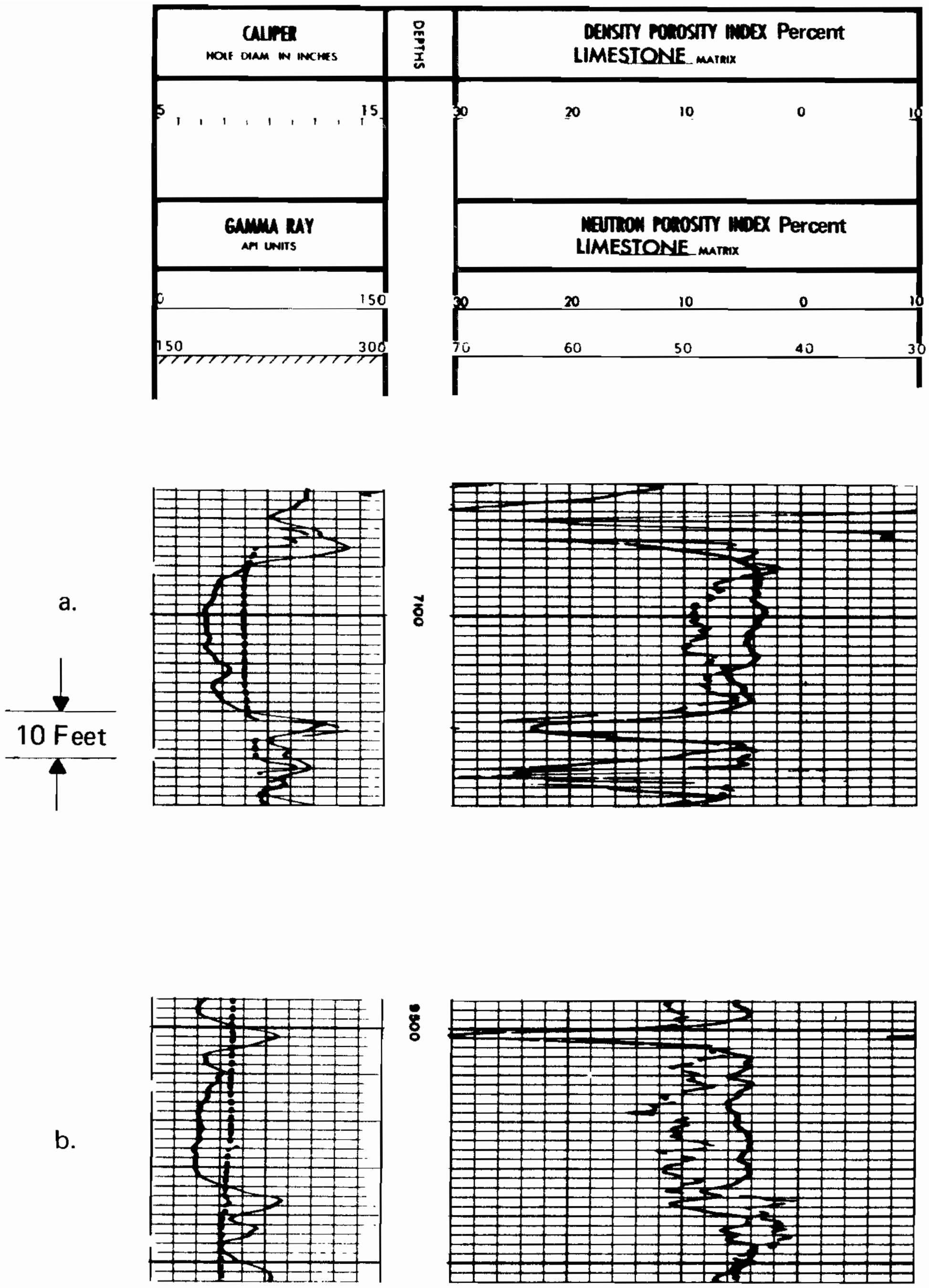

Figure 7.—Method for identifying gas-bearing intervals by comparing the compensated neutron- and density-porosity logs.

a. The mirror-image type crossover of the two curves between 7,097 and 7,110 feet indicates a clean gas-bearing interval in which invasion by drilling fluid either is almost nil or more likely in this example, is at least 9 to 12 inches.

b. The non-mirror-image type crossover of the two curves indicates a clean gas-bearing interval in which invasion by drilling fluid probably is 4 to 7 inches. That the interval is relatively free of shale can be seen by examining the gamma-ray log.

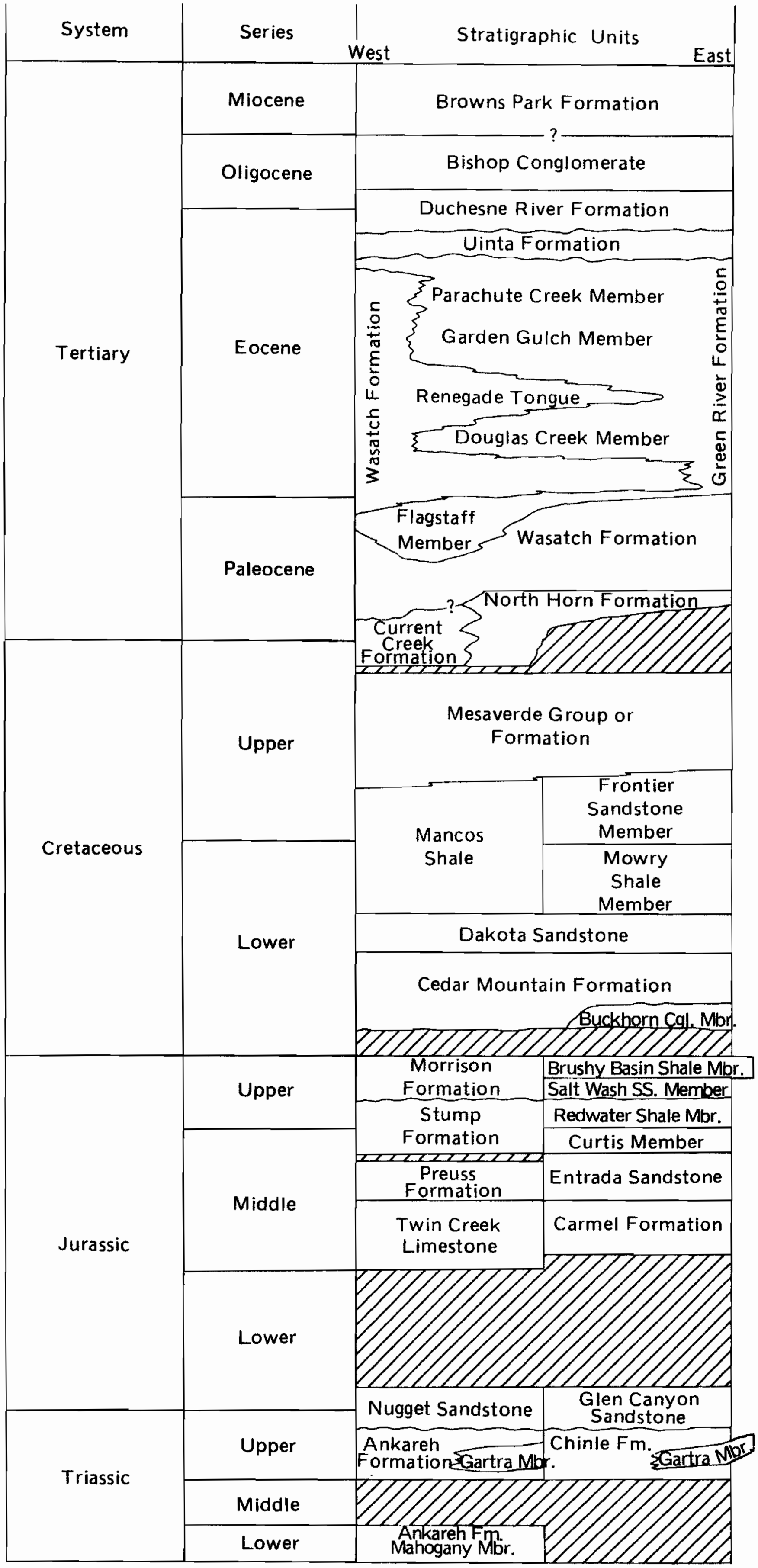

Figure 8.—Major bedrock stratigraphic units in the Uinta Basin.

System	Series	Stratigraphic Units (West)	Stratigraphic Units (East)
Triassic	Lower	Thaynes Formation	Moenkopi Formation
		Woodside Formation	
Permian		Phosphoria Formation	Park City Formation
Pennsylvanian	Upper	Weber Sandstone	Weber Sandstone
	Middle	Morgan Formation	Morgan Formation
	Lower	Round Valley Limestone	Round Valley Limestone
Mississippian	Upper	Doughnut Shale	Doughnut Shale
		Humbug Formation	Humbug Formation
		Deseret Limestone	Deseret Limestone
	Lower	Madison Limestone	Madison Limestone
Devonian			
Silurian			
Ordovician			
Cambrian	Upper		Lodore Formation
	Middle	Tintic Quartzite	
	Lower		
Middle Proterozoic		Uinta Mountain Group: Red Pine Shale	Uinta Mountain Group: Red Pine Shale
		Uinta Mountain Group: Unnamed Quartzite Unit	Uinta Mountain Group: Unnamed Quartzite Unit
Early Proterozoic		?	?
Late Archean		Red Creek Quartzite	Red Creek Quartzite

Figure 8.—Major bedrock stratigraphic units in the Uinta Basin—Continued.

the Summerville Formation, of Jurassic age; the Kaibab Limestone, Coconino Sandstone, Elephant Canyon Formation of Baars (1962), and various units of the Cutler Formation, all of Permian age; the Rico, Hermosa (about 1,600 feet of the Paradox Member was reported in one oil test), Molas, and Oquirrh Formations of Pennsylvanian age; and, possibly, the Ouray and Elbert Formations of Devonian age and the Ajax and Lynch Dolomites, Maxfield Limestone, and Ophir Shale of Cambrian age.

The area that is now the Uinta Basin may have been, in Late Archean, an aulacogen, although some investigators (Bryant, 1985) believe that the area was off the southern coast of a continent. Geosynclinal deposits in the area that is now the Uinta uplift exceeded 28,000 feet in thickness. These deposits then were metamorphosed, deformed and faulted, and probably eroded. During the middle of the Middle to Late Proterozoic, renewed deposition in this geosyncline exceeded 24,000 feet. Some investigators believe that these geosynclinal deposits do not underlie the Uinta structural basin, but only the Uinta Mountain block. Realignment and shifting of crustal plates in Late Proterozoic resulted in elevation of the area that is now the Uinta Basin above sea level and its shift from being either an aulacogen or on the southern margin of a continent to being on the western border of a continent. From then until final withdrawal of the western or northern sea in Late Jurassic, the area was on the eastern margin of the Cordilleran geosyncline; usually as part of the stable shelf, but sometimes as the western (seaward) end of an intracratonal trough.

In the Early and Middle Cambrian, the area subsided, but the site of the future Uinta Mountains remained above sea level as a chain of islands. The region generally remained below sea level until the Early Devonian except possibly for an interval in the late Early Ordovician when it may have been emergent. Emergence in the Early Devonian subjected the area to extensive erosion until middle Early Mississippian, except for a short period in middle Late Devonian when the region sagged below sea level. This long erosional interval apparently removed most sediments deposited during the Cambrian, Ordovician, Silurian, and Devonian. During the Mississippian, the region oscillated slowly above and below sea level except for an erosional episode of low-relief emergence during the middle Late Mississippian. The Uncompahgre uplift, in the southern part of the basin, may have been slightly above sea level during part of the Mississippian. Subsidence in latest Mississippian probably marked the end of the area of the present-day Uinta Mountain block as a positive structural element until the Late Cretaceous. Except for a period of emergence and erosion from latest Early to early Middle Pennsylvanian, most of the area of the modern Uinta Basin remained a depositional trough until the middle of the Early Permian. Then, the region was uplifted and subjected to erosion until the end of the Permian. The southern part of the basin may have been emergent for much of the Pennsylvanian and Permian as the northwestern end of the Uncompahgre uplift, which achieved high relief as the ancestral Rocky Mountains at that time.

The area of the modern Uinta Basin was again below sea level as part of a broad shelf during the Early Triassic. Emergence in the latest Early Triassic lasted until the early Middle Jurassic. During this interval, episodes of erosion were interspersed with accumulation of continental deposits. Subsidence and marine invasion occurred from the middle of the Middle Jurassic to the late Middle Jurassic. The final marine transgression from the Cordilleran trough occurred in the late Middle Jurassic and lasted until the middle Late Jurassic. The final Jurassic emergence lasted until the late Early Cretaceous when the region was invaded by a westward transgressing epicontinental sea. During this emergence, erosional episodes were followed by accumulation of predominantly fluvial and lacustrine deposits. Deposition in the eastern sea lasted from the late Early to middle Late Cretaceous. Deposition of the Mesaverde Formation (or Group) generally marked the end of marine deposition in the region.

The Uinta Basin of today is both a structural and topographic basin that has formed as a result of uplift and deformation that began in the Late Cretaceous. The basin trends east and east-southeast in northeastern Utah and northwestern Colorado. The structural axis of the basin roughly parallels the axis of the Uinta Mountain uplift to the north; the two structural axes are about 26 miles apart near Strawberry Reservoir, 18 miles apart near Roosevelt, and 45 miles apart near the Colorado State line. Strata on the northern flank of the basin dip steeply toward the basin axis, but beds on the southern flank of the basin dip gently. Formation and subsidence of the basin were contemporaneous with uplift of adjacent highlands--the Uinta Mountains and Wasatch Range of Utah, the Sierra Madre uplift in Colorado and Wyoming, the Park, Sawatch, and White River uplifts in Colorado, San Raphael Swell in Utah, Douglas Creek arch in Colorado, and a reactivated Uncompaghre uplift in Utah and Colorado (fig. 9).

In the Paleocene and most of the Eocene, the Uinta Basin was occupied by a series of lakes of varying size that began to form after the region emerged from the sea in the Late Cretaceous. At maximum lacustrine development, a single lake may have filled much of the Uinta Basin of Utah and Colorado, the Green River Basin of Wyoming and Utah, the Piceance and Coyote Basins of Colorado, the Sand Wash Basin of Colorado and Wyoming, and the Washakie and Red Desert Basins of Wyoming. Erosion of the highlands around the Uinta Basin has filled it with as much as 20,000 feet of sediment since retreat of the sea in the Late Cretaceous.

Ground-water hydrology of the Uinta Basin is controlled primarily by the geologic structure of the region. The major secondary control on the ground-water system is stratigraphic--lithology and, particularly for fluvial and lacustrine rocks of the Paleocene and Eocene, facies changes. An important tertiary control on the ground-water system is the widespread faulting and fracturing of the rocks.

Because of the structure (fig. 10), the area may be a ground-water basin of internal drainage. If there is a deep outlet for the basin, it is along or near the axis of the Uinta Basin at its western edge where the basin's axis turns south between the San Rafael uplift and the Wasatch Range. The general pattern of ground-water flow is radial, inward from areas of major recharge at exposures of permeable strata near the rim of the basin. Most remaining

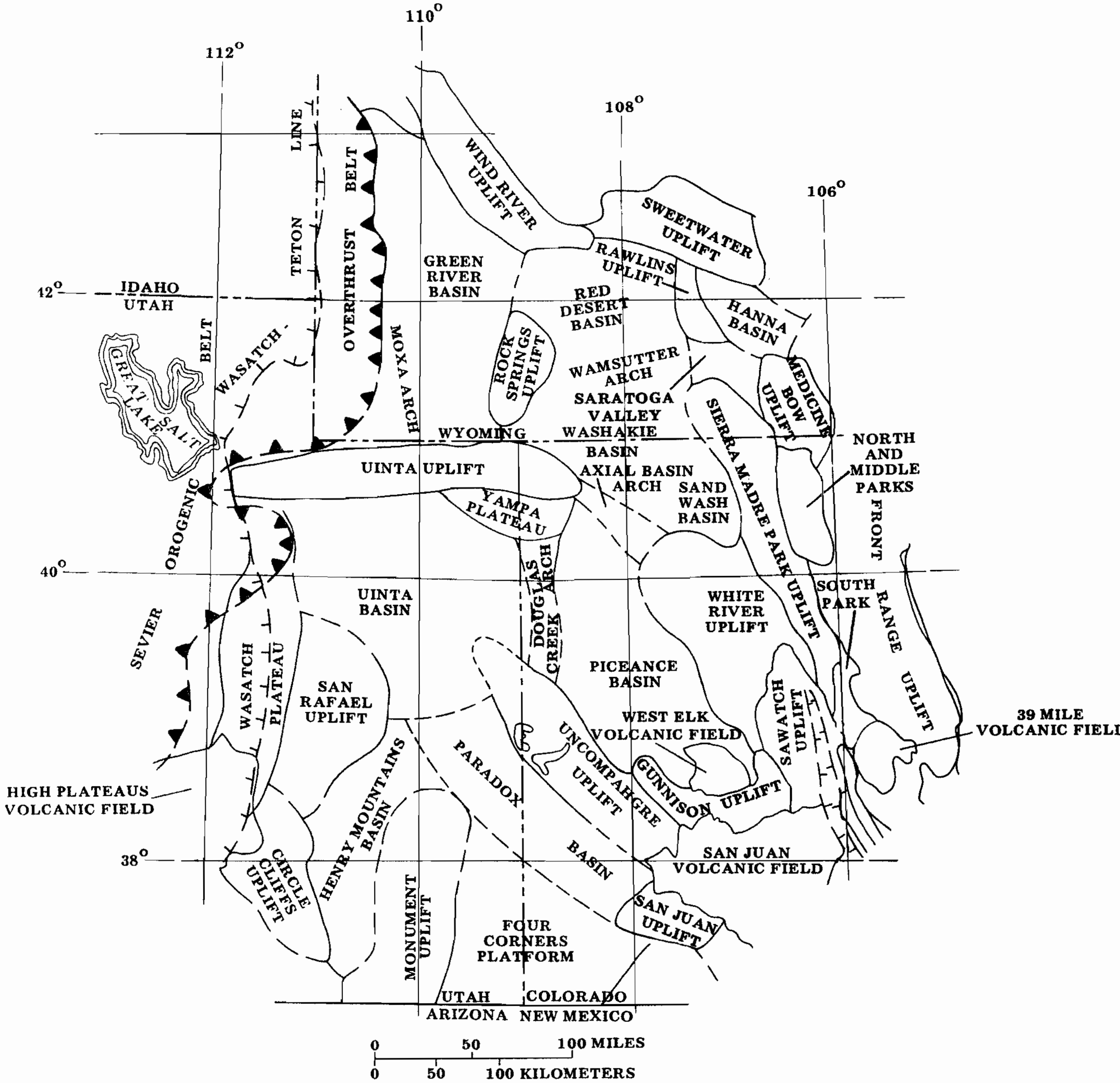

Figure 9.—Modern major regional tectonic elements
(modified from Gross, 1972, fig. 1).

recharge is on Eocene and Oligocene formations of the interior of the basin. Recharge is greatest near the northern edge of the basin.

Shales and other relatively impermeable rocks are barriers to the movement of water unless they are fractured or, in the case of dense carbonates, unless they contain solution channels. Conglomerates, sandstones, and other rocks that contain interconnected pore space are permeable and serve as conduits for the movement of, and as reservoirs for the storage of, ground water. In rocks of fluvial and lacustrine origin, such as those of the Tertiary in the Uinta Basin, the complex intercalation of beds of various depositional environments causes ground water to follow a tortuous path in its movement.

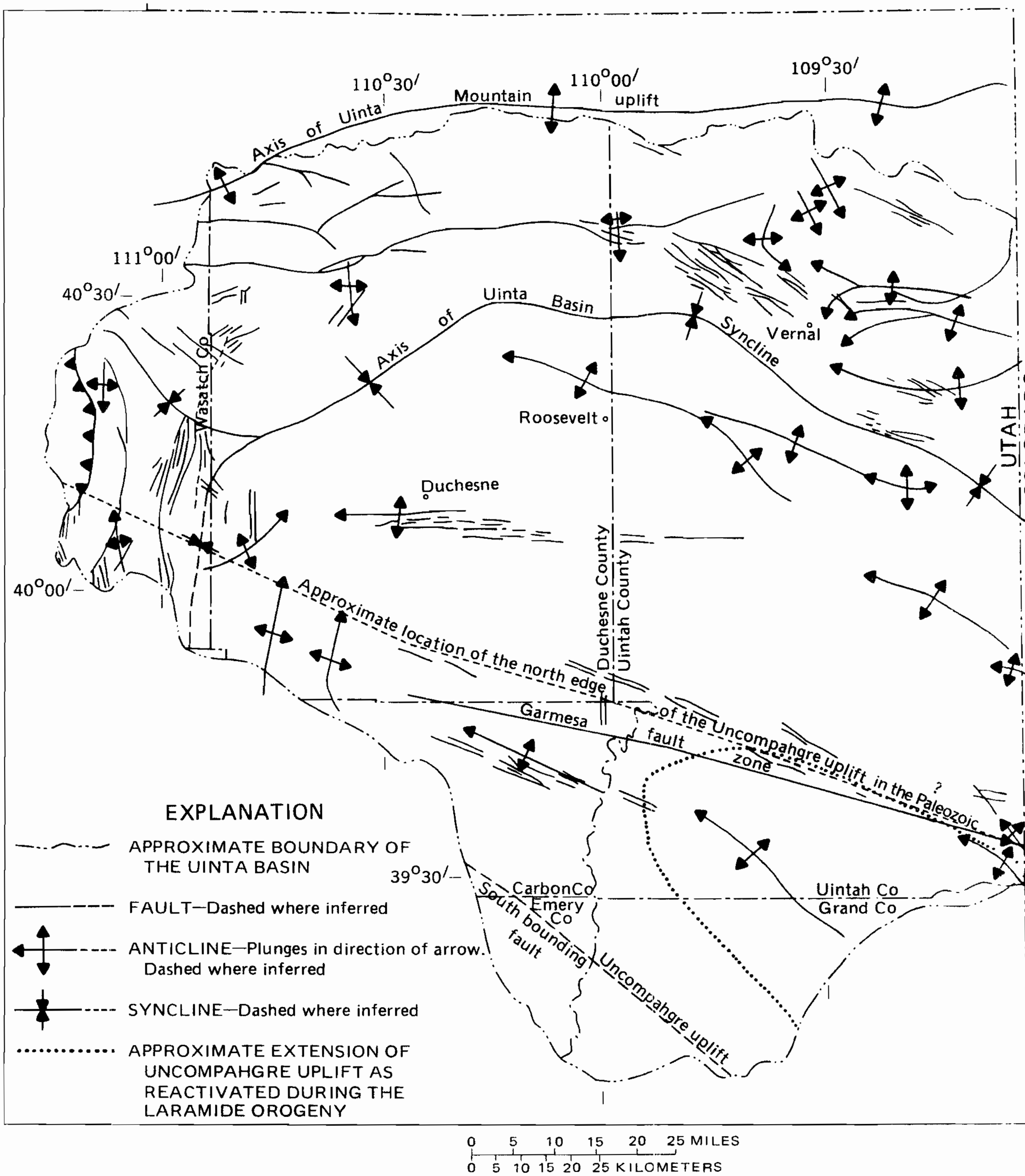

Figure 10.—Major tectonic and structural elements of the Uinta Basin in Utah.

The forces that deformed the region into a basin also caused many flexures, much faulting, and abundant fracturing. The faults and fractures, in many parts of the basin, provide productive permeability in otherwise relatively impermeable rocks, as well as avenues for the vertical movement of water.

During the wide-spread lacustrine phase of the basin's development, the region was a surface-water basin of internal drainage for long intervals. Although no massively bedded evaporite deposits have been found, thin beds and disseminated grains of evaporites are common and are so concentrated in the upper part of the Green River Formation that one interval is informally known as the "saline facies."

Short descriptions of the major bedrock formations and an outline of the hydrologic significance of those units is given in table 1.

The chemical quality of ground water in the Uinta Basin has been discussed by Goode and Feltis (1962), Feltis (1966), Maxwell and others (1971), Price and Miller (1975), Hood and others (1976), Hood (1977a, b), Hood and Fields (1978), Holmes (1980), Fiske and Clyde (1981), Lindskov and others (1983), and summarized by Holmes (1985): The concentration of dissolved solids in ground water ranges from 19 to 112,000 mg/L. The freshest water comes from rocks of Precambrian age in the Uinta Mountains; this water usually is of calcium bicarbonate type. Water in younger rocks near their recharge areas commonly contains somewhat more dissolved solids, but still is fresh, and is of calcium bicarbonate to calcium magnesium bicarbonate carbonate type. As the ground water moves down the hydraulic gradient, the salinity increases and the water type changes in response to geochemical reactions caused by changes in the physical (temperature, pressure, and so forth) and mineralogical environments, including exposure to some comparatively unusual minerals such as nahcolite (sodium bicarbonate) and trona (hydrated sodium carbonate-sodium bicarbonate), which are common in the Uinta Basin. The changes in water type generally are from calcium bicarbonate to calcium magnesium bicarbonate to sodium bicarbonate to sodium sulfate to sodium chloride. Locally, in the Glen Canyon Sandstone and Park City, Moenkopi, and Morrison Formations, the water may be of sodium or calcium sulfate type because of exposure to evaporite minerals such as glaubers salt, anhydrite, or glauberite. Water in the Uinta and Green River Formations generally is very saline to briny and of sodium chloride type at depth; however, it is fresh to moderately saline and generally of sodium bicarbonate type at shallow depths. In some areas the sodium bicarbonate water may be a brine and extend to greater depth.

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 contains very saline to briny water had to be more than 500 feet thick and contain no permeable bed of fresh to moderately saline water more than 30 feet thick.

Table 1. Generalized stratigraphic column describing the major bedrock units and some of their hydrologic characteristics
[modified from Hood, 1976, table 1]

Erathem or Era	System	Series	Formation or rock unit	Maximum known thickness (feet)	Description	Hydrologic significance
CENOZOIC	TERTIARY	Miocene	Browns Park Formation	1,200	Extremely variable deposits of sandstone, tuffaceous rock, and conglomerate.	Very low to moderate permeability. Yields small quantities of fresh water to springs and wells in the Brush Creek and Diamond Mountain areas north and northeast of Vernal. Probable source of some springs on the slopes of the central Uinta Mountains.
		Oligocene	Bishop Conglomerate	300	Conglomerate of sandstone, quartzite, metamorphic, and volcanic rock fragments. Considered by some geologists to be the basal part of the overlying Browns Park Formation.	
			Extrusive igneous rock	100(?)	Mostly andesitic pyroclastics; may be the Keetley Volcanics or equivalent. Present as erosional remnants on the highest hills near Wolf Creek Pass.	Yields water to some small springs; most of these springs are along fractures or formation contacts.
		Oligocene / Eocene	Duchesne River Formation	3,800	A mostly fluvial facies. Shale, mostly red, siltstone, marlstone, sandstone, and conglomerate, unconformably underlying younger rocks from near the Colorado State line to near Strawberry Reservoir. Coarsest grain sizes are near the basin margins where the formation interfingers with other formations. In the central part of the basin it is gradational with the underlying Uinta Formation and consists of interbedded sandstone and shale. Sandstone is most abundant in the lower part and, with conglomerate, is found in the upper part. The sandstone is of two types: a light-colored (commonly yellow) channel deposit, and a darker, more compacted, better cemented interchannel (?) lenticular deposit. In most of its extent the formation is slightly to strongly fractured. Fractures are locally re-cemented with calcium sulfate.	Very low to very high permeability. The horizontal intergranular permeability of 19 sandstone samples ranged from 0.000033 to 3.28 ft/d (feet per day). Porosity ranged from 7 to 32 percent. Aquifer permeability is enhanced by fracturing. Yields of wells and springs range from less than 1 to more than 300 gpm (gallons per minute), usually with large drawdowns in wells. The most permeable rocks seem to be near edges of outcrops west of Roosevelt in the central basin; the least permeable rocks seem to be in areas north and east of Fort Duchesne. Water movement may be impeded locally by gilsonite dikes. Near recharge areas, or where the formation is fractured or is moderately permeable, the water usually is fresh. At greater depths where the formation is of very low permeability, the water is slightly saline to briny. Confined conditions are common. In the lower parts of the basin, such as near Roosevelt, artesian heads may be more than 100 feet above land surface, but in higher parts of the basin water levels are below land surface.
		Eocene	Uinta Formation	4,000	Calcareous shale, some limestone, claystone, siltstone, and sandstone. It is a fluvial facies in the eastern and western ends of the basin that interfingers with rocks similar in appearance to the overlying Duchesne River Formation. Grades laterally into thinner bedded calcareous lake deposits in the center of the basin.	Very low to very high permeability. Largest primary intergranular permeability of the sandstone seems to be about the same as that of the median for sandstone in the Duchesne River Formation. Most of the formation is finer grained, and, therefore, of lower primary permeability than the Duchesne River Formation. Permeability is greatly increased where the Uinta Formation is fractured. In most of the area, the formation yields only a few gallons per minute of saline water to wells and springs. In some areas the water has high fluoride and boron concentrations. Locally, flowing wells yield fresh to slightly saline water. In the fluvial facies, particularly where the rocks are fractured, yields are larger.
		Paleocene and Eocene	Green River Formation	7,000	Mostly lacustrine shale that contains some limestone, marlstone, and siltstone. The formation includes beds of oil shale and of carbonate evaporite. The Green River interfingers with both the overlying Uinta and underlying Wasatch Formations, as well as laterally with other formations near the edges of the basin.	Very low to low permeability except where fractured. Sandstones near oil-shale beds have values of transmissivity from 0.9 to 2.4 ft^2/day (feet squared per day). In most of the basin the formation yields only saline or briny water, though in and near the area of outcrop in the southern part of the basin the water is fresh to slightly saline, and in the area of outcrop near Strawberry Reservoir the water is fresh where the formation is fractured.
			Wasatch Formation	5,000	In most of the basin is mainly lacustrine shale, sandstone, and conglomerate. Interfingers with the overlying and underlying formations and laterally with the North Horn, Currant Creek, and Green River Formations. Crops out only in the far eastern end of the northern Uinta Basin and in the canyons of deeply-incised streams in the southern Uinta Basin.	Very low to low permeability except where fractured. In the Greater Altamont-Bluebell oil field the Wasatch sands reportedly have only 4 to 5 percent porosity, but are permeable because of fracturing. Much of the water produced with petroleum is moderately saline to very saline; generally, however, the water is less mineralized than is water from the Green River Formation.
MESOZOIC AND CENOZOIC	CRETACEOUS AND TERTIARY	Upper Cretaceous and Paleocene	Currant Creek Formation	4,800	Currant Creek Formation.--Fluvial deposits of very coarse conglomerate and crossbedded conglomeratic sandstone, tightly cemented. Diameters of the largest boulders exceed 3 feet. Interfingers laterally with the North Horn and Wasatch Formations. May interfinger with the underlying Mesaverde Group. Thins southeastward from the northwestern corner of the basin.	Low to very high permeability. Primary permeability of a sample from the outcrop in the Duchesne River valley was 1.44 ft/d and porosity was 23.6 percent; these probably are maximum primary values for the formation. Fractured rock has a permeability of more than 200 ft/d in well U(C-2-10)20aac-1. Water probably is unconfined in areas of outcrop. In and near the outcrop, water in the formation is fresh.
			North Horn Formation	2,500	North Horn Formation.--Fluvial shale, sandstone, conglomerate, and lacustrine limestone, tightly cemented. Interfingers laterally with the Currant Creek and Wasatch Formations and may interfinger with the underlying Mesaverde Formation. Thins eastward.	Low to very high permeability. Primary permeability is low. Permeability may be high where the formation is fractured.
		Upper Cretaceous	Mesaverde Group or Formation	4,000	Continental deposits of shale, sandstone, and coal beds. Interfingers with the upper part of the underlying Mancos Shale and may interfinger with the overlying Currant Creek and North Horn Formations. Maximum thickness ranges from 550 to 4,000 feet in the western part of the basin and from 400 to 1,160 feet in the eastern part of the basin.	Very low to high permeability. In areas of outcrop, water in the formation is fresh to slightly saline, but samples of water from petroleum tests in the eastern part of the basin reportedly were very saline to briny.

Table 1. Generalized stratigraphic column describing the major bedrock units and some of their hydrologic characteristics--Continued

Erathem or Era	System	Series	Formation or rock unit	Maximum known thickness (feet)	Description	Hydrologic significance
MESOZOIC	CRETACEOUS	Upper Cretaceous	Mancos Shale	5,000	Soft, gray marine shale. Contains an unnamed upper shale member, a middle unit, the Frontier Sandstone Member, and a lower unit, the Mowry Shale Member. Maximum thickness ranges from 2,900 to 3,700 feet in the western part of the basin to about 5,000 feet in the eastern part of the basin. In the western part of the Uinta Basin, the Frontier Sandstone Member is made up of crossbedded, lenticular, thick sandstone beds that contain a middle shale unit and some coal beds in the upper part. The Frontier thickens westward from 400 to 600 feet and interfingers with the upper shale unit of the Mancos. In the eastern part of the basin the Frontier is 210 to 250 feet of fine-grained sandstone that contains some shale interbeds and some thin beds of coal in the upper part. The Frontier thins and becomes more shaly to the southeast.	The shale beds have very low permeability and are barriers to the movement of water. Water obtained from the formation, or from younger rocks containing erosional derivatives of it, is saline.
		Lower Cretaceous	Dakota Sandstone	180	Marine to near-shore marine sandstone and siltstone interbedded with shale. Locally may be highly fractured.	Very low to moderate permeability except where fractured. Measured permeability ranged from 0.00018 to 80 ft/d. The water in these two formations probably is fresh in and near areas of outcrop and is saline where they are deeply buried.
			Cedar Mountain Formation	1,000	Continental deposits of sandstone and siltstone, locally conglomeratic. Locally may be highly fractured.	
	JURASSIC	Upper Jurassic	Morrison Formation	1,550	Continental deposits. In the western Uinta Basin the Morrison consists of as much as 1,550 feet of multicolored shale, siltstone, sandstone, and conglomerate, and a few thin beds of fresh-water limestone. The formation thins eastward to less than 900 feet of variegated shale and siltstone, red and gray fine-grained silty sandstone, medium- to coarse-grained pebbly sandstone, and thin beds of anhydrite. The formation is variable and individual beds are highly lenticular. Probably fractured in most of the basin.	Very low to moderate permeability except where fractured. Wells completed in the Morrison Formation are mostly in the eastern end of the basin. The few water analyses available for this formation are from areas in or near outcrops and were of fresh water. Where the formation is deeply buried the water in it probably is saline and is of sodium sulfate type except near the center of the basin where it probably is of sodium chloride type.
			Stump Formation	270	Marine (in part coastal) deposits. In the western part of the basin, the formation includes a lower, fine-grained, friable, glauconitic sandstone of variable thickness and an upper unit of shale and thin-bedded limestone. In the eastern part of the basin the lower sandstone is medium to coarse grained and the color is darker.	Very low to moderate permeability except where fractured. Yields fresh water to springs in its area of outcrop. Water in the formation probably is saline in the deeper parts of the basin.
		Middle Jurassic	Preuss Formation / Entrada Formation	800/160	The Preuss, in the western part of the basin, is the marine facies, and the Entrada, in the eastern part of the basin, is the continental facies of this episode of deposition. The Preuss consists of mostly red silty and sandy shale, thin-bedded, nonresistant siltstone, and fine- to medium-grained sandstone. The Preuss thins eastward and grades laterally into and interbeds with the Entrada Sandstone, which consists of less than 160 feet of massive, crossbedded, fine- to medium-grained, friable sandstone. Probably strongly fractured in areas of faulting and sharp folding.	Low to moderate permeability except where fractured. Yields fresh water to wells and springs in the eastern part of the basin. Water from oil wells in the Ashley Valley is fresh to slightly saline and is suitable for irrigation. In both areas the water is of calcium bicarbonate type. The salinity of water from these formations elsewhere in the basin is unknown, but the water probably is fresh in and near areas of outcrop.
			Twin Creek Limestone / Carmel Formation	950/190	The Twin Creek Limestone, in the western part of the basin, is the marine facies, and the Carmel Formation, in the eastern part of the basin, is the continental facies of this episode of deposition. The Twin Creek is made up of limestone, shale, and sandy shale beds that contain a few (probably fluvial) red beds near the top and more red beds and thin anhydrite layers near the center of the basin. The Twin Creek grades laterally into and interbeds with the mostly fluvial Carmel Formation which consists of less than 190 feet of fine-grained silty sandstone, siltstone, and limy shale that thins eastward.	Very low permeability except where fractured or where limestone beds contain solution channels. The water probably is saline where the formations are deeply buried or where they contain anhydrite or gypsum.
	TRIASSIC AND JURASSIC	Upper Triassic and Lower Jurassic	Nugget Sandstone or Glen Canyon Sandstone	1,310	In the western part of the basin this formation is light-orange, fine- to medium-grained, eolian sandstone; it is massive and has large-scale crossbedding. It thickens slightly eastward and an increasing part of the section becomes white. In the eastern part of the basin the formation thins to less than 900 feet of white to gray, massive, crossbedded eolian sandstone that is strongly jointed and fractured where flexed or faulted.	Very low to moderate permeability except where jointed or fractured. Measured permeability ranged from 0.002 to 1.44 ft/d and porosity was more than 20 percent. Yields water to springs and wells in the eastern part of the basin from north of LaPoint eastward into Colorado. At or near the outcrop, water in the formation is fresh and of calcium bicarbonate type. Deeper within the basin, at 6,000 feet in depth, the water is slightly saline and of sodium sulfate type and, near Ouray, at 17,350 feet in depth, the water is briny and of sodium chloride type.

Table 1. Generalized stratigraphic column describing the major bedrock units and some of their hydrologic characteristics—Continued

Erathem or Era	System	Series	Formation or rock unit	Maximum known thickness (feet)	Description	Hydrologic significance
MESOZOIC	TRIASSIC	Upper Triassic	Ankareh Formation or Chinle Formation	1,100 /300	In the western part of the basin this unit is called the Ankareh Formation and contains three members, the middle of which is called the Gartra Member. In the eastern part of the basin this formation is called the Chinle and it contains two units, the lower of which is the Gartra Member. The upper unit consists, in the west, of as much as 380 feet of variegated mudstone and siltstone, mostly thin bedded. The upper unit appears to thicken toward the center of the basin and to thin toward the east. Near Vernal, where it consists of about 260 feet of mostly variegated shale, the upper one-third is red, ripple-marked sandstone interbedded with thin layers of red shale. The Gartra Member, in the west, is from a few feet to 40 feet thick, and consists of massive, crossbedded, coarse-grained, arkosic sandstone and conglomerate. It thickens slightly toward the middle of the basin and then thins toward the east, where it consists of from less than an inch to more than 60 feet of crossbedded, medium- to coarse-grained sandstone that contains streaks of quartzite pebbles. Locally, in the east, the Gartra Member occupies channels cut 20 to 25 feet into the underlying Moenkopi Formation. The lower unit of the Ankareh Formation, often called the Mahogany Member, consists of as much as 700 feet of thin-bedded red to purple shale and siltstone. The Mahogany Member was deposited in a shallow-water marine environment, but the Gartra and the top-most, unnamed, member are continental (mostly fluvial) deposits.	The upper, unnamed, member has low to very low permeability, unless fractured, and probably could yield only small quantities of saline water to wells. The Gartra Member has low to moderate permeability. The largest yields to wells probably would be where the unit is thickest and fractured. The few existing wells have modest yields of calcium bicarbonate and sodium bicarbonate sulfate type water. The lower (Mahogany) unit of the Ankareh Formation has low to very low permeability.
		Lower Triassic	Thaynes Formation; Woodside Formation; Moenkopi Formation	600; 1,100; 1,000	The Moenkopi, in the eastern part of the basin, is the mostly continental eastern facies of the marine Thaynes and Woodside Formations. Near Vernal, the Moenkopi consists of about 175 feet of thin-bedded siltstone and very fine-grained sandstone overlain by about 570 feet of thin-bedded red shale, red siltstone, and fine-grained sandstone. There are a few thin beds of anhydrite in a stratigraphically narrow range near the middle of the section. The light-colored lower part of the Moenkopi is gradational with the underlying Park City Formation or Phosphoria Formation and appears to thicken eastward. To the west the Moenkopi grades into and interfingers with the Thaynes and Woodside. The Thaynes Formation has two members, the upper of which is as much as 400 feet thick and consists of shale and siltstone. The lower member is as much as 200 feet thick and consists of fine-grained silty sandstone interbedded with thin-bedded limestone. Anhydrite layers and fracture fillings and salt-crystal casts are present locally. The Woodside Formation consists of thin-bedded, red-brown siltstone and shale. It thins westward across the upper Duchesne River.	Very low to low permeability except where fractured. Probably would yield water to wells only where fractured. Such water probably would be saline except near areas of recharge (outcrop).
PALEOZOIC	PERMIAN	Upper Permian	Phosphoria Formation or Park City Formation	650	Marine deposits that are called the Park City Formation by some geologists and the Phosphoria Formation by others. In the western part of the basin the interval has three members. The lower member is brecciated, very fine-grained, friable, porous sandstone and dolomitic, locally brecciated, silty and sandy, thin-bedded limestone. The middle member consists of about 40 feet of black phosphatic shale interbedded with gray shale and thin-bedded limestone. The upper member is thin-bedded to massive, silty and sandy, cherty, dolomitic limestone. In the eastern part of the basin the interval consists of 24 to 28 feet of phosphatic shale and phosphate rock overlain by thin-bedded, cherty and sandy, dolomitic limestone interbedded with shale and fine-grained sandstone. The interval thins eastward.	Very low to low permeability except where fractured or where solution channels have developed in the limestone. In the Ashley Valley, and about 13 miles north of Altamont (well U(B-2-3)22dcc-1), the basal section that overlies the Weber Sandstone contains fresh to slightly saline water.
		Lower Permian	Diamond Creek Sandstone; Kirkman Limestone; Weber Sandstone	1,600	The Weber Sandstone is a continental deposit that, in the western part of the basin consists of 1,400 to 1,600 feet of very fine-grained, medium-bedded, partly crossbedded sandstone that contains chert and, locally, thin-bedded cherty limestone, commonly near the top. Strongly fractured, especially near faults and folds. The formation thins to about 1,200 feet in the eastern part of the basin. There it is massive, fine- to coarse-grained sandstone that has locally well-developed crossbedding in the upper part. Some cores show that, where deeply buried, the Weber is dense, very fine-grained sandstone. North of Strawberry Reservoir, the easternmost tip of a thrust plate includes several thousand feet of rock believed to be Oquirrh Formation and Kirkman Limestone and Diamond Creek Sandstone. As these units are probable equivalents of the Pennsylvanian Weber Sandstone and Morgan Formation section of the Uinta Mountains, they are not included in the description.	Very low to very high permeability. Primary permeability is very low to moderate, depending on location both geographically and stratigraphically. Measured permeabilities ranged from 0.000021 to 0.28 ft/d and porosities ranged from 11 to 19 percent. The Weber is a source of large-yield springs in areas where it is strongly faulted and fractured. Most wells and springs that tap the Weber yield fresh water. The formation yields fresh to slightly saline water from depths of 4,000 to 5,000 feet in the Ashley Valley.
	PENNSYLVANIAN	Upper Pennsylvanian; Middle Pennsylvanian	Oquirrh Formation; Weber Sandstone			

Table 1. Generalized stratigraphic column describing the major bedrock units and some of their hydrologic characteristics—Continued

Erathem or Era	System	Series	Formation or rock unit	Maximum known thickness (feet)	Description	Hydrologic significance
PALEOZOIC	PENNSYLVANIAN	Middle Pennsylvanian	Oquirrh Formation / Morgan Formation	1,400	The Morgan is a continental deposit that in the western part of the basin is mostly red, very fine-grained sandstone interbedded with some mudstone and siltstone, and in the eastern part of the basin is red sandy shale, crossbedded sandstone, and a few beds of limestone. Locally, the Morgan is strongly faulted and fractured.	Very low to very high permeability. Primary permeability is very low to low. Fracturing locally results in very high permeability. In such places, the formation acts as a vertical conduit for water from underlying rocks. The formation is involved in the transmission of water to large springs such as Big Brush Creek Spring, (D-2-21)24cbb-S1, and it is the source of about 30 ft^3/s (cubic feet per second) of water discharged from fractures associated with faulting at the Jones Hole Spring area, (D-3-25)1b. Water from springs or wells in the area of the outcrop is fresh and commonly contains less than 200 mg/L of dissolved solids.
		Lower Pennsylvanian	Round Valley Limestone	350	Light-grey marine limestone, partly dolomitic and cherty. Contains some interbedded shale.	Very low to very high permeability. Primary permeability is very low to low. Fractures and solution channels locally cause very high permeability.
	MISSISSIPPIAN	Upper Mississippian	Doughnut Shale	400	This is the Manning Canyon Formation of Stokes (1964) or the black shale unit of earlier investigators. It is a marine deposit of black shale, interbedded with a few thin beds of limestone, siltstone, and sandstone, that thins to about 300 feet in Whiterocks Canyon, to about 100 feet north of Vernal, and to 25 feet or less in the eastern end of the basin.	Very low to low permeability and a barrier to the movement of water except where fractured.
			Humbug Formation	400	A marine deposit of limestone breccia, sandstone breccia, and limestone.	All three units: Very low to very high permeability. Primary permeability is very low, but where fractures or solution channels have developed, permeability can be very high. Large, active caves have developed in some areas, as has karst topography. Karst topography also developed in the past during Mississipian and later intervals of exposure and weathering of these rocks. Relict secondary permeability may contribute to present permeability. The Mississippian carbonate rocks are extensively faulted, fractured, and, in and near areas of outcrop, riddled with cavernous zones. These units provide water to springs such as Big Spring [U(B-1-8)17cbb-S1] on the Upper Duchesne River, a large spring [U(B-2-7)25cab-S1] on Rock Creek, and the large spring [U(B-2-2)5dbb-S1] on the Uinta River. In general, almost all water produced from these rocks on the south slope of the Uinta Mountains is fresh and of calcium bicarbonate type. However, where these formations are deeply buried, they may contain very saline or briny water.
			Deseret Limestone	650	A marine deposit of thin-bedded to massive limestone and dolomite that contains abundant chert. May have a few feet of phosphatic black shale at the base.	
		Lower Mississippian	Madison Limestone	250	Thin-bedded limestone that contains locally abundant chert and shaly partings.	
	CAMBRIAN	Upper Cambrian; Middle Cambrian	Lodore Formation; Tintic Quartzite	500/155	Lodore Formation.—A marine sandstone found in the eastern part of the basin, that thins and disappears westward. The Lodore is a thick-bedded, coarse-grained, feldspathic sandstone that is glauconitic and contains beds of micaceous shale. Tintic Quartzite.—A marine deposit of quartzitic sandstone found in the western part of the basin that thins and disappears eastward. The Tintic has a wide range of grain size and contains thin beds and partings of pebble conglomerate, siltstone, and shale.	Very low to high permeability. Primary permeability is low but, where the rock is fractured, permeability may be high. In and near the area of outcrop the formation contains fresh water.
MIDDLE PROTEROZOIC			Uinta Mountain Group	24,000+	The Uinta Mountain Group consists of two units: an upper unit called the Red Pine Shale, and a lower, unnamed, quartzite unit. The Red Pine Shale is a dark sericitic shale interbedded with thin beds of dark arkosic sandstone. Probably fractured near major fault zones. The formation thins eastward and may be only a few hundred feet thick in the eastern part of the basin. The unnamed quartzite unit is mostly a purple to dark reddish-brown orthoquartzite, but it does include white to red quartzitic sandstone. These rocks are strongly faulted and have many shattered zones associated with the faulting.	The Red Pine Shale has very low to low permeability and is a barrier to the movement of water except where fractured. The unnamed quartzite unit has very low to low permeability except where faulted or fractured, or where near-surface weathering and jointing have increased permeability. Wells and springs that tap this formation produce water that has a low dissolved-solids concentration—19 to 88 mg/L. Where the formation is fractured, large yields locally may be possible.
LATE ARCHEAN AND EARLY PROTEROZOIC			? Red Creek Quartzite	28,000+	Moderately high-grade metamorphic rock that consists mostly of white metaquartzite, but includes schist, gneiss, marble, and dikes and veins of felsic igneous intrusive rocks.	Very low permeability unless faulted and fractured. Water from springs or wells is fresh.

The 10,000 mg/L isoconcentration surface defined by interpretation of geophysical logs and available water-quality information for this study is shown on plates 1 and 2. In the northern part of the basin (pl. 1), the surface as defined by the sea level, and higher, contours includes a large triangular mound whose base is in the southern part of the basin (about 4 to 12 miles into the area shown on plate 2) and whose sides extend from an apex about 9 miles north-northeast of Bluebell to the Colorado State line on the east and to the Wasatch County line on the west. The mound of very saline to briny water within this triangle appears to terminate abruptly along its northwestern and northeastern sides. Available chemical data and well-log interpretation indicate the possibility that this mound of very saline to briny water may be a lens (occupying the middle of the Uinta Basin) that is both overlain and underlain by fresh to moderately saline water. The base of the lens of very saline to briny water may be at a depth of about 9,000 to 10,000 feet along the northern edge of the greater Altamont-Bluebell field, at depths of from 6,400 to 10,000 feet on the southwestern edge of the field and from 8,000 to more than 14,000 feet within the interior of the field. South of Roosevelt, near the southern boundary of the area shown on plate 1, the base of the very saline to briny water is at a depth of more than 12,000 feet. Near the southeastern corner of this area, the base is from 6,000 to (if present) more than 18,000 feet below land surface.

In addition to the large triangular mound, three small, isolated mounds are present in the base of the moderately saline water shown on plate 1. These small mounds are in U(B-2-1)20, U(C-1-11)26, and in the heavily faulted southwestern corner of the area.

In the southern part of the basin (pl. 2), the configuration of the 10,000 mg/L isoconcentration surface includes the southern part of the large mound of very saline to briny water shown on plate 1, a large area of very saline to briny water that underlies much of the southern part of the basin, and two smaller, apparently isolated, areas of very saline water, one in the southernmost part of the basin, the other near the northwestern corner of the area shown on plate 2. The slope of the surface of the large mound that occupies much of the southern part of the basin is less steep than that of the large mound shown on plate 1 and the northern part of plate 2.

The large mound in the southern part of the basin seems to be on and adjacent to the northern edge of the Uncompahgre uplift or approximately aligned with the western extension of the Garmesa fault zone. The southern edge of this mound is on the southwestern flank of the Uncompahgre uplift and parallels its southwestern boundary fault. The small mound of very saline to briny water in the southernmost part of the basin overlies the south bounding fault of the Uncompahgre uplift and seems to be aligned with it. The other small mound of very saline to briny water seems to be on and aligned with the trend of the Uncompahgre uplift, but appears to be bounded at its western end by a series of north-trending faults.

The presence throughout the basin of an interval of fresh to moderately saline water below the body of very saline to briny water can not be established with certainty from available data, because wells do not penetrate the full thickness of sedimentary strata to the Precambrian basement in most of the area where the basement is 10,000 to 30,000 or more feet below land surface. However, many analyses of production water and of water collected during drill-stem tests from depths of 10,000 to 20,000 feet disclose fresh to moderately saline water throughout the area. Two exceptions are in the eastern Red Wash field, where samples of water from swab tests of the Weber Sandstone between depths of 18,000 and 18,500 feet contained as much as 130,000 mg/L of dissolved solids, and in (D-9-20)22ccb, where a sample of water from a drill-stem test of the Madison Limestone between depths of 19,326 and 20,052 feet contained 122,500 mg/L dissolved solids. Very few chemical analyses were available for wells and test holes south of Township 11 South.

The 10,000 mg/L concentration surface shown on plates 1 and 2 is generalized. The true configuration of that surface undoubtedly is far more complex; that complexity is due partly to the vertical movement of water through the extensive system(s) of fractures present in the basin.

The concentration of dissolved solids in ground water in the Uinta Basin ranged from 17 to more than 215,000 mg/L. A maximum of almost 300,000 mg/L may have been present in production water from one oil well, which was reported to have an R_w of 0.039 ohm-meter.

Ground water from areas of outcrop of Precambrian rocks contained from 17 to 52 mg/L dissolved solids. The water was of calcium bicarbonate or calcium magnesium bicarbonate type.

In post-Precambrian rocks, changes in salinity and in water type, with increasing distance from recharge areas at formation outcrops, with depth, and with changes in geologic formations, mineralogy, and lithofacies, generally are as suggested by previous investigators. As water moves down the hydraulic gradient from the basin rim to the basin interior, the dissolved-solids concentration increases and the water type changes. Commonly, water type changes from calcium bicarbonate to sodium bicarbonate, to sodium sulfate, to sodium chloride. Locally, depending on the chemical composition of evaporites or other minerals and on temperature and pressure, the water may be of calcium or magnesium sulfate or calcium chloride type. In that part of the basin underlain by the Green River Formation, much of the water in the Green River, and the overlying Uinta and underlying Wasatch Formations is very saline to briny and commonly is of sodium chloride type. At depths of less that 5,000 feet, the water often is of sodium bicarbonate type.

The salinity and composition of dissolved constituents of water in the Uinta, Green River, and Wasatch Formations probably are caused by dissolution of evaporite minerals, particularly from the saline facies of the upper part of the Green River Formation. Halite, nahcolite, trona, anhydrite, glauberite, and glaubers salt are present as thin beds or disseminated veins. There is also an apparent abundance of what have been considered rare minerals, such as eitelite, shortite, northupite, and other evaporite minerals thus far found in only a few sites such as in the Green River Formation near Duchesne, Utah, and at other locations in Utah and Wyoming (Dyni and others, 1985). Also, investigators have reported solution breccias elsewhere in the area within the same stratigraphic interval, which indicates past removal of much soluble material by ground water.

✳ Locally, aquifers in unconsolidated surficial deposits, such as alluvium and outwash, and in shallow permeable intervals in consolidated rocks may contain water that is very saline or briny. In consolidated rocks, such intervals may have a total thickness, including both permeable and intervening relatively impermeable beds, of as much as several hundred feet.

* The Duchesne River Formation apparently contains mostly fresh water. Of 63 analyses, only 4 in U(C-1-2)28 indicated saline to briny water of sodium chloride type, and only 1 indicated slightly to moderately saline water of sodium sulfate type water. Thirty-two analyses were of calcium magnesium bicarbonate carbonate water; 7, calcium magnesium sulfate water; and 17, sodium bicarbonate water. The information available was insufficient to determine areal or vertical distribution of water types.

Much of the Uinta Formation contains fresh to moderately saline water except within the area underlain by the mounds of very saline to briny water (pls. 1 and 2). Within those areas, the Uinta Formation generally contains fresh to moderately saline water where it is within 3,000 to 5,000 feet of the land surface except over the highest parts of the mounds. About one-third of the analyses were of sodium bicarbonate type water, about one-fifth each were calcium magnesium bicarbonate, calcium magnesium sulfate, and sodium sulfate type water; the rest of the analyses indicated sodium chloride type water. Again, no areal or vertical pattern of distribution of water types was discerned except that the greater the depth of the interval sampled, the greater the probability that the water is of sodium chloride type, that between Myton and Bluebell the water is of calcium magnesium sulfate type, and that in two areas very saline to briny water seemed to occur in northwest to southeast linear or slightly arcuate trends at a shallower depth (900 to 4,000 feet) than elsewhere. These trends, which are sub-parallel to major fracture systems in the basin, run from approximately U(C-3-6)12 through U(C-4-5)14 to U(C-5-4)13 and (D-5-20)13 through (D-6-21)27 toward (D-7-22)14. In the first of these trends, the water is of sodium bicarbonate type to the northwest and sodium chloride type to the southeast, whereas in the second trend all the water is of sodium chloride type.

Where the Green River Formation is within 3,000 feet of the land surface, most of the water is fresh to moderately saline except where the saline facies still contains undissolved evaporite minerals. Within the area underlain by the large mound shown on plate 1 and the northern part of plate 2, the formation contains very saline to briny water to its top. In the area underlain by the large southern mound, shown on plate 2, the Green River Formation commonly is exposed at land surface and contains very saline to briny water to within less than 1,000 feet of land surface only where the crest of the mound is above an altitude of 5,000 feet. Sodium bicarbonate type water is widely distributed, whereas sodium sulfate type water has been reported from only a few areas, all less than 3,000 feet in depth. More than one-third of the analyses of sodium sulfate type water are from springs. Calcium magnesium bicarbonate type water has been reported from a few sites, about one-half of them springs. Calcium magnesium sulfate type water also has been reported from a few places, almost all of them springs. No sodium chloride type water was found above a depth of 2,300 feet (it was found at that depth in U(C-3-5)). This type of water generally is at depths of 6,000 to 10,000 feet in the greater Altamont-Bluebell field and from a depth of almost 8,000 feet in (D-5-20), about 10 miles southwest of Vernal, to about 3,600 feet in the eastern part of the Red Wash field (D-7-24).

South of Altamont and Bluebell, the upper part of the Wasatch Formation contains very saline to briny water throughout most of the area within the mound shown on plate 1 and the northern part of plate 2. In general, the proportion of the formation that contains very saline to briny water thickens with distance from the edge of the mound. In some places, particularly the southern part of the mound, all of the water in the Wasatch may be very saline to briny. The very saline to briny water is reported to be of sodium chloride type, except south of Vernal near the southern boundary of the area shown on plate 1 where the water was reported to be of calcium chloride type, and in U(C-1-5)36, about 6 miles west of Altamont, where it was reported to be of sodium sulfate type. Fresh to moderately saline water from the Wasatch Formation seems to be mostly sodium bicarbonate or sodium sulfate type in and near areas where the formation crops out; elsewhere, it is mostly sodium chloride type, though some is sodium bicarbonate type.

Relatively little information is available about water quality in rocks of Mesozoic and Paleozoic age at depths of more than 2,000 feet except in the southern part of the basin. All of the available information for the northern part of the basin is from sites that are within or within a few miles of the outcrops of such rocks. The Mississippian rocks, thought to be major conduits for movement of ground water into the basin from areas of recharge on the slopes of the Uinta Mountains, contain calcium bicarbonate type water, except for a sample of briny sodium chloride type water from the Madison Limestone obtained from well (D-9-20)22ccb-1 near the northern boundary of the southern part of the basin. Most analyses of water from the Weber Sandstone showed fresh water, mostly calcium magnesium bicarbonate type (some calcium magnesium sulfate type), to a depth of more than 5,000 feet. The only samples from the Weber at a greater depth were of briny sodium chloride type water from well (D-7-24)21dda-1. The remaining formations of Mesozoic and Paleozoic age show similar characteristics in water quality--mostly fresh to moderately saline, calcium magnesium bicarbonate water to depths of 10,000 feet or more. Down gradient, there is a trend for water type to change to calcium magnesium sulfate or sodium bicarbonate. Within the northern Uinta Basin sodium chloride type water was found in only the Cretaceous beds and the Weber Sandstone. In the southern Uinta Basin sodium chloride type water was found in all Paleozoic and Mesozoic rocks for which water analyses were available.

Locally, salinity of production water may change significantly within a few months or years. In the greater Altamont-Bluebell field, for example, the concentration of dissolved solids in production water decreased from 15,900 to 10,300 mg/L between March 1973 and July 1976 at well U(C-1-2)21ac-1 and decreased from 13,000 to 6,900 mg/L between March and October 1975 at well U(C-3-5)9aca-1. In contrast, the concentration increased from 12,500 to 22,600 mg/L between June 1974 and August 1975 at well U(C-1-2)21ac-1 and increased from 34,400 mg/L to 86,600 mg/L between April 1969 and May 1973 at well U(C-1-2)2cdb-1. In the Red Wash field, the concentration of dissolved solids in production water from well (D-7-22)22acc-1 increased from 16,000 to 31,900 mg/L between September 1957 and May 1970. Information available for this study was not sufficient to evaluate the significance of such changes in water salinity or to permit detection of any vertical or areal pattern of changes (if any) with time. Changes in salinity that are occurring probably reflect the importance of fractures and faults on the vertical movement of water that has been induced by production of hydrocarbons and water from oil and gas wells.

CONCLUSIONS

The base of the moderately saline water was mapped by using available water-quality data and by determining formation-water resistivities from geophysical well logs based on the resistivity-porosity, spontaneous-potential, and resistivity-ratio methods. The contour map developed from this information showed that a mound of very saline to briny ground water occupies much of the thickness of the Uinta, Green River, and Wasatch Formations in the Uinta Basin in an area that extends from near the Wasatch County line on the west to Colorado State line on the southeast and from about 9 miles north-northeast of Bluebell on the north to the south flank of the Uncompaghre uplift on the south. Within the area of this mound, very saline to briny ground water is present at depths of less than 1,000 feet in some places. In much of the area, the main body of very saline to briny water is underlain by fresh to moderately saline water. In the east-central part of the mound, however, very saline water may extend to greater depths and to formations at least as low stratigraphically as the Madison Limestone.

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U.S. GEOLOGICAL SURVEY

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1987 PLATE 1

EXPLANATION

- DUCHESNE RIVER FORMATION AND UNDERLYING TERTIARY ROCKS—Either at land surface or underlying alluvial and glacial deposits, the Bishop Conglomerate, and Browns Park Formation
- MESOZOIC AND PALEOZOIC ROCKS—Either at land surface of underlying alluvial and glacial deposits, the Bishop Conglomerate, and Browns Park Formation
- PRECAMBRIAN ROCKS—Either at the land surface or underlying alluvial and glacial deposits, the Bishop Conglomerate, and Browns Park Formation
- KNOWN OIL AND GAS FIELDS
- 1,000 — WATER-QUALITY-ZONE CONTOUR—Shows altitude of base of moderately saline water (3,000 to 10,000 milligrams per liter dissolved solids). Dashes where approximately located. Contour intervals 1,000 and 500 feet. National Geodetic Vertical Datum of 1929
- Boundary between the Salt Lake meridian and base line survey system and the Uinta meridian and base line survey system
- Boundary of the Uinta Basin drainage in Utah
- b-3429 WELL OR TEST HOLE AND ALTITUDE, IN FEET—Water salinity determined from geophysical logs. Horizontal line indicates a well in which one or more intervals of fresh to moderately saline water is known (from chemical analysis) or believed (from analysis of logs) to occur more than 500 feet below the base of moderately saline water shown. Vertical line indicates that well is at least 10,000 feet deep. "a" indicates the base of moderately saline is at or above the altitude listed. Altitude given is of the highest permeable interval shown on the geophysical logs. "b" indicates that either no very saline to briny water is present at the indicated site or the base of moderately saline water is below the bottom of the logs analyzed. Number shown is the altitude either of well bottom (water salinity from a chemical analysis) or of the lowest point logged. National Geodetic Vertical Datum of 1929

Base from U. S. Geological Survey 1:250,000 series: Salt Lake City, Utah, Wyoming, 1954; and Vernal, Utah, Colorado, 1958

GENERALIZED MAP OF MODERATELY SALINE GROUND WATER IN THE NORTHERN UINTA BASIN, UTAH

DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the
UTAH DIVISION OF OIL, GAS, AND MINING

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PLATE 2

EXPLANATION

DUCHESNE RIVER FORMATION AND UNDERLYING TERTIARY ROCKS—Either at land surface or underlying alluvial and glacial deposits, the Bishop Conglomerate, and Browns Park Formation

PALEOCENE AND UPPER CRETACEOUS ROCK UNDIFFERENTIATED—Mostly North Horn and Currant Creek Formations, but may include some basal Wasatch and uppermost Mesaverde Formations

KNOWN OIL AND GAS FIELDS

1,000 — WATER-QUALITY-ZONE CONTOUR—Shows altitude of base of moderately saline water (3,000 to 10,000 milligrams per liter dissolved solids). Dashes where approximately located. Contour intervals 1,000 and 500 feet. National Geodetic Vertical Datum of 1929

Boundary between the Salt Lake meridian and base line survey system and the Uinta meridian and base line survey system

Boundary of the Uinta Basin drainage in Utah

b 2,133 • WELL OR TEST HOLE AND ALTITUDE, IN FEET—Water salinity determined from geophysical logs. Horizontal line (⦵) indicates a well in which one or more intervals of fresh to moderately saline water is known (from chemical analysis) or believed (from analysis of logs) to occur more than 500 feet below the base of moderately saline water shown. Vertical line (⦶) indicates that well is at least 10,000 feet deep. "a" indicates the base of moderately saline is at or above the altitude listed. Altitude given is of the highest permeable interval shown on the geophysical logs. "b" indicates that either no very saline to briny water is present at the indicated site or the base of moderately saline water is below the bottom of the logs analyzed. Number shown is the altitude either of well bottom (water salinity from a chemical analysis) or of the lowest point logged. National Geodetic Vertical Datum of 1929

Base from U. S. Geological Survey 1:250,000 series: Grand Junction, 1962; Price, 1962; Salt Lake City, 1963; and Vernal 1965

5 0 5 10 15 20 MILES
5 0 5 10 15 20 25 30 KILOMETERS

GENERALIZED MAP OF MODERATELY SALINE GROUND WATER IN THE SOUTHERN UINTA BASIN, UTAH