HYDROGEOLOGY OF THE LEADVILLE LIMESTONE AND OTHER PALEOZOIC ROCKS IN NORTHWESTERN COLORADO, WITH RESULTS OF AQUIFER TESTS AT GLENWOOD SPRINGS

By Arthur L. Geldon

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METRIC CONVERSION FACTORS

Inch-pound units used in this report may be converted to International System of Units (SI) by using the following factors:

Multiply inch-pound units	*By*	*To obtain SI units*
barrel per day (bbl/d)	1.84×10^{-3}	liter per second
centipoise (cp)	0.01	gram per centimeter per second
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.06309	liter per second
gallon per minute per foot (gal/min/ft)	2.071×10^{-4}	square meter per second
inch (in.)	2.540	centimeter
mile (mi)	1.609	kilometer (km)
millidarcy (md)	9.87×10^{-12}	square centimeter
pound per square inch (lb/in^2)	0.6895	newton per square meter

Degree Fahrenheit (°F) may be converted to degree Celsius (°C) by using the following equation: °C = 5/9(°F-32).

The following term and abbreviation also is used in this report:

milligram per liter (mg/L)

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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ABSTRACT

Paleozoic rocks in northwestern Colorado were investigated during the U.S. Geological Survey's Regional Aquifer-System Analysis of the Upper Colorado River Basin. Paleozoic rocks in the study area are grouped into 11 hydrostratigraphic units on the basis of lithologic and hydrologic properties. Devonian and Mississippian carbonate rocks and Pennsylvanian and Permian sandstone are regional aquifers, with natural discharges that commonly exceed 50 gallons per minute. Discharges from the Devonian and Mississippian carbonate rocks to artesian wells and springs can be as much as 3,200 gallons per minute. Other hydrostratigraphic units in the area are either local aquifers or confining layers, with discharges that rarely exceed 50 gallons per minute.

Hydraulic-conductivity values for the Devonian and Mississippian carbonate rocks hydrostratigraphic unit range from less than 0.001 to more than 100 feet per day; transmissivity values range from less than 0.1 to 47,000 square feet per day. The storage coefficient determined from a flowing-well test at Glenwood Springs is 5×10^{-4}. Hydraulic-conductivity values for the Pennsylvanian and Permian sandstone hydrostratigraphic unit range from less than 0.0001 to 20 feet per day. Hydraulic-conductivity values for local aquifers typically range from less than 0.0001 to 2 feet per day. Hydraulic-conductivity values for confining layers range from less than 0.0001 to 0.25 foot per day.

The Devonian and Mississippian carbonate rocks hydrostratigraphic unit in the Glenwood Springs area consists of the Dyer Dolomite and the Leadville Limestone. The temperature and chemistry of water discharging from the Leadville Limestone in 18 hot springs and seepage areas at Glenwood Springs indicate that most of the water originated in highlands to the south. Moisture from precipitation and snowmelt in the Lookout Mountain and Grand Hogback areas descends to the Leadville Limestone and Dyer Dolomite through several thousand feet of upper Paleozoic, Mesozoic, and Tertiary sedimentary rocks; locally, the moisture descends through Tertiary basalt. The water is heated as it descends through the overburden and becomes saline by dissolution of halite and gypsum in the Eagle Valley Evaporite. The hot, saline water moves through fractures and solution channels in the Leadville Limestone and Dyer Dolomite toward the Glenwood Springs area, where it mixes with cool,

freshwater from the White River Plateau, and discharges as hot springs or seeps into stream alluvium. Artesian flow from wells completed in the Leadville Limestone at Glenwood Springs affects discharges from nearby hot springs and water levels in the alluvium.

Recharge to the Devonian and Mississippian carbonate rocks hydrostratigraphic unit is provided by incident precipitation in outcrop areas on the flanks of uplifts and by fracture leakage through overlying rocks. Water in the hydrostratigraphic unit flows toward the valleys of the Colorado, Green, Yampa, and White Rivers and to structural basins on the eastern and western sides of the study area. Discharge from the hydrostratigraphic unit sustains streams draining the White River Plateau, hot springs at Glenwood Springs and Dotsero, and flowing wells in the McCoy and Glenwood Springs areas. In the Piceance, Sand Wash, and Burns basins, water from the hydrostratigraphic unit percolates into overlying Paleozoic rocks.

INTRODUCTION

Paleozoic rocks in northwestern Colorado were investigated as part of the U.S. Geological Survey's Regional Aquifer-System Analysis (RASA) of the Upper Colorado River Basin. Early in this investigation, it became apparent that quantitative hydrologic information for rocks of Paleozoic age was concentrated selectively in areas of oil and gas exploration and distributed sparsely elsewhere. Opportunities to acquire additional data were pursued as they were identified.

In 1983, an opportunity was presented to the U.S. Geological Survey to participate in an aquifer test of a well being developed for geothermal-energy use at Glenwood Springs, Colo. Based on previous investigations, it was apparent that the aquifer supplying the well, the Leadville Limestone, is a major source of ground water, not only in the Glenwood Springs area, but also throughout the Upper Colorado River Basin. The new information gained from the test would be invaluable in assessing the local hydrologic system and in expanding previous regional and local studies of the Leadville Limestone and the hydrology of northwestern Colorado.

Purpose and Scope

This report summarizes the extent, thickness, composition, and hydrologic properties of Paleozoic rocks in northwestern Colorado. The report modifies stratigraphic material, presented in a guidebook article by Geldon (1986), that was based mainly on examination of unpublished petroleum-industry borehole logs and measured stratigraphic sections contained in reports by the following: Tweto and others (1947), Abrassart and Clough (1955), Kinney (1955), Chronic (1957), Mallory (1957, 1971), Wilson (1957), Hallgarth (1959), Bass and Northrop (1963), Freeman (1971), Tweto and Lovering (1977), Bryant (1979), and Teller and Welder (1983). Modifications made in this report of the original material are based on examination of additional measured sections that appear in reports by the following: Vanderwilt (1937), Brill (1944), Thomas and others (1945), Donner (1949), Tweto (1949), Singewald (1951), Langenheim (1952, 1954), Untermann and Untermann (1954), and Hansen and others (1983).

The main part of this report describes and interprets aquifer tests at Glenwood Springs, Colo., that were done from 1981 to 1985 by Wright Water Engineers[1], Chaffee Geothermal Ltd., and the U.S. Geological Survey. The hydrogeology of the test site, organization and methodology of the tests, and test results are discussed. The test results are interpreted in the context of: (1) The regional distribution of hydraulic conductivity within the tested aquifer, and (2) the regional flow system.

Previous Investigations

Prior investigations of ground water in the Paleozoic rocks of northwestern Colorado have focused primarily on availability and quality of water in parts of the area. Such local studies include those of Bryant (1972), Hampton (1974), Brogden and Giles (1976), Sumsion (1976), Barrett and Pearl (1977), Galloway (1982), URS Corporation (1982, 1983), and Teller and Welder (1983). Regional studies, including those of Iorns and others (1965), Boettcher (1972), and Price and Arnow (1974), also primarily described ground-water availability and quality.

This report is based on the previously published information but also is based on unpublished hydrologic data. This unpublished information includes: drill-stem test results and core analyses compiled by Petroleum Information Corporation, Denver; injection-test data supplied by the U.S. Bureau of Reclamation (written commun., 1984-85); and pumping and bailing-test data compiled by the Colorado Division of Water Resources, Office of the State Engineer. Representative hydrologic data for Paleozoic formations in northwestern Colorado are listed in Supplement A, in the "Supplemental Information" section at the back of this report.

This report is presented as part of the U.S. Geological Survey's Regional Aquifer-System Analysis (RASA) of the Upper Colorado River Basin. The plan of study for this RASA is discussed by Taylor and others (1983). Other RASA reports pertaining to Paleozoic rocks in northwestern Colorado include: (1) A generalized presentation of geologic, hydrologic, and geochemical information for selected hydrologic units by Lindner-Lunsford and others (1985); (2) a compilation of drill-stem test results by Teller and Chafin (1986); and (3) a discussion of the regional hydrogeology, including thickness and lithofacies maps for most aquifers and confining layers, by Geldon (1986).

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[1]The use of trade, brand, or firm names in this report is for identification or location purposes only, and does not constitute endorsement of products by the U.S. Geological Survey, nor impute responsibility for any present or potential effects on the natural resources.

System of Numbering Wells and Springs

Wells and springs are numbered in this report according to the U.S. Bureau of Land Management system. The first one or two letters in the site identifier represent the principal survey meridian. In the vicinity of the study area, these meridians include:

S - Sixth (northwestern Colorado and Wyoming),
NM - New Mexico (southwestern Colorado and northwestern New Mexico),
G - Gila and Salt River (Arizona, exclusive of Navajo Reservation),
N - Navajo (Navajo Reservation, Arizona),
SL - Salt Lake (eastern Utah, exclusive of Uinta Mountains), and
U - Uinta (Uinta Mountains, Utah).

Subsequent letters and numbers in the site identifier refer, in order, to quadrant, township, range, section, quarter section, quarter-quarter section, quarter-quarter-quarter section, and number of well or spring within the smallest physical boundary (multiple ground-water sites within the smallest physical boundary are numbered consecutively). Quadrant and section divisions are labeled from A to D in a counter-clockwise direction. Quadrant designations usually are upper case; section division designations usually are lower case. Zeros or dashes are used to separate quadrant, township, range, and section designations. As an example, a well numbered SC06-89-09 bda_1 is the first well in the northeast quarter of the southeast quarter of the northwest quarter of Section 9, Township 6 South, Range 89 West, in the southwest quadrant of the Sixth principal survey meridian.

Acknowledgments

The author is indebted to Mike Galloway (Terra Therma, Inc.) for arranging and assisting in the aquifer test that inspired this report. The author also would like to thank Redstone Corporation, Wright Water Engineers, Glenwood Springs Hot Springs Lodge and Pool, the U.S. Bureau of Reclamation (Grand Junction, Denver, and Salt Lake City), and the Colorado Division of Water Resources, Office of the State Engineer (Denver) for furnishing information used in this investigation.

REGIONAL HYDROGEOLOGY

Northwestern Colorado encompasses parts of four physiographic provinces (fig. 1)--the Colorado Plateaus, Southern Rocky Mountains, Wyoming Basin, and Middle Rocky Mountains. These four provinces are segmented into 13 uplifts and 4 basins.

Paleozoic rocks in the study area comprise 27 geologic units with an aggregate thickness that generally increases from northwest to southeast. The Paleozoic rocks range from less than 2,000 ft to more than 3,000 ft thick in the Uinta Mountains and Sand Wash basin and are as much as 18,000 ft thick in the Elk Mountains. The Paleozoic rocks are absent in the center of the Park Range, Gore Range, Rabbit Ears Range, Middle Park basin, Front Range, Sawatch

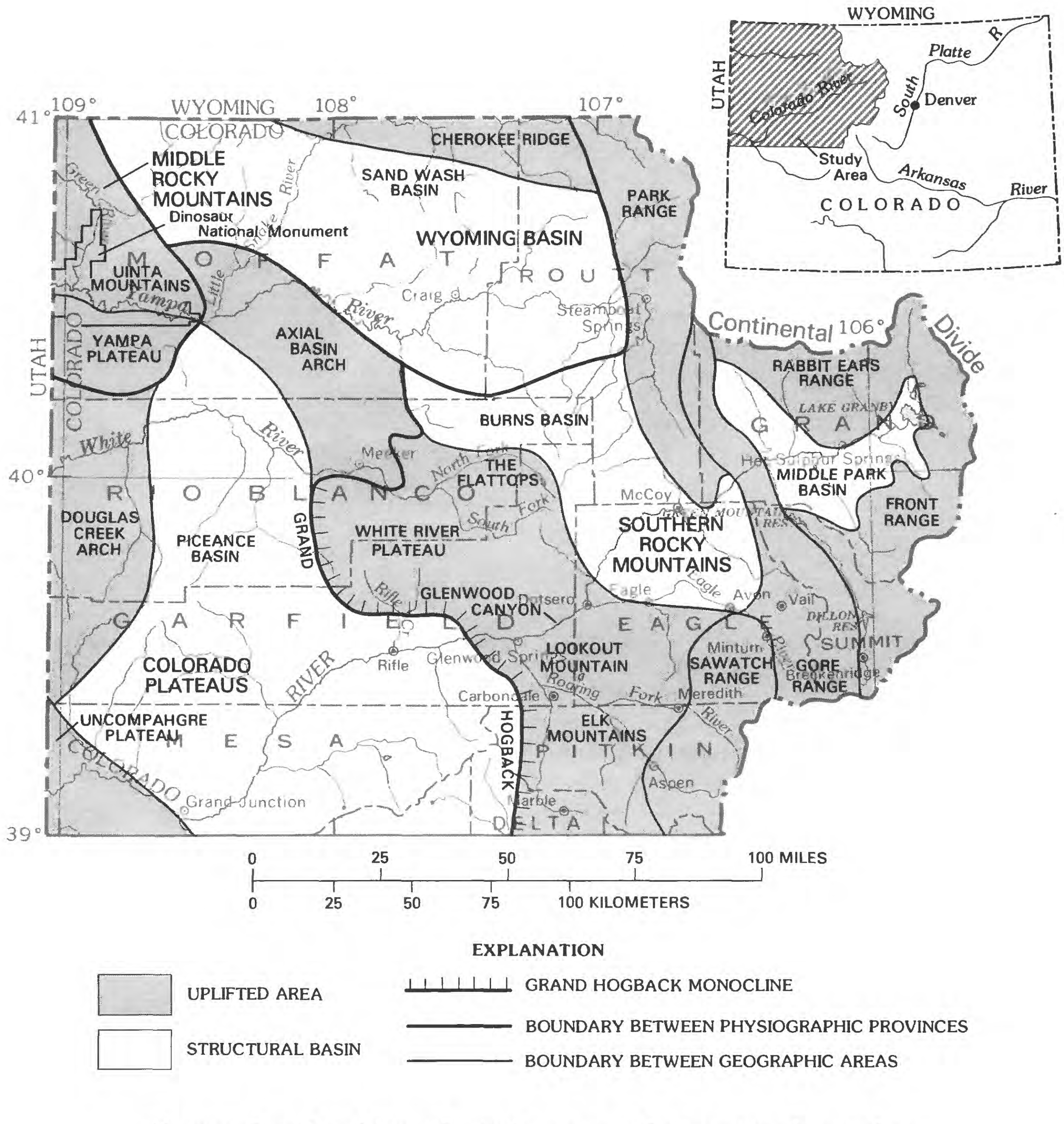


Figure 1.--Location of study area and structural setting.

Range, and Uncompahgre Plateau because of erosion or nondeposition. Paleozoic rocks are underlain by Precambrian sedimentary, igneous and metamorphic rocks (Tweto, 1980) and generally are overlain by Triassic formations consisting mostly of shale. Triassic formations are absent only in the Elk Mountains, southeastern Piceance basin, and Front Range; in these areas, the Entrada Sandstone of Jurassic age overlies the Paleozoic rocks.

Based on lithologic and hydrologic properties, the Paleozoic rocks in northwestern Colorado are grouped into 11 hydrostratigraphic units. As used in this report, the term "hydrostratigraphic unit" includes regional aquifers, local aquifers, and confining layers. Regional aquifers are hydrostratigraphic units typically composed of sandstone, limestone, or dolomite that generally yield usable supplies of water throughout most of a region. Local aquifers are hydrostratigraphic units typically composed of sandstone, limestone, and dolomite with shale layers, sedimentary textures, or secondary structures that in some locations may inhibit extracting usable supplies of water from the unit. Confining layers are hydrostratigraphic units typically composed of fine-grained clastic, biogenic, or chemical sedimentary rocks or crystalline rocks that generally do not yield usable supplies of water throughout most of a region. Hydrostratigraphic units in northwestern Colorado are listed in table 1, together with component geologic units, maximum thickness in several geographic areas, and formations comprising Precambrian and Triassic confining layers.

Regional Aquifers

Regional aquifers in the study area include the Devonian and Mississippian carbonate rocks hydrostratigraphic unit and the Pennsylvanian and Permian sandstone hydrostratigraphic unit. Spring discharges, artesian well flows, and drill-stem test yields from these units commonly exceed 50 gal/min (Hampton, 1974; Hood, 1976; Sumsion, 1976; Barrett and Pearl, 1977; Galloway, 1982; Teller and Welder, 1983). Discharges of several hundred to 3,200 gal/min can occur from the Devonian and Mississippian carbonate rocks unit; discharges of 100 to 600 gal/min can occur from the Pennsylvanian and Permian sandstone unit. Hydraulic-conductivity values for the Devonian and Mississippian carbonate rocks unit range from less than 0.001 ft/d in basins to more than 100 ft/d in uplifted areas. Hydraulic-conductivity values for the Pennsylvanian and Permian sandstone unit range from less than 0.0001 ft/d in basins to 20 ft/d in uplifted areas.

The Devonian and Mississippian carbonate rocks unit includes the Dyer Dolomite of Devonian age, the Gilman Sandstone of Devonian and Mississippian(?) age, the Madison Limestone of Devonian(?) and Mississippian age, and the Leadville Limestone of Mississippian age. The unit consists mostly of limestone and dolomite (see description by Untermann and Untermann, 1954, p. 29-30, of the Madison Limestone; and descriptions by Bass and Northrop, 1963, p. 17-29, and Tweto and Lovering, 1977, p. 27-32, of the Leadville Limestone, Gilman Sandstone, and Dyer Dolomite). However, shale layers may be present in preserved karsts at the top of the Mississippian section, and shale and sandstone layers usually occur at the Devonian to Mississippian

Table 1.--*Generalized chart of hydrostratigraphic units of Precambrian, Paleozoic, and Triassic age in northwestern Colorado*

[Thicknesses are listed in feet; regional aquifers are shaded light gray; local aquifers are shaded dark gray; confining layers are unshaded]

System	Hydrologic unit of Lindner-Lunsford and others, (1985)	Hydrostratigraphic unit in this report	GEOGRAPHIC AREAS: Uinta Mountains and Yampa Plateau		Piceance Basin and Douglas Creek Arch		White River Plateau and Axial Basin Arch		Sawatch Range and Elk Mountains		Sand Wash Basin and Park Range		Burns Basin and Gore Range	
			Geologic unit	Maximum thickness	Geologic unit	Maximum thickness	Geologic unit	Maximum thickness	Geologic unit	Maximum thickness	Geologic unit	Maximum thickness	Geologic unit	Maximum thickness
Triassic	Lower Mesozoic confining layers	Triassic confining layer	Moenkopi Formation		Wingate, Chinle, State Bridge[1], and Moenkopi Formations		State Bridge[1] and Moenkopi Formations		Absent[2]		Goose Egg[1] and Moenkopi Formations		State Bridge Formation[1]	
Permian	Upper Paleozoic aquifers	Permian shale and carbonate rocks	Park City Formation	150	State Bridge and Park City Formations	200	State Bridge and Park City Formations	600	Absent	0	Goose Egg and Park City Formations	500	State Bridge Formation	300
Permian and Pennsylvanian	Upper Paleozoic aquifers	Pennsylvanian and Permian sandstone	Weber Sandstone	1,300	Weber Sandstone	1,300	Weber Sandstone	800	Absent	0	Weber Sandstone	900	Weber Sandstone	400
Permian and Pennsylvanian	Upper Paleozoic aquifers	Pennsylvanian and Permian red beds and carbonate rocks	Morgan Formation	1,000	Maroon and Minturn Formations	1,500	Morgan, Maroon, and Minturn Formations	7,000	Maroon, Minturn, and Gothic[3] Formations	16,000	Morgan and Minturn Formations	800	Maroon and Minturn Formations	11,000
Pennsylvanian	Upper Paleozoic confining layers	Pennsylvanian carbonate rocks and evaporites	Round Valley Limestone	300	Eagle Valley Formation	1,500	Eagle Valley Evaporite (Formation)	4,000	Eagle Valley Evaporite	2,000	Eagle Valley Evaporite and Round Valley Limestone	500	Eagle Valley Evaporite	5,000
Pennsylvanian and Mississippian	Upper Paleozoic confining layers	Mississippian and Pennsylvanian shale and carbonate rocks	Doughnut Shale	300	Belden Formation Molas Formation	800	Belden Formation Molas Formation	3,000	Belden Formation Molas Formation	900	Belden Formation Molas Formation	500	Belden Formation Molas Formation	4,000

Table 1.--*Generalized chart of hydrostratigraphic units of Precambrian, Paleozoic, and Triassic age in northwestern Colorado*--Continued

System	Hydrologic unit of Lindner-Lunsford and others, (1985)	Hydrostratigraphic unit in this report	GEOGRAPHIC AREAS: Uinta Mountains and Yampa Plateau: Geologic unit	Maximum thickness	Piceance Basin and Douglas Creek Arch: Geologic unit	Maximum thickness	White River Plateau and Axial Basin Arch: Geologic unit	Maximum thickness	Sawatch Range and Elk Mountains: Geologic unit	Maximum thickness	Sand Wash Basin and Park Range: Geologic unit	Maximum thickness	Burns Basin and Gore Range: Geologic unit	Maximum thickness
Mississippian	Middle Paleozoic aquifers	Mississippian carbonate and clastic rocks	Humbug Formation	250	Humbug Formation	200	Absent	0	Absent	0	Humbug Formation	200	Absent	0
Mississippian and Devonian		Devonian and Mississippian carbonate rocks	Madison Limestone	700	Leadville Limestone	700	Leadville Limestone	600	Leadville Limestone	350	Madison Limestone	800	Leadville Limestone	500
					Dyer Dolomite		Dyer Dolomite		Gilman Sandstone				Gilman Sandstone	
									Dyer Dolomite				Dyer Dolomite	
Devonian		Devonian carbonate and clastic rocks	Parting Formation	50	Parting Formation	150	Parting Formation	150	Parting Formation	100	Parting Formation	50	Parting Formation	150
Ordovician and Cambrian	Lower Paleozoic confining layers and aquifers	Cambrian and Ordovician carbonate rocks	Absent	0	Absent	0	Absent	0	Fremont Limestone	400	Absent	0	Absent	0
			Absent		Absent		Absent		Harding Sandstone		Absent		Harding Sandstone	100
			Absent		Manitou Dolomite	200	Manitou Dolomite	200	Manitou Dolomite		Absent		Manitou Dolomite	
			Dotsero Formation	50	Dotsero Formation	200	Dotsero and Peerless Formations	200	Peerless Formation	100	Dotsero Formation	300	Peerless Formation	100
Cambrian		Cambrian shale	Unnamed shale	200	Unnamed shale	100	Unnamed shale	50	Absent	0	Unnamed shale	450	Unnamed shale	50
	Basal Paleozoic aquifer	Cambrian sandstone	Lodore Formation	300	Sawatch Quartzite and Lodore Formation	850	Sawatch Quartzite	600	Sawatch Quartzite	500	Lodore Formation	700	Sawatch Quartzite	500

Table 1.--*Generalized chart of hydrostratigraphic units of Precambrian, Paleozoic, and Triassic age in northwestern Colorado*--Continued

System	Hydrologic unit of Lindner-Lunsford and others, (1985)	Hydrostratigraphic unit in this report	GEOGRAPHIC AREAS											
			Uinta Mountains and Yampa Plateau		Piceance Basin and Douglas Creek Arch		White River Plateau and Axial Basin Arch		Sawatch Range and Elk Mountains		Sand Wash Basin and Park Range		Burns Basin and Gore Range	
			Geologic unit	Maximum thickness	Geologic unit	Maximum thickness	Geologic unit	Maximum thickness	Geologic unit	Maximum thickness	Geologic unit	Maximum thickness	Geologic unit	Maximum thickness
		Precambrian confining layer	Uinta Mountain Group (quartzite, sandstone, and shale)	24,000	Uinta Mountain Group, granitic rocks and metasedimentary rocks		Uinta Mountain Group, granitic rocks, metasedimentary rocks, and metavolcanic rocks		Granitic rocks, metasedimentary rocks, and metavolcanic rocks		Uinta Mountain Group, granitic rocks and metavolcanic rocks		Granitic rocks, metasedimentary rocks, and metavolcanic rocks	
Aggregate thickness of Paleozoic formations[4]				4,200		5,500		13,000		18,000		3,500		12,000

[1]Above stratigraphically highest carbonate layer.
[2]Paleozoic rocks are overlain by Entrada Sandstone of Jurassic age in the Elk Mountains.
[3]Of Langenheim (1952).
[4]Aggregate thickness was determined by adding the thicknesses of the 11 hydrostratigraphic units at grid-centers on a 10-mile by 10-mile grid. Aggregate thickness cannot be obtained by adding the maximum thicknesses of the 11 units in a geographic area because individual units do not thicken and thin concordantly.

transition. Shale and sandstone layers generally comprise no more than 10 percent of the hydrostratigraphic unit. In and near outcrop areas, the unit tends to be cavernous (fig. 2). The unit thickens in a general northwesterly direction, increasing from less than 200 ft thick in the Sawatch Range to more than 700 ft thick on the Douglas Creek arch. There also is an abrupt thickening in the eastern Sand Wash basin and Burns basin, at the site of a Mississippian seaway; the unit is 500 to 800 ft thick in this area. The Devonian and Mississippian carbonate rocks unit is absent extensively only in the center of the Uinta Mountains and Sawatch Range, from the Park and Gore Ranges east to the Continental Divide, and in the area south of Grand Junction, Colo.

The Pennsylvanian and Permian sandstone hydrostratigraphic unit includes the Weber Sandstone and the sandstone of the Frying Pan River (Freeman, 1971, p. 8-9), which, herein, is considered an erosional outlier of the Weber Sandstone. The Weber Sandstone consists mostly of tan and grayish-white quartz sandstone, which varies texturally from friable to quartzitic or calcareous (Untermann and Untermann, 1954, p. 36-37; Kinney, 1955, p. 45-48).

Figure 2.--Leadville Limestone of the Devonian and Mississippian carbonate rocks hydrostratigraphic unit at Glenwood Springs, Colo. Several caves are visible on the cliff face.

As seen in Dinosaur National Monument (fig. 3), the sandstone is massively bedded; cross bedding is prominent in some areas. At the depositional edges of the Weber Sandstone, where it intertongues with the Maroon Formation, shale layers comprise as much as 30 percent of the formation. Toward the west, carbonate rocks comprise as much as 5 percent of the formation. The Weber Sandstone thickens abruptly from its depositional edges south of the Glenwood Springs area and east of the Minturn area and attains a thickness of about 1,300 ft on the southern side of the Yampa Plateau.

Figure 3.--Deeply incised Weber Sandstone of the Pennsylvanian and Permian sandstone hydrostratigraphic unit at the confluence of the Green and Yampa Rivers. Steamboat Rock, a prominent landmark, is in the foreground.

Local Aquifers

Local aquifers in the study area include: the Cambrian sandstone, Cambrian and Ordovician carbonate rocks, Mississippian carbonate and clastic rocks, and Pennsylvanian and Permian red beds and carbonate rocks hydrostratigraphic units. Spring discharges, artesian-well flows, and drill-stem test yields from these units generally do not exceed 50 gal/min, but yields of several hundred gallons per minute can occur, particularly from very fractured intervals. Average values of site hydraulic conductivity range from less than 0.0001 to 2 ft/d; hydraulic-conductivity values for some sandstone intervals can be as large as 10 ft/d.

The Cambrian sandstone hydrostratigraphic unit includes the Sawatch Quartzite and the Lodore Formation. These formations consist mostly of tan and grayish-white quartzite and quartzitic, glauconitic, and calcareous sandstone (see description of Sawatch Quartzite by Bass and Northrop, 1963, p. 4-7, and description of Lodore Formation by Kinney, 1955, p. 22-24). Interbedded dolomite layers occur in the upper part of the Sawatch Quartzite (fig. 4*A*). Interbedded shale layers occur in the upper part of the Lodore Formation (fig. 4*B*). The hydrostratigraphic unit is an aquifer where sandstone layers predominate; it is a confining layer where quartzite is the dominant rock type. The unit thickens northwestward from less than 200 ft in the Sawatch and Gore Ranges to more than 700 ft in the Piceance basin and on the Douglas Creek arch. The unit decreases in thickness to less than 100 ft over the Axial Basin arch but again thickens to the north and is about 700 ft thick at the Wyoming State line.

As dolomite layers in the upper part of the Sawatch Quartzite thicken eastward, they merge with the overlying Dotsero Formation and grade into the Peerless Formation. The Dotsero and Peerless Formations, of Cambrian age, and the Manitou Dolomite (fig. 5), Harding Sandstone, and Fremont Limestone, of Ordovician age, comprise the Cambrian and Ordovician carbonate rocks hydrostratigraphic unit (see descriptions of Cambrian and Ordovician rocks by Mallory, 1957; Bass and Northrop, 1963, p. 8-19; Tweto and Lovering, 1977, p. 15-23; and Bryant, 1979, p. 12-17).

Cambrian rocks in this hydrostratigraphic unit predominantly consist of limestone, dolomite, and flat-pebble dolomite conglomerate, but sandstone and shale comprise as much as 60 percent of the rock material in the southeastern part of the area. Ordovician rocks in the hydrostratigraphic unit consist mostly of massive dolomite, but sandstone and shale layers occur, and in the vicinity of Minturn, they comprise the entire section.

Cambrian rocks in the hydrostratigraphic unit are present only in a northwest-trending band across the central part of the area; thicknesses increase from 100 ft or less south of the White River to as much as 300 ft near the Wyoming State line. Ordovician rocks in the hydrostratigraphic unit are present only in an east-west-trending band across the south-central part of the area; thicknesses increase toward the center of this band to about 200 ft in the western part of the area and to about 400 ft in the eastern part of the area. The distribution of Cambrian rocks in the hydrostratigraphic unit indicates that present limits in the study area probably coincide with the edges of a narrow marine embayment at the time of deposition. The Ordovician rocks seem to be erosional remnants of a formerly extensive marine deposit.

The Mississippian carbonate and clastic rocks hydrostratigraphic unit includes only the Humbug Formation in the study area. The Humbug Formation consists of red, tan, and gray sandstone, dolomite, and shale (Untermann and Untermann, 1954, p. 30-33). It is restricted to the Uinta Mountains, Yampa Plateau, and immediate vicinity. The maximum thickness in the area is about 300 ft.

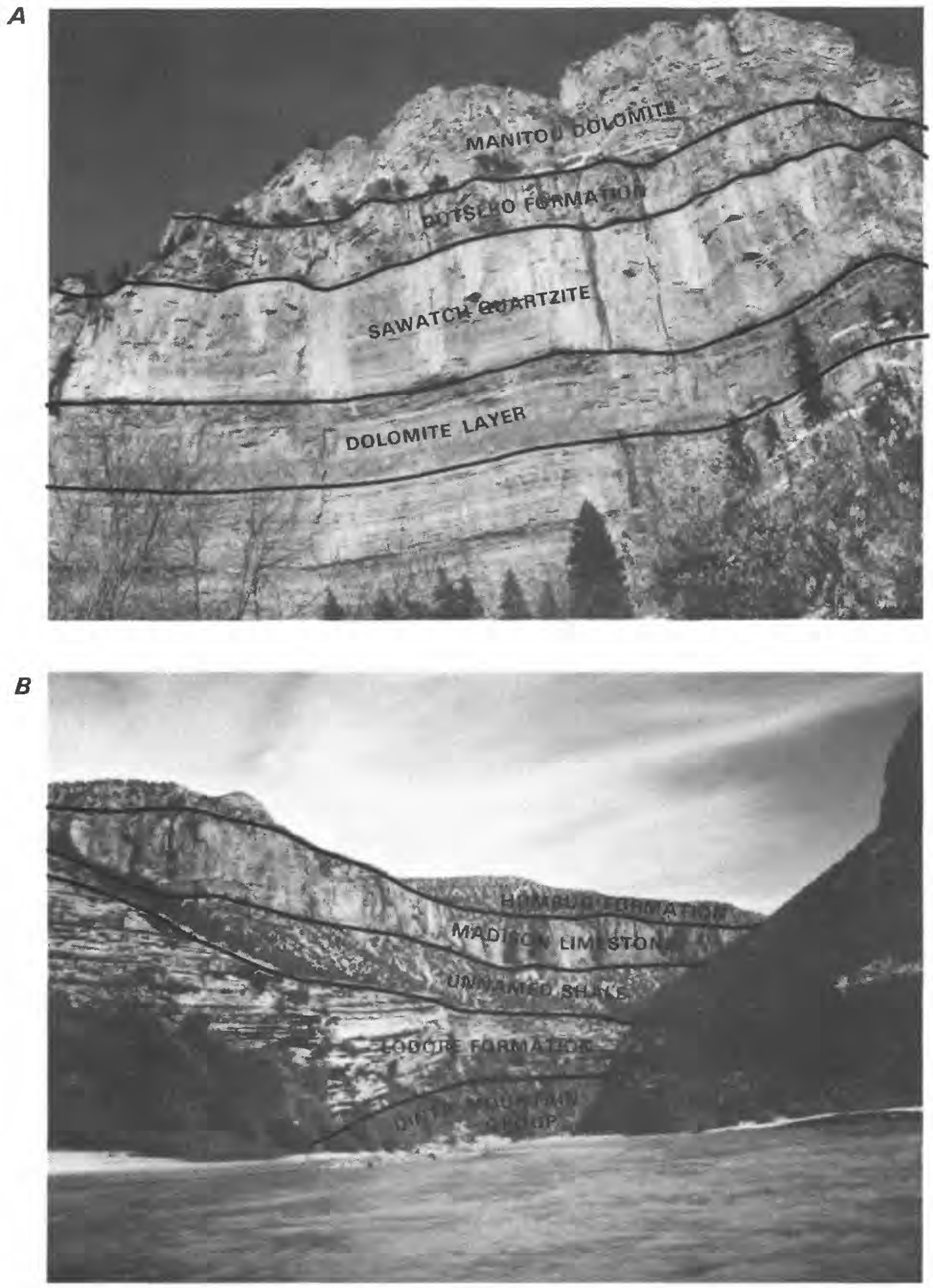


Figure 4.--Cambrian sandstone hydrostratigraphic unit: *A*, Sawatch Quartzite overlain by Dotsero Formation and Manitou Dolomite in Glenwood Canyon at Hanging Lake trailhead; medium gray band above trees is a 75-foot-thick layer of dolomite; *B*, Lodore Formation along the Green River in Dinosaur National Monument. The Cambrian Lodore Formation is underlain by the Precambrian Uinta Mountain Group and overlain by unnamed shale of Cambrian age and the Madison Limestone and Humbug Formation of Mississippian age.

Figure 5.--Large joint in the Manitou Dolomite of the Cambrian and Ordovician carbonate rocks hydrostratigraphic unit, west of the upstream entrance to Glenwood Canyon.

The Pennsylvanian and Permian red beds and carbonate rocks hydrostratigraphic unit includes the Minturn, Morgan, and Maroon Formations and the Gothic Formation of Langenheim (1952). This hydrostratigraphic unit contains a diverse assemblage of rocks. The Minturn and Gothic Formations (see descriptions by Tweto and Lovering, 1977, p. 38-53; and Bryant, 1979, p. 25-29), which compose the lower part of the hydrostratigraphic unit in the southern part of the area, predominantly consist of buff, gray, green and brown sandstone, gravelly sandstone, conglomerate, and shale, with thin layers of limestone and dolomite (fig. 6*B*). Overlying the Minturn and Gothic Formations, the Maroon Formation (Brill, 1944; Langenheim, 1954; Bass and Northrop, 1963, p. 46-54; Bryant, 1979, p. 131-136) consists of maroon, reddish-brown, and red, fine-grained to quartzitic sandstone, conglomerate, and shale (fig. 6*A*). The Morgan Formation, which comprises the entire hydrostratigraphic unit in the northern and northwestern parts of the area (Untermann and Untermann, 1954, p. 33-35; Abrassart and Clough, 1955; Kinney, 1955, p. 38-45), consists of pink, gray, and tan sandstone, limestone, and dolomite with interbedded red, green, and purple shale (fig. 6*C*). The thickness of this hydrostratigraphic unit is less than 1,500 ft north of the White River, but 2,000 to 7,000 ft on the edges of the White River Plateau and northwestern Elk Mountains, and 10,000 to 16,000 ft in the southeastern Elk Mountains, Sawatch Range, and Gore Range. The unit is absent in the center of the White River Plateau and Uinta Mountains and on the southern and eastern edges of the area.

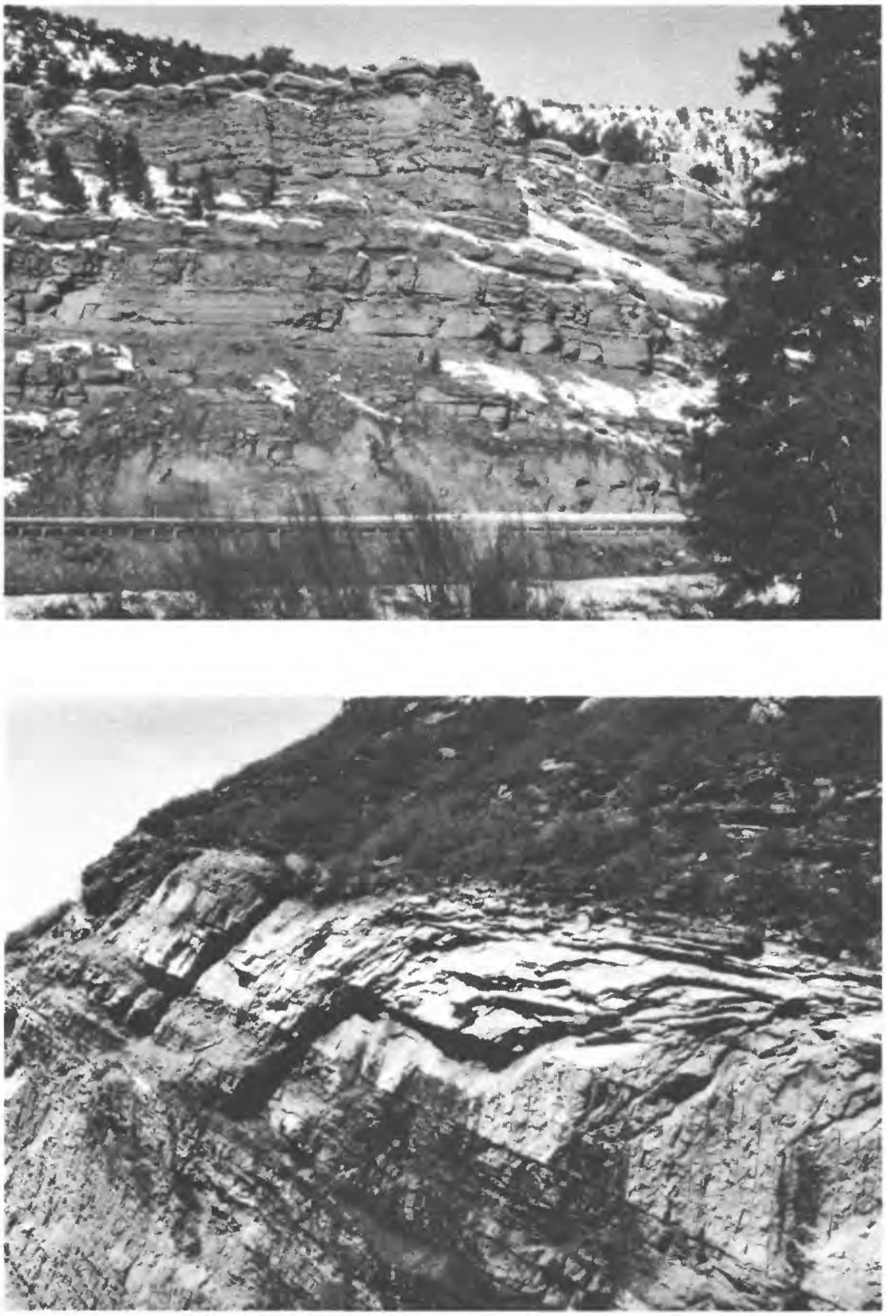


Figure 6.--Pennsylvanian and Permian red beds and carbonate rocks hydrostratigraphic unit: *A*, Maroon Formation near Eagle; *B*, Minturn Formation near Vail; *C*, Morgan Formation overlain by Weber Sandstone in Dinosaur National Monument.

C

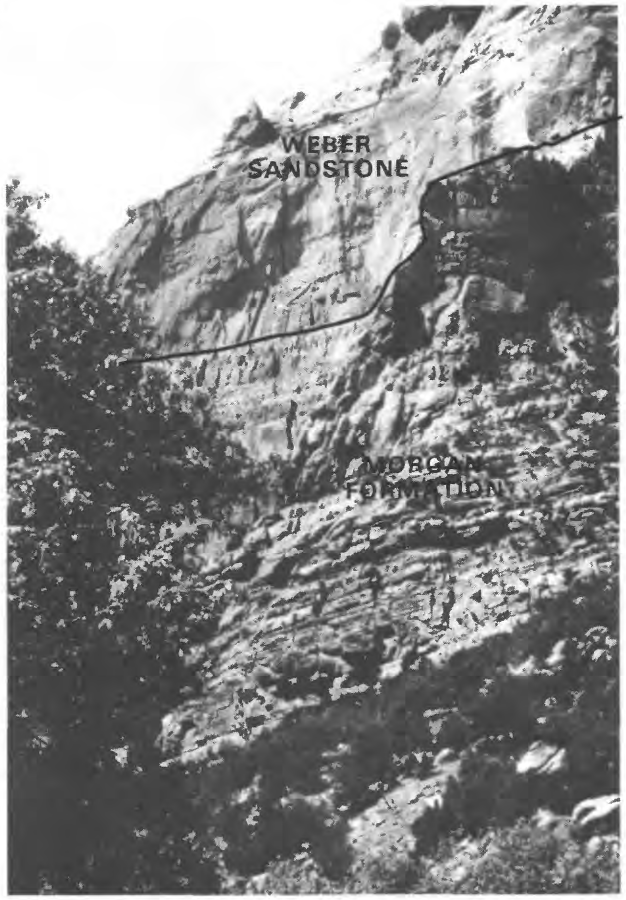


Figure 6.--Pennsylvanian and Permian red beds and carbonate rocks hydrostratigraphic unit: *A*, Maroon Formation near Eagle; *B*, Minturn Formation near Vail; *C*, Morgan Formation overlain by Weber Sandstone in Dinosaur National Monument--Continued.

In the Elk Mountains and Gore Range, the unit was beveled by pre-Jurassic erosion and is overlain by the Entrada Sandstone (Brill, 1944, p. 639; Lovering and Goddard, 1950, p. 36; Langenheim, 1952, p. 563).

Confining Layers

Confining layers in the study area include the Cambrian shale, Devonian carbonate and clastic rocks, Mississippian and Pennsylvanian shale and carbonate rocks, Pennsylvanian carbonate rocks and evaporites, and Permian shale and carbonate rocks hydrostratigraphic units. In the confining layers, spring discharges, artesian-well flows, and drill-stem test yields commonly are less than 25 gal/min. Very fractured rocks and relatively shale-free intervals of sandstone or limestone may yield water at rates of 25 to 100 gal/min. Average values of site hydraulic conductivity range from less than 0.0001 to 0.25 ft/d. Hydraulic-conductivity values for some limestone and sandstone intervals can be as large as 1 ft/d.

The Cambrian shale hydrostratigraphic unit in the study area consists of an unnamed shale sequence that evolves from the upper part of the Lodore Formation on the southeastern edge of the Uinta Mountains and is equivalent to the Gros Ventre Formation of Wyoming. The unnamed shale sequence (fig. 4*B*) consists of gray-green, brown, and red shale with scattered interbeds of dolomite and sandstone. Untermann and Untermann (1954) considered this sequence to be the top of the Lodore Formation in text descriptions and measured sections, such as the Jones Hole Section. Based on sparsely distributed drilling data, the unnamed shale sequence apparently ranges from less than 100 to about 400 ft thick in and near the Uinta Mountains and Sand Wash basin but is absent throughout most of the study area.

The Devonian carbonate and clastic rocks hydrostratigraphic unit includes only the Parting Formation in the study area. The Parting Formation varies substantially in lithology across the area, changing westward from gray, white, and pink sandstone and quartzite, to interbedded black and tan dolomite, black and green shale, and green and tan quartzite, to gray dolomite with sandstone and shale interbeds (Bass and Northrop, 1963, p. 17-21; Tweto and Lovering, 1977, p. 24-26). The formation generally is less than 100 ft thick south and east of the Glenwood Springs area, but thickens to about 150 ft northeast and northwest of Glenwood Springs. The formation generally is thin to absent north of the Yampa River, southwest of the White River Plateau, and east of the Sawatch Range.

The Mississippian and Pennsylvanian shale and carbonate rocks hydrostratigraphic unit includes the Molas Formation, Belden Formation, and Doughnut Shale. The Doughnut Shale consists of red shale and sandstone overlain by black to dark-gray carbonaceous shale with interbeds of greenish sandstone, green and tan sandy limestone, black shaly limestone, and bituminous coal (Untermann and Untermann, 1954, p. 30-32; Kinney, 1955, p. 33-38; Hansen and others, 1983). The lower part of the Doughnut Shale grades into the Molas Formation, which typically is a discontinuous deposit of poorly stratified, purplish-red and ochre claystone and siltstone containing boulders of limestone and chert; thicknesses of the deposit range from inches to 130 ft (Bass and Northrop, 1963, p. 30). The upper part of the Doughnut Shale grades into the Belden Formation. As described by Brill (1944), Bass and Northrop (1963, p. 31-41), and Tweto and Lovering (1977, p. 34-38), the Belden Formation generally consists of interbedded dark-gray to black shale and limestone, with subordinate gypsum layers, and, on the northern, southern, and eastern edges of its occurrence, interbeds of gray, brown, and green micaceous sandstone, conglomerate, and shale (fig. 7). The thickness of the hydrostratigraphic unit increases from about 300 ft in the vicinity of the Uinta Mountains to between 500 and 1,000 ft in the southern and western White River Plateau and Elk Mountains, and to about 4,000 ft in the Burns basin. The unit thins north and east of the Burns basin and south and west of the Elk Mountains because of pre-Jurassic erosion and is absent in the northeastern and southwestern parts of the study area.

Figure 7.--Belden Formation of the Mississippian and Pennsylvanian shale and carbonate rocks hydrostratigraphic unit near Dotsero. The formation here consists of interbedded black shale and greenish-tan sandstone.

The Pennsylvanian carbonate rocks and evaporites hydrostratigraphic unit includes the Eagle Valley Evaporite (Formation) and the Round Valley Limestone. The Eagle Valley Evaporite in an area extending from the Burns basin on the northeast to Carbondale on the southwest (see fig. 1 for locations) consists mostly of gray gypsum, anhydrite and shale (see descriptions of this formation and its equivalents by Mallory, 1971; Dodge and Bartleson, 1986). In several places, notably Ruedi Reservoir southeast of Glenwood Springs, the Cattle Creek drainage near Carbondale, the area between Avon and Dotsero along the Eagle River, and two areas east of Meeker, gypsum and halite form the core of thick diapiric intrusions (fig. 8). The flowage of gypsum and halite into these diapirs removed or depleted evaporite deposits from other areas. As a result, the thickness of the Eagle Valley Evaporite varies markedly within

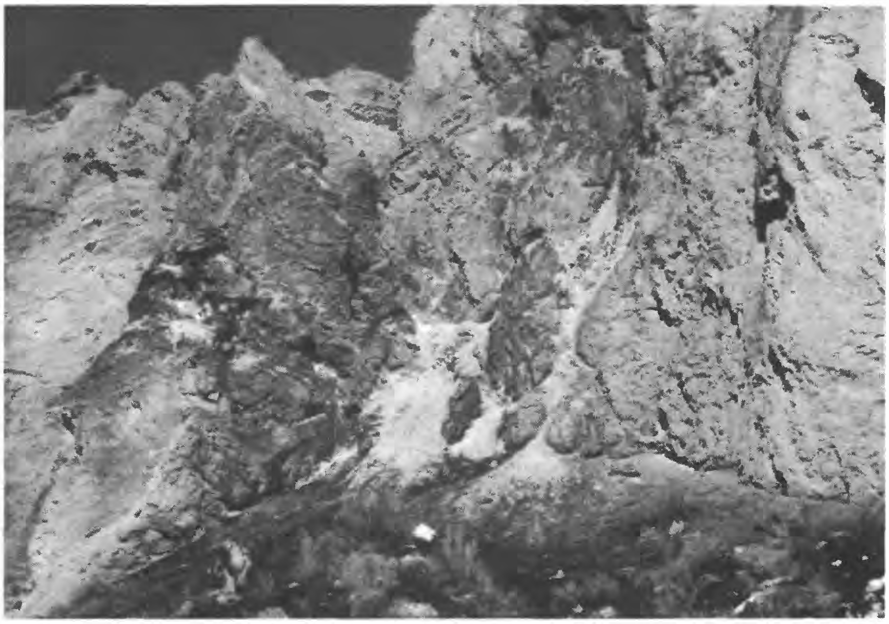


Figure 8.--Eagle Valley Evaporite of the Pennsylvanian carbonate rocks and evaporites hydrostratigraphic unit near Eagle. The formation here has been deformed into a contorted mass of gypsum by overburden pressure.

short distances. For example, on the southwestern side of the White River Plateau, within a horizontal distance of about 30 mi, measured thicknesses vary from 81 ft to more than 3,000 ft (Brill, 1944; Thomas and others, 1945; Mallory, 1971). On the southeastern side of the White River Plateau and the western side of the Burns basin, measured thicknesses within 6 mi vary from 1,553 ft to more than 4,700 ft (Brill, 1944; Bass and Northrop, 1963; Mallory, 1971). At its depositional edges on the southern and eastern sides of the area, the Eagle Valley Evaporite intertongues with the Minturn Formation and the Gothic Formation of Langenheim (1952). On the western edge of the area, the Eagle Valley Evaporite intertongues with the Morgan Formation (Mallory, 1971).

North and west of the White River Plateau, the Pennsylvanian carbonate rocks and evaporites hydrostratigraphic unit gains sandstone and carbonate layers as evaporites pinch out. In the vicinity of Meeker, the Eagle Valley Evaporite consists of interbedded sandstone, shale, and carbonate rocks, with anhydrite layers (Dodge and Bartleson, 1986, p. 115). Because evaporite layers no longer predominate, the unit in this area more properly is called the Eagle Valley Formation. In the Uinta Mountains and Sand Wash basin, carbonate rocks with shale interbeds characterize the unit, which is called the Round Valley Limestone (Hansen and others, 1983). Thicknesses of the Round Valley Limestone and Eagle Valley Formation commonly range from 100 to 300 ft.

The Permian shale and carbonate rocks hydrostratigraphic unit includes the Park City Formation and the lower parts of the State Bridge and Goose Egg Formations. The Park City Formation, as described by Untermann and Untermann (1954, p. 38-40) and Kinney (1955, p. 48-55), consists of tan, red, and gray sandstone, limestone, and shale in the Uinta Mountains and Yampa Plateau (fig. 9). Eastward, it grades into greenish-gray shale with scattered limestone layers. With further decreases in limestone content, the greenish-gray shale facies of the Park City Formation and the Triassic Moenkopi Formation evolve into the State Bridge and Goose Egg Formations in the eastern Sand Wash basin and south of the White River. The Permian-Triassic boundary in the State Bridge Formation in this report arbitrarily is placed at the top of the stratigraphically highest carbonate interval, which is known as the South Canyon Creek Dolomite Member. The corresponding interval in the Goose Egg Formation is called the Ervay Limestone Member. The State Bridge and Goose Egg Formations consist of red, reddish-brown, and green shale with subordinate sandstone, carbonate, and gypsum/anhydrite layers. The carbonate layers pinch out from west to east. Where they are absent, Permian and Triassic parts of the State Bridge and Goose Egg Formations are indistinguishable, and the two formations arbitrarily are considered part of the Triassic confining layer (table 1).

The Permian shale and carbonate rocks hydrostratigraphic unit generally is less than 100 ft thick in the vicinity of the Uinta Mountains, but thickens to 500 ft in the Sand Wash basin and 600 ft in the northern White River Plateau. South and west of the White River Plateau and east of the Burns basin, pre-Jurassic erosion has thinned the unit to less than 200 ft and removed it entirely from most areas.

GLENWOOD SPRINGS AQUIFER TESTS

Glenwood Springs, in Garfield County (see fig. 1 for location), was the site of several aquifer tests of the Leadville Limestone between 1981 and 1985. Glenwood Springs is situated at the confluence of the Colorado and Roaring Fork Rivers. Prominent topographic features in the area include the White River Plateau (seen in fig. 10 at the site of aquifer tests in 1982 and 1984) on the northern side of Glenwood Springs, Lookout Mountain (an extension of the White River Plateau south of the Colorado River) on the southeastern side of Glenwood Springs, and the Grand Hogback (the western edge of the White River Plateau) on the southwestern side of Glenwood Springs.

Twelve hot springs and 6 seepage areas, collectively known as the Glenwood Hot Springs Group, occur along both banks of the Colorado River on the northeastern and northwestern sides of Glenwood Springs (fig. 11). These springs and seepage areas cumulatively discharge at a rate between 4,000 and 5,000 gal/min (table 2). All springs issue from either the Leadville Limestone or alluvium overlying the Leadville Limestone and Belden Formation;

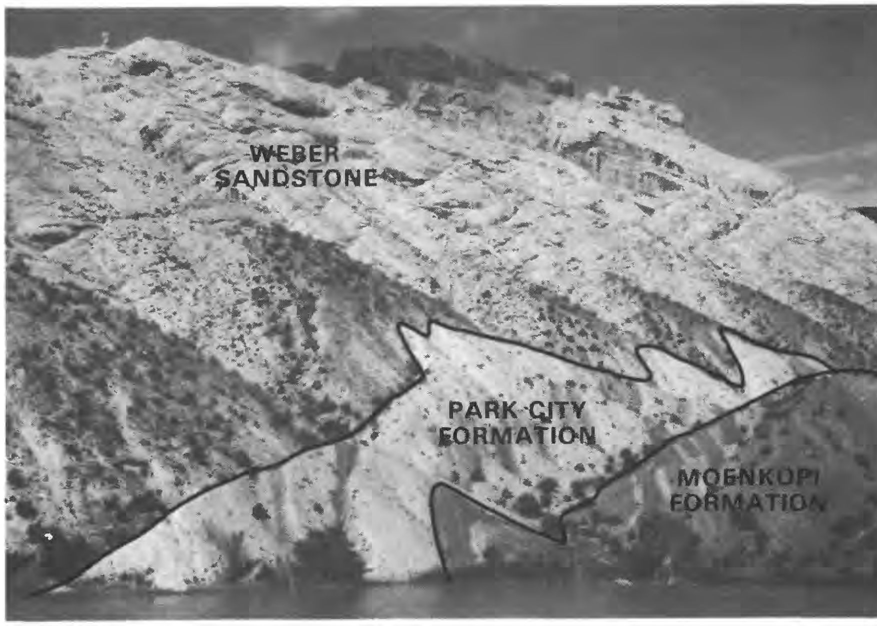


Figure 9.--Park City Formation of the Permian shale and carbonate rocks hydrostratigraphic unit underlain by Weber Sandstone and overlain by Moenkopi Formation in Dinosaur National Monument.

Figure 10.--The White River Plateau and Colorado River at the site of aquifer tests of the Leadville Limestone in 1982 and 1984 at Glenwood Springs. View is to the north.

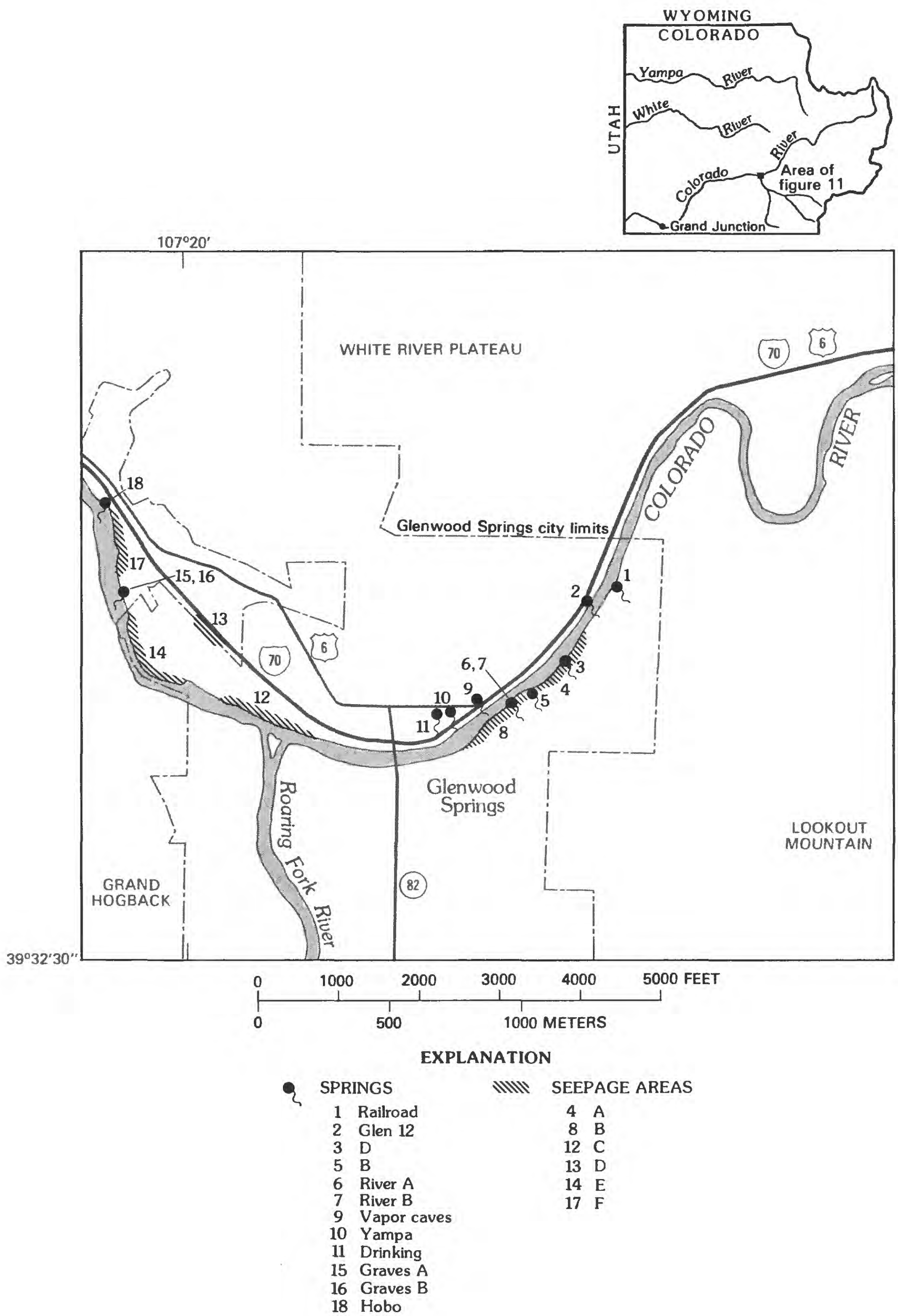


Figure 11.--Locations of springs and seepage areas at Glenwood Springs.

Table 2.--*Discharges of springs and seeps in the Glenwood Hot Springs Group*

[All measurements are instantaneous, except URS Corporation (1982), which are averages for 1972-80; dashes indicate no data]

Map number (fig. 11)	Spring name (alternate name in parentheses)	Discharge, in gallons per minute, by source: Barrett and Pearl (1977)	URS Corporation (1982)	U.S. Geological Survey files: 1965	U.S. Geological Survey files: 1984	Estimated average from all sources
1	Railroad Spring (Glen 10)	75	153	--	--	153
2	Glen 12 Spring	--	115	--	--	115
3	Spring D (Glen 20)	74	299	--	--	299
4	Seepage area A (Spring C)	2-3	--	--	--	10
5	Spring B (Glen 30-40)	75-110	216	--	--	216
6	River Spring A	10	--	--	--	10
7	River Spring B	50	--	--	--	50
8	Seepage area B (Spring A)	2-3	--	--	--	10
9	Vapor Caves Spring	5	58	--	--	58
10	Yampa Spring (Big Spring)	2,263			2,800-2,950	2,700
11	Drinking Spring	140-161	--	54	--	150
12	Seepage area C	--	--	--	--	10
13	Seepage area D:					
	(Glen 76)	--	48	--	--	205 (Glen 76, 78, 80 combined)
	(Glen 78)	--	45	--	--	
	(Glen 80)		112			
14	Seepage area E					10
15	Graves Spring A (Glen 90, with 16)	5 (with 16)	109 (15 and 16 combined)	33		109 (15 and 16 combined)
16	Graves Spring B			80	59	
17	Seepage area F	--	--	--	--	10
18	Hobo Spring (Glen 100)	--	221	160	--	221
	Estimated average total (rounded)-----					4,300

springs issuing from the alluvium are believed to be supplied by water migrating up from the Leadville Limestone through fractures and faults (Barrett and Pearl, 1977, p. 92).

The largest spring in the area, the Yampa (Big) Spring (fig. 12) was first developed for recreational use in 1888. Successive modifications have made measurement of its discharge difficult. Currently, the spring flows upward into a 60-ft diameter, rock-lined caisson with four outlets, one each to the Glenwood Springs Lodge and Pool, and two to the Colorado River. The spring discharge varies as the water level in the caisson is changed by manipulation of gates to the swimming pool and river. Barrett and Pearl (1977, p. 92) report a discharge of 2,263 gal/min from this spring. Average discharge from the caisson when all flow is diverted through the river gate is about 2,500 to 2,700 gal/min (Tom Zancanella, Wright Water Engineers, oral commun., 1985). Estimated discharge from the spring during the second Redstone well test (1984) varied between 2,800 and 2,950 gal/min as a result of pool operations (derivation of these figures is discussed later in this report).

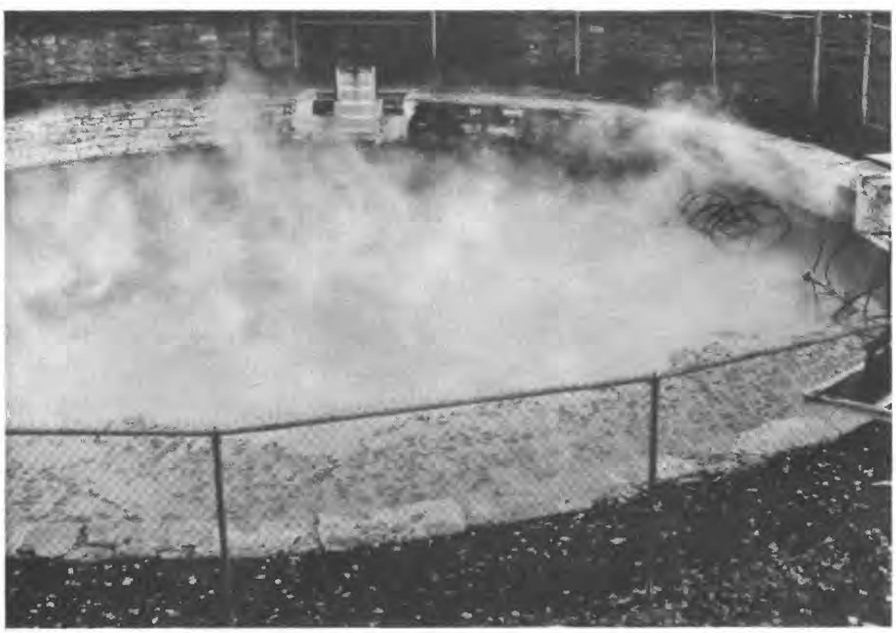


Figure 12.--The Yampa Spring at Glenwood Springs. This hot spring is the largest of 12 springs in the area. It has supplied large commercial swimming pools that have made the town a popular resort since 1888.

Site Geology and General Hydrology

As seen in figure 13, rocks ranging in age from Precambrian to Permian crop out in the vicinity of Glenwood Springs. The oldest rocks are Precambrian granite and Cambrian, Ordovician, and Devonian sedimentary rocks consisting of the Sawatch Quartzite, Dotsero Formation, Manitou Dolomite, and Parting Formation. The Precambrian, Cambrian, Ordovician, and Devonian rocks crop out in Glenwood Canyon, east of Glenwood Springs, where the total thickness of the lower Paleozoic rocks and Parting Formation is about 580 ft (fig. 14). This entire Precambrian to Devonian sequence is either crystalline or fine-grained, with quartzite and fine-grained dolomite as the predominant sedimentary rock types. Large joints that transect geologic formations may be the only conduits for ground-water movement.

Middle Paleozoic rocks in the area, in addition to the Parting Formation, include the Devonian Dyer Dolomite and the Mississippian Leadville Limestone. The latter two formations crop out at the mouth of Glenwood Canyon and form prominent hogbacks on the southwestern flank of the White River Plateau. Their combined thickness in the area is about 280 ft (fig. 14). Typically, the Dyer Dolomite consists of dolomitic limestone overlain by fine-grained dolomite with shale layers. The Leadville Limestone consists of interbedded sandy, cherty, fine-grained and finely crystalline limestone and dolomite layers that are overlain by massive, oolitic limestone. Limestone comprises about two-thirds of the Dyer Dolomite and Leadville Limestone at Glenwood Springs. Based on analyses of core from equivalent geologic formations throughout the Upper Colorado River Basin and local lithologic composition, it is estimated that porosity in the Dyer Dolomite and Leadville Limestone at Glenwood Springs averages only about 2 to 3 percent. However, fractures, vugginess, and cavern development are characteristic features of these formations in the area, enabling them to transmit large quantities of water.

Upper Paleozoic rocks include the Pennsylvanian Molas Formation, Belden Formation, Eagle Valley Evaporite, and Minturn Formation; the Pennsylvanian and Permian Maroon Formation and Weber Sandstone; and Permian members of the State Bridge Formation. The Pennsylvanian and Permian formations underlie Lookout Mountain and the Grand Hogback, on the southeastern and southwestern sides of Glenwood Springs. Their combined thickness in the area probably averages about 5,200 ft (fig. 14), assuming an average thickness of about 600 ft for the Eagle Valley Evaporite (which varies by several thousand feet in the area). The Molas Formation, Belden Formation, Eagle Valley Evaporite, and State Bridge Formation predominantly consist of fine-grained rocks, such as claystone, siltstone, anhydrite, limestone, and dolomite, that transmit water only where they are extensively fractured. Locally, as in fault zones, flows of 100 gal/min are possible (as indicated by drilling data supplied by the U.S. Bureau of Reclamation, written commun., 1985). In contrast, the Maroon Formation and Weber Sandstone predominantly consist of sandstone and conglomerate. The Maroon Formation is used extensively as an aquifer in the area for domestic and small public water supplies. The Weber Sandstone potentially is an aquifer, also, but it probably is unsaturated in the immediate vicinity of Glenwood Springs.

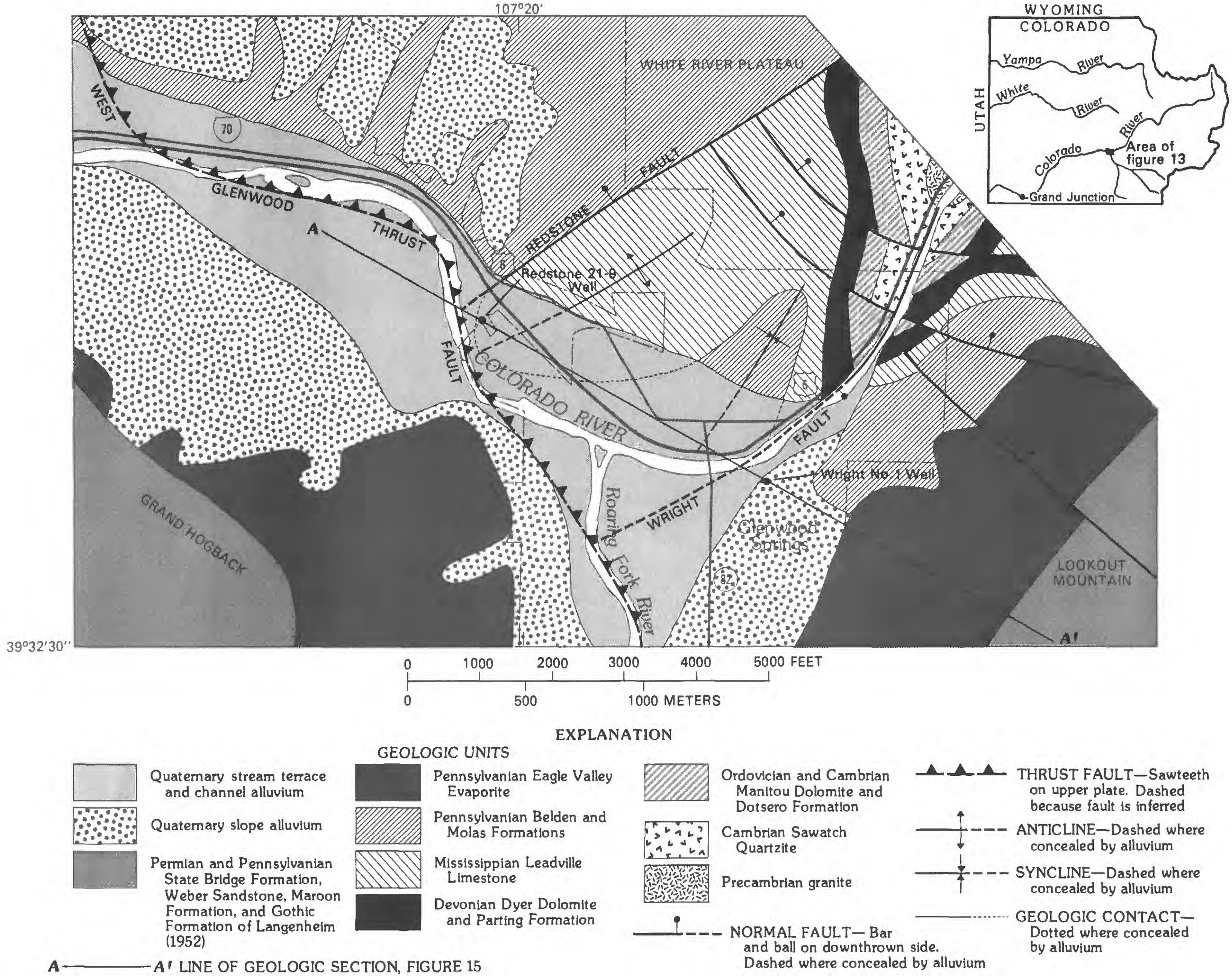


Figure 13.--Geology of Glenwood Springs and vicinity (modified from Bass and Northrop, 1963, pl. 1).

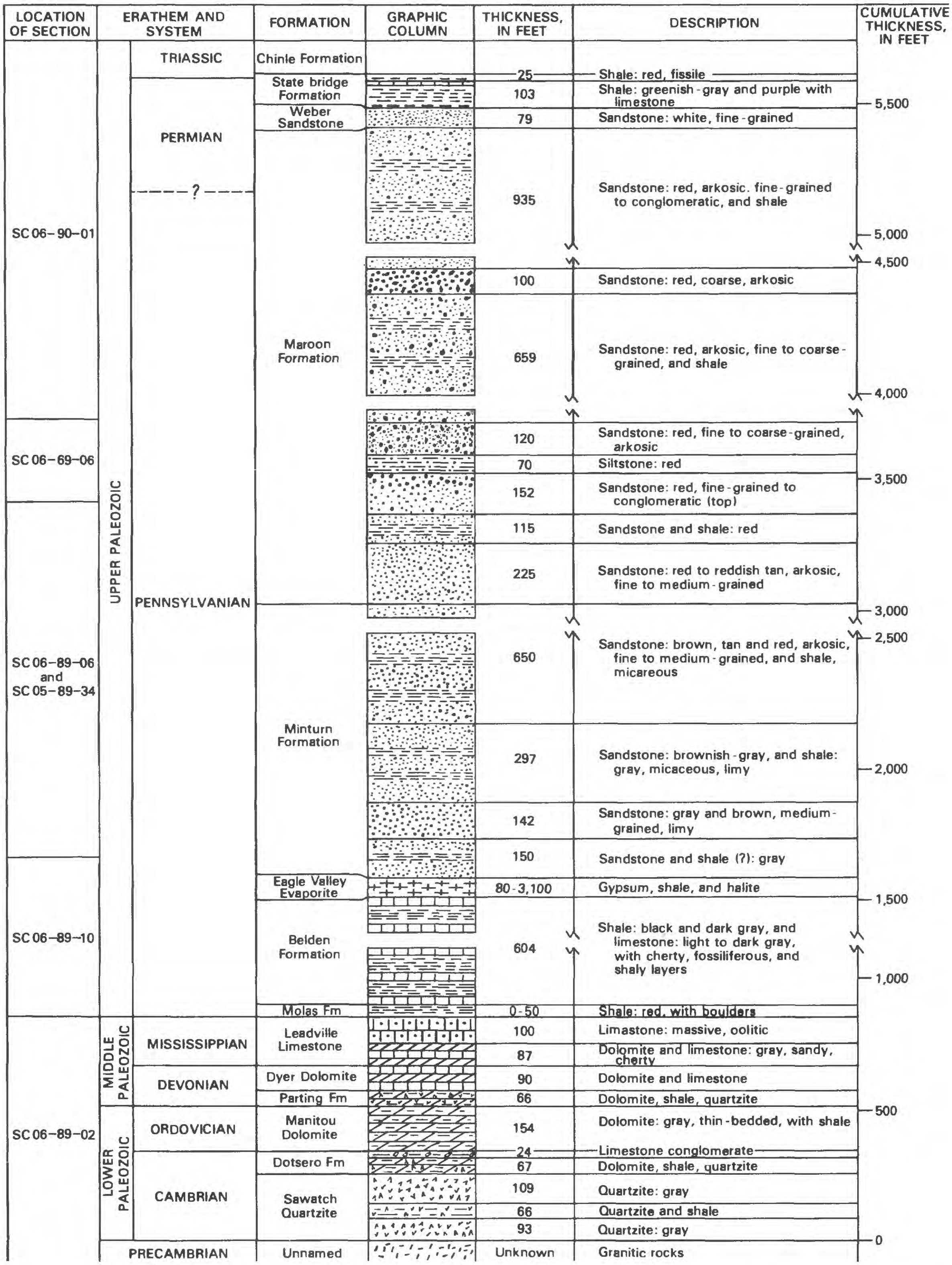


Figure 14.--Composite stratigraphic column for the Glenwood Springs area (compiled from Brill, 1944; Tweto and others, 1947, p. 28; Bass and Northrop, 1963; and U.S. Bureau of Reclamation unpublished engineering reports for Ruedi Dam project).

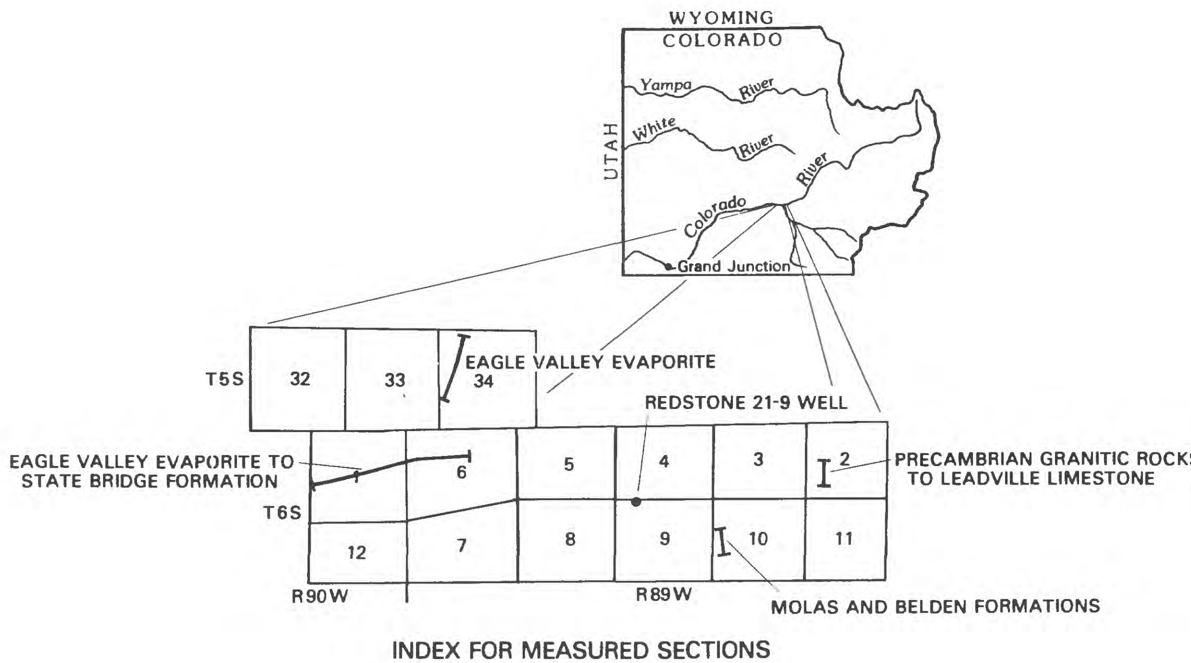


Figure 14.--Composite stratigraphic column for the Glenwood Springs area (compiled from Brill, 1944; Tweto and others, 1947, p. 28; Bass and Northrop, 1963; and U.S. Bureau of Reclamation unpublished engineering reports for Ruedi Dam project)--Continued.

The Paleozoic rocks are arched into an anticline that is breached at the crest by two steeply dipping normal faults (fig. 15). From east to west, these faults informally are called the "Wright fault" and the "Redstone fault" (see fig. 13 for locations), after geothermal wells located in each fault zone. At the crest of the breached anticline, the Paleozoic rocks are refolded into a small syncline and anticline. The eastern limb of the breached anticline is thrust over its western limb by a gently dipping thrust fault, which informally is called the "West Glenwood thrust fault" (see fig. 13 for location). According to Bass and Northrop (1963, p. 64), the plane of this thrust fault probably dips northeastward at an angle of less than 10 degrees.

Contrary to Bass and Northrop (1963, pl. 1), the West Glenwood thrust fault probably is an extension of the Dolan Gulch thrust fault, and not the Storm King thrust fault, because of the structural identities of the three faults. The Dolan Gulch thrust fault and the West Glenwood thrust fault separate a block of lower and middle Paleozoic rocks on the east from a block of upper Paleozoic rocks on the west. However, the Storm King thrust fault seems to be mainly a bedding plane fault within the Maroon Formation. In the

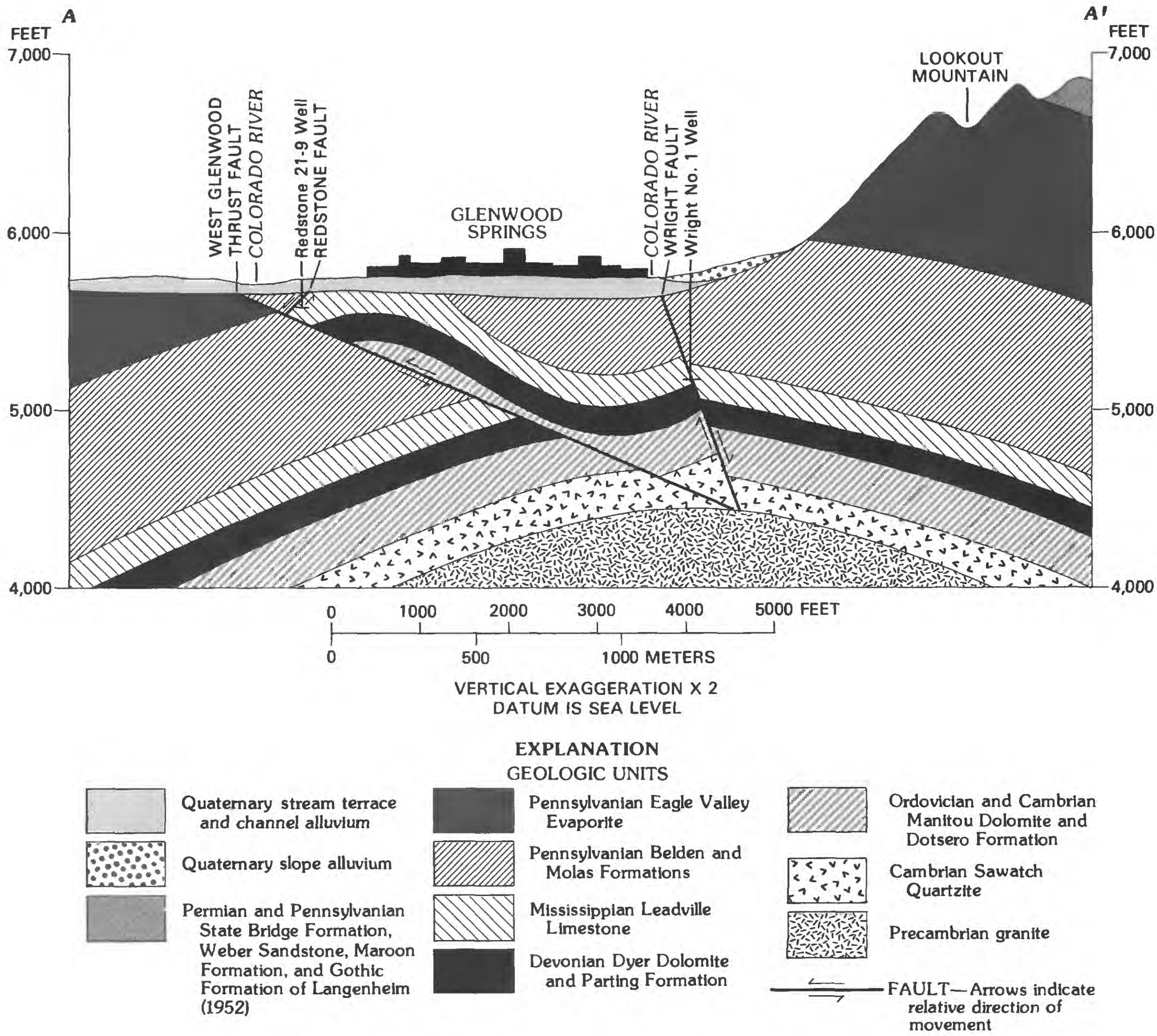


Figure 15.--Geology and structure at Glenwood Springs.

simplest interpretation, the Dolan Gulch thrust fault becomes the West Glenwood thrust fault with a change in orientation of the fault plane. The Storm King thrust fault ceases within the Maroon Formation.

Southwest of Glenwood Springs, in the Grand Hogback, the Paleozoic rocks are overlain by sedimentary rocks of Triassic to Eocene age. Southeast of Glenwood Springs, the Paleozoic rocks are capped by Tertiary basalt (see Bass and Northrop, 1963, p. 54-63, for a description of Mesozoic and Tertiary rocks in the area).

Adjacent to the Colorado and Roaring Fork Rivers, erosional surfaces incised into the Paleozoic rocks are overlain by stream, terrace, and channel alluvium of Quaternary age. The terrace alluvium on the northern side of Glenwood Springs consists of sand-capped gravel, 55 to 80 ft thick (URS Corporation, 1983, Attachment 2). The saturated thickness of this alluvium ranged from 45 to 80 ft in 1982. Some wells in the alluvium contain zones of warm water. In 1982, the water table in the alluvium sloped toward the Colorado and Roaring Fork Rivers with gradients of 300 to 800 ft/mi (fig. 16). A pumping test from November 8 to December 8, 1982, indicated average values of transmissivity in the alluvium of 3,500 ft^2/d within 100 ft of the Colorado River and 26,000 ft^2/d elsewhere north of the river (URS Corporation, 1983, Attachment 2). These transmissivity values were determined by the method of Boulton (1963).

On hillsides surrounding Glenwood Springs, the Paleozoic rocks are overlain by various unconsolidated deposits of Quaternary age, collectively grouped in this report as "slope alluvium." This material includes gravel to boulder-sized alluvium deposited as much as 2,700 ft above the present river surface by predecessors of the Colorado River, fan alluvium, and landslide debris (Bass and Northrop, 1963, p. 60-61).

All water sampled in the area from wells completed in the Leadville Limestone and from springs issuing from this formation or hydraulically connected alluvium consistently is a sodium chloride type (table 3). Sulfate, in concentrations of 1,120 to 2,450 mg/L, is the second most abundant anion. The dissolved-solids concentration in this water ranges from 18,100 to 22,200 mg/L. Minor and trace constituents include fluoride, boron, lithium, barium, iron, and strontium. The water contains dissolved hydrogen sulfide in concentrations of 1.2 to 2.1 mg/L. The temperature of the water ranges from 111 to 126 °F. Temperature measurements in the Wright no. 1 well indicate a geothermal gradient of 1.8 °F/100 ft (Wright Water Engineers, written commun., 1984).

Site Aquifer-Test History and Monitoring Networks

Aquifer tests at Glenwood Springs were done from 1981 to 1985 by private consultants and Federal agencies for three purposes: (1) To quantify resources for geothermal development, (2) to analyze the feasability of decreasing the salt load in the Colorado River through diversion of hot springs flowing into the river, and (3) to obtain information about the hydrologic properties of the Leadville Limestone and Dyer Dolomite, including the nature of ground-water movement through these formations. Participants in these studies included Wright Water Engineers, Chaffee Geothermal Ltd. (and its successor, Terra Therma Inc.), the U.S. Bureau of Reclamation, and the U.S. Geological Survey.

Geothermal-resource investigations began in 1981. In October of that year, Wright Water Engineers drilled the Wright no. 1 well with the intention of using the hot water produced to heat a planned office building. The Wright no. 1 well was drilled to a depth of 571 ft, but the bottom 65 ft collapsed 1 month after drilling ended. The well is cased to a depth of 130 ft and is open from 130 ft to the bottom. The casing has a diameter of 12 in. The open

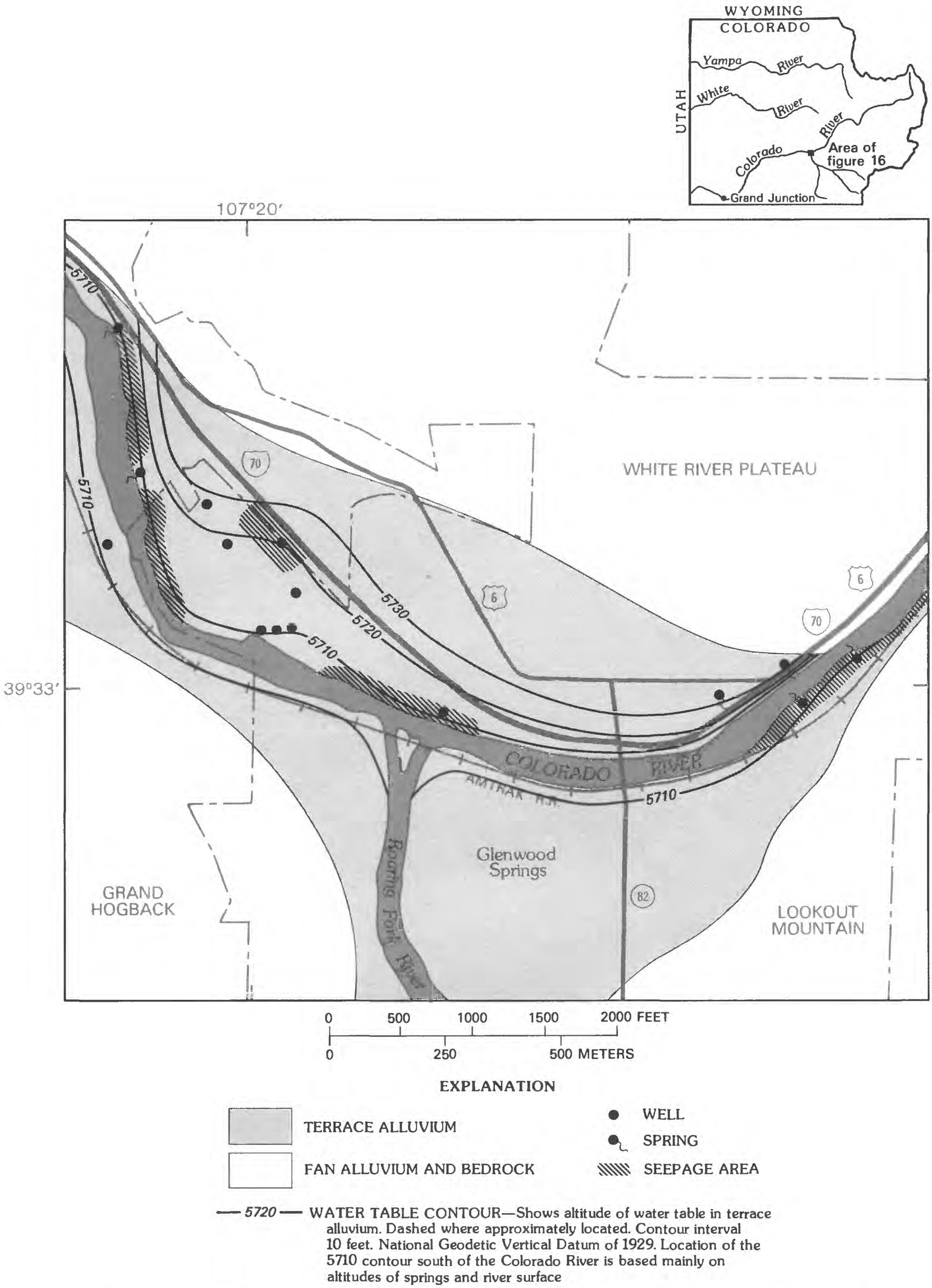


Figure 16.--Water table in alluvium at Glenwood Springs in December 1982.

Table 3.--*Representative chemical analyses of water from*

[Sources of data include URS Corporation, 1983; Terra Therma Inc. and Wright Water
all concentrations are in milligrams

Site name	Site location	Date sampled	Temperature (°F)	pH	Calcium (Ca)	Magnesium (Mg)	Potassium (K)	Sodium (Na)	Bicarbonate (HCO_3)	Sulfate (SO_4)
Yampa Spring-----	SC06-89-09ada$_1$	10/10/65	126	8.0	427	---	133	6,810	424	1,240
Wright no. 1 well	SC06-89-09adc	02/26/82	---	6.3	450	87	---	7,560	790	1,300
Redstone 21-9 well----------	SC06-89-09bba$_1$	09/15/81	122	7.2	820	135	425	6,880	695	2,450
		11/12/84	121	6.4	760	140	150	7,600	684	2,000
Graves Spring B--	SC06-89-09bba$_3$	10/10/65	115	8.5	753	138	16	7,150	635	2,210
								Average Composition		
Hobo Spring------	SC06-89-04ccc	1972-80	---	---	714	133	169	6,590	715	1,980
Spring B---------	SC06-89-10bca	1972-80	---	---	456	84	178	6,440	736	1,120
Spring D---------	SC06-89-10bbd	1972-80	---	---	452	84	168	6,330	733	1,130
Railroad Spring---------	SC06-89-10bab$_1$	1972-80	---	---	478	87	183	6,920	722	1,190
Glen 12 spring---	SC06-89-10bab$_2$	1972-80	---	---	478	87	200	6,920	776	1,180
Seepage area D---	SC06-89-09bac	1972-80	---	---	683	122	192	6,070	730	1,790
Vapor Caves Spring---------	SC06-89-09ada$_2$	1972-80	---	---	452	83	170	6,510	730	1,140

the Leadville Limestone at Glenwood Springs

Engineers, written commun., 1984; and U.S. Geological Survey, unpublished data; per liter; dashes indicate no data]

Chloride (Cl)	Fluoride (Fl)	Nitrogen (N)	Silica (SiO_2)	Barium (Ba)	Iron (Fe)	Manganese (Mn)	Lithium (Li)	Boron (B)	Strontium (Sr)	Carbon dioxide (CO_2)	Hydrogen sulfide (H_2S)	Hardness	Dissolved solids
10,000	2.6	0.7	32	---	----	----	---	0.8	--	---	---	1,380	19,300
11,000	---	---	32	1.8	0.59	----	---	---	--	110	1.3	1,490	19,700
10,800	3.5	<.1	24	.4	.81	.05	1.0	1.0	--	---	1.2	-----	22,200
11,000	2.9	---	38	---	.66	.05	.7	1.0	15	---	2.1	-----	22,000
10,500	3.4	.6	38	---	----	----	---	.8	--	---	---	2,450	22,000
10,100	---	---	--	---	----	----	---	---	--	---	---	-----	19,500
9,830	---	---	--	---	----	----	---	---	--	---	---	-----	18,500
9,860	---	---	--	---	----	----	---	---	--	---	---	-----	18,100
10,700	---	---	--	---	----	----	---	---	--	---	---	-----	19,600
10,600	---	---	--	---	----	----	---	---	--	---	---	-----	19,700
9,370	---	---	--	---	----	----	---	---	--	---	---	-----	18,800
10,000	---	---	--	---	----	----	---	---	--	---	---	-----	18,500

hole narrows from 2 to 3 ft at the top to about 1 ft at the bottom, as indicated by caliper logging. The well now stands open only in the Belden Formation, although it originally stood open in the Leadville Limestone also (fig. 17). However, as revealed by aquifer tests discussed later, the well still is connected hydraulically to the Leadville Limestone through the rubble in the collapsed part of the well.

A pumping test in the Wright no. 1 well was done on February 23 and 24, 1982. Data from this test indicated leakage from either a confining layer or the well annulus during drawdown and recovery phases of the test. Hydraulic properties were not determined from the test data because aquifer tests of the Redstone 21-9 well (discussed later in this section) were better documented and could be analyzed more reliably.

Chaffee Geothermal Ltd., as consultant to Redstone Corporation, also began evaluating geothermal resources in the Glenwood Springs area in 1981. Redstone Corporation drilled the Redstone 21-9 well in 1981 with the intention of using hot water for heating the Mid-Continent Resources Building (location shown in fig. 18). The Redstone 21-9 well was drilled to a depth of 155 ft. The well is cased to a depth of 81 ft and open from 81 ft to the bottom. The casing has a diameter of 12.5 in. The open hole is about 1 ft wide. The well is completed in the Leadville Limestone, of which 35 ft is faulted and brecciated (fig. 17). The Leadville Limestone is overlain by 78 ft of alluvium. The well is a flowing artesian type.

Barometric efficiencies of the Redstone 21-9 and Wright no. 1 wells were determined from atmospheric pressure and water-level data collected from December 9, 1981 to January 5, 1982. Barometric efficiency, as defined by Ferris and others (1962, p. 85), is the net change in the water level in a well corresponding to the net change in atmospheric pressure, both expressed in feet of water.

After a shut-in period of more than 2 months, a flowing-well test of the Redstone 21-9 well was done during January 5-14, 1982. This test is called the first Redstone well test in this report. The Wright no. 1 well was used as an observation well during this test. The Wright no. 1 well is about 4,400 ft southeast of the Redstone 21-9 well. Documentation of the first Redstone well test is provided by Galloway (1982). The test data were reanalyzed during the present (RASA) study, and test results are discussed in the section "First Redstone Well Test" and interpreted in the section "Interpretation of Test Data."

An investigation by the U.S. Bureau of Reclamation to determine the feasibility of decreasing the salt load in the Colorado River by diverting spring inflows at Glenwood Springs began in October 1982 with the drilling of 10 boreholes and associated surface resistivity monitoring. The 10 boreholes were drilled to depths of 70 to 87 ft. All were completed in alluvium using perforated casing and bottomed in the upper few feet of bedrock. After a preliminary step-drawdown test in November 1982 to determine the optimum pumping rate for a constant-rate test, a pumping test was done from November 8 to December 8, 1982. Some of the test results were cited previously in this report, but more extensive documentation by the contractor for the testing, URS Corporation, is available (URS Corporation, 1983).

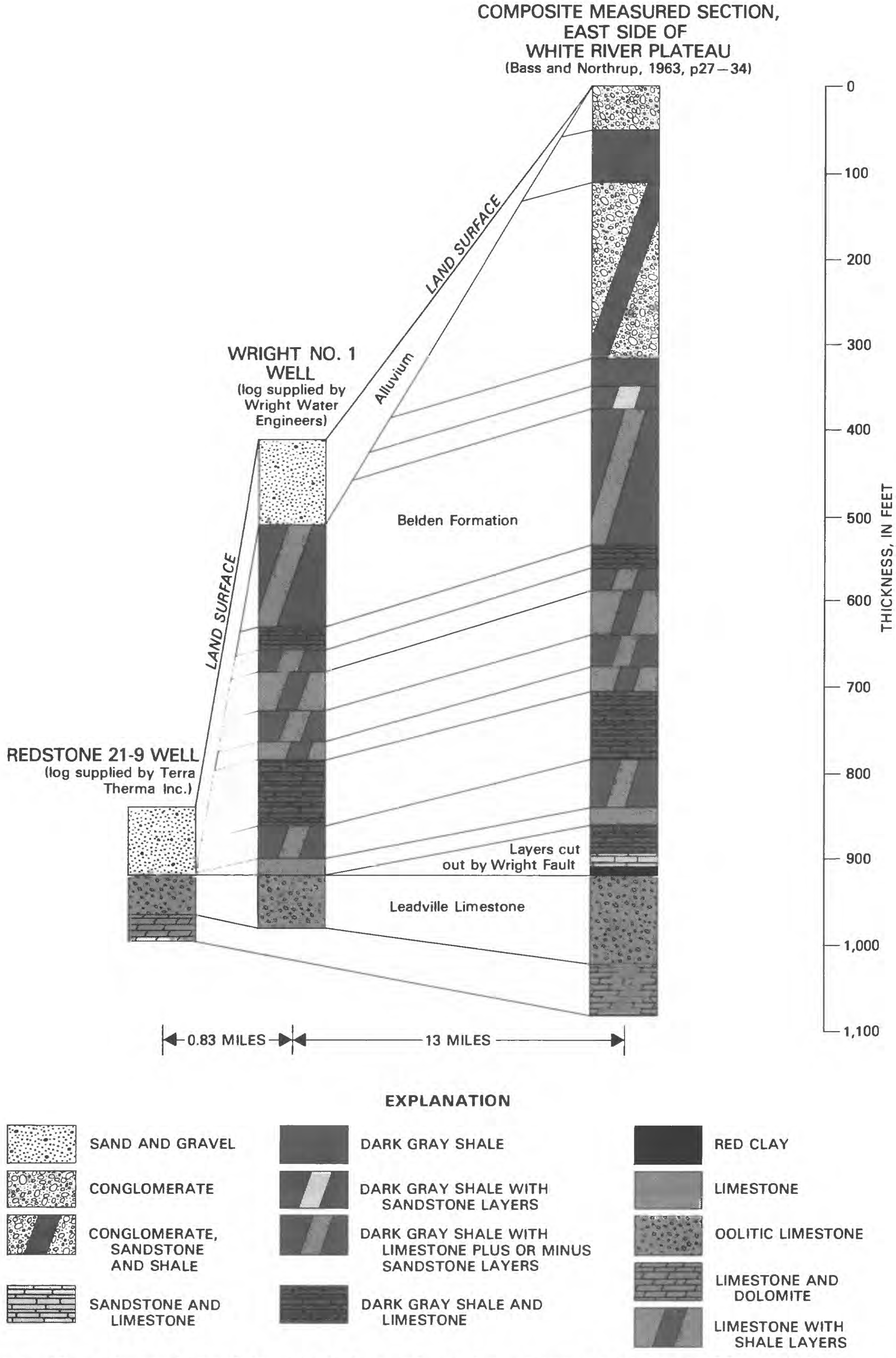


Figure 17.--Stratigraphic position of rocks penetrated by wells used in aquifer tests of the Leadville Limestone at Glenwood Springs in 1982 and 1984. The lower 65 feet of the Wright no. 1 well collapsed after drilling, but the well still is connected hydraulically to the Leadville Limestone through the rubble in the collapsed part of the well. The locations of these wells are shown in figure 18.

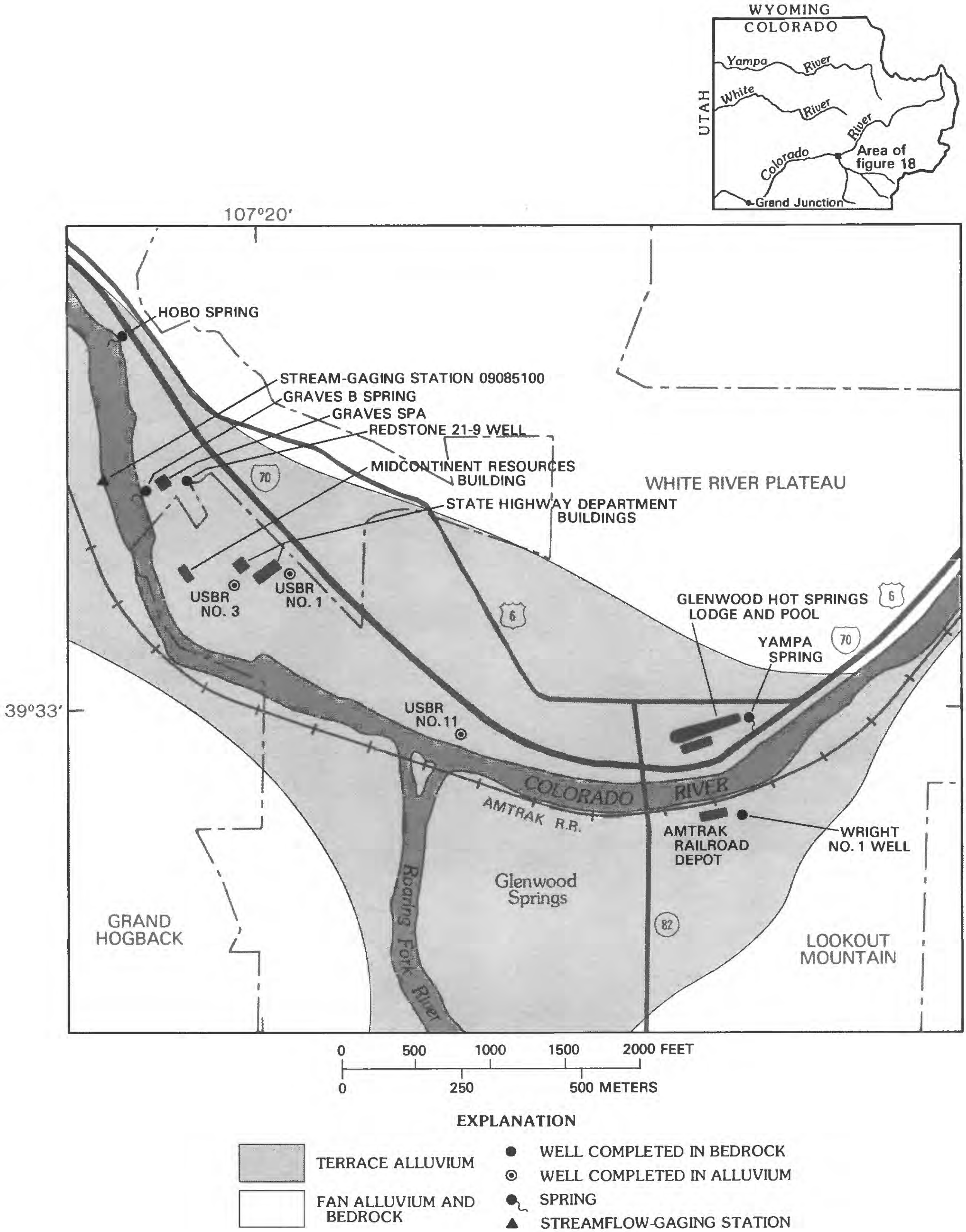


Figure 18.--Location of monitoring network for aquifer tests of the Leadville Limestone at Glenwood Springs in 1982 and 1984.

The U.S. Geological Survey became involved in the tests in 1984 when Terra Therma, Inc., the successor to Chaffee Geothermal Ltd., decided to determine the effects of discharge from the Redstone 21-9 well on surrounding wells and springs. The U.S. Geological Survey volunteered monitoring equipment and personnel for the test and was authorized by Redstone Corporation to use the test data in conjunction with its ongoing study of the regional hydrology. After an extended shut-in period, the Redstone 21-9 well was flow tested during November 12-20, 1984. This test is called the second Redstone well test in this report. Test results are discussed in the section "Second Redstone Well Test" and interpreted in the section "Interpretation of Test Data." The Wright no. 1 well, three U.S. Bureau of Reclamation wells (USBR nos. 1, 3, and 11), and three springs (Hobo, Graves B, and Yampa) were monitored also. The monitoring network for the Redstone well tests is shown in figure 18.

First Redstone Well Test

The first Redstone well test was a flowing-well test (see Lohman, 1979, p. 23-27, for discussion of test principles, derivation of analytical solutions, and examples of use for this kind of test). The monitoring network for this test included the Redstone 21-9 well (production) and the Wright no. 1 well (observation). In addition, a recording barometer was set up near the test site.

The Redstone 21-9 well (fig. 19) was instrumented for indirect measurement of potentiometric head. A 12-ft-high insulated standpipe was erected next to the well casing and connected to the casing by a 1.5-in.-diameter plastic pipe. A Stevens Type F continuous analog recorder was placed on top of the standpipe to record water levels. A 0.375-in. plastic piezometer tube and steel tape calibrated in hundredths of a foot were attached to the outside of the standpipe to visually verify the recorder readings. Potentiometric heads were calculated from water levels in the standpipe.

Discharge from the well was measured with a 9-in.-orifice plate attached to a horizontal steel discharge pipe. The discharge pipe had a diameter of 12 in. As recommended by the U.S. Water and Power Resources Service (1981, p. 234), a 0.375-in.-diameter plastic piezometer tube was inserted into the discharge pipe 3 diameters (36 in.) behind the orifice plate. The piezometer tube and a steel tape calibrated in hundredths of a foot were attached to a vertical support at the point where the piezometer tube was inserted into the discharge pipe (fig. 20 shows the discharge monitoring apparatus). Discharge was calculated from an equation developed by the U.S. Water and Power Resources Service (1981, p. 235).

Potentiometric heads in the Wright no. 1 well (fig. 21) also were calculated from water levels. A Stevens Type F recorder placed directly on the well casing was used to record water levels in the well. Recorder readings were verified periodically by lowering a weighted measuring tape into the well.

A recording barometer was set up near the test site to detect changes in atmospheric pressure associated with storms moving through the area. Changes

Figure 19.--Redstone 21-9 well at Glenwood Springs. Potentiometric heads during 1982 and 1984 aquifer tests were calculated from water levels in the standpipe attached to the well (photograph taken in November 1984).

in atmospheric pressure can affect water levels in wells that are completed in a confined aquifer, such as the tested formation. Increases in atmospheric pressure can lower the water level in a well. Conversely, decreases in atmospheric pressure can increase the water level in a well. However, the potentiometric head in a confined aquifer tapped by a well does not change in response to changes in atmospheric pressure. Thus, water levels used to determine changes in a potentiometric head in a confined aquifer must be adjusted to eliminate increments that result from fluctuating atmospheric pressure.

Figure 20.--Discharge-monitoring apparatus on Redstone 21-9 well used during 1982 and 1984 aquifer tests (photograph taken in November 1984).

A hypothetical example illustrates the effect of atmospheric-pressure changes on water levels and heads. Suppose the land-surface datum of a flowing artesian well is 5,700 ft and the water level in the well is +6.00 ft (relative to the land-surface datum). The potentiometric head in the aquifer tapped by this well equals 5,700 ft + 6.00 ft or 5,706.00 ft. In the next hour, the atmospheric pressure increases by an increment of 0.02 ft of water. Assuming the well is 100-percent efficient, the increased atmospheric pressure would lower the water level in the well by 0.02 ft, and the observed water level would be +5.98 ft. The apparent potentiometric head calculated from this water level would be 5,705.98 ft. However, if an increment of 0.02 ft was added to the observed water level to correct for the suppression due to the increase in atmospheric pressure, the water level, due to artesian pressure alone, still would be +6.00 ft. The actual potentiometric head in the aquifer still would be 5,706.00 ft.

Figure 21.--Wright no. 1 well at Glenwood Springs in November 1984. A water-level recorder is concealed within the metal box on top of the well casing.

In a nonflowing artesian well, water levels are below land-surface datum, but corrections for changes in atmospheric pressure still are applied in the same way as for flowing artesian wells. Suppose, for example, the land-surface datum of a nonflowing artesian well is 5,700 ft, and the water level in the well is -6.00 ft. The potentiometric head in the aquifer tapped by the well equals 5,700 ft - 6.00 ft or 5,694.00 ft. In the next hour, the atmospheric pressure increases by an increment of 0.02 ft of water. The water level in the well decreases 0.02 ft, and the observed water level is -6.02 ft. The apparent potentiometric head based on this water level would be 5,603.98 ft. However, had an increment of 0.02 ft been added to the observed water level to correct for the change in atmospheric pressure, the water level, due to artesian pressure alone, still would be -6.00 ft, and the potentiometric head still would be 5,694.00 ft.

Because wells generally are not 100-percent efficient, the incremental adjustment for a change in atmospheric pressure has to be multiplied by the barometric efficiency of the well. The barometric efficiency of the Redstone 21-9 well, as calculated from simultaneous measurements of water levels and atmospheric pressures during a 4-week period in 1981 and 1982, is 0.75; the barometric efficiency of the Wright no. 1 well, as calculated from data collected during the same period, is 0.25 (Galloway, 1982, p. 6).

The first Redstone well test lasted from January 5 to 14, 1982, and included a flow period of 6.8 days and a recovery period of 1.8 days. Discharge from the Redstone 21-9 well decreased from 1,860 gal/min at the start of the flow period to 1,480 gal/min at the end of the flow period. The average discharge during the flow period was 1,540 gal/min. Potentiometric head in the Redstone 21-9 well, adjusted for atmospheric pressure changes, decreased 5.72 ft during the flow period; the residual drawdown 1.8 days later was 0.79 ft. Potentiometric head in the Wright no. 1 well, adjusted for atmospheric pressure changes, decreased 1.02 ft during the flow period and recovered completely 1.6 days later.

After adjustment for atmospheric-pressure effects, Galloway (1982, p. 6) noted two additional extraneous effects on recorded water levels during the first Redstone well test. Broad, sinusoidal fluctuations in water levels during the test were attributed to earth tides. Sharp spikes in the water-level record during the test were attributed to passing trains. However, aberrations in the data caused by earth tides and passing trains were not sufficient to affect conventional methods of data analysis and were ignored in determining hydraulic properties.

Second Redstone Well Test

The second Redstone well test was similar to the first test but involved a more extensive monitoring network. Additional observation points included alluvial wells USBR no. 1, 3, and 11, the Yampa, Graves B, and Hobo Springs, and the U.S. Geological Survey's streamflow-gaging station 09085100. Except for minor changes, instrumentation for the production (Redstone 21-9) well and the observation (Wright no. 1) well was the same as in the previous test.

Potentiometric heads in the three U.S. Bureau of Reclamation wells were calculated from water levels. Wells USBR no. 1 (fig. 22) and USBR no. 3 (fig. 23) had Stevens Type F continuous analog recorders installed, with floats attached to record water levels. Readings from both recorders were checked periodically by lowering a weighted measuring tape into the wells. Water levels in well USBR no. 11 (fig. 24) were checked daily with a weighted measuring tape.

Discharges from the Graves B and Hobo Springs were measured directly with 90° V-notch weirs. The Hobo Spring (fig. 25) was equipped with a Stevens Type-F recorder, with a float attached to continuously register the height of water above the weir. Discharges from the spring were calculated using the formula for a 90° V-notch weir (Anderson, 1977, p. 150). After the test, leakage around the weir was discovered (John Ozga, U.S. Bureau of Reclamation, oral commun., 1985). As a result, discharges from this spring recorded during the test are inaccurate. However, changes in discharge recorded during the test probably are accurate. The Graves B Spring (fig. 26) was not equipped with a recorder. The height of water above the weir was read periodically with a steel tape calibrated in hundredths of a foot. Discharges from the spring were calculated using the weir formula.

Figure 22.--Well USBR no. 1 at Glenwood Springs in November 1984. A water-level recorder is concealed within the wooden box on top of the casing.

Figure 23.--Well USBR no. 3 at Glenwood Springs in November 1984. A water-level recorder is concealed within the wooden box on top of the casing.

Figure 24.--Well USBR no. 11 at Glenwood Springs in November 1984. The well is at the base of the stake.

Figure 25.--The Hobo Spring at Glenwood Springs in November 1984. The spring flows through a 90° V-notch weir at the base of the cistern. A recorder that registers the height of water above the weir is concealed within the box on top of the cistern. The Colorado River and seepage area F on the right bank are visible behind the spring. View is upstream.

Figure 26.--The Graves B Spring at Glenwood Springs in November 1984. The spring rises through a cistern and flows through a 90° V-notch weir. The spring is on the right bank of the Colorado River. The cylindrical object on the left bank slightly downstream from the spring is the stilling well for U.S. Geological Survey streamflow-gaging station 09085100.

Discharges from the Yampa Spring were calculated indirectly from rates of water-level change in the spring caisson. Water levels in the caisson were continuously recorded during the test with a Stevens Type-A recorder.

The stage of the Colorado River at the test site was monitored continuously during the test to separate river-induced changes in potentiometric head in the aquifer from changes in potentiometric head caused by the Redstone 21-9 well discharge. Stage was recorded at the U.S. Geological Survey's streamflow-gaging station 09085100 across the Colorado River from the Redstone 21-9 well (fig. 26). Instrumentation included a digital recorder and a

Stevens Type A analog recorder. The streamflow-gaging station was visited daily to obtain the stage record.

During the flow phase of the second Redstone well test, freezing of water in the standpipe and attached piezometer tube affected the water-level record for the Redstone 21-9 well. The record was salvageable, however, because the standpipe and piezometer tube were drained periodically for water samples and other operational requirements. Water levels recorded after the standpipe and piezometer tube refilled were used to correct the ice-affected record.

Extraneous effects on potentiometric head noted in the first Redstone well test--atmospheric pressure, earth tides, and passing trains--also affected the second Redstone well test. Corrections to water levels for these effects in the calculation of potentiometric heads were applied exactly as in the first test.

Unlike the first test, potentiometric heads observed in the Wright no. 1 well during the second Redstone well test were affected not only by discharge from the Redstone 21-9 well but also by commercial manipulation of the Yampa Spring (fig. 27). Eighteen hours before flow from the Redstone 21-9 well began, the Yampa Spring was diverted from the Glenwood Hot Springs Lodge and Pool to the Colorado River, increasing the discharge from the spring and lowering the potentiometric head in the Wright no. 1 well. When flow from the Redstone 21-9 well began, potentiometric head in the Wright no. 1 well decreased further. Seventy-two hours into the flow phase of the test, the Yampa Spring was diverted back to its original outlets. This decreased the discharge of the spring and initiated recovery of potentiometric head in the Wright no. 1 well. After flow from the Redstone 21-9 well was terminated, additional recovery of potentiometric head in the Wright no. 1 well occurred.

Separation of total drawdown and recovery into components caused by the Yampa Spring or Redstone 21-9 well alone had to be accomplished to analyze the hydraulic conductivity between the Redstone 21-9 and Wright no. 1 wells. This separation was accomplished by application of principles of superposition. When the Yampa Spring and Redstone 21-9 well were causing drawdown in the Wright no. 1 well, the total drawdown was equal to the sum of the drawdowns that would have occurred had either the Yampa Spring or Redstone 21-9 well been operating independently. When the Yampa Spring discharge was decreased to its prediversion rate, but the Redstone 21-9 well was still flowing, the drawdown in the Wright no. 1 well equaled the drawdown caused by the Redstone 21-9 well minus the recovery caused by decreased discharge from the Yampa Spring. When flow from the Redstone 21-9 well was terminated, the residual drawdown in the Wright no. 1 well equaled the difference between drawdown that would have resulted had the Redstone 21-9 well continued to flow and recovery caused by terminating flow from the Redstone 21-9 well and restoring the Yampa Spring discharge to its prediversion level.

The method by which the Redstone 21-9 well and Yampa Spring components of drawdown and recovery in the Wright no. 1 well were identified is illustrated in figure 28. Before flow from the Redstone 21-9 well began, all drawdown in the observation well was caused by the Yampa Spring (curve A). The Yampa Spring-caused drawdown between the time flow from the Redstone 21-9 well began and the Yampa Spring was diverted back to its original outlets (curve B) was

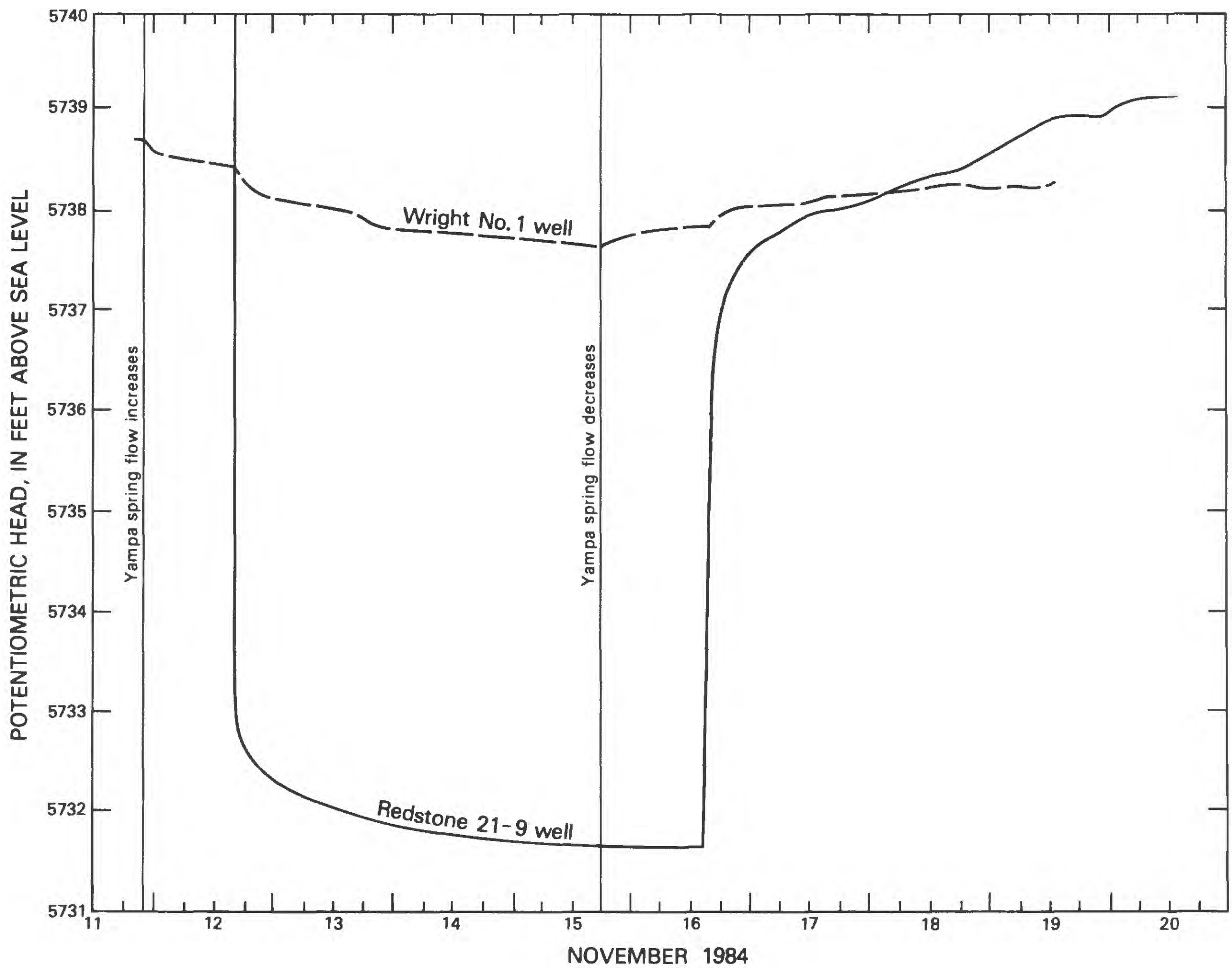


Figure 27.--Water-level records of bedrock wells in aquifer test of November 12-20, 1984, at Glenwood Springs.

found by extrapolation of the pretest drawdown curve (curve A). During this phase of the test, drawdown from the Redstone 21-9 well alone (curve C) was calculated as the residual between total drawdown and Yampa Spring-caused drawdown (curve B). After diversion of the Yampa Spring back to the lodge and pool, total drawdown was equal to the sum of Redstone 21-9 well-caused drawdown (extrapolated curve D) and residual Yampa Spring-caused drawdown (curve E). The residual Yampa Spring-caused drawdown was calculated as the difference between total drawdown and Redstone 21-9 well-caused drawdown.

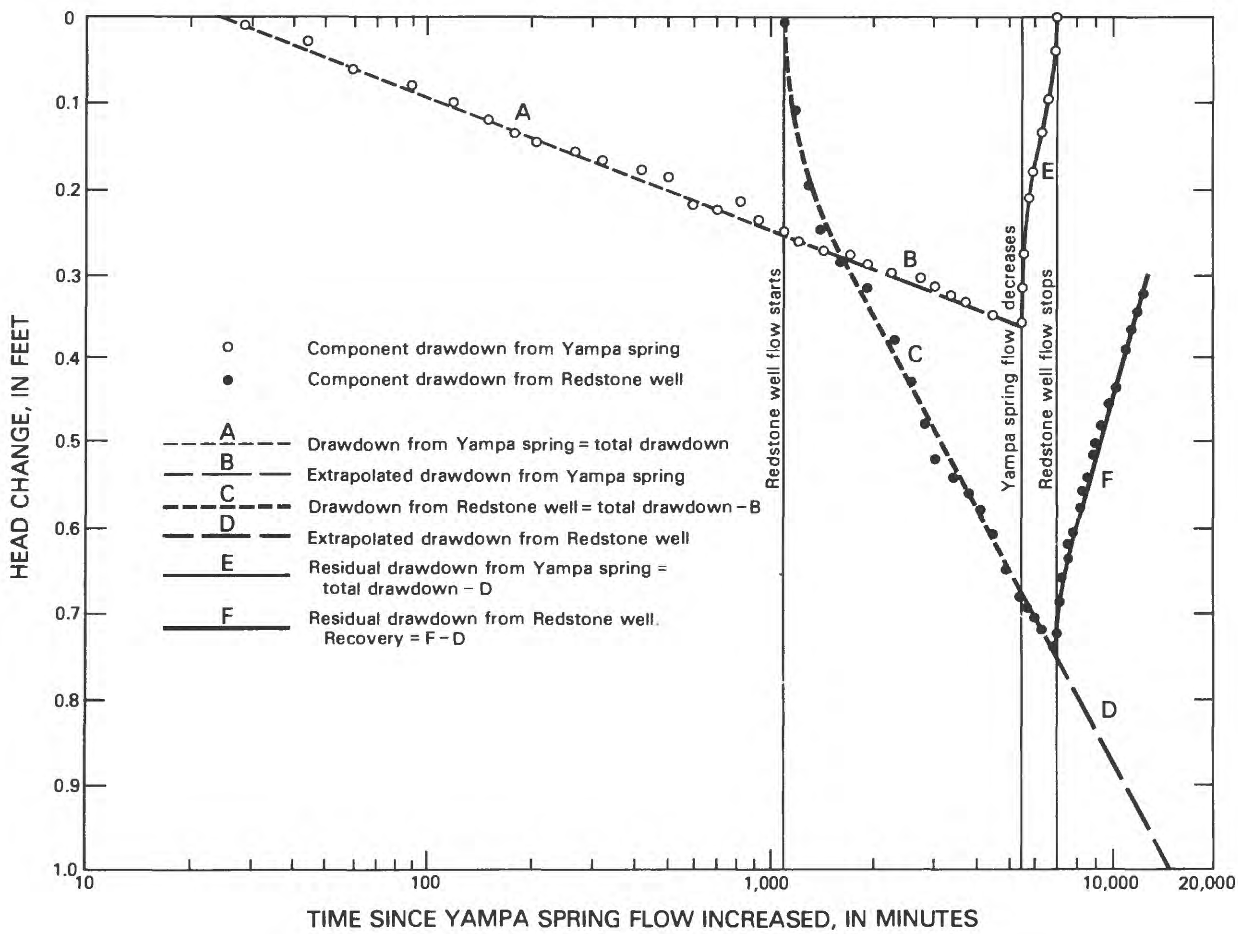


Figure 28.--Separation of recorded drawdown and recovery in Wright no. 1 well into Yampa Spring and Redstone 21-9 well components, November 11-20, 1984.

Recovery after the Redstone 21-9 well flow stopped was calculated as total residual drawdown in the observation well (curve F) minus residual Yampa Spring-caused drawdown (curve E) minus extrapolated Redstone 21-9 well-caused drawdown (curve D).

The second Redstone well test occurred from November 12 to 20, 1984, and included a flow period of 4.0 days and a recovery period of 3.9 days (table 4). Discharge from the Redstone 21-9 well decreased from 2,300 gal/min at the start of the flow period to 1,740 gal/min when closing of the flow valve began. (Because of valve corrosion during the test, approximately 45 min was required to shut the valve completely). During the flow period,

Table 4.--*Discharge of the Yampa Spring and data from the*

[Dashes indicate not applicable;

Date November	Hour	Time since Yampa Spring flow increased (minutes)	Time since Redstone 21-9 well flow started (minutes)	Time since Yampa Spring flow decreased (minutes)	Time since Redstone 21-9 well flow stopped (minutes)	Atmospheric pressure (feet of water)	Colorado River stage (feet)	Estimated Yampa Spring flow (gallons per minute)	Redstone 21-9 well flow (gallons per minute)
11	2000	0	------	-----	-----	34.28	4.41	2,800	0.4
11	2130	0	------	-----	-----	34.29	4.41	2,800	.4
11	2145	15	------	-----	-----	34.29	4.42	2,850	.4
11	2200	30	------	-----	-----	34.29	4.42	2,900	.4
11	2215	45	------	-----	-----	34.29	4.42	2,950	.4
11	2230	60	------	-----	-----	34.29	4.42	2,950	.4
11	2300	90	------	-----	-----	34.29	4.42	2,950	.4
11	2330	120	------	-----	-----	34.29	4.42	2,950	.4
11	2400	150	------	-----	-----	34.29	4.42	2,950	.4
12	0030	180	------	-----	-----	34.29	4.42	2,950	.4
12	0100	210	------	-----	-----	34.30	4.42	2,950	.4
12	0200	270	------	-----	-----	34.30	4.42	2,950	.4
12	0300	330	------	-----	-----	34.30	4.42	2,950	.4
12	0430	420	------	-----	-----	34.30	4.42	2,950	.4
12	0600	510	------	-----	-----	34.30	4.42	2,950	.4
12	0730	600	------	-----	-----	34.30	4.42	2,950	.4
12	0900	690	------	-----	-----	34.32	4.42	2,950	.4
12	1100	810	------	-----	-----	34.31	4.41	2,950	.4
12	1300	930	------	-----	-----	34.21	4.41	2,950	.4
12	1545	1,095	0	-----	-----	34.18	4.41	2,950	.4
12	1547	1,097	2	-----	-----	34.18	4.41	2,950	2,300
12	1548	1,098	3	-----	-----	34.18	4.41	2,950	2,260
12	1549	1,099	4	-----	-----	34.18	4.41	2,950	2,270
12	1550	1,100	5	-----	-----	34.18	4.41	2,950	2,270
12	1551	1,101	6	-----	-----	34.18	4.41	2,950	2,240
12	1552	1,102	7	-----	-----	34.18	4.41	2,950	2,300
12	1553	1,103	8	-----	-----	34.18	4.41	2,950	2,240
12	1554	1,104	9	-----	-----	34.18	4.41	2,950	2,270
12	1555	1,105	10	-----	-----	34.18	4.41	2,950	2,210
12	1557	1,107	12	-----	-----	34.18	4.41	2,950	2,190
12	1559	1,109	14	-----	-----	34.18	4.41	2,950	2,190
12	1601	1,111	16	-----	-----	34.18	4.41	2,950	2,170
12	1603	1,113	18	-----	-----	34.18	4.41	2,950	2,180
12	1605	1,115	20	-----	-----	34.18	4.41	2,950	2,180
12	1610	1,120	25	-----	-----	34.18	4.41	2,950	2,190
12	1615	1,125	30	-----	-----	34.18	4.41	2,950	2,150
12	1620	1,130	35	-----	-----	34.18	4.41	2,950	2,110
12	1625	1,135	40	-----	-----	34.18	4.41	2,950	2,120
12	1630	1,140	45	-----	-----	34.18	4.41	2,950	2,150
12	1635	1,145	50	-----	-----	34.19	4.41	2,950	2,150
12	1645	1,155	60	-----	-----	34.19	4.41	2,950	2,090
12	1655	1,165	70	-----	-----	34.19	4.41	2,950	2,080
12	1705	1,175	80	-----	-----	34.19	4.41	2,950	2,070
12	1715	1,185	90	-----	-----	34.19	4.41	2,950	2,060
12	1725	1,195	100	-----	-----	34.19	4.41	2,950	2,040

aquifer test in the Redstone 21-9 well, November 11-20, 1984

ND indicates no data]

Redstone 21-9 well		Wright no. 1 well			USBR no. 1 well		USBR no. 3 well	Graves Spring flow (gallons per minute)	Hobo Spring flow (gallons per minute)
Drawdown (feet)	Recovery (feet)	Drawdown (feet) Yampa Spring	Drawdown (feet) Redstone 21-9 well	Recovery (feet)	Drawdown (feet)	Recovery (feet)	Drawdown (feet)		
----	----	0	----	----	----	----	----	ND	61
----	----	0	----	----	----	----	----	ND	61
----	----	0	----	----	----	----	----	ND	61
----	----	.01	----	----	----	----	----	ND	61
----	----	.03	----	----	----	----	----	ND	61
----	----	.06	----	----	----	----	----	ND	61
----	----	.08	----	----	----	----	----	ND	61
----	----	.10	----	----	----	----	----	ND	61
----	----	.12	----	----	----	----	----	ND	61
----	----	.14	----	----	----	----	----	ND	61
----	----	.15	----	----	----	----	----	ND	61
----	----	.16	----	----	----	----	----	ND	61
----	----	.17	----	----	----	----	----	ND	61
----	----	.18	----	----	----	----	----	ND	61
----	----	.19	----	----	----	----	----	ND	61
----	----	.22	----	----	----	----	----	ND	61
----	----	.23	----	----	----	----	----	ND	61
----	----	.22	----	----	----	----	----	59	61
----	----	.24	----	----	----	----	----	59	61
0	----	.25	0	----	0	----	0	59	61
6.25	----	.25	0	----	0	----	0	59	61
6.30	----	.25	0	----	0	----	0	59	61
6.30	----	.25	0	----	0	----	0	59	61
6.33	----	.25	.01	----	0	----	0	59	61
6.33	----	.25	.01	----	0	----	0	59	61
6.35	----	.25	.01	----	0	----	0	59	61
6.35	----	.25	.01	----	0	----	0	59	61
6.44	----	.25	.02	----	0	----	0	59	61
6.46	----	.25	.02	----	0	----	0	59	61
6.53	----	.25	.02	----	0	----	0	59	61
6.55	----	.25	.02	----	0	----	0	59	61
6.57	----	.25	.03	----	0	----	0	59	61
6.61	----	.25	.03	----	0	----	0	59	61
6.67	----	.25	.04	----	0	----	0	59	61
6.75	----	.25	.04	----	0	----	0	59	61
6.79	----	.25	.05	----	0	----	0	59	61
6.85	----	.26	.05	----	0	----	0	59	61
6.87	----	.26	.06	----	0	----	0	59	61
6.91	----	.26	.06	----	0	----	0	59	61
6.92	----	.26	.07	----	0	----	0	59	61
6.95	----	.26	.08	----	0	----	0	59	61
7.01	----	.26	.09	----	0	----	0	59	61
7.02	----	.26	.10	----	0	----	0	59	61
7.04	----	.26	.11	----	0	----	0	59	61
7.06	----	.26	.12	----	0	----	0	59	61

Table 4.--*Discharge of the Yampa Spring and data from the aquifer*

Date November	Hour	Time since Yampa Spring flow increased (minutes)	Time since Redstone 21-9 well flow started (minutes)	Time since Yampa Spring flow decreased (minutes)	Time since Redstone 21-9 well flow stopped (minutes)	Atmospheric pressure (feet of water)	Colorado River stage (feet)	Estimated Yampa Spring flow (gallons per minute)	Redstone 21-9 well flow (gallons per minute)
12	1745	1,215	120	-----	-----	34.20	4.41	2,950	2,030
12	1805	1,235	140	-----	-----	34.20	4.41	2,950	2,020
12	1830	1,260	165	-----	-----	34.20	4.41	2,950	2,020
12	1900	1,290	195	-----	-----	34.21	4.41	2,950	2,020
12	2000	1,350	255	-----	-----	34.22	4.41	2,950	2,020
12	2100	1,410	315	-----	-----	34.24	4.41	2,950	2,010
12	2200	1,470	375	-----	-----	34.25	4.41	2,950	2,000
12	2300	1,530	435	-----	-----	34.26	4.41	2,950	1,980
12	2400	1,590	495	-----	-----	34.26	4.41	2,950	1,950
13	0200	1,710	615	-----	-----	34.25	4.41	2,950	1,950
13	0400	1,830	735	-----	-----	34.24	4.40	2,950	1,940
13	0600	1,950	855	-----	-----	34.20	4.41	2,950	1,930
13	0800	2,070	975	-----	-----	34.19	4.41	2,950	1,920
13	1230	2,340	1,245	-----	-----	33.99	4.43	2,950	1,900
13	1600	2,550	1,455	-----	-----	33.95	4.44	2,950	1,880
13	2000	2,790	1,695	-----	-----	33.95	4.42	2,950	1,870
13	2400	3,030	1,935	-----	-----	34.00	4.42	2,950	1,860
14	0600	3,390	2,295	-----	-----	34.10	4.41	2,950	1,850
14	1200	3,750	2,655	-----	-----	34.18	4.46	2,950	1,830
14	1800	4,110	3,015	-----	-----	34.24	4.48	2,950	1,810
14	2400	4,470	3,375	-----	-----	34.34	4.44	2,950	1,780
15	0800	4,950	3,855	-----	-----	34.43	4.42	2,950	1,760
15	1615	5,445	4,350	0	-----	34.29	4.39	2,950	1,760
15	1630	5,460	4,365	15	-----	34.29	4.38	2,900	1,750
15	1645	5,475	4,380	30	-----	34.29	4.38	2,850	1,750
15	1700	5,490	4,395	45	-----	34.29	4.38	2,800	1,750
15	1730	5,520	4,425	75	-----	34.29	4.38	2,800	1,750
15	1800	5,550	4,455	105	-----	34.30	4.38	2,800	1,750
15	1900	5,610	4,515	165	-----	34.31	4.37	2,800	1,750
15	2000	5,670	4,575	225	-----	34.34	4.37	2,800	1,750
15	2200	5,790	4,695	345	-----	34.34	4.38	2,800	1,750
15	2400	5,910	4,815	465	-----	34.34	4.39	2,800	1,750
16	0200	6,030	4,935	585	-----	34.31	4.41	2,800	1,750
16	0400	6,150	5,055	705	-----	34.30	4.42	2,800	1,750
16	0800	6,390	5,295	945	-----	34.27	4.41	2,800	1,740
16	1200	6,630	5,535	1,185	-----	34.18	4.39	2,800	1,740
16	1431	6,781	5,686	1,336	-----	34.06	4.39	2,800	1,740
16	1445	6,795	5,700	1,350	-----	34.05	4.39	2,800	1,450
16	1502	6,812	5,717	1,367	2	34.04	4.39	2,800	400
16	1503	6,813	5,718	1,368	3	34.04	4.39	2,800	200
16	1504	6,814	5,719	1,369	4	34.04	4.39	2,800	100
16	1505	6,815	5,720	1,370	5	34.04	4.39	2,800	50
16	1506	6,816	5,721	1,371	6	34.04	4.39	2,800	25
16	1507	6,817	5,722	1,372	7	34.04	4.39	2,800	12
16	1508	6,818	5,723	1,373	8	34.04	4.39	2,800	6

test in the Redstone 21-9 well, November 11-20, 1984--Continued

Redstone 21-9 well		Wright no. 1 well			USBR no. 1 well		USBR	Graves Spring	Hobo Spring
Drawdown (feet)	Recovery (feet)	Drawdown (feet)		Recovery (feet)	Drawdown (feet)	Recovery (feet)	no. 3 well Drawdown (feet)	flow (gallons per minute)	flow (gallons per minute)
		Yampa Spring	Redstone 21-9 well						
7.09	----	0.26	0.14	----	0	----	0.01	59	61
7.13	----	.26	.16	----	0	----	.01	59	61
7.16	----	.26	.18	----	.01	----	.01	59	61
7.18	----	.26	.20	----	.02	----	01	59	61
7.20	----	.26	.23	----	.03	----	.01	58	61
7.29	----	.27	.25	----	.04	----	.02	58	60
7.32	----	.27	.27	----	.04	----	.02	58	60
7.34	----	.27	.28	----	.11	----	.02	58	60
7.40	----	.27	.29	----	.11	----	.03	58	60
7.47	----	.28	.30	----	.18	----	.03	57	60
7.52	----	.28	.31	----	.19	----	.03	57	60
7.56	----	.29	.32	----	.19	----	.02	57	59
7.62	----	.29	.34	----	.21	----	.03	56	59
7.73	----	.30	.38	----	.31	----	.01	56	59
7.79	----	.30	.43	----	.34	----	.03	55	59
7.83	----	.31	.48	----	.35	----	.04	55	59
7.89	----	.32	.52	----	.38	----	.06	54	58
7.94	----	.33	.54	----	.35	----	.09	53	58
7.99	----	.34	.56	----	.53	----	.10	52	58
8.01	----	.34	.58	----	.59	----	.10	51	57
8.03	----	.35	.61	----	.59	----	.12	50	57
8.07	----	.35	.65	----	.59	----	.13	49	56
8.09	----	.36	.68	----	.73	----	.12	48	55
8.09	----	.35	.68	----	.73	----	.12	48	55
8.09	----	.33	.68	----	.74	----	.12	48	55
8.09	----	.32	.68	----	.74	----	.13	47	55
8.09	----	.30	.68	----	.75	----	.13	47	55
8.09	----	.29	.68	----	.75	----	.13	47	55
8.10	----	.26	.69	----	.76	----	.14	47	55
8.10	----	.24	.69	----	.76	----	.14	47	55
8.10	----	.22	.70	----	.76	----	.14	47	54
8.10	----	.21	.70	----	.76	----	.15	47	54
8.11	----	.19	.71	----	.77	----	.14	46	54
8.11	----	.18	.71	----	.77	----	.15	46	54
8.11	----	.14	.72	----	.77	----	.14	46	54
8.12	----	.10	.73	----	.82	----	.15	46	54
8.12	----	.09	.74	----	.83	----	.15	46	54
7.28	0.84	.10	.74	----	.83	----	.14	46	54
5.05	3.07	.10	.74	0	.83	0	.14	46	54
4.95	3.17	.10	.74	0	.83	0	.14	46	54
4.87	3.25	.10	.74	0	.83	0	.14	46	54
4.81	3.31	.10	.74	0	.83	0	.14	46	54
4.73	3.39	.10	.74	0	.83	0	.15	46	54
4.65	3.47	.10	.74	0	.83	0	.15	46	54
4.63	3.49	.10	.74	0	.83	0	.15	46	54

Table 4.--*Discharge of the Yampa Spring and data from the aquifer*

Date November	Hour	Time since Yampa Spring flow increased (minutes)	Time since Redstone 21-9 well flow started (minutes)	Time since Yampa Spring flow decreased (minutes)	Time since Redstone 21-9 well flow stopped (minutes)	Atmospheric pressure (feet of water)	Colorado River stage (feet)	Estimated Yampa Spring flow (gallons per minute)	Redstone 21-9 well flow (gallons per minute)
16	1510	6,820	5,725	1,375	10	34.04	4.39	2,800	1.5
16	1512	6,822	5,727	1,377	12	34.04	4.39	2,800	.4
16	1514	6,824	5,729	1,379	14	34.04	4.39	2,800	.4
16	1517	6,827	5,732	1,382	17	34.04	4.39	2,800	.4
16	1520	6,830	5,735	1,385	20	34.04	4.39	2,800	.4
16	1523	6,833	5,738	1,388	23	34.04	4.39	2,800	.4
16	1527	6,837	5,742	1,392	27	34.04	4.39	2,800	.4
16	1531	6,841	5,746	1,396	31	34.03	4.39	2,800	.4
16	1541	6,851	5,756	1,406	41	34.03	4.39	2,800	.4
16	1551	6,861	5,766	1,416	51	34.03	4.39	2,800	.4
16	1601	6,871	5,776	1,426	61	34.03	4.39	2,800	.4
16	1621	6,891	5,796	1,446	81	34.03	4.39	2,800	.4
16	1630	6,900	5,805	1,455	90	34.03	4.39	2,800	.4
16	1650	6,920	5,825	1,475	110	34.02	4.39	2,800	.4
16	1710	6,940	5,845	1,495	130	34.02	4.39	2,800	.4
16	1730	6,960	5,865	1,515	150	34.02	4.39	2,800	.4
16	1800	6,990	5,895	1,545	180	34.02	4.39	2,800	.4
16	1830	7,020	5,925	1,575	210	34.02	4.39	2,800	.4
16	1900	7,050	5,955	1,605	240	34.02	4.39	2,800	.4
16	2000	7,110	6,015	1,665	300	34.02	4.39	2,800	.4
16	2130	7,200	6,105	1,755	390	34.02	4.40	2,800	.4
16	2300	7,290	6,195	1,845	480	34.02	4.41	2,800	.4
17	0030	7,380	6,285	1,935	570	34.02	4.40	2,800	.4
17	0200	7,470	6,375	2,025	660	34.02	4.38	2,800	.4
17	0415	7,605	6,510	2,160	795	34.02	4.37	2,800	.4
17	0600	7,710	6,615	2,265	900	34.02	4.34	2,800	.4
17	0800	7,830	6,735	2,385	1,020	34.04	4.32	2,800	.4
17	1200	8,070	6,975	2,625	1,260	34.04	4.28	2,800	.4
17	1600	8,310	7,215	2,865	1,500	33.98	4.35	2,800	.4
17	2000	8,550	7,455	3,105	1,740	34.03	4.34	2,800	.4
17	2400	8,790	7,695	3,345	1,980	34.08	4.33	2,800	.4
18	0400	9,030	7,935	3,585	2,220	34.08	4.33	2,800	.4
18	0800	9,270	8,175	3,825	2,460	34.11	4.31	2,800	.4
18	1300	9,570	8,475	4,125	2,760	34.03	4.30	2,800	.4
18	1900	9,930	8,835	4,485	3,120	34.03	4.33	2,800	.4
19	0300	10,410	9,315	4,965	3,600	34.14	4.37	2,800	.4
19	1200	10,950	9,855	5,505	4,140	34.20	4.26	2,800	.4
19	2000	11,430	10,335	5,985	4,620	34.21	4.16	2,800	.4
20	0400	11,910	10,815	6,465	5,100	34.34	4.24	2,800	.4
20	1300	12,450	11,355	7,005	5,640	34.16	4.45	2,800	.4

test in the Redstone 21-9 well, November 11-20, 1984--Continued

Redstone 21-9 well Drawdown (feet)	Redstone 21-9 well Recovery (feet)	Wright no. 1 well Drawdown (feet) Yampa Spring	Wright no. 1 well Drawdown (feet) Redstone 21-9 well	Wright no. 1 well Recovery (feet)	USBR no. 1 well Drawdown (feet)	USBR no. 1 well Recovery (feet)	USBR no. 3 well Drawdown (feet)	Graves Spring flow (gallons per minute)	Hobo Spring flow (gallons per minute)
4.55	3.57	0.10	0.74	0	0.83	0	0.15	46	54
4.45	3.67	.10	.74	0	.83	0	.15	46	54
4.37	3.75	.10	.74	0	.83	0	.15	46	54
4.25	3.86	.10	.74	0	.83	0	.15	46	54
4.09	4.03	.10	.74	0	.83	0	.15	46	54
4.03	4.09	.10	.74	0	.83	0	.15	46	54
3.93	4.19	.10	.74	0	.83	0	.15	46	54
3.84	4.28	.10	.74	0	.83	0	.15	47	54
3.61	4.51	.08	.74	0	.83	0	.15	47	54
3.47	4.65	.07	.74	0	.83	0	.15	47	54
3.33	4.79	.06	.74	0	.83	0	.15	47	54
3.14	4.98	.04	.74	0	.83	0	.15	47	54
3.06	5.07	.04	.74	.01	.83	.01	.15	47	54
2.91	5.22	.01	.74	.01	.83	.01	.15	47	54
2.81	5.32	.01	.74	.01	.83	.01	.15	47	54
2.69	5.44	0	.74	.01	.83	.01	.16	48	54
2.59	5.55	0	.73	.02	.82	.02	.16	48	54
2.51	5.63	0	.72	.03	.81	.04	.16	48	54
2.43	5.71	0	.71	.04	.77	.08	.16	48	54
2.33	5.82	0	.69	.07	.78	.07	.16	49	54
2.22	5.93	0	.66	.10	.78	.08	.17	49	55
2.15	6.00	0	.65	.11	.74	.12	.17	50	55
2.08	6.08	0	.64	.12	.71	.16	.17	50	55
2.02	6.14	0	.63	.13	.71	.17	.17	51	55
1.97	6.20	0	.62	.15	.69	.19	.17	51	56
1.90	6.27	0	.62	.16	.69	.20	.18	52	56
1.87	6.31	0	.61	.17	.67	.22	.18	52	56
1.74	6.45	0	.58	.21	.65	.25	.20	53	56
1.70	6.49	0	.56	.24	.62	.30	.20	54	56
1.65	6.54	0	.55	.25	.62	.31	.20	54	57
1.59	6.61	0	.52	.29	.61	.33	.21	55	57
1.53	6.68	0	.51	.31	.59	.36	.21	55	57
1.48	6.74	0	.48	.35	.59	.37	.22	55	57
1.39	6.84	0	.44	.39	.52	.45	.22	56	58
1.25	6.99	0	.46	.38	.53	.46	.22	56	58
1.05	7.21	0	.44	.41	.52	.49	.23	56	59
.82	7.46	0	.39	.47	.48	.55	.24	56	60
.74	7.55	0	.37	.51	.47	.57	.27	57	60
.65	7.65	0	.35	.54	.47	.59	.27	57	61
.61	7.70	0	.33	.57	.43	.65	.29	58	61

discharge from the well surged as much as 120 gal/min, possibly because of cyclic steam build up and release. The average discharge during the flow period was 1,830 gal/min. Potentiometric head in the Redstone 21-9 well, adjusted for atmospheric pressure changes, decreased 8.12 ft during the flow period and recovered 7.70 ft, 3.9 days later.

Potentiometric heads in the Wright no. 1 and USBR no. 1 wells (fig. 29) responded in phase with the production well, but potentiometric heads in other wells decreased throughout the test. Potentiometric head in the Wright no. 1 well, adjusted for atmospheric-pressure changes and fluctuations in the discharge of the Yampa Spring, decreased 0.74 ft during the flow period and recovered 0.57 ft, 3.9 days later. Potentiometric head in the USBR no. 1 well decreased 0.83 ft during the flow period and recovered 0.65 ft, 3.9 days later. Potentiometric head in the USBR no. 3 well (fig. 29) decreased 0.29 ft throughout the flow and recovery periods. Potentiometric head in the USBR no. 11 well decreased 0.18 ft throughout the flow and recovery periods.

Discharges from the Hobo and Graves B Springs (fig. 30) responded in phase with the production well. Discharge from the Hobo Spring decreased 7 gal/min during the flow period and recovered completely 3.5 days later. Discharge from the Graves B Spring decreased 13 gal/min during the flow period and recovered within 1 gal/min of the initial discharge, 3.9 days later.

Discharge from the Yampa Spring could not be determined accurately, except during filling of the spring caisson, 3 days into the test. The filling rate of the caisson indicated a discharge comparable to discharges observed prior to the second Redstone well test. However, Tom Zancanella, a hydrologist with Wright Water Engineers, reported that the filling rate during this test was slightly slower than in previous fillings (oral commun., 1985). If so, discharge from the Yampa Spring was decreased by a small but unquantifiable amount by discharge from the Redstone 21-9 well.

Interpretation of Test Data

Hydraulic Properties of Leadville Limestone and Dyer Dolomite

The data from the first and second Redstone well tests were analyzed to interpret the transmissivity, storage coefficient, and hydraulic conductivity of the Leadville Limestone and, by inference, the lithologically similar Dyer Dolomite at the test site. Test data from the Redstone 21-9 well were analyzed by straight-line methods of Cooper and Jacob (1946) and Jacob and Lohman (1952). Test data from the Wright no. 1 well were analyzed using the method of Hantush (1960). Assumptions implicit in these and other methods used to interpret aquifer test data during this study are stated in table 5.

Although Lohman (1979, p. 23) recommended straight-line solutions for flowing-well tests, type-curve matching was necessary to analyze the Wright no. 1 well test data because of the large distance between the Wright no. 1 and Redstone 21-9 wells. This large distance prevented achieving constant

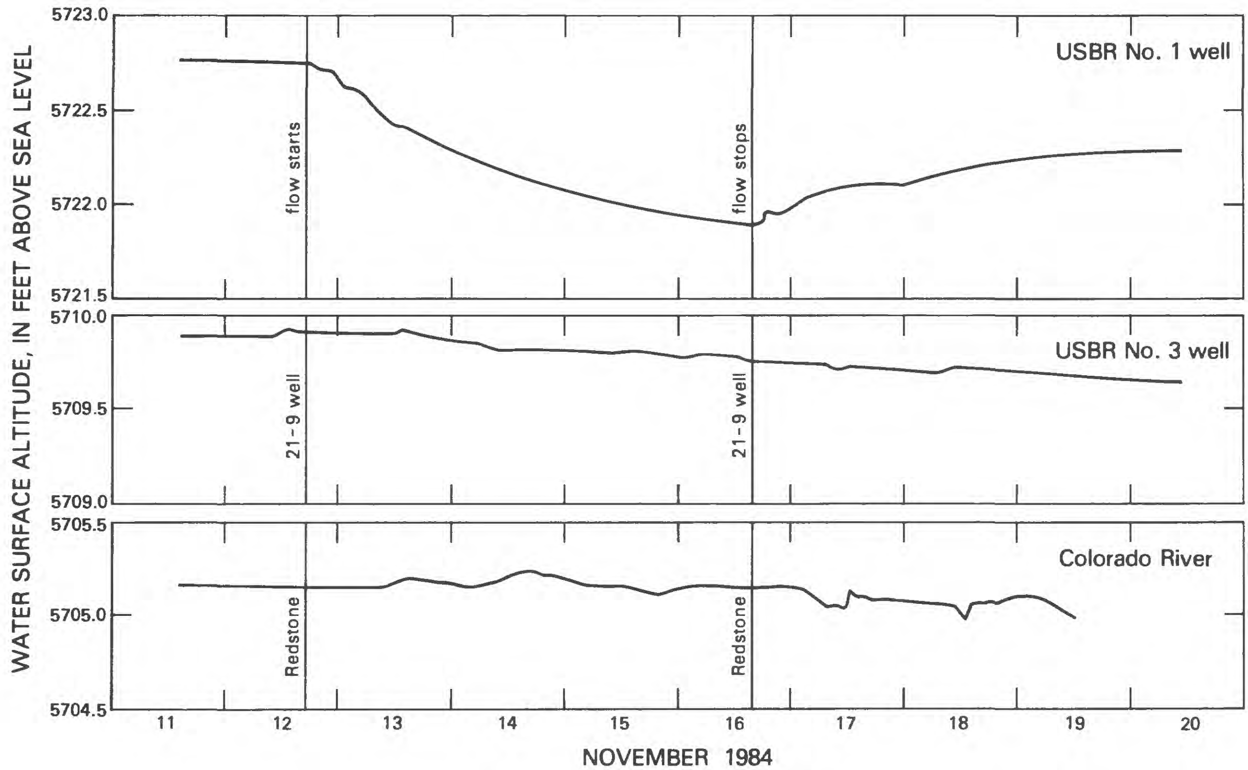


Figure 29.--Water levels in alluvium and stage of the Colorado River at Glenwood Springs, November 11-20, 1984.

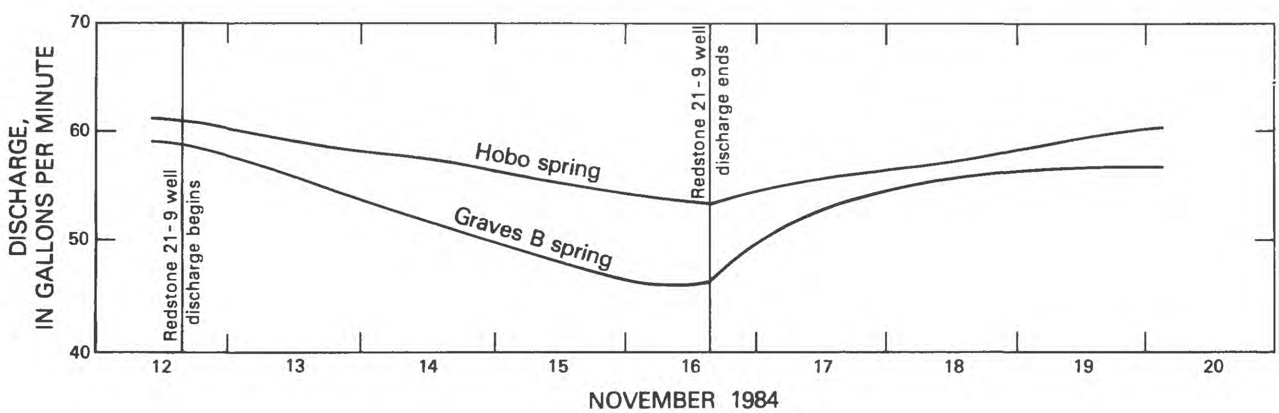


Figure 30.--Measured discharges of springs at Glenwood Springs, November 12-20, 1984.

Table 5.--*Types of aquifer tests and methods of analysis used in Regional Aquifer-System Analysis of the Upper Colorado River Basin*

[T, transmissivity; S, storage coefficient; K, hydraulic conductivity; k, intrinsic permeability; N/A, not applicable]

Category	Type of test	Assumed test conditions[1]			Test phase	Applicability	Methods of analysis			Results
		Constant	Changing	Confining layer			Type-curve matching	Straight-line	Numerical	
I	Pump	Discharge	Potentiometric head	Non-leaky	Production	Production well	Theis (1935)	Cooper and Jacob (1946)	Lohman (1979)	T
	Pump	Discharge	Potentiometric head	Non-leaky	Recovery	Production well	Theis (1935)	Theis (1935), Cooper and Jacob (1946)	N/A	T
	Pump	Discharge	Potentiometric head	Non-leaky	Production, recovery	Observation well	Theis (1935)	Cooper and Jacob (1946)	N/A	T,S
	Pump	Discharge	Potentiometric head	Leaky	Production, recovery	Production well	Hantush (1960)	N/A	N/A	T
	Pump	Discharge	Potentiometric head	Leaky	Production, recovery	Observation well	Hantush (1960)	N/A	N/A	T,S
II	Flowing well	Potentiometric head	Discharge	Non-leaky	Production	Production well	Jacob and Lohman (1952)	Jacob and Lohman (1952)	Lohman (1979)	T
	Flowing well	Potentiometric head	Discharge	Leaky	Production	Production well	Hantush (1959)	N/A	N/A	T
	Drill stem	Discharge	Potentiometric head	Non-leaky	Recovery	Production well	N/A	Horner (1951)	Earlougher (1977), (Supplement B, this report)	K
III	Pressure injection	Potentiometric head, discharge	Not relevant	Not relevant	Entire	Injection well	N/A	N/A	U.S. Bureau of Reclamation (1974)	K
	Slug injection	Fluid volume	Potentiometric head	Not relevant	Entire	Injection well	Cooper and others (1967)	Ferris and Knowles (1963)	N/A	T
IV	Permeameter	Fluid volume	Potentiometric head	Not relevant	Entire	Rock samples	N/A	N/A	Todd (1959)	k
	Permeameter	Discharge, potentiometric head	Not relevant	Not relevant	Entire	Rock samples	N/A	N/A	Todd (1959)	k

[1]All analytical methods for categories I and II assume full penetration of aquifer and no borehole storage.

drawdown in the Wright no. 1 well, one of the requirements for straight-line solution of a flowing-well test, until the recovery monitoring was nearly over. Type curves prepared by Hantush (1960) and plotted by Reed (1980) for a situation in which a leaky confining layer is present were considered appropriate because a 410-ft-thick section of Belden Formation, a leaky confining layer, overlies the Leadville Limestone and Dyer Dolomite in the Wright no. 1 well. The β curve selected for the Hantush analysis was based on the thickness of the Leadville Limestone and Dyer Dolomite in the area (280 ft) and the mean ratio of vertical to horizontal permeability (1:10) in core samples from equivalent formations throughout the Upper Colorado River Basin.

Transmissivity values of the Leadville Limestone and Dyer Dolomite obtained in 9 analyses of data from the Redstone 21-9 and Wright no. 1 wells ranged from 27,000 to 70,000 ft^2/d. Storage coefficient values obtained in 4 analyses of data from the Wright no. 1 well ranged from 0.2×10^{-4} to 7×10^{-4}. Transmissivity and storage coefficient values are listed in table 6. Analyzed hydraulic properties are based on specific discharge (drawdown divided by discharge), residual drawdown, and recovery data for the Redstone 21-9 well and drawdown and recovery data for the Wright no. 1 well.

Plots of the 9 analyses that were done are shown in figures 31 through 37. In the straight-line analyses, sinusoidal divergence of the data from straight lines reveals the effects of earth tides on potentiometric head. In the plot of specific discharge versus time for the first Redstone well test (fig. 31), the erratic divergence of early-time specific-discharge data from a straight line is interpreted as measurement error, because a similar plot for the second Redstone well test (fig. 34) showed no such divergence. In matching curve analyses (figs. 33 and 37), erratic divergence of data from the $\beta = 0.7$ type curve (such as drawdown values above the curve between 700 and 1,800 min in fig. 33) are attributable to imprecision of the measuring and analytical techniques in assessing the hydrologic system.

The transmissivity values obtained agree closely. Excluding the largest and smallest values, the remaining 7 values range from 38,000 to 48,000 ft^2/d, with a best-fit value of 47,000 ft^2/d. This value probably approximates the average transmissivity of the Leadville Limestone and Dyer Dolomite at the site.

The storage coefficient values obtained also agree closely, if one outlier is excluded. Three of the four values range from 3×10^{-4} to 7×10^{-4}, with a best-fit value of 5×10^{-4}. This value probably approximates the average storage coefficient of the Leadville Limestone and Dyer Dolomite at the site. Specific storage in the Leadville Limestone and Dyer Dolomite, based on the storage coefficient and thickness of these rocks at Glenwood Springs, is 1.8×10^{-6} ft^{-1}.

The hydraulic conductivity of the Leadville Limestone and Dyer Dolomite at the test site cannot be determined with certainty. If the average transmissivity is divided by the thickness of the fault zone penetrated by the

Table 6.--*Results of aquifer tests of the Leadville Limestone, 1982-84*

[Dashes indicate not determined]

Test dates	Well name	Test component plotted against time	Method of analysis	Transmissivity (feet squared per day)	Storage coefficient
January 5-12, 1982	Redstone 21-9	Specific discharge	Jacob and Lohman (1952)	47,000	---
January 12-14, 1982	Redstone 21-9	Residual drawdown	Cooper and Jacob (1946)	39,000	---
January 5-12, 1982	Wright no. 1	Drawdown	Hantush (1960)	38,000	5×10^{-4}
January 12-20, 1982	Wright no. 1	Recovery	Hantush (1960)	27,000	7×10^{-4}
November 12-16, 1984	Redstone 21-9	Specific discharge	Jacob and Lohman (1952)	38,000	---
November 16-20, 1984	Redstone 21-9	Residual drawdown	Cooper and Jacob (1946)	46,000	---
November 16-20, 1984	Redstone 21-9	Recovery[1]	Cooper and Jacob (1946)	48,000	---
November 12-16, 1984	Wright no. 1	Drawdown	Hantush (1960)	70,000	3×10^{-4}
November 16-19, 1984	Wright no. 1	Recovery	Hantush (1960)	47,000	$.2 \times 10^{-4}$

[1]Recovery from projected drawdown.

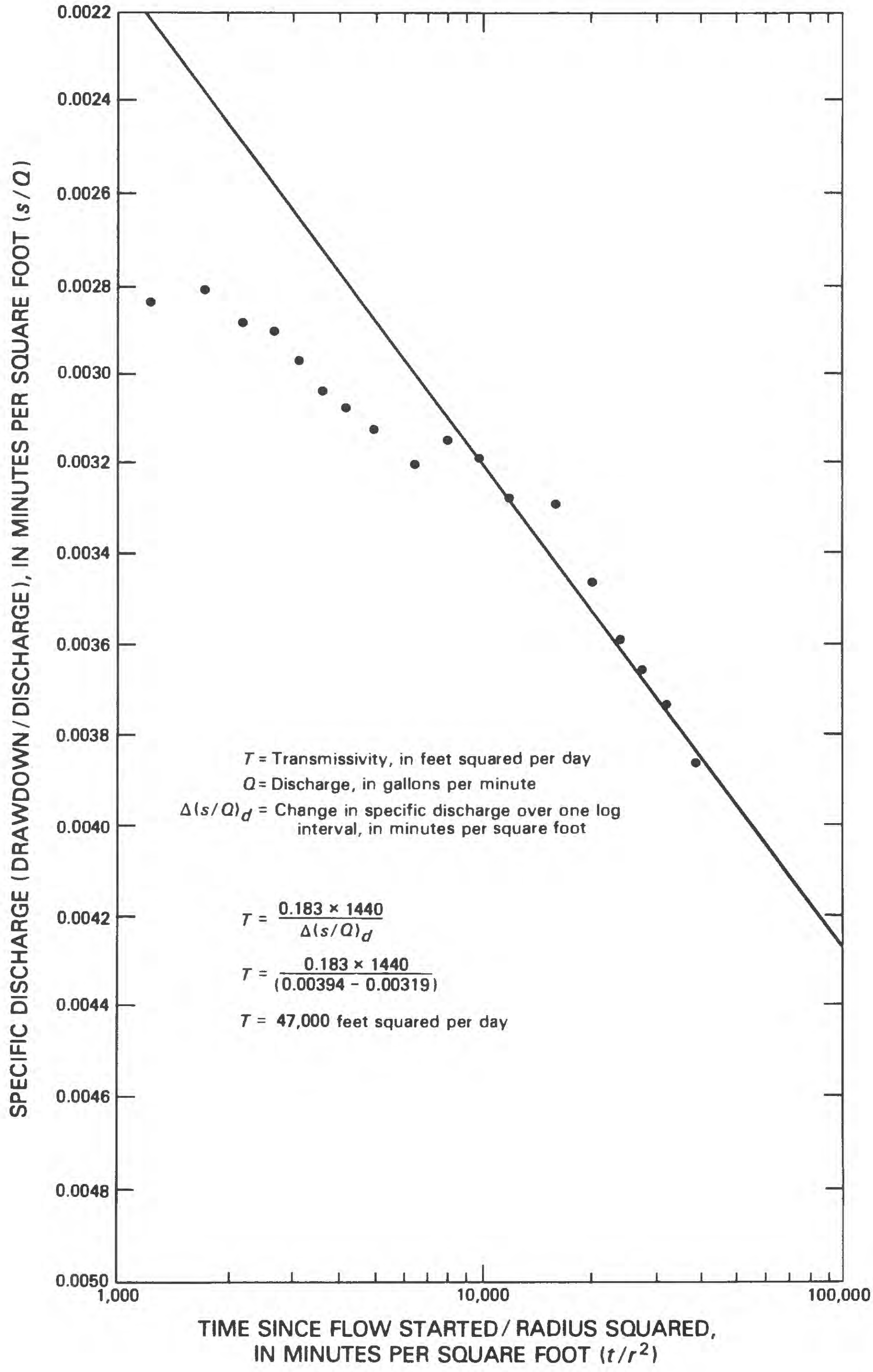


Figure 31.--Specific discharge in Redstone 21-9 well, January 5-12, 1982.

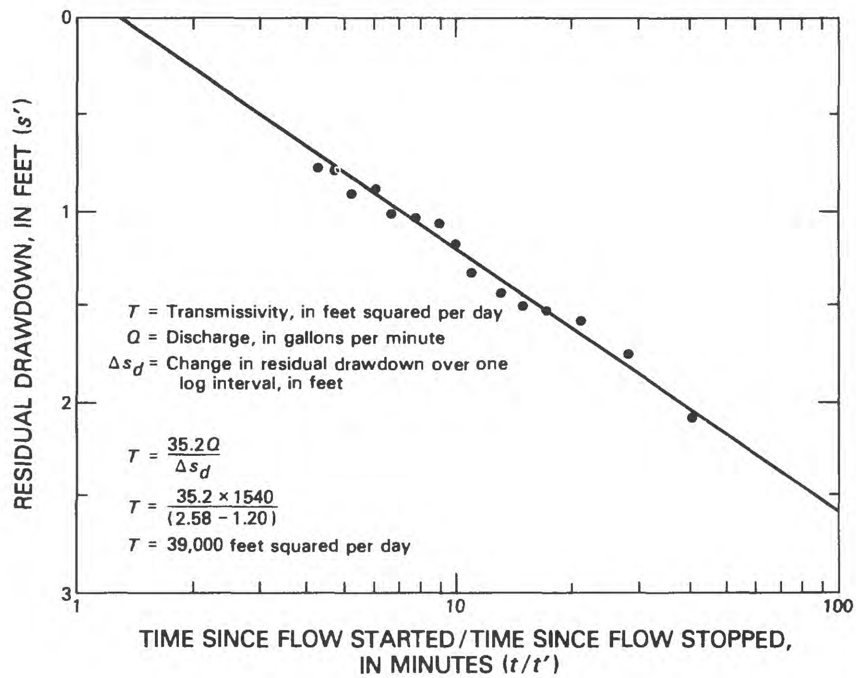


Figure 32.--Residual drawdown in Redstone 21-9 well, January 12-14, 1982.

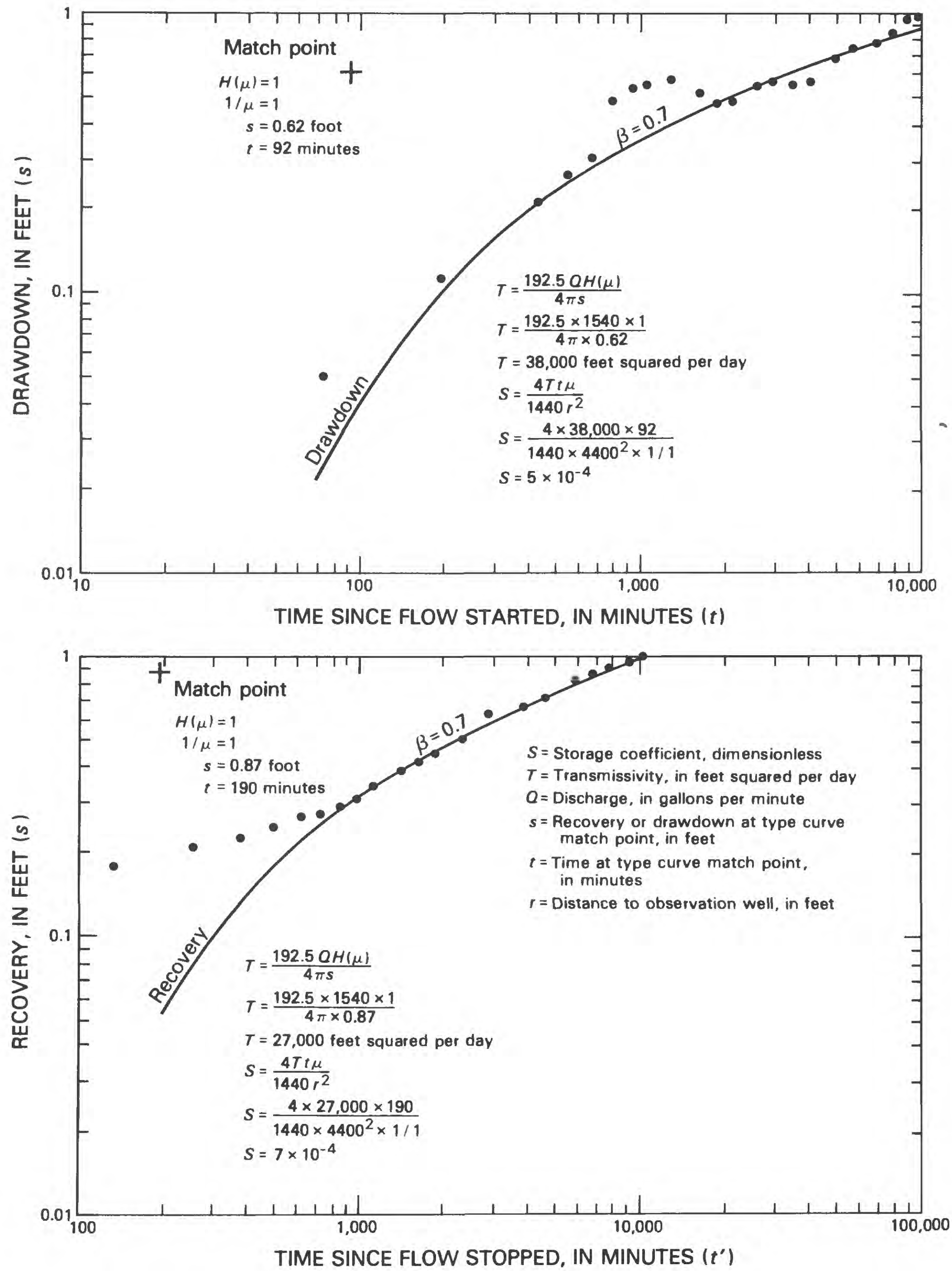


Figure 33.--Drawdown and recovery in Wright no. 1 well, January 5-20, 1982.

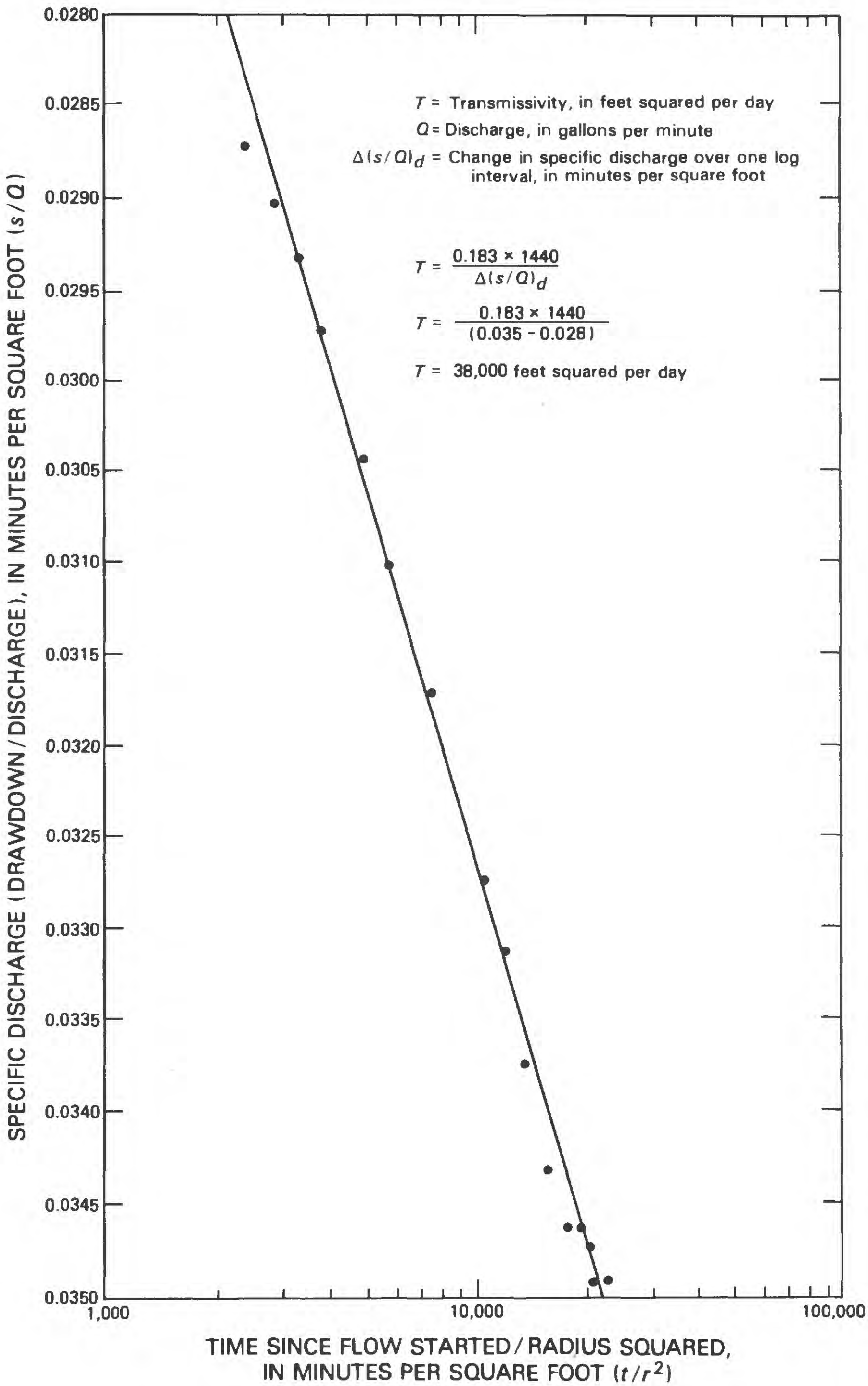


Figure 34.--Specific discharge in Redstone 21-9 well, November 12-16, 1984.

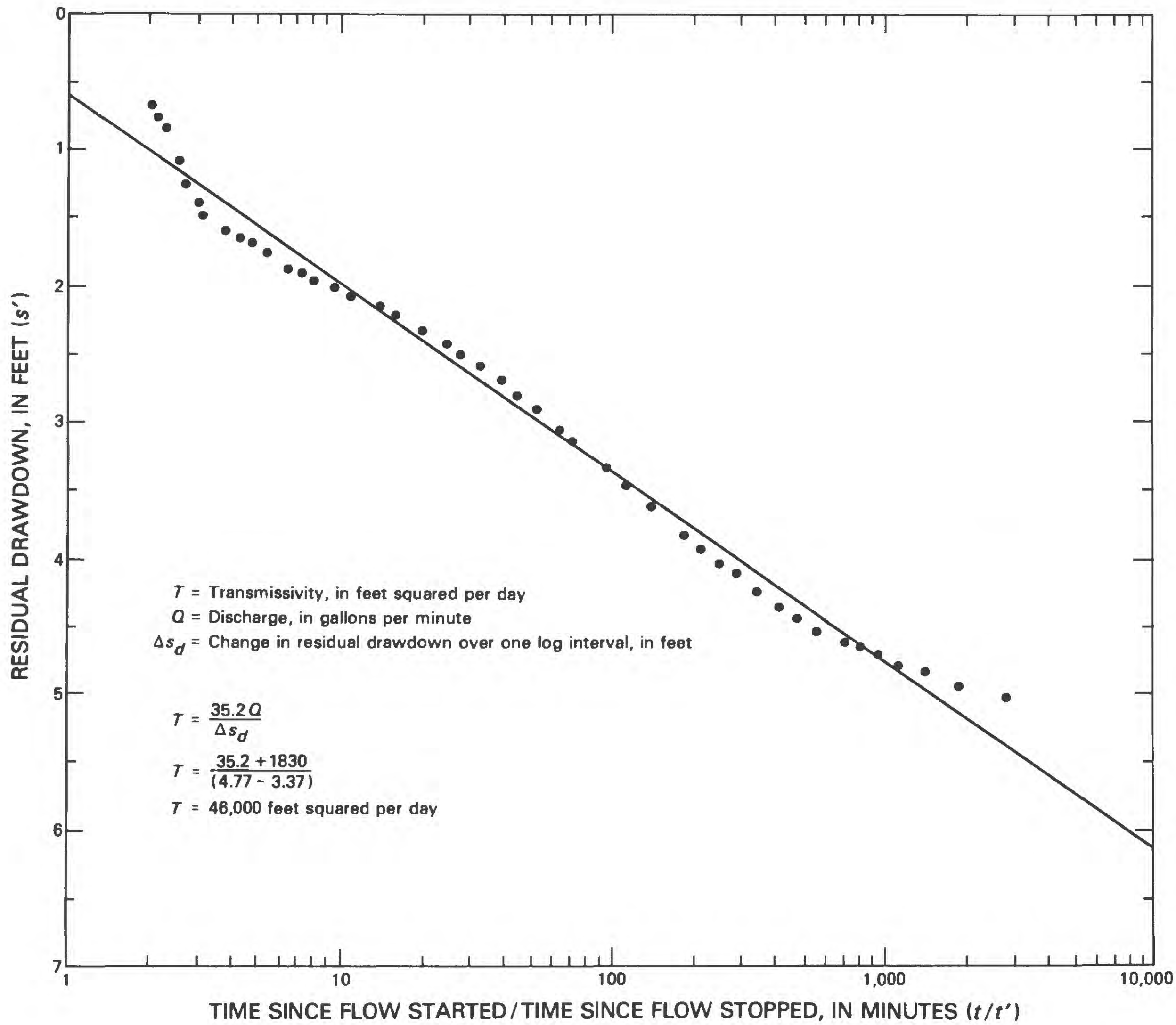


Figure 35.--Residual drawdown in Redstone 21-9 well, November 12-16, 1984.

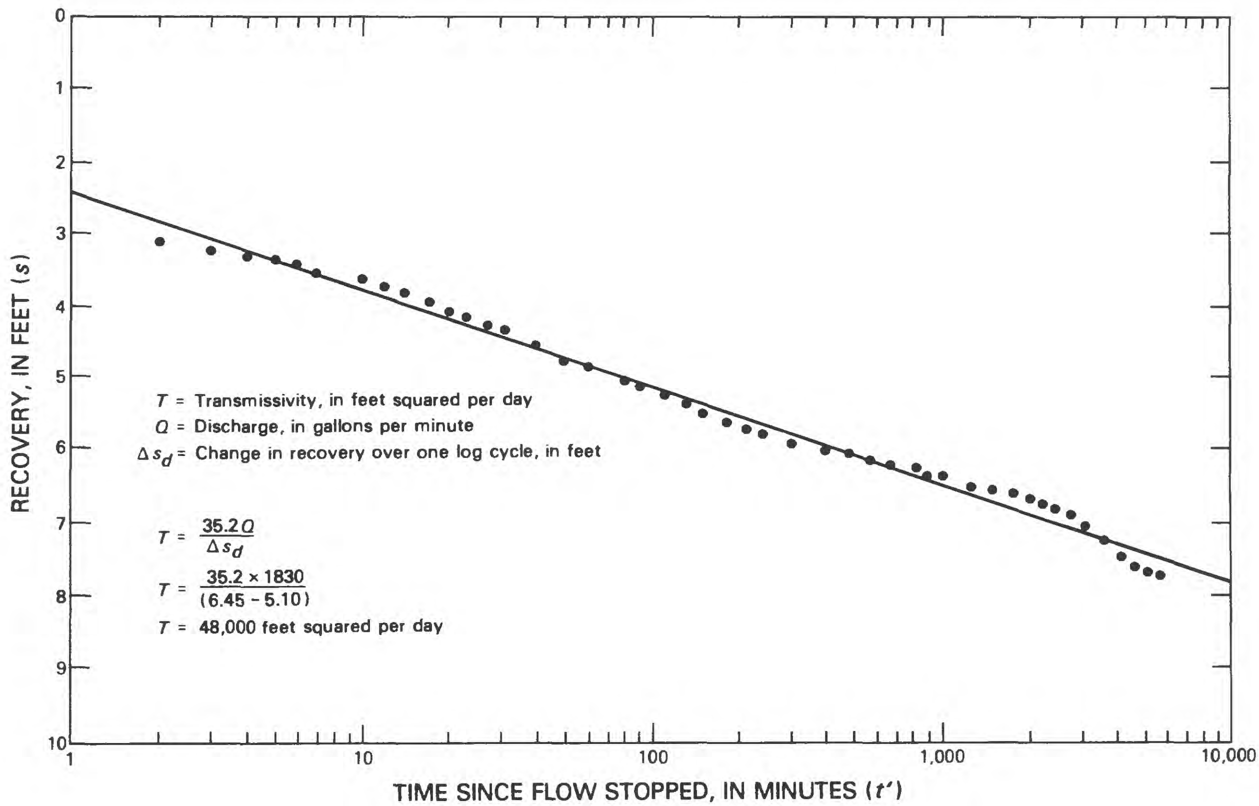


Figure 36.--Recovery in Redstone 21-9 well, November 16-20, 1984.

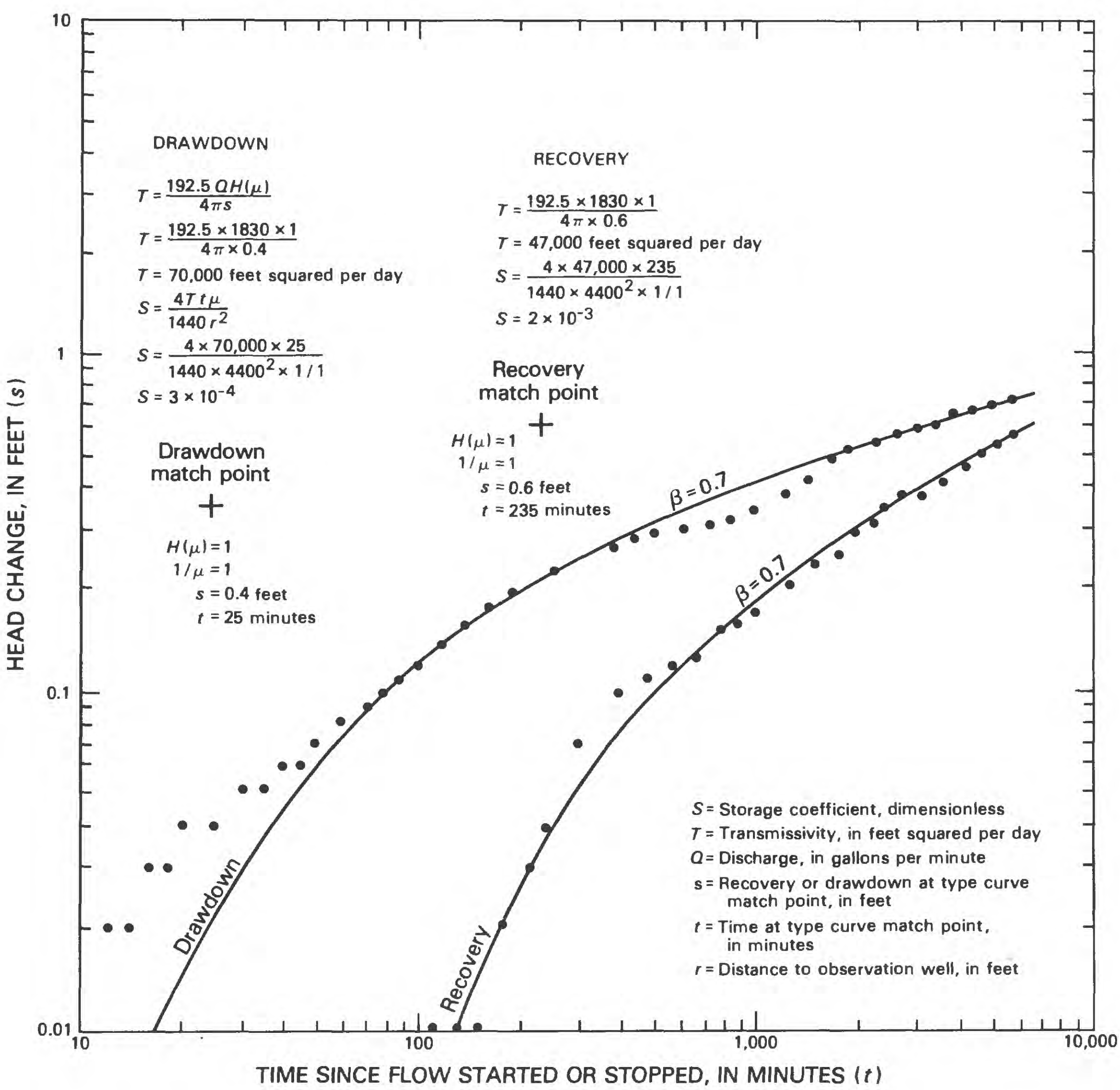


Figure 37.--Drawdown and recovery in Wright no. 1 well, November 12-19, 1984.

Redstone 21-9 well (35 ft), the calculated hydraulic conductivity would be 1,300 ft/d. If the average transmissivity is divided by the open interval of Leadville Limestone in the Redstone 21-9 well (74 ft), the calculated hydraulic conductivity would be 640 ft/d. If the average transmissivity is divided by the thickness of Leadville Limestone at Glenwood Springs (187 ft), the calculated hydraulic conductivity would be 250 ft/d. Finally, if the average transmissivity is divided by the combined thickness of the Leadville Limestone and Dyer Dolomite at Glenwood Springs (280 ft), the calculated hydraulic conductivity would be 170 ft/d. The value of 640 ft/d was reported by Geldon (1985) in a preliminary presentation of information from the RASA study. In retrospect, the value based on the combined thickness of the Leadville Limestone and Dyer Dolomite in the area, 170 ft/d, might be a better estimate of hydraulic conductivity at the test site because fractures extending through the entire thickness of the two formations probably contribute water to the well.

Results of the Redstone well tests should be used with caution because several of the assumptions underlying the analytical techniques used were violated. (1) All of the analytical techniques assume that the aquifer is homogeneous, isotropic, and of infinite areal extent. In fact,there are several faults in the area that could act as either conduits for or barriers to ground-water movement. Although the analytical techniques were developed assuming porous-media flow, interconnected fractures and solution channels in the Leadville Limestone and Dyer Dolomite probably transmit most of the water. If the fractures are aligned and not randomly oriented, hydrologic properties and ground-water movement in the Leadville Limestone and Dyer Dolomite would be distinctly anisotropic. (2) The Cooper and Jacob (1946) and Jacob and Lohman (1952) methods assume that a nonleaky confining layer is present. However, alluvium present above the Leadville Limestone in the vicinity of the Redstone 21-9 well and the Belden Formation present above the Leadville Limestone in the vicinity of the Wright no. 1 well functioned as recharge boundaries during the test by virtue of decreased outflow to them. Because of decreased springflow and seepage to Colorado River alluvium, the river, too, might be considered a recharge boundary during the test. (3) To be strictly applicable, the Hantush (1960) method assumes that all leakage is supplied by a confining layer of infinite areal extent. Neither the alluvium nor the Belden Formation extends across the entire area affected by flow from the Redstone 21-9 well. (4) Finally, the Cooper and Jacob (1946) method assumes constant discharge and variable drawdown. However, a flowing-well test involves constant drawdown and gradually declining discharge. Nevertheless, Lohman (1979, p. 27) considered the Cooper and Jacob (1946) method to be a valid corroborative check of the more appropriate Jacob and Lohman (1952) method.

Discharge of Yampa Spring

As mentioned earlier in the report, the discharge of the Yampa Spring is difficult to measure directly because of the complex plumbing system constructed around the spring. The spring issues from the Leadville Limestone through overlying alluvium. The spring can be diverted to the Glenwood Hot Springs Lodge and Pool or released to the Colorado River by manipulation of gates into a 60-ft-diameter spring caisson. In the normal operational mode, most of the springflow is routed to the lodge and pool, but some springflow leaks from the plumbing system into the river. Tom Zancanella, from Wright Water Engineers, estimated this leakage to be about 1 ft^3/s or 450 gal/min (oral commun., 1985).

Changing the operational mode affects the spring's discharge and the potentiometric head in the Leadville Limestone near the spring. When the spring is released to the river, back pressure on the spring openings into the caisson decreases, and the spring discharge increases. This increased discharge lowers the potentiometric head in the Leadville Limestone below the equilibrium level established by years of spring use. When the springflow is diverted back to the lodge and pool, back pressure on the spring openings increases, and the spring discharge decreases. Potentiometric head in the Leadville Limestone returns to its equilibrium (higher) state. In other words, potentiometric heads in the Leadville Limestone near the spring adjust to the change in spring discharge and not to the actual discharge in each operational mode.

Commercial manipulation of the Yampa Spring and effects of this manipulation on potentiometric head recorded in the Wright no. 1 well enabled calculation of the spring discharge during the second Redstone well test. On November 11, one day prior to the test, the Glenwood Hot Springs pool was drained for cleaning and repairs. Gates to the pool and lodge were closed, and the gate to the river was opened. This procedure took about 30 minutes. For the next 3.77 days, all of the spring flow was routed to the Colorado River. On November 15, the gate to the Colorado River was closed, and the gates to the lodge and pool were again opened. This procedure again took about 30 minutes.

Discharge from the Yampa Spring when most flow is to the lodge and pool can be calculated volumetrically from the filling rate of the spring caisson between the closing of the river gate and the opening of the gates to the lodge and pool on November 15. During the time when all gates were closed, a period lasting 11 minutes, water levels in the caisson rose 1.22 ft, entirely from the discharge of the spring. The equation applicable in this analysis is:

$$Q = \frac{7.48\ \pi\ d^2 \Delta h}{4 \Delta t}\ ; \qquad (1)$$

where Q = discharge of Yampa Spring, in gallons per minute;
d = diameter of spring caisson, in feet;
Δh = change in height of water in spring caisson, in feet; and
Δt = time elapsed during caisson filling, in minutes.

From data given above, d = 60 ft; Δh = 1.22 ft; and Δt = 11 min. The calculated discharge, Q = 2,350 gal/min. Adding this discharge to the estimated leakage from the plumbing system (450 gal/min) gives a value of 2,800 gal/min for the springflow during equilibrium conditions prior to the second Redstone well test.

The increase in discharge caused by routing the Yampa Spring to the Colorado River can be calculated from the resulting drawdown of potentiometric head in the Wright no. 1 well, 700 ft to the south. During the 3.77 days that the spring was routed to the river, potentiometric head in the Wright no. 1 well decreased 0.36 ft, independently of atmospheric pressure changes and flow from the Redstone 21-9 well (table 4). The change in discharge required to cause the observed drawdown was calculated using an equation given by Lohman (1979, p. 52) to estimate transmissivity from specific capacity. The equation, modified and rearranged to calculate the unknown variable in the case of the Yampa Spring, incremental discharge, is:

$$\Delta Q = \frac{4\pi T\Delta h}{192.5\times \ln \frac{2.25Tt}{r^2S}} \quad ; \qquad (2)$$

where ΔQ = increase in Yampa Spring discharge, in gallons per minute;
T = transmissivity of Leadville Limestone, in feet squared per day;
Δh = drawdown in Wright no. 1 well, in feet;
t = time river gate open, in days;
r = distance between Yampa Spring and Wright no. 1 well, in feet; and
S = storage coefficient of Leadville Limestone, dimensionless.

From data given above, T = 47,000 ft^2/d; Δh = 0.36 ft; t = 3.77 d; r = 700 ft; and $S = 5\times10^{-4}$. The calculated increase in discharge, ΔQ = 150 gal/min. Adding this increase in discharge to the pretest discharge (2,800 gal/min) gives a discharge of 2,950 gal/min when the Yampa Spring was routed to the Colorado River during the second Redstone well test.

Aquifer Interconnection

Part of the second Redstone well test involved analyses of the connection between the Leadville Limestone and overlying alluvium. During this test, the Redstone 21-9 well, which is completed in the Leadville Limestone, discharged continuously for 4 days at an average rate of 1,830 gal/min, resulting in the removal of 10.5 million gallons (1.4 million cubic feet) of water from the limestone. Water-level fluctuations in 3 alluvial wells, USBR nos. 1,3, and 11, and discharge fluctuations of 3 springs, Graves B, Hobo, and Yampa, were monitored as flow from the Redstone 21-9 well was manipulated. These observations indicated that a connection exists between the Leadville Limestone and the alluvium that is modified by proximity to the Colorado River.

Responses of alluvial wells and springs during the second Redstone well test varied considerably (see table 4 and figs. 29 and 30). Water levels in the USBR no. 1 well decreased 0.83 ft during the flow phase of the test, began recovering as soon as the flow phase ended, and recovered 0.65 ft by the end of the recovery-monitoring period. Water levels in the USBR no. 3 well decreased 0.29 ft from the start of the flow period to the end of the recovery period. Water levels in the USBR no. 11 well remained constant during the flow period and decreased 0.18 ft during the recovery period. The discharge of the Graves B Spring decreased 13 gal/min during the flow phase of the test; the discharge of the Hobo Spring decreased 7 gal/min during the flow phase of the test. Both springs returned to pretest discharge rates by the end of the recovery period. No observed changes in the discharge of the Yampa Spring during the test could be attributed to flow from the Redstone 21-9 well; all observed changes are believed to have been caused by commercial manipulation of the spring outlets.

The amount of response exhibited by monitored wells and springs to the Redstone 21-9 well during the study primarily was determined by the distance from the production well. The Graves B Spring, 315 ft from the production well, had the largest decrease in discharge during the test. The Hobo Spring, about 1,000 ft from the production well, had a smaller decrease in discharge; the Yampa Spring, about 4,200 ft from the production well, had no detectable change in discharge due to the Redstone 21-9 well. Well USBR no. 1, about 790 ft from the production well, had the largest drawdown of all monitored alluvial wells. Well USBR no. 11, about 2,500 ft from the production well, had the smallest drawdown of the monitored alluvial wells. Well USBR no. 3, about 590 ft from the Redstone 21-9 well, was closer to the production well than USBR no. 1 but had a smaller drawdown. Drawdown and recovery in the alluvial wells were in phase with the production well only in USBR no. 1. Except for USBR no. 3, the monitored wells and springs clearly demonstrated a decreasing affect of the production well with increasing distance from it.

The fluctuation of water-levels in USBR no. 3 is enigmatic until the stage record of the Colorado River at the test site is examined. The stage of the Colorado River decreased only 0.03 ft during the flow period of the test, but declined another 0.23 ft during the first 3.2 days of the recovery period (table 4). The decrease in the water level in USBR no. 3 during the flow period was 0.15 ft, too large to be attributable to a 0.03 ft decrease in stage of the Colorado River. It probably was caused by flow from the Redstone 21-9 well. The water level in USBR no. 3 decreased another 0.14 ft after flow from the Redstone 21-9 well had ended. By then, the river stage was declining rapidly. USBR no. 3 is less than 500 ft from the river. At this distance, hydraulic connection with the river is likely. The declining stage of the river could have prevented recovery in USBR no. 3 and caused the additional water-level decrease in the well.

Water-level fluctuations in USBR no. 11 were completely out of phase with flow from the Redstone 21-9 well. Water levels in USBR no. 11 remained constant while the Redstone 21-9 well was flowing and declined after flow stopped. This pattern indicates that USBR no. 11 was not affected by the Redstone 21-9 well but was affected by some other factor. Like USBR no. 3, USBR no. 11 is less than 500 ft from the Colorado River. In fact, it is located nearly at the rim of the river's north bank. The water level in USBR no. 11 remained constant while the river stage was nearly constant and began declining only when the stage of the river began declining. A water-level decrease of 0.18 ft in the well is consistent with a stage decrease of 0.23 ft. The fluctuation of water levels in USBR no. 11 indicates a strong hydraulic connection to the Colorado River and no detectable hydraulic connection to the Redstone 21-9 well. This is consistent with USBR no. 11's being the closest monitored well to the river and the farthest from the production well.

Water levels in USBR no. 1 may or may not have been affected by the Colorado River. USBR no. 1 is about 700 ft from the river. At that distance, the effects of the Redstone 21-9 well obscured any obvious effects from stage fluctuation in the river. However, incomplete recovery in USBR no. 1 by the end of the monitoring period possibly could have been caused by the declining river stage.

This study clearly demonstrated that hydraulic connection exists between alluvium, the Leadville Limestone, and the Colorado River at the Glenwood Springs test site. Within a radius determined by the rate and duration of discharge, alluvial wells near a well discharging from the Leadville Limestone will have lowered water levels; springs near the discharging well will discharge water at decreased rates. The magnitudes of these declines generally can be expected to decrease with distance from the discharging bedrock well. However, near the Colorado River, fluctuations in stage also affect water levels in alluvial wells. Rises in river stage may prevent or diminish water-level decreases in alluvial wells near discharging bedrock wells. Declines in river stage can prevent recovery of water levels in alluvial wells after flow from a bedrock well has ceased. Thus, the water level in an alluvial well near a discharging bedrock well and the Colorado River should be intermediate between the levels expected because of proximity to either the bedrock well or the river.

Origin of Hot Water at Glenwood Springs

The origin of hot water at Glenwood Springs can be inferred from the temperature and chemistry of the water and the location of points where the water discharges from the hydrologic system. Included in this interpretation is the identification of local recharge areas for the Leadville Limestone and Dyer Dolomite.

Bedrock aquifers typically are recharged in topographically high areas, where the bedrock crops out or is near the surface. Potential recharge areas for the Leadville Limestone and Dyer Dolomite in the vicinity of Glenwood Springs include the White River Plateau to the north, Lookout Mountain to the southeast, and the Grand Hogback to the southwest.

Extensive outcrops of the Leadville Limestone and Dyer Dolomite in the White River Plateau (fig. 10) receive a considerable influx of precipitation. However, much of this precipitation discharges as springs into rivers and creeks that drain the plateau. For example, in the East Fork of Rifle Creek upstream from Rifle Falls (fig. 38), springflow entering the creek over a distance of 4 mi equals 126,600 gal/min (calculated from data in Teller and Welder, 1983, p. 11). Apparently very little of the water entering the Leadville Limestone and Dyer Dolomite in the White River Plateau circulates deeply enough to discharge at Glenwood Springs.

Water temperatures at Glenwood Springs are consistent with Lookout Mountain (fig. 39) and the Grand Hogback being the principal recharge areas for the Leadville Limestone and Dyer Dolomite in the vicinity. Temperatures of water discharging from the Leadville Limestone at Glenwood Springs consistently range from 111 °F to 126 °F. If the geothermal gradient at depth is as large as 1.8 °F/100 ft, which is the gradient recorded in the Wright no. 1 well between depths of 260 and 506 ft, only 4,300 ft of overburden would be required to heat water from the mean annual air temperature at Glenwood Springs (48 °F) to the maximum recorded ground-water temperature of 126 °F. At Lookout Mountain, Paleozoic formations above the Leadville Limestone are about 5,200 ft thick where they have not been eroded. Tertiary lava flows of unknown thickness overlie the Paleozoic rocks locally. The combined thickness of Paleozoic rocks and Tertiary lava is sufficient to heat descending ground water to temperatures observed at Glenwood Springs. In the Grand Hogback, the combined thickness of Paleozoic, Mesozoic, and Tertiary rocks probably requires some mixing of shallow and deep ground water to achieve the ground-water temperatures observed in the discharge area (assuming a geothermal gradient comparable to that in the Wright no. 1 well). The source of the shallow water entering the system could be the White River Plateau.

The chemistry of water discharging from the Leadville Limestone at Glenwood Springs indicates that water in the limestone must be in contact with evaporite deposits. Water in the Leadville Limestone at Glenwood Springs is a sodium chloride type with a large sulfate concentration and a dissolved-solids concentration of 18,000 to 22,000 mg/L. Such water is atypical of carbonate rocks where they crop out, but could occur if the water contained dissolved halite and gypsum. These rock types occur in the Eagle Valley Evaporite above the Leadville Limestone, north, east, and south of Glenwood Springs. However, geological and structural discontinuities probably allow water to percolate from the Eagle Valley Evaporite into the Leadville Limestone only to the south of Glenwood Springs. Lookout Mountain and the Grand Hogback, located in the identified area, again seem to be the principal recharge areas for the Leadville Limestone and Dyer Dolomite in the vicinity of Glenwood Springs.

Recorded potentiometric heads in bedrock and alluvium support the identification of Glenwood Springs as a discharge area. In November 1984, potentiometric heads in the Leadville Limestone were at least 30 ft higher than the water table in the alluvium at the confluence of the Colorado and Roaring Fork Rivers. This potentiometric head difference indicates the potential for upward leakage of water from the Leadville Limestone into the alluvium that manifests itself as hot water in alluvial wells and, ultimately, as hot springs. The alignment of hot springs, seepage areas, and geothermal wells along the Redstone, Wright, and West Glenwood faults (compare figures 11 and 13) indicates that discharge from the Leadville Limestone and Dyer Dolomite at Glenwood Springs is aided by these faults.

Figure 38.--Rifle Falls near Rifle. Sustained by springflow, the East Fork of Rifle Creek plunges over a ledge of cavernous travertine.

Figure 39.--Lookout Mountain on the southeastern side of Glenwood Springs. The plateau is capped by the Maroon Formation and Tertiary basalt and is underlain by rocks of Precambrian to Pennsylvanian age.

The conceptual model of ground-water flow in the Glenwood Springs area, as shown in figure 40, involves the following processes. Water from a gradually melting snowpack and storms infiltrates Tertiary basalt and upper Paleozoic sedimentary rocks at Lookout Mountain and in the Grand Hogback south of Glenwood Springs. This water percolates down to the Leadville Limestone and Dyer Dolomite through fractures and faults in overlying aquifers and confining layers. As the water descends through the Eagle Valley Evaporite, it dissolves bedded halite and gypsum and becomes saline. After reaching the Leadville Limestone and Dyer Dolomite, the hot, saline water flows through pores, bedding planes, joints, faults, and solution channels toward discharge areas at Glenwood Springs. At Glenwood Springs, the water from Lookout Mountain and the Grand Hogback mixes with cool, relatively fresh water flowing south from the White River Plateau, seeps into overlying alluvium, and discharges as hot springs along fault zones on the northeastern and northwestern edges of the city.

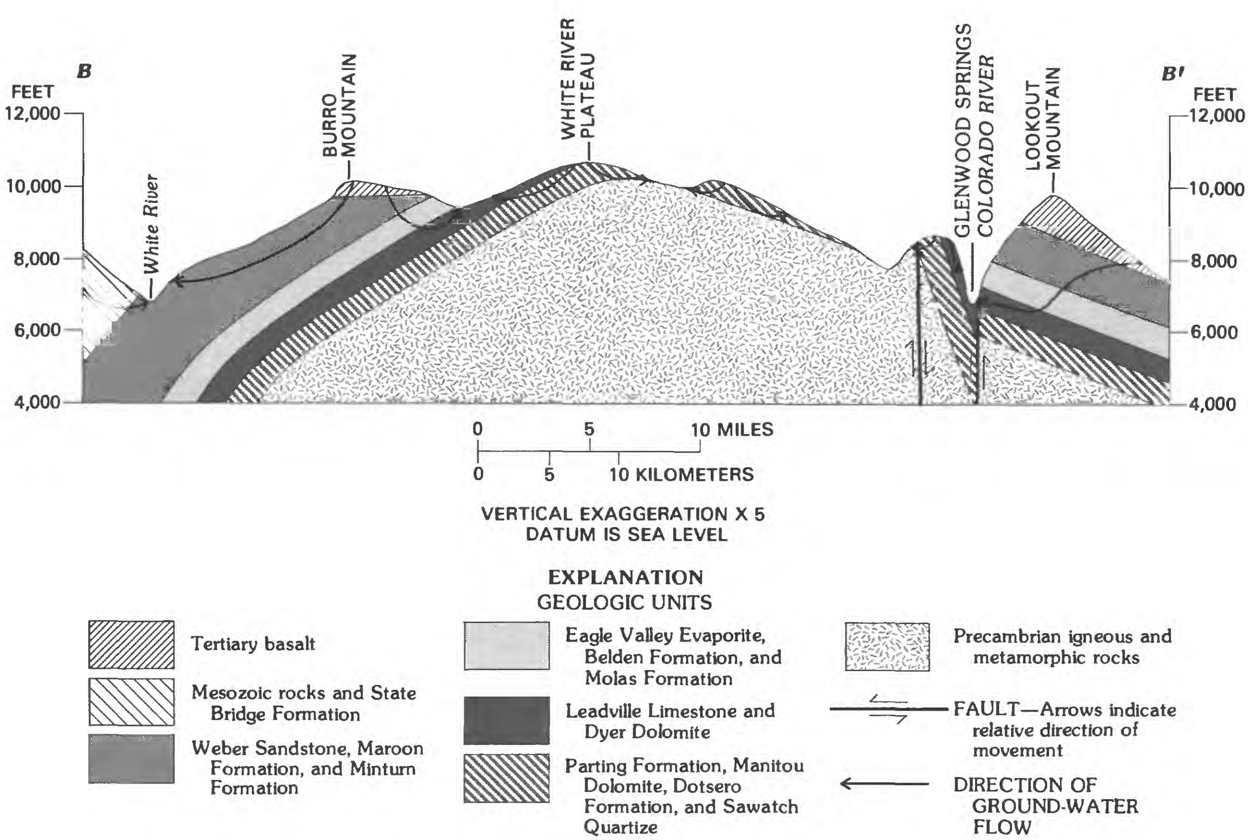


Figure 40.--Generalized geologic section across the White River Plateau showing the ground-water flow system (approximate location shown in fig. 41).

DEVONIAN AND MISSISSIPPIAN CARBONATE ROCKS HYDROSTRATIGRAPHIC UNIT--A REGIONAL HYDROLOGIC SYNTHESIS

The Devonian and Mississippian carbonate rocks hydrostratigraphic unit occurs extensively throughout northwestern Colorado. Its thickness ranges from 0 to 800 ft (fig. 41). The hydrostratigraphic unit, as shown in figure 42, consists of interbedded limestone and dolomite, containing as much as 10 percent shale and sandstone interbeds near uplifted areas. Sparsely distributed quantitative data indicate that hydrologic properties characteristic of the water-transmitting capability of the unit vary by six orders of magnitude within the area of study.

Hydraulic Conductivity and Transmissivity

Aquifer-test data for the Devonian and Mississippian carbonate rocks hydrostratigraphic unit in northwestern Colorado were obtainable at only five sites. Additional data were obtained at two sites in Utah and Wyoming within 25 mi of the study area. Aquifer tests analyzed to determine hydraulic conductivity included five drill-stem tests, one pumping test, and the two flowing-well tests at Glenwood Springs that were discussed previously. Sources of data for tests other than those at Glenwood Springs included Petroleum Information Corporation, Colorado Division of Water Resources, and ARCO (written commun., 1984-85). Hydraulic conductivity was calculated from the drill-stem test data by the methods of Horner (1951) and Earlougher (1977), and by a method described in Supplement B in the "Supplemental Information" section at the back of this report. Hydraulic conductivity was calculated from the pumping test data by the method of Lohman (1979, p. 52).

Hydraulic-conductivity values calculated from the analyzed test data increase from structural basins to uplifted areas (fig. 43). Hydraulic-conductivity values indicated by drill-stem tests in the Uinta, Piceance, and Sand Wash basins range from 0.00057 to 0.0097 ft/d. In contrast, hydraulic-conductivity values indicated by two drill-stem tests and a pumping test on the flanks of the Sawatch Range, Park Range, and Uinta Mountains range from 0.49 to 0.99 ft/d. Hydraulic conductivity on the intensely faulted southwestern flank of the White River Plateau at Glenwood Springs is at least 170 ft/d. The available data, though limited, indicate that hydraulic-conductivity values in the center of uplifted areas are at least three orders of magnitude larger than in the center of adjacent basins.

Transmissivity, like hydraulic conductivity, also is larger in uplifted areas than in structural basins (fig. 44). Transmissivity values in the study area were obtained directly from aquifer tests only at Glenwood Springs and near Aspen. Elsewhere in the study area, transmissivity was calculated from the product of hydrostratigraphic unit thickness and measured or estimated hydraulic conductivity at grid centers on a 10-mi by 10-mi grid. This analysis indicates that transmissivity in the hydrostratigraphic unit ranges from less than 0.1 to 10 ft^2/d in structural basins and from 10 to more than 1,000 ft^2/d in uplifted areas. The transmissivity in the vicinity of Glenwood Springs, as indicated by the first and second Redstone well tests, is 47,000 ft^2/d.

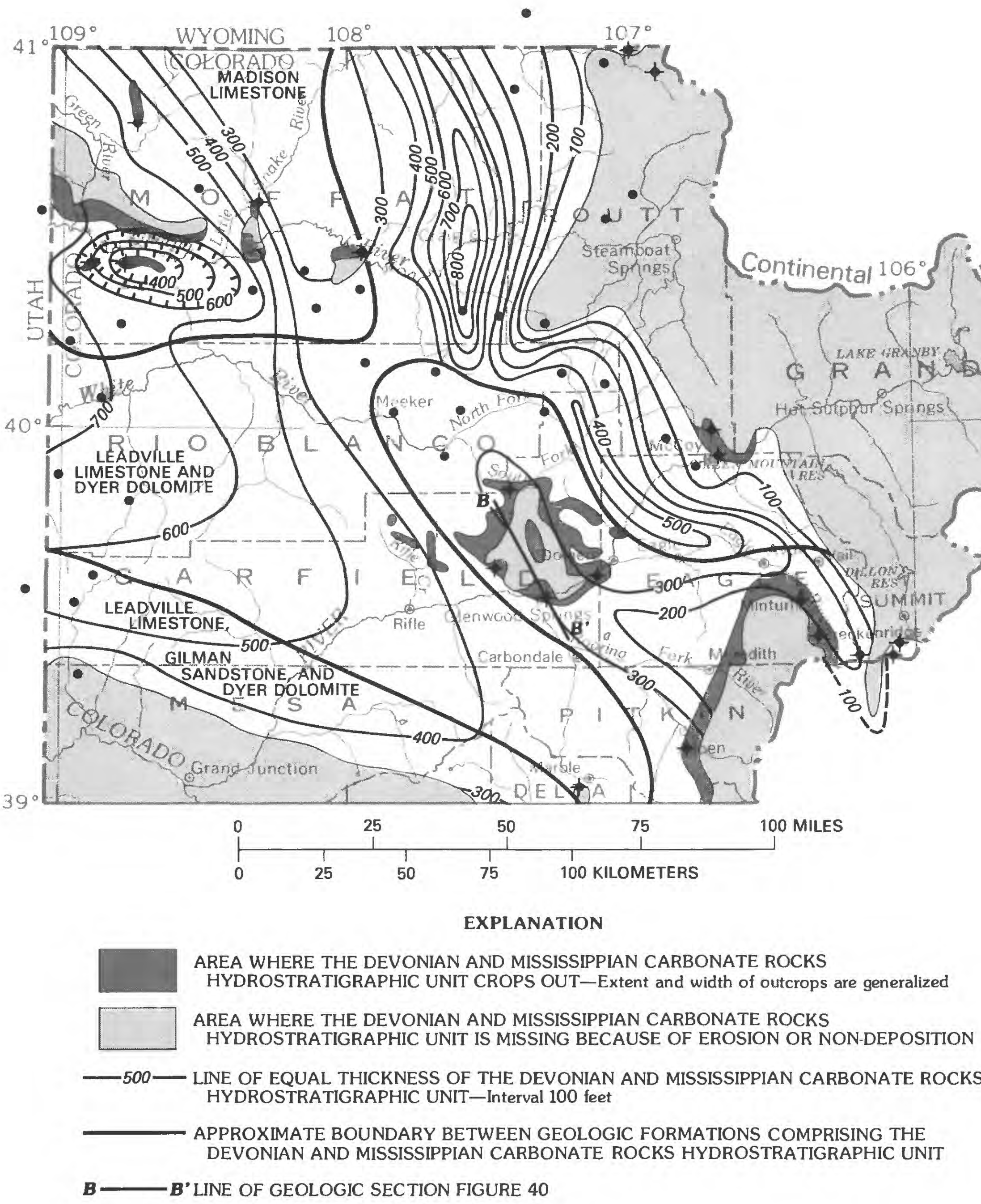


Figure 41.--Extent and thickness of the Devonian and Mississippian carbonate rocks hydrostratigraphic unit.

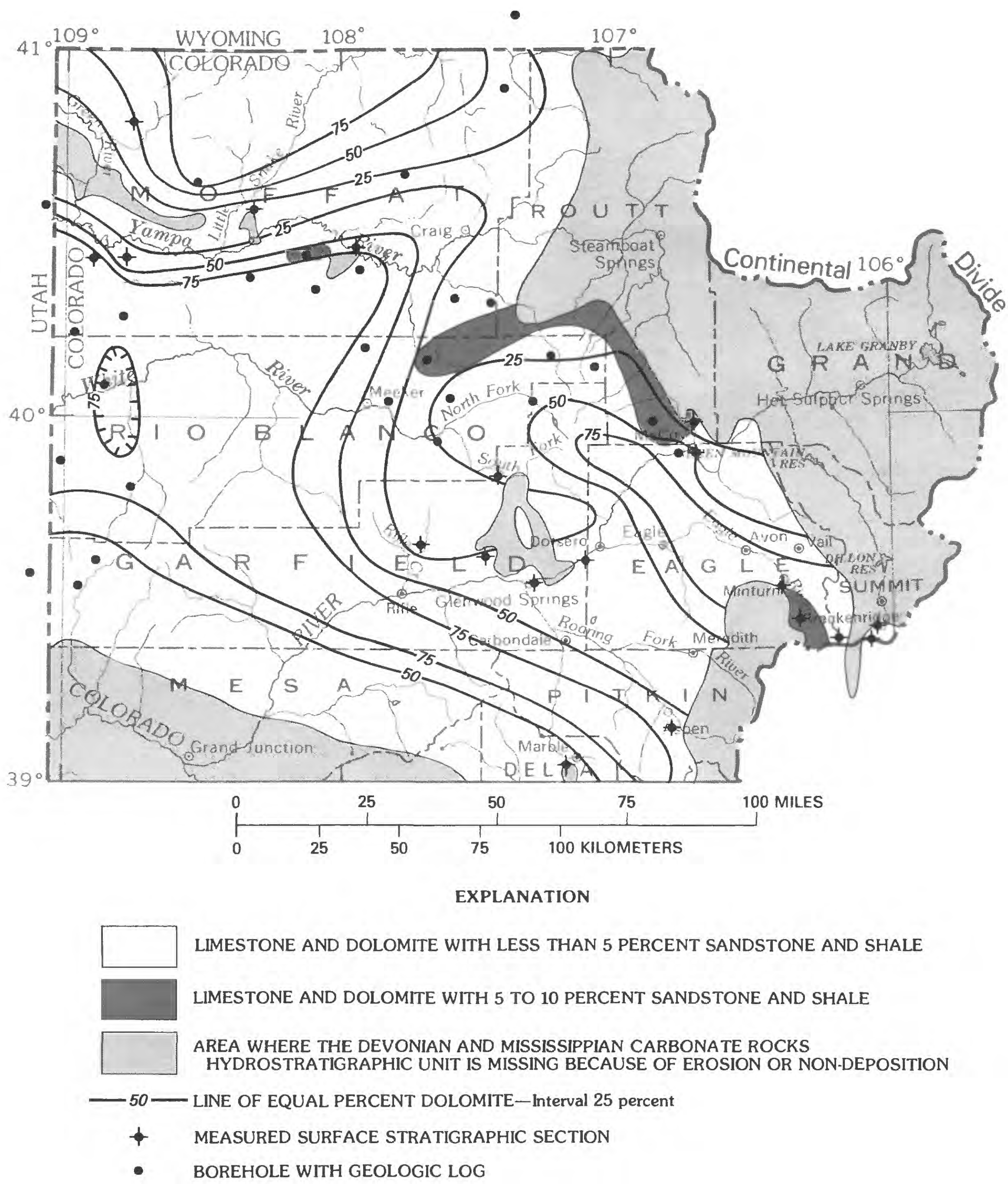
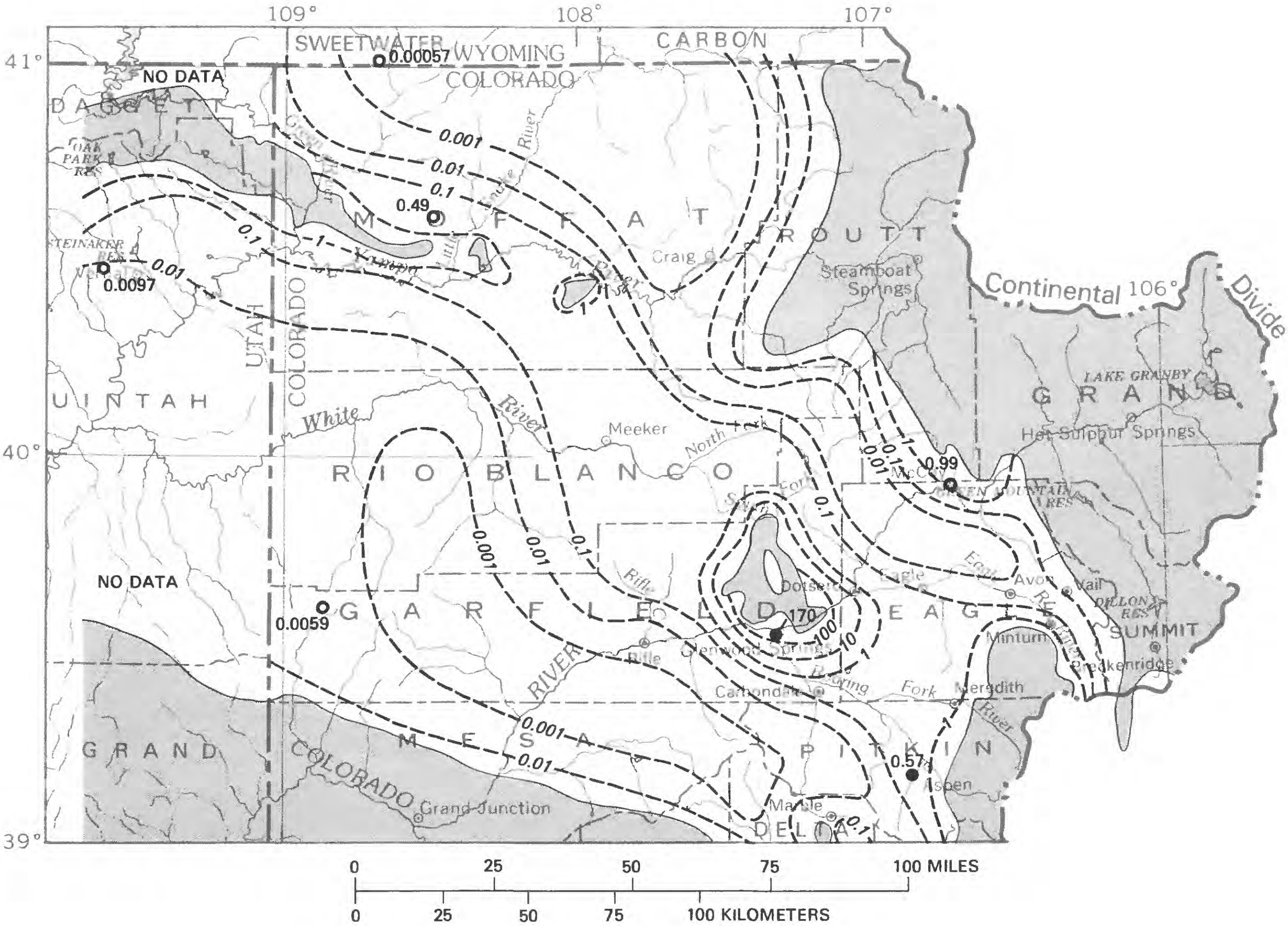


Figure 42.--Lithologic composition of the Devonian and Mississippian carbonate rocks hydrostratigraphic unit.



EXPLANATION

AREA WHERE THE DEVONIAN AND MISSISSIPPIAN CARBONATE ROCKS HYDROSTRATIGRAPHIC UNIT IS MISSING BECAUSE OF EROSION OR NON-DEPOSITION

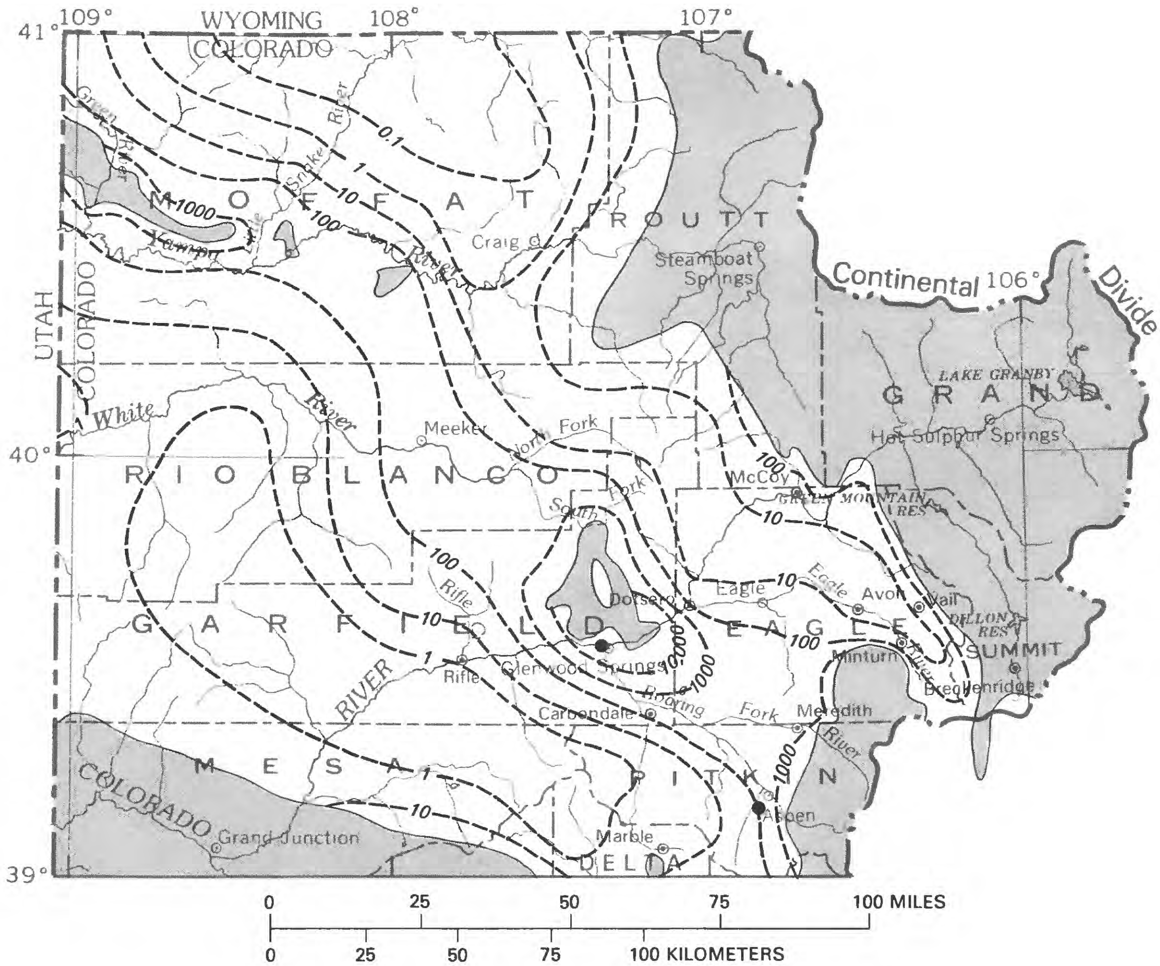
— — *0.1* — — LINE OF EQUAL ESTIMATED HYDRAULIC CONDUCTIVITY, IN FEET PER DAY—Location inferred from structural setting and considered approximate. Interval is variable

DATA SITES—Number is hydraulic conductivity, in feet per day

● Pumping test or flowing-well test. Hydraulic conductivity calculated from transmissivity

○ Drill-stem test. Hydraulic conductivity calculated from permeability

Figure 43.--Estimated regional distribution of hydraulic conductivity in the Devonian and Mississippian carbonate rocks hydrostratigraphic unit.



EXPLANATION

AREA WHERE THE DEVONIAN AND MISSISSIPPIAN CARBONATE ROCKS HYDROSTRATIGRAPHIC UNIT IS MISSING BECAUSE OF EROSION OR NON-DEPOSITION

——*100*—— LINE OF EQUAL ESTIMATED TRANSMISSIVITY, IN FEET SQUARED PER DAY—Location is approximate and is based on product of estimated hydraulic conductivity and extrapolated thickness at grid centers on a ten-mile by ten-mile grid

● PUMPING OR FLOWING-WELL TEST

Figure 44.--Estimated regional distribution of transmissivity in the Devonian and Mississippian carbonate rocks hydrostratigraphic unit.

Hydrodynamics

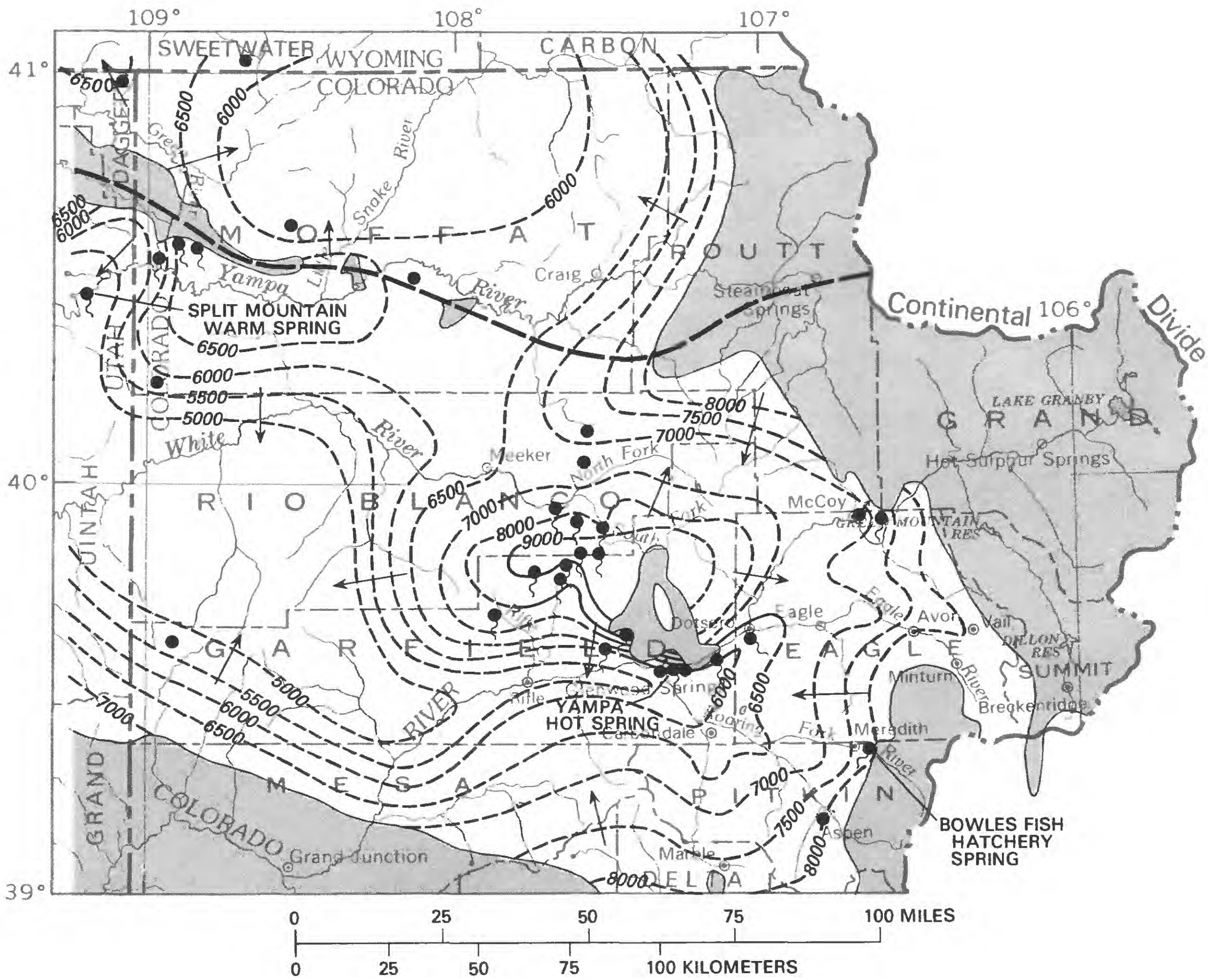
A composite potentiometric surface map was prepared from all available potentiometric head and spring-altitude data in northwestern Colorado (fig. 45). This map indicates that water in the Devonian and Mississippian carbonate rocks hydrostratigraphic unit generally flows toward structural basins and river valleys from topographically and structurally high areas on the east and south and in the center of the study area. A major ground-water divide extends between the Uinta Mountains on the west and the Park Range on the east.

South and east of Glenwood Springs, water in the Devonian and Mississippian carbonate rocks hydrostratigraphic unit generally flows northwestward, from recharge areas in the Sawatch Range, White River Plateau, and Elk Mountains to the Colorado River. Recharge occurs from precipitation and snowmelt infiltrating outcrops or seeping down through overlying aquifers and confining layers. Streams incised into the Devonian and Mississippian carbonate rocks unit in recharge areas drain some of the water in circulation. Near Meredith, for example, a spring flowing into a tributary of the Frying Pan River discharges at a rate of about 1,200 gal/min (Boettcher, 1972, p. 8). However, most of the discharge south and east of Glenwood Springs is to the Colorado River. According to URS Corporation (1983, p. 3-25), 22 springs and diffuse seepage entering the Colorado River between Dotsero and Glenwood Springs have a combined discharge of 13,500 gal/min (30.2 ft^3/s). Some of the water discharging to the Colorado River at Glenwood Springs is intercepted by the Redstone 21-9 well, which has a flowing discharge of 1,400 to 2,300 gal/min. Water not discharged to wells, springs, or streams enters the Piceance basin as subsurface flow.

In the White River Plateau, water in the Devonian and Mississippian carbonate rocks unit flows radially towards the Colorado River, South Fork White River, North Fork White River, Rifle Creek and other small streams, and to the Burns basin (fig. 40 is a cross section across the plateau, showing ground-water movement to the Colorado and White Rivers). Recharge occurs by infiltration of precipitation, mainly snowmelt, over broad areas of outcrop or subcrop. However, much of this recharge is intercepted by springs within the area and either evaporates or flows into surface drainages. Seventy of these springs in Garfield and Rio Blanco Counties have a combined discharge of 2,600 gal/min (Teller and Welder, 1983, p. 13-16). Streams draining the plateau gain substantially from springs. For example, the streamflow in Rifle Creek upstream from the Rifle Falls Fish Hatchery increases by 12,600 gal/min (28 ft^3/s) from springs entering within a 4-mi reach (Teller and Welder, 1983, p. 12).

In the Burns basin, water enters the hydrostratigraphic unit from outcrop areas on the flanks of the Park Range, Gore Range, and White River Plateau. A well near McCoy tapping this water supply discharges at a rate of 3,200 gal/min, with a head of 300 ft above land surface (Hampton, 1974, p. 60). In the center of the basin, water slowly percolates into overlying hydrostratigraphic units.

A divide extending along the Uinta Mountains, Axial Basin arch, and Park Range directs ground-water movement north to the Sand Wash basin or south to



EXPLANATION

AREA WHERE THE DEVONIAN AND MISSISSIPPIAN CARBONATE ROCKS HYDROSTRATIGRAPHIC UNIT IS MISSING BECAUSE OF EROSION OR NON-DEPOSITION

—6000— POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly-cased wells. Dashed where approximately located. Contour interval 500 feet except in White River Plateau, where interval is 1000 feet. National Geodetic Vertical Datum of 1929

GROUND-WATER DIVIDE

APPROXIMATE DIRECTION OF GROUND-WATER FLOW—Flow direction may not be perpendicular to potentiometric contours because of variable water density

BOREHOLE WITH MEASURED POTENTIOMETRIC HEAD

FLOWING WELL WITH MEASURED POTENTIOMETRIC HEAD

SPRING—Altitude above National Geodetic Vertical Datum of 1929 plotted as approximate potentiometric head. Springs with a discharge of 1,000 gallons per minute or more are labeled

Figure 45.--Composite 1945-85 potentiometric surface and approximate flow directions in the Devonian and Mississippian carbonate rocks hydrostratigraphic unit.

the Piceance basin. Additional recharge areas south of the divide include the White River Plateau and Uncompahgre Plateau. Water in the Sand Wash basin percolates into overlying hydrostratigraphic units or leaves the area by subsurface flow into the Washakie basin of Wyoming. Water in the Piceance basin either percolates into overlying hydrostratigraphic units or, mixing with water from the Uinta basin of Utah and the Uinta Mountains, discharges to springs and streams in the vicinity of the confluence of the Green and Yampa Rivers. The largest spring in this area, Split Mountain Warm Spring, discharges at a rate of 2,700 gal/min (Sumsion, 1976, p. 45).

SUMMARY AND CONCLUSIONS

1. Twenty-seven geologic units of Paleozoic age in northwestern Colorado can be grouped into eleven hydrostratigraphic units on the basis of lithologic and hydrologic properties. Regional aquifers include the Devonian and Mississippian carbonate rocks hydrostratigraphic unit and the Pennsylvanian and Permian sandstone hydrostratigraphic unit. Local aquifers in the study area include the Cambrian sandstone, Cambrian and Ordovician carbonate rocks, Mississippian carbonate and clastic rocks, and Pennsylvanian and Permian red beds and carbonate rocks hydrostratigraphic units. Confining layers in the study area include the Cambrian shale, Devonian carbonate and clastic rocks, Mississippian and Pennsylvanian shale and carbonate rocks, Pennsylvanian carbonate rocks and evaporites, and Permian shale and carbonate rocks hydrostratigraphic units.

2. Natural discharges of water from regional aquifers commonly exceed 50 gal/min. Discharges of as much as 3,200 gal/min can occur from the Devonian and Mississippian carbonate rocks unit. The Yampa Spring at Glenwood Springs had an estimated discharge of 2,800 to 2,950 gal/min in November 1984. The nearby Redstone 21-9 well flowed water at rates of 1,740 to 2,300 gal/min in November 1984. Discharges of several hundred gallons per minute are possible from the Pennsylvanian and Permian sandstone unit. Discharges from local aquifers and confining layers rarely exceed 50 gal/min, but flows of several hundred gallons per minute can occur from some intervals, particularly if they are extensively fractured.

3. Hydraulic conductivities generally increase from structural basins to uplifted areas. Hydraulic-conductivity values for the Devonian and Mississippian carbonate rocks hydrostratigraphic unit range from less than 0.001 to more than 100 ft/d. Hydraulic-conductivity values for the Pennsylvanian and Permian sandstone hydrostratigraphic unit range from less than 0.0001 to 20 ft/d. Hydraulic-conductivity values for local aquifers typically range from less than 0.0001 to 2 ft/d but can be as large as 10 ft/d for some sandstone layers. Hydraulic-conductivity values for confining layers typically range from less than 0.0001 to 0.25 ft/d but can be as large as 1 ft/d for some sandstone or limestone layers.

4. Transmissivity values in the Devonian and Mississippian carbonate rocks hydrostratigraphic unit increase from less than 0.1 ft^2/d in structural basins to more than 1,000 ft^2/d in uplifted areas. In the Glenwood

Springs area, this hydrostratigraphic unit consists of the Leadville Limestone and Dyer Dolomite. Aquifer tests of the Leadville Limestone at Glenwood Springs indicated a transmissivity of 47,000 ft^2d. This relatively large value is believed to be a consequence of faulting and associated fracturing in the area.

5. The storage coefficient of the Leadville Limestone and Dyer Dolomite at Glenwood Springs determined from aquifer tests is 5×10^{-4}. Specific storage in these formations, based on their combined thickness and storage coefficient at Glenwood Springs, is 1.8×10^{-6} ft^{-1}.

6. Flow from artesian wells completed in the Leadville Limestone at Glenwood Springs can lower water levels in nearby alluvial and bedrock wells and decrease discharge from springs. In November 1984, a cumulative discharge of 10.5 million gallons from the Redstone 21-9 well at Glenwood Springs interfered with alluvial wells and springs as much as 1,100 ft away. The Wright no. 1 well, which is completed in bedrock 4,400 ft from the production well, was affected also.

7. Most of the water discharging from the Leadville Limestone and Dyer Dolomite at Glenwood Springs is estimated to come from the direction of Lookout Mountain and the Grand Hogback, south of the city. Some of the water discharging at Glenwood Springs is estimated to come from the White River Plateau north of the city. In the Lookout Mountain and Grand Hogback areas, water from a gradually melting snowpack infiltrates the Leadville Limestone and Dyer Dolomite through fractures extending into overlying rocks. This water is heated to temperatures of 111 to 126 °F as it descends through thousands of feet of Paleozoic, Mesozoic, and Tertiary rocks. As the water descends through the Eagle Valley Evaporite, it becomes saline by dissolution of bedded gypsum and halite.

8. Water in the Devonian and Mississippian carbonate rocks hydrostratigraphic unit generally flows from mountains and plateaus to stream valleys and structural basins. Water movement is affected strongly by the White River Plateau and by a divide extending between the Uinta Mountains and Park Range. Streams, springs, and wells intercept some of the water in circulation. Water in the Sand Wash, Piceance, and Burns basins percolates into overlying Paleozoic rocks. Regional discharge south of the Uinta Mountains-Park Range divide is toward the confluence of the Green and Yampa Rivers.

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SUPPLEMENTAL INFORMATION

SUPPLEMENT A

Table 7.--*Representative hydrologic data for northwestern Colorado and adjacent areas*

[The following abbreviations are used in this table:

TEST TYPE: dst = drill stem test; lab = laboratory permeameter test; inject = well injection test; flow = flowing well test; pump = pumping test.

FORMATIONS: 317SBDG = STATE BRIDGE FORMATION; 317GSEG = GOOSE EGG FORMATION; 317PRKC = PARK CITY FORMATION; 317PSPR = PHOSPHORIA FORMATION; 321TSLP = TENSLEEP SANDSTONE; 321WEBR = WEBER SANDSTONE; 324AMSD = AMSDEN FORMATION; 324EGLV = EAGLE VALLEY EVAPORITE; 324MNRN = MINTURN FORMATION; 324MRGN = MORGAN FORMATION; 324MRON = MAROON FORMATION; 327BLDN = BELDEN FORMATION; 331HMBG = HUMBUG FORMATION; 337LDVL = LEADVILLE LIMESTONE; 337MDSN = MADISON LIMESTONE; 341OURY = OURAY LIMESTONE; 371LODR = LODORE FROMATION; 374FLTD = FLATHEAD SANDSTONE; 420UNMN = UINTA MOUNTAIN GROUP.

Blank space indicates no data available, N/A indicates not applicable, springs are identified by zeros in the top and bottom columns]

Site	Depth to top (feet)	Depth to bottom (feet)	Test type	Permeability (millidarcies)	Hydraulic conductivity (feet per day)	Yield (gallons per minute)	Lithology
				317GSEG			
sb13-88-36ca	7546.0	7641.0	dst			25.0000	
sb15-91-11bac	10,088.0	10,100.0	dst			0.3900	
				317PRKC			
sb01-93-06cb	5,440.0	5,490.0	dst			12.0000	
sb03-103-16ba	8,735.0	8,870.0	dst			58.0000	
sb08-99-16bcd	3,340.0	3,400.0	dst	1.90000	0.004600		Limestone and sandstone
sb13-105-35adb	14,699.0	14,818.0	lab	0.13000	0.000310		Limy dolomite
sb14-103-10ad	8,995.0	9,042.0	dst			44.0000	
sb16-101-11ddc	14,070.0	14,243.0	lab	8.70000	0.021000		Fine-grained, sucrose, and vuggy limestone
sb16-104-16ddb	5,459.0	5,489.0	dst			18.0000	
sla03-22-34ba	2,972.0	3,021.0	dst			21.0000	
sla03-24-22bda	8,753.0	8,968.0	lab	0.07000	0.000170		Phosphatic sandstone and siliceous dolomite
sld02-21-33dcd	0.0	0.0	N/A			20.0000	
sld02-22-24ccd	0.0	0.0	N/A			400.0000	
sld04-21-36cd	7,798.0	7,841.0	dst			8.1000	
sld04-22-35dbc	4,745.0	4,779.0	dst			19.0000	
sld04-23-23dda	0.0	0.0	N/A			4.0000	
sld05-22-23cba	4,053.0	4,063.0	lab	6.20000	0.015000		Sandy dolomite
sld05-22-26bca	4,372.0	4,393.0	dst			14.0000	
sld05-23-18cca	4,117.0	4,215.0	lab	3.50000	0.008600		Limestone and limy to quartzitic sandstone
sld06-24-05acd	0.0	0.0	N/A			0.1000	
sld06-24-05cdc	1,181.0	1,210.0	dst			10.0000	
				321TSLP (Equivalent of 321WEBR)			
sb13-88-36ca	7,644.0	7,672.0	dst			61.0000	
sb14-88-34cb	7,025.0	7,030.0	lab	0.33000	0.000800		Slightly glauconitic sandstone
sb14-91-13bab	11,048.0	11,086.0	lab	0.41000	0.000990		Quartzitic sandstone
sb15-103-08bc	6,670.0	6,720.0	dst			56.0000	
sb15-105-11dac	11,435.0	11,610.0	dst	3.50000	0.008400		Shaly quartzitic sandstone
sb15-91-11bac	10,280.0	10,307.0	dst			8.6000	
sb16-101-11ddc	14,282.0	14,485.0	lab	0.62000	0.001500		Fine to medium-grained sandstone
sb16-104-16ddb	5,700.0	5,756.0	dst	0.39000	0.000950		Quartzitic sandstone
sb16-104-21aca	6,065.0	6,172.0	dst			40.0000	
sb16-90-31abd	10,082.0	10,191.0	dst	18.00000	0.043000	9.2000	Friable, quartzitic sandstone
sb16-91-08dd	10,865.0	10,913.0	dst	20.00000	0.048000		Quartzitic sandstone
sb16-92-12db	11,137.0	11,180.0	dst			1.4000	

SUPPLEMENT A--Continued

Table 7.--*Representative hydrologic data for northwestern Colorado and adjacent areas*--Continued

Site	Depth to top (feet)	Depth to bottom (feet)	Test type	Permeability (millidarcies)	Hydraulic conductivity (feet per day)	Yield (gallons per minute)	Lithology
				321WEBR			
sb01-91-31bac1	29.8	40.0	inject	16,000.00000	38.000000		Very fractured sandstone
sb01-91-31bac1	40.0	50.0	inject	2,600.00000	6.400000		Very fractured sandstone
sb01-91-31bac1	50.0	60.0	inject	2,600.00000	6.700000		Very fractured sandstone
sb01-91-31bac1	60.0	70.0	inject	1,300.00000	3.200000		Very fractured sandstone
sb01-91-31bac1	70.0	80.0	inject	1,300.00000	3.300000		Very fractured sandstone
sb01-91-31bac1	80.0	89.9	inject	1,300.00000	2.800000		Very fractured sandstone
sb01-91-31bac2	70.5	101.4	inject	2,000.00000	4.800000		Moderately jointed sandstone with fracture zones
sb01-91-31bac3	21.4	27.6	inject	25,000.00000	61.000000		Moderately jointed sandstone with fracture zones
sb01-91-31bac3	27.6	42.4	inject	4,400.00000	11.000000		Moderately jointed sandstone with fracture zones
sb01-91-31bac3	42.4	49.4	inject	17,000.00000	41.000000		Moderately jointed sandstone with fracture zones
sb01-91-31bac3	49.4	74.2	inject	1,200.00000	3.000000		Moderately jointed sandstone with fracture zones
sb01-91-31bac3	74.2	77.7	inject	960.00000	2.300000		Fault contact with 324MRON; sandstone and gouge
sb01-93-06cb	5,440.0	5,490.0	dst	20.00000	0.049000		Quartz sandstone
sb02-101-31bdc	6,310.0	6,377.0	dst			0.1700	
sb02-101-31dab	6,160.0	6,439.0	lab	0.54000	0.001300		Silty sandstone
sb02-102-17ba	6,575.0	6,598.0	dst	0.35000	0.000850		Slightly limy fine-grained quartz sandstone
sb02-102-17ba	6,686.0	6,709.0	dst	0.61000	0.001500		Slightly limy fine-grained quartz sandstone
sb02-102-21bc	6,578.0	6,605.0	dst			1.5000	
sb02-102-36bbb	5,930.0	6,377.0	lab	1.40000	0.003400		Sandstone
sb02-103-11ddc	6,569.0	6,611.0	lab	7.00000	0.017000		Sandstone
sb02-103-15cb	6,794.0	6,816.0	dst			8.0000	
sb02-88-10ddb	2,052.0	2,118.0	lab	1.00000	0.002500		Clayey sandstone
sb02-92-06cca	9,261.0	9,325.0	dst			20.0000	
sb02-94-04cd	10,540.0	10,598.0	dst	0.80000	0.001900		Quartz sandstone (includes some 317SBDG shale)
sb03-100-12ba	3,323.0	3,425.0	dst			57.0000	
sb03-101-03acd			lab	0.06400	0.000150		Hard sandstone
sb03-103-12bb	9,520.0	9,763.0	dst			31.0000	
sb03-104-12bba	9,303.0	9,449.0	lab	0.81000	0.002000		Fine-grained sandstone
sb03-90-26baa	6,070.0	6,194.0	dst			2.4000	
sb03-91-08ddc	4,416.0	4,496.0	dst	0.76000	0.001900		Limy and quartzitic sandstone
sb03-97-29dba	11,940.0	12,045.0	dst	0.01400	0.000034		Limy and quartzitic sandstone
sb04-103-32cc	1,140.0	1,180.0	dst	1.70000	0.004200		Quartzitic sandstone
sb04-104-36bcd	1,340.0	1,410.0	dst			16.0000	
sb04-104-36ddd	1,370.0	1,380.0	lab	4.30000	0.011000		Deep core; hard sandstone
sb04-92-13adc	5,533.0	5,554.0	dst	39.00000	0.096000		Quartzitic sandstone with shale layers
sb04-92-14dc	4,865.0	4,883.0	dst	160.00000	0.380000		Quartzitic sandstone with shale layers
sb04-92-22dc	4,622.0	4,652.0	dst			1.8000	
sb04-98-08b	7,979.0	8,033.0	dst	26.00000	0.062000		Quartz sandstone
sb04-99-12aaa	8,808.0	8,886.0	lab	0.20000	0.000490		Limy and medium-grained sandstone
sb05-91-33dd	6,081.0	6,097.0	dst	30.00000	0.073000	3.6000	Quartz sandstone
sb05-94-09dc	2,941.0	2,982.0	dst	7.70000	0.019000		Quartz sandstone
sb05-94-17cb	3,007.0	3,022.0	dst			77.0000	
sb05-95-02bab	2,199.0	2,274.0	lab	0.07600	0.000190		Fine-grained sandstone and siltstone
sb05-95-02bab	2,351.0	2,385.0	lab	0.25000	0.000600		Fine-medium grained sandstone

SUPPLEMENT A--Continued

Table 7.--*Representative hydrologic data for northwestern Colorado and adjacent areas*--Continued

Site	Depth to top (feet)	Depth to bottom (feet)	Test type	Permeability (millidarcies)	Hydraulic conductivity (feet per day)	Yield (gallons per minute)	Lithology
				324AMSD (Equivalent of 324MRGN)			
sb16-104-16ddb	6,150.0	6,173.0	dst			12.0000	
				324EGLV			
sb01-93-08dd	6,081.0	6,131.0	dst	2.00000	0.004800	49.0000	Sandstone with limestone and dolomite layers
sb01-93-17ac	5,234.0	5,386.0	dst			42.0000	
				324MNRN			
sb02-87-13ddc	8,021.0	8,126.0	dst	0.78000	0.001900		Quartzitic sandstone and shale
sb02-92-15cc	2,302.0	2,350.0	dst	15.00000	0.037000	5.2000	Sandstone
sc01-83-20ca	387.0	407.0	pump	24.00000	0.049000		Sandstone and shale
sc08-84-17bac2	37.0	60.0	inject	2,400.00000	5.900000		Very fine-grained sandstone
sc08-84-17bac2	60.0	104.0	inject	1,600.00000	4.000000		Siltstone
sc08-84-17bac2	104.0	137.0	inject	490.00000	1.200000		Claystone
				324MRGN			
sb04-101-19ab	1,790.0	1,820.0	dst			1.4000	
sb06-94-18acd	41.0	56.0	inject	386.00000	0.940000		Limestone with a few shale layers
sb06-94-18acd	66.0	81.0	inject	339.00000	0.820000		Limestone with a few shale layers
sb06-94-18acd	238.0	255.0	inject	62.00000	0.150000		Sandstone and shale
sb06-94-18acd	255.0	264.0	inject	107.00000	0.260000		Sandstone
sb06-94-18acd	264.0	278.0	inject	34.50000	0.084000		Sandstone and shale
sb06-94-18acd	278.0	287.5	inject	15.20000	0.037000		Shale
sb06-94-18dba	14.0	24.0	inject	300.00000	0.730000		Shale with limestone nodules
sb06-94-18dba	24.0	35.0	inject	107.00000	0.260000		Shale with limestone nodules
sb06-94-18dba	34.0	44.0	inject	470.00000	1.100000		Unjointed limestone
sb06-94-18dba	42.7	57.7	inject	57.00000	0.120000		Shale with limestone layers
sb06-94-18dba	57.0	69.0	inject	82.10000	0.200000		Shale with limestone nodules
sb06-94-18dba	95.0	106.0	inject	28.30000	0.069000		Limestone
sb06-94-18dba	167.0	177.0	inject	41.00000	0.100000		Limestone
sb07-103-20dbc	0.0	0.0	N/A			580.0000	
sb07-104-13bca	0.0	0.0	N/A			50.0000	
sb13-99-18bb	17,079.0	17,745.0	dst	0.03200	0.000077		
sc02-104-12bca	10,713.0	10,742.0	dst			8.7000	
sld05-22-01cc	7,148.0	7,232.0	dst	0.07400	0.000180	6.6000	Sandstone, siltstone, and shale
				324MRON			
sb01-91-31bac1	89.9	100.0	inject	1,000.00000	2.400000		Slightly to highly fractured sandstone
sb01-91-31bac1	100.0	109.9	inject	1,000.00000	2.600000		Slightly to highly fractured sandstone
sb01-91-31bac1	109.9	129.9	inject	1,000.00000	2.500000		Slightly to highly fractured sandstone
sb01-91-31bac1	129.9	149.9	inject	1,000.00000	2.400000		Slightly to highly fractured sandstone
sb01-91-31bac1	149.9	169.9	inject	1,000.00000	2.300000		Slightly to highly fractured sandstone
sb05-95-02dda	2,525.0	2,582.0	dst			11.0000	
sb05-96-14ab	6,548.0	6,600.0	dst			11.0000	
sb06-102-18add	0.0	0.0	N/A			15.0000	
sb06-102-22baa	0.0	0.0	N/A			2.0000	
sb06-103-07bbb	0.0	0.0	N/A			20.0000	
sb06-94-10cc	3,950.0	4,076.0	dst			0.3300	

SUPPLEMENT A--Continued

Table 7.--*Representative hydrologic data for northwestern Colorado and adjacent areas*--Continued

Site	Depth to top (feet)	Depth to bottom (feet)	Test type	Permeability (millidarcies)	Hydraulic conductivity (feet per day)	Yield (gallons per minute)	Lithology
324MRON--Continued							
sb07-103-32adb	63.5	300.0	pump	7,300.00000	17.000000		Fractured sandstone; 150 gallons per minute flow
sb07-103-32adb	165.0	300.0	dst			35.0000	
sb07-87-13	5,535.0	5,607.0	dst			9.0000	
sb07-95-32bb	2,070.0	2,107.0	dst			17.0000	
sb08-99-16bcd	3,675.0	3,725.0	dst			20.0000	
sb10-101-25da	1,855.0	1,907.0	dst			16.0000	
sb12-104-17cac	14,214.0	14,295.0	dst			20.0000	
sb13-105-35adb	14,855.0	15,010.0	lab	0.12000	0.000300		Limy and quartzitic sandstone
sb13-88-08dc	8,010.0	8,089.0	dst	2.20000	0.005300		Gravelly quartzitic sandstone
sb14-101-18bbd	12,771.0	12,800.0	dst	0.28000	0.000680	4.6000	Quartzitic sandstone with anhydrite layers
sc05-92-03cba	1,486.0	1,679.0	lab	0.05900	0.000140		Sandstone
sla03-22-34ba	3,203.0	3,277.0	dst			23.0000	
sla03-24-22bda	9,040.0	9,356.0	lab	0.17000	0.000410		Fine-medium-grained sandstone
sla03-25-28bb	11,675.0	11,885.0	dst	0.14000	0.000300	4.8000	Dolomitic and quartzitic sandstone
sld02-22-13ccd	0.0	0.0	N/A			500.0000	
sld02-22-29dcd	167.0	630.0	pump	1,500.00000	3.000000	628.0000	Quartz sandstone (storage co-efficient = 0.005)
sld02-22-31adc	0.0	0.0	N/A			1,350.0000	
sld02-22-32bcb	91.0	1,573.0	pump	42.00000	0.094000	488.0000	Quartz sandstone with a storage coefficient = 0.001 (including some 324MRGN)
sld03-21-20bba	148.0	210.0	dst			10.0000	
sld03-21-30ddc	214.0	2,715.0	dst			250.0000	
sld03-22-30ddd	5,484.0	5,517.0	dst			41.0000	
sld03-25-11dcc	0.0	0.0	N/A			100.0000	
sld04-21-36cd	7,798.0	7,841.0	dst	0.90000	0.002200		Limy quartz sandstone (including some 317PRKC shale and chert)
sld04-23-25b	0.0	0.0	N/A			3.0000	
sld04-23-36cda	7,808.0	7,817.0	lab	5.00000	0.012000		Fine-medium-grained sandstone
sld04-24-35dad	30.0	300.0	dst			14.0000	
sld04-25-31cca	0.0	0.0	N/A			117.0000	
sld05-22-06ca	7,035.0	7,085.0	dst	1.60000	0.003800		Quartzitic sandstone
sld05-22-22add	4,195.0	4,293.0	lab	6.00000	0.015000		Sandstone and limy sandstone
sld05-22-23cba	4,047.0	4,169.0	dst	17.00000	0.042000		Quartzitic sandstone (including some 317PRKC dolomite)
sld05-22-26cc	4,781.0	4,820.0	dst			34.0000	
sld05-23-20ccc	3,752.0	3,766.0	dst			56.0000	
sld05-23-21aaa	3,334.0	3,345.0	lab	10.00000	0.025000		Fine-coarse-grained limy sandstone
sld05-24-11dac	0.0	0.0	N/A			50.0000	
sld05-24-32	0.0	0.0	N/A			10.0000	
sld06-23-01bad	2,077.0	2,650.0	dst			200.0000	
sld06-23-05dad	5,805.0	5,929.0	dst			30.0000	
sld06-24-05	0.0	0.0	N/A			10.0000	
sld06-24-05cdc	1,181.0	1,210.0	dst	27.00000	0.065000		Limy quartz sandstone
sld06-25-05da	3,264.0	3,300.0	dst			19.0000	
sb01-91-31bac1	169.9	200.1	inject	770.00000	1.900000		Fractured siltstone
sb01-91-31bac1	200.1	220.1	inject	770.00000	1.500000		Fractured siltstone
sb01-91-31bac1	220.1	240.1	inject	490.00000	1.200000		Very fractured sandstone
sb01-91-31bac1	240.1	259.8	inject	490.00000	0.970000		Very fractured sandstone
sb01-91-31bac3	77.7	106.0	inject	1,200.00000	2.900000		Sandstone and shale with fracture zones
sc01-91-18acb	109.6	138.7	inject	110.00000	0.270000		Thin-bedded sandstone with siltstone layers
sc01-91-18acb	138.7	157.8	inject	33.00000	0.080000		Fine-grained sandstone and siltstone
sc01-91-18acb	157.8	167.3	inject	350.00000	0.850000		Mostly coarse-grained sandstone
sc01-91-18acb	167.3	179.1	inject	30.00000	0.070000		Fine-grained sandstone; thin-bedded with gouge zones

SUPPLEMENT A--Continued

Table 7.--*Representative hydrologic data for northwestern Colorado and adjacent areas*--Continued

Site	Depth to top (feet)	Depth to bottom (feet)	Test type	Permeability (millidarcies)	Hydraulic conductivity (feet per day)	Yield (gallons per minute)	Lithology
				324MRON--Continued			
sc01-91-18acb	179.1	189.9	inject	82.00000	0.200000		Fine-grained sandstone; thin-bedded with calcite-filled joints
sc01-91-18acb	189.9	211.9	inject	55.60000	0.136000		Fine-grained sandstone; thin-bedded with calcite-filled joints
sc01-91-18bdd	7.9	27.6	inject	69.00000	0.170000		Sandstone with siltstone beds
sc01-91-18bdd	45.3	64.9	inject	247.00000	0.602000		Sandstone with siltstone beds
sc01-91-18bdd	74.8	91.8	inject	147.00000	0.359000		Sandstone with siltstone beds
sc01-91-18bdd	91.8	120.4	inject	11.10000	0.027000		Sandstone
sc01-91-18bdd	120.4	137.1	inject	120.00000	0.292000		Sandstone with siltstone beds
sc01-91-18bdd	146.9	156.8	inject	62.70000	0.153000		Sandstone with siltstone beds
sc01-91-18bdd	186.0	204.0	inject	77.40000	0.189000		Sandstone with siltstone beds
sc01-91-18bdd	223.7	242.7	inject	194.00000	0.472000		Sandstone with siltstone beds
sc02-83-04	0.0	0.0				15.0000	
sc07-87-09ca	200.0	235.0	pump	920.00000	1.800000		Red beds
sc07-88-10cc	80.0	115.0	pump	1,600.00000	3.000000		Red beds
sc07-88-14bc	235.0	275.0	pump	1,200.00000	2.400000		Red beds
sc07-89-01aa	150.0	180.0	pump	110.00000	0.210000		Red beds
sc08-84-06cd	156.0	336.0	pump	740.00000	1.400000		Red beds with limestone layers
sc08-84-18bab	35.0	165.5	inject	110.00000	0.260000		Fine-grained sandstone
sc08-84-18bab	165.5	172.5	inject	49.00000	0.120000		Shale with fine-grained sandstone layers
sc08-84-18bab	172.5	184.0	inject	36.00000	0.087000		Sandstone and shale
sc08-84-18bab	184.0	206.0	inject	400.00000	0.980000		Fine-grained and coarse-grained sandstone
sc08-84-18bab	206.0	300.0	inject	22.00000	0.054000		Sandstone and shale
sc08-84-18bad	31.0	364.5	inject	640.00000	1.500000		Fine-grained to medium-grained sandstone with shale layers
sc08-86-01cc	74.0	115.0	pump	1,800.00000	1.400000		Fractured arkosic sandstone with shale layers
sc08-86-04ca	220.0	255.0	pump	3,900.00000	7.900000		Red beds
sc08-86-08aa	100.0	120.0	pump	4,100.00000	5.900000		Fractured arkosic sandstone
sc09-87-26db	215.0	255.0	pump	240.00000	0.420000		Red beds
sc10-88-04	0.0	0.0	N/A			50.0000	
sc10-88-04ba	0.0	0.0	N/A			10.0000	
sc10-88-29cc	214.0	350.0	pump	25.00000	0.051000		Red beds
sc11-87-35	0.0	0.0	N/A			898.0000	
sc12-85-16	0.0	0.0	N/A			50.0000	
sc12-85-21	0.0	0.0	N/A			75.0000	
				327BLDN			
sb04-91-10bbb	9,480.0	9,550.0	dst	1.60000	0.003900	4.0000	Limestone and shale
sb08-84-14baa	242.0	297.0	dst			100.0000	
				331HMBG			
sb08-99-17	5,085.0	5,150.0	dst	292.00000	0.710000	34.0000	Dolomite sandstone and shale
sld05-23-18cca	6,076.0	6,089.0	lab	4.30000	0.011000		Fine-grained sandstone
				337LDVL			
sb01-91-18db	3,546.0	3,656.0	dst			7.8000	
sb02-92-36cb	5,167.0	5,300.0	dst			16.0000	
sb03-103-03cb	4,384.0	4,563.0	dst			28.0000	
sb04-92-22dcb	7,463.0	7,485.0	dst			197.0000	
sc01-83-30ddb	912.0	992.0	dst	360.00000	0.990000		Limestone and dolomite (including 341OURY)

SUPPLEMENT A--Continued

Table 7.--*Representative hydrologic data for northwestern Colorado and adjacent areas*--Continued

Site	Depth to top (feet)	Depth to bottom (feet)	Test type	Permeability (millidarcies)	Hydraulic conductivity (feet per day)	Yield (gallons per minute)	Lithology
				337LDVL--Continued			
sc01-91-32bcc	0.0	0.0	N/A			0.9700	
sc01-92-36daa	0.0	0.0	N/A			1.5000	
sc02-90-19bdd	0.0	0.0	N/A			370.0000	
sc02-91-06acb	0.0	0.0	N/A			34.0000	
sc03-90-07aba	0.0	0.0	N/A			102.0000	
sc03-91-10cad	0.0	0.0	N/A			266.0000	
sc03-92-23baa	0.0	0.0	N/A			400.0000	
sc03-92-33bbc	0.0	0.0	N/A			23.0000	
sc03-93-25bab	0.0	0.0	N/A			37.0000	
sc04-90-07dcd	0.0	0.0	N/A			5.8000	
sc04-91-06aad	0.0	0.0	N/A			1.9000	
sc04-92-11bba	0.0	0.0	N/A			142.0000	
sc04-94-25add	0.0	0.0	N/A			5.8000	
sc05-103-25cc	8,553.0	8,600.0	dst	2.40000	0.005900		Limestone and dolomite
sc05-86-05	0.0	0.0	N/A			450.0000	
sc05-87-12bd	0.0	0.0	N/A			650.0000	
sc05-88-34	0.0	0.0	N/A			674.0000	
sc05-91-01bbb	0.0	0.0	N/A			120.0000	
sc06-89-09ad	0.0	0.0	N/A			2,700.0000	
sc06-89-09bba	80.0	155.0	flow	13,5000.00000	640.000000		Faulted limestone and dolomite; storage coefficient = 0.0005
sc08-83-09	0.0	0.0	N/A			1,120.0000	
sc10-84-07ac	40.0	120.0	pump	320.00000	0.570000		Fractured limestone and dolomite
				337MDSN			
sb06-96-35ccd	3,731.0	3,817.0	dst			47.0000	
sb07-103-20cad	0.0	0.0	N/A			450.0000	
sb08-99-16bcd	5,871.0	5,877.0	dst			46.0000	
sb08-99-16bcd	5,877.0	5,960.0	dst	202.00000	0.490000		Dolomite
sb12-101-24cc	16,600.0	16,760.0	dst	0.24000	0.000570	20.0000	Dolomite and cherty dolomite
sb16-101-11ba	15,013.0	15,035.0	dst	2.50000	0.006100	27.0000	Limestone and dolomite
sb16-104-16ddb	7,074.0	7,130.0	dst			23.0000	
sla03-24-22bdb	10,764.0	10,912.0	dst			40.0000	
sld04-24-16cdd	0.0	0.0	N/A			2,700.0000	
				371LODR			
sc05-103-25cc	9,165.0	6,210.0	dst	0.41000	0.001000	2.3000	Dolomitic quartz sandstone
				374FLTD (Equivalent of 371LODR)			
sb16-101-11ba	16,350.0	16,497.0	dst			1.5000	
				420UNMN			
sld01-20-12dca	90.0	160.0	pump	880.00000	1.600000		Qusrtzite

SUPPLEMENT B

NUMERICAL METHOD FOR ESTIMATING PERMEABILITY FROM DRILL-STEM TEST DATA

Horner Plot Method

Much of the hydraulic conductivity and permeability information used in this report was obtained from drill-stem tests. The best method for analyzing permeability from drill-stem tests is the Horner plot (Horner, 1951). Pressure in the well bore is plotted against log $(t + \Delta t)/\Delta t$, where t is the flow period, in minutes, and Δt is the shut-in period, in minutes. A straight line is fitted through the points on the plot. Permeability is determined by equation 1:

$$k = \frac{162.6qv}{\Delta ph} \; ; \qquad (1)$$

where k = permeability, in millidarcies;
q = discharge rate, in barrels/day;
Δp = change in well-bore pressure, in pounds per square inch, over one log cycle;
h = thickness of the tested interval, in feet; and
v = viscosity, in centipoise.

If the viscosity is unknown, it can be estimated from the bottom-hole temperature by using temperature-viscosity tables or the equations:

$$v = 1.93 - 0.818 \log (0.556 \text{ BHT} - 22.8), \text{ if BHT} = 50 \text{ to } 120\ ^{\circ}\text{F}; \qquad (2)$$

$$v = 0.935 - 0.367 \log (0.556 \text{ BHT} - 57.8), \text{ if BHT} = 120 \text{ to } 425\ ^{\circ}\text{F}; \qquad (3)$$

where BHT = bottom-hole temperature, in degrees Fahrenheit; and
v = viscosity, in centipoise.

The discharge rate is determined by the equation:

$$q = 20.5\ R/t; \qquad (4)$$

where q = the discharge rate, in barrels/day;
R = length of fluid-filled drill stem, in feet; and
t = the flow period, in minutes.

The recovered fluid must be at least 75 percent water, or some form of water, such as muddy water, salty water, oil-cut water, or gas-cut water. The constant, 20.5, is based on a standard drill-stem diameter and is equal to 0.01422 (barrels/day)/foot × 1,440 minutes/day.

Two Flow-Period Method

Where data are insufficient for a Horner plot, summary information for the test may be used to estimate permeability. Such estimates are comparable in accuracy to transmissivity values based on specific capacity values.

The Horner plot method solves the equation:

$$pw = po - \frac{162.6qv \log [(t + \Delta t)/\Delta t]}{kh} ; \tag{5}$$

where pw = well-bore pressure, in pounds per square inch;
po = undisturbed formation pressure, in pounds per square inch; and all other variables are the same as in previous equations.

Equation 5 has two unknowns, po and k. By rearrangement:

$$k = \frac{162.6qv \log [(t + \Delta t)/\Delta t]}{h\ (po - pw)} . \tag{6}$$

If the information from two flow periods and two shut-in periods is substituted simultaneously into equation 6, one of the unknowns, k, can be eliminated by setting the two new equations equal to each other and solving for po:

$$po = \frac{pw_1 \log [(t_2 + \Delta t_2)/\Delta t_2] - pw_2 \log [(t_1 + \Delta t_1)/\Delta t_1]}{\log [(\Delta t_1/\Delta t_2) \times (t_2 + \Delta t_2)\ /\ (t_1 + \Delta t_1)]} ; \tag{7}$$

where t_1 = the initial flow period, in minutes;
t_2 = the final flow period, in minutes;
Δt_1 = the initial shut-in period, in minutes;
Δt_2 = the final shut-in period, in minutes;
pw_1 = the reported pressure, in pounds per square inch during initial shut-in period; and
pw_2 = the reported pressure, in pounds per square inch during final shut-in period.

However, if it is not necessary to know the undisturbed formation pressure, equations 6 and 7 can be combined to solve directly for k:

$$k = \frac{162.6\ vq \log [(\Delta t_1/\Delta t_2) \times (t_2 + \Delta t_2)\ /\ (t_1 + \Delta t_1)]}{h\ (pw_1 - pw_2)} . \tag{8}$$

The two flow-period method will work only if certain criteria are met:

1. The initial shut-in pressure must be greater than the final shut-in pressure.

2. The ratio of initial shut-in period to initial flow period must be significantly different from the ratio of final shut-in period to final flow period.
3. The initial flow period should be at least 3 to 5 minutes.
4. The difference between the initial shut-in period and the initial flow period should be no more than about an hour.
5. The difference between the two flow periods should be no more than about 2.5 hours.

One Flow-Period Method

In drill-stem tests with an initial flow period of less than about 3 minutes or in tests where data from the presumably short initial flow period are lacking, permeability may be estimated using a method suggested by Earlougher (1977). This method uses the equation:

$$k = \frac{162.6\ qv\ \beta \log [(t + \Delta t)/\Delta t]}{h\ (pw_1 - pw_2)}\ ; \qquad (9)$$

where β = a formation constant ranging from 0.99 to 1.06 (β can be ignored if unknown because it approximately = 1); and
all other variables are the same as in previous equations.

The initial shut-in pressure also must exceed the final shut-in pressure for this method to work.

The Horner plot gives the most reliable results. Both the two flow-period method and the one flow-period method give results within an order of magnitude of the Horner plot (Jay Weigle, U.S. Geological Survey, Salt Lake City, written commun., 1986).

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