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Hydrology of the Ferron Sandstone Aquifer and Effects of Proposed Surface-Coal Mining in Castle Valley, Utah

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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

HYDROLOGY OF THE FERRON SANDSTONE AQUIFER AND EFFECTS OF PROPOSED SURFACE-COAL MINING IN CASTLE VALLEY, UTAH

By Gregory C. Lines and Daniel J. Morrissey

With a section on Stratigraphy by Thomas A. Ryer and a section on Leaching of Overburden by Richard H. Fuller

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CONVERSION FACTORS

Most numbers are given in this report in inch-pound units. For those readers who may prefer to use metric units, the conversion factors for the terms used in this report are listed below. Multiply the inch-pound unit by the factor to obtain the metric equivalent.

Inch-pound Unit (multiply)	Abbreviation	(by)	Metric unit (to obtain)
Acre		0.4047	Square hectometer
Acre-foot	acre-ft	0.001233	Cubic hectometer
Acre-foot per square mile	acre-ft/mi^2	476.1	Cubic meter per square kilometer
Cubic foot per second	ft^3/s	0.02832	Cubic meter per second
Foot	ft	0.3048	Meter
Foot per mile	ft/mi	0.1894	Meter per kilometer
Gallon per minute	gal/min	0.06309	Liter per second
Inch	in.	25.40	Millimeter
		2.540	Centimeter
Mile	mi	1.609	Kilometer
Square foot	ft^2	0.0920	Square meter
Square mile	mi^2	2.590	Square kilometer
Ton (short, 2,000 pounds)		0.9072	Megagram (metric ton)

Chemical concentration and water temperature are given in metric units. Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter (ug/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is about the same as for concentrations in parts per million.

Water temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation: °F=1.8(°C)+32.

Radioactive concentration is given in picocuries per liter, which is a unit quantity of any radioactive material in which 3.7 x 10^{-2} disintegrations occur per second (picocurie) per unit volume (liter) of water.

NATIONAL GEODETIC VERTICAL DATUM OF 1929

National Geodetic Vertical Datum of 1929 is used in this report. It is 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".

HYDROLOGY OF THE FERRON SANDSTONE AQUIFER AND EFFECTS
OF PROPOSED SURFACE-COAL MINING IN CASTLE VALLEY, UTAH

By Gregory C. Lines and Daniel J. Morrissey

ABSTRACT

Coal in the Ferron Sandstone Member of the Mancos Shale of Cretaceous age has traditionally been mined by underground techniques in the Emery Coal Field in the southern end of Castle Valley in east-central Utah. However, approximately 99 million tons are recoverable by surface mining. Ground water in the Ferron is the sole source of supply for the town of Emery, but the aquifer is essentially untapped outside the Emery area.

The Ferron Sandstone Member crops out along the eastern edge of Castle Valley and generally dips 2° to 10° to the northwest beneath the surface. Sandstones in the Ferron are enclosed between relatively impermeable shale in the Tununk and Blue Gate Members of the Mancos Shale. Along the outcrop, the Ferron ranges in thickness from about 80 feet in the northern part of Castle Valley to 850 feet in the southern part. The Ferron also generally thickens in the subsurface downdip from the outcrop. Records from wells and test holes indicate that the full thickness of the Ferron is saturated with water in most areas downdip from the outcrop area.

Tests in the Emery area indicate that transmissivity of the Ferron sandstone aquifer ranges from about 200 to 700 feet squared per day where the Ferron is fully saturated. Aquifer transmissivity is greatest near the Paradise Valley-Joes Valley fault system where permeability has been increased by fracturing. Storage coefficient ranges from about 10^{-6} to 10^{-3} where the Ferron sandstone aquifer is confined and probably averages 5×10^{-2} where it is unconfined.

The largest source of recharge to the Ferron sandstone aquifer in the Emery area is subsurface inflow from the Wasatch Plateau to the west (about 2.4 cubic feet per second during 1979), most of which moves laterally through the more permeable zone along the Paradise Valley-Joes Valley fault system. Little water is recharged to the aquifer by the 8 inches of normal annual precipitation on the outcrop area. Natural discharge from the aquifer is mainly leakage to alluvium along streams in the outcrop area and leakage to the enclosing shales in the Tununk and Blue Gate Members. Discharge from wells that tap the Ferron in Castle Valley averaged about 0.3 cubic foot per second during 1979. Discharge from the underground Emery Mine averaged about 0.7 cubic foot per second during 1979 and was the largest manmade discharge from the aquifer.

The largest quantities of water are available from the Ferron sandstone aquifer within about 2 miles of the Paradise Valley-Joes Valley fault system in the Emery area. Most wells in this area naturally flow at the land surface at rates less than 100 gallons per minute, but yields could be increased by pumping. Wells that fully penetrate the aquifer in this area could be expected to produce 100 to 500 gallons per minute if pumped. In the northern two-thirds of Castle Valley the Ferron would probably not yield more than 10 gallons per minute to individual wells.

The concentration of dissolved solids in water from the Ferron sandstone aquifer in the Emery area increases eastward from the Paradise Valley-Joes Valley fault system toward the outcrop area of the Ferron, in the general direction of ground-water movement. Dissolved-solids concentrations also increase upward in the aquifer in areas downdip from the outcrop. In the Emery area, dissolved-solids concentrations in water from the Ferron ranged from less than 500 to more than 8,000 mg/L (milligrams per liter) during 1979. Deterioration in water quality in the Emery area usually is due to increased concentrations of dissolved sodium and sulfate. In the northern two-thirds of Castle Valley, dissolved-solids concentrations usually exceed 3,000 mg/L, and several test holes and gas wells have yielded water from the Ferron with chloride concentrations greater than 10,000 mg/L and dissolved-solids concentrations greater than 20,000 mg/L.

Quitchupah Creek, near the underground Emery Mine, and Christiansen Wash, downstream from a proposed surface-coal mine in the Emery area, were gaged during the 1979 water year, and stream discharges averaged 6.7 and 2.8 cubic feet per second. There were large seasonal variations in water quality in both streams during the water year. Observed dissolved-solids concentrations at the gaging station on Quitchupah Creek ranged from 695 to 3,960 mg/L, and observed suspended-sediment concentrations ranged from 111 to 27,000 mg/L. At the station on Christiansen Wash, observed dissolved-solids concentrations ranged from 582 to 4,470 mg/L and suspended-sediment concentrations ranged from 3 to 4,870 mg/L.

A three-dimensional digital-computer model was used to simulate ground-water flow in the Ferron sandstone aquifer in the Emery area. The model also was used to predict the effects of dewatering of a proposed surface mine on aquifer potentiometric surfaces and the base flow of streams. The computer model was calibrated with water-level data collected during 1979. Mainly because it was not possible to verify the model with historic data for aquifer response to manmade discharges, predictions made with the model are considered to be semiquantitative.

Discharge from the proposed surface mine is predicted to average about 0.3 cubic foot per second during the 15 years of mine operation. Dewatering of the mine would affect the potentiometric surfaces of all sections of the Ferron sandstone aquifer, but the greatest effects would be in the upper section. Drawdowns in the potentiometric surface of the upper section of the aquifer greater than 5 feet are predicted to extend about 2 miles from the surface mine after 15 years of operation. Mine dewatering would also induce downward leakage of water into the Ferron from shale in the Blue Gate Member, and this could cause a deterioration in water quality in the upper section of the aquifer in some areas. West of the surface mine, however, the quality of water in the upper section of the aquifer might improve as the amount of saline water leaking downward from the Blue Gate Member would be small in comparison to the amount of water that would move laterally through the aquifer from the west.

Modeling results indicate that, except for Christiansen Wash, the dewatering of the proposed surface mine would not affect the base flow of streams. If water from the mine were discharged into Christiansen Wash, the base flow would increase accordingly. The dissolved-solids concentration of water in Christiansen Wash also would be increased, at least during some periods, if mine water were discharged into the stream.

Laboratory experiments indicate that if only precipitation were allowed to infiltrate mine spoil, water in the spoil would be of better quality than most ground water in the mine area and about the same quality as water in Christiansen Wash. However, the management of the spoil to reduce surface-water infiltration and spoil placement so that pyritic material is mixed with calcareous material would minimize the deterioration of water quality in Christiansen Wash.

Sediment loads of streams downstream from the mine would not increase significantly if reclaimed slopes were graded to the least possible angle, if revegetation were prompt so as to stabilize the stockpiled topsoil and backfilled overburden, if runoff were channeled from the disturbed mine area through sediment ponds, and if Christiansen Wash were permanently diverted around the mine area. The long-term sediment yield from the disturbed area could actually decrease if vegetative cover were improved from premining conditions and if sediment ponds were properly maintained.

INTRODUCTION

Problem and objectives

Coal traditionally has been recovered by underground-mining techniques in the Emery Coal Field in the southern end of Castle Valley in east-central Utah. (See figs. 1 and 2.) The coal is in a number of seams in the Ferron Sandstone

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Figure 1 (caption on next page) near here

Member of the Mancos Shale of Cretaceous age. The total coal resource of the area has been estimated at 2.06 billion tons (Doelling, 1972, p. 437). Of this total, approximately 99 million tons is recoverable by surface-mining techniques (Affolter and others, 1979, p. 1), and plans have been made for a surface mine in the area.

Ground water from the Ferron sandstone aquifer is the sole source of supply for the town of Emery (population about 370). Water from the Ferron also is used for stock watering, for a small amount of irrigation, and for a coal-washing plant in the southern end of the Emery Coal Field. The aquifer is essentially unused in the northern two-thirds of Castle Valley.

Water supplies throughout Castle Valley are being stressed by increased population that is associated with the increase in coal production from not only the Emery Coal Field but also nearby coal fields in the Wasatch Plateau and Book Cliffs. In addition to three existing coal-fired powerplants now in operation in Castle Valley, a coal-gasification plant has been proposed near Emery. The gasification plant reportedly will require 5 million tons of coal and 10,000 acre-feet of water per year.

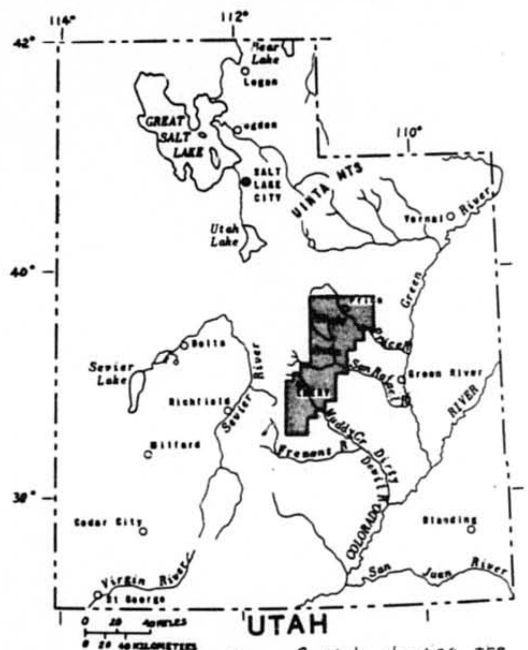

Figure 1.--Map of Utah showing the study area.

In order to anticipate the effects of increased coal mining and related energy developments on the hydrology of the area, the U.S. Geological Survey in cooperation with the U.S. Bureau of Land Management conducted a study from October 1977 through September 1980. The objectives of the study were to determine: (1) the aquifer characteristics, recharge-discharge relationships, and the quantity and quality of water that is available from the Ferron sandstone aquifer in Castle Valley; (2) the effects of proposed surface-coal mining and associated mine dewatering on existing wells and springs, on the base flow and quality of water in streams, and on the quality of water in the Ferron sandstone aquifer; and (3) the effects of solution and erosion of stockpiled overburden at the proposed surface mine on the quality of surface water and stream aquatic life.

Methods of investigation

Fieldwork for the study was started in October 1977 and concluded in January 1980. During this time a complete well inventory was made in Castle Valley. Wells, test holes, and springs in Castle Valley where ground-water data are available are shown in figure 2. As part of the study, 16 observation wells were constructed

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from a number of sources, including abandoned seismic-test holes and coal-test holes that were drilled by the Bureau of Land Management and the Geological Survey. In addition, four test holes were drilled and tested with expandable packers in the Emery area.

In the Emery area, the water level or shut-in water pressures were measured monthly at 18 wells. In addition, water-level data were obtained at about 40 other sites during the course of the study.

Figure 2.--Map showing location of selected wells, springs, and test holes in and near Castle Valley, Utah, where ground-water information is available, 1980.

Instantaneous discharge of the pump that dewaters the underground Emery Mine was measured three times, and total discharge was calculated from records of pumping time supplied by Consolidation Coal Co. Withdrawals from the Emery municipal well were obtained from meter records supplied by town officials, and the discharge of other wells were measured.

Aquifer tests were conducted at nine locations to provide information on the hydraulic properties of the Ferron sandstone aquifer. Four of the tests involved a pumping well and at least one observation well, and the other tests were conducted at flowing wells or test holes.

Water samples for determination of dissolved inorganic chemical constituents were collected from about 60 wells, test holes, and springs in Castle Valley. Water samples were also collected from seepage areas in the Emery Mine. In an attempt to determine the age of water in the Ferron sandstone aquifer, carbon-14 and tritium determinations were made for water collected in the Emery Mine and from selected wells.

As part of the hydrologic monitoring in coal areas by the Geological Survey, stream-gaging stations were installed on Christiansen Wash and Quitchupah Creek near the Emery Mine and the proposed surface mine. The stations were operational by August 1978. Water samples were collected monthly for determination of major inorganic chemical constituents and quarterly for determinations of suspended-sediment concentration, nutrients, trace metals, and benthic invertebrates. To supplement the scheduled quarterly sampling, additional sediment samples were collected during floods and during periods of high runoff in the spring.

Laboratory experiments were conducted to determine which minerals could be leached from the rocks that overlie the strippable coal at the proposed surface mine. The rock samples were obtained from cores collected at test holes drilled for the Bureau of Land Management. Other laboratory work included determinations of porosity, horizontal and vertical hydraulic conductivity, and grain size of core samples that were typical of rocks in the Emery Coal Field.

A three-dimensional digital-computer model of the Ferron sandstone aquifer was developed to evaluate the effects of dewatering the proposed surface mine on the potentiometric surface of the aquifer and the base flow of streams.

Previous investigations

Lupton (1916) conducted a comprehensive study of the geology and coal resources of Castle Valley. Additional geologic information on the Emery Coal Field was presented by Doelling (1972). Information on the stratigraphy and depositional history of the Ferron Sandstone Member was presented by Katich (1951, 1953, and 1954), Davis (1954), Hale (1972), and Cotter (1975a, b and 1976).

Ground water in bedrock aquifers in the Colorado Plateau, including the Ferron sandstone aquifer, was described by Feltis (1966). During the 1970's, several hydrologic studies were conducted in Castle Valley. The quality of surface water in the Price River and Dirty Devil River basins was described by Mundorff (1972 and 1979). Hydrologic conditions in the Wasatch Plateau and Book Cliffs Coal Fields were described by Waddell, Contratto, Sumsion, and Butler (1979). Some hydrologic data from the Emery area are included in reports by Waddell, Vickers, Upton, and Contratto (1978) and Sumsion (1979). Reclamation of possible surface-mine lands in the Emery Coal Field was described by Geoscientific Systems and Consulting (1979).

Acknowledgments

The writers wish to express their appreciation to Consolidation Coal Co., Hidden Valley Coal Co., and Western States Minerals Co. for supplying geologic and hydrologic information from their testing and monitoring programs and for allowing access to their property for test drilling and other studies. We are grateful to the townspeople of Emery for supplying records of water use and for allowing an aquifer test to be conducted on the municipal well. Thanks are also given to the many landowners in Castle Valley who granted permission to drill test holes and to sample and test wells.

Well-, spring-, and site-numbering system

The system of numbering wells and springs in Utah is based on the cadastral land-survey system of the U.S. Government. The number, in addition to designating the well or spring, describes its position in the land net. By the land-survey system, the State is divided into four quadrants by the Salt Lake base line and meridian, and these quadrants are designated by the uppercase letters A, B, C, and D, indicating the northeast, northwest, southwest, and southeast quadrants, respectively. Numbers designating the township and range (in that order) follow the quadrant letter, and all three are enclosed in parentheses. The number after the parentheses indicates the section, and is followed by three letters indicating the quarter section, the quarter-quarter section, and the quarter-quarter-quarter section--generally 10 acres_/; the letters a, b, c, and d indicate, respectively, the northeast, northwest, southwest, and southeast quarters of each subdivision. The number after the letters is the serial number of the well or spring with the 10-acre tract; the letter "S" preceding the serial number denotes a spring. If a well or spring cannot be located within a 10-acre tract, one or two location letters are used and the serial number is omitted. Thus (D-22-6)23adb-1 designates the first well constructed or visited in the NW¼SE¼NE¼ sec 23, T. 22 S., R. 6 E. Other sites where hydrologic data were collected are numbered in the same manner, but three letters are used after the section number and no serial number is used. The numbering system is illustrated in figure 3.

_/Although the basic land unit, the section, is theoretically 1 mi^2, many sections are irregular. Such sections are subdivided into 10-acre tracts, generally beginning at the southeast corner, and the surplus or shortage is taken up in the tracts along the north and west sides of the section.

Figure 3 (caption on next page) near here

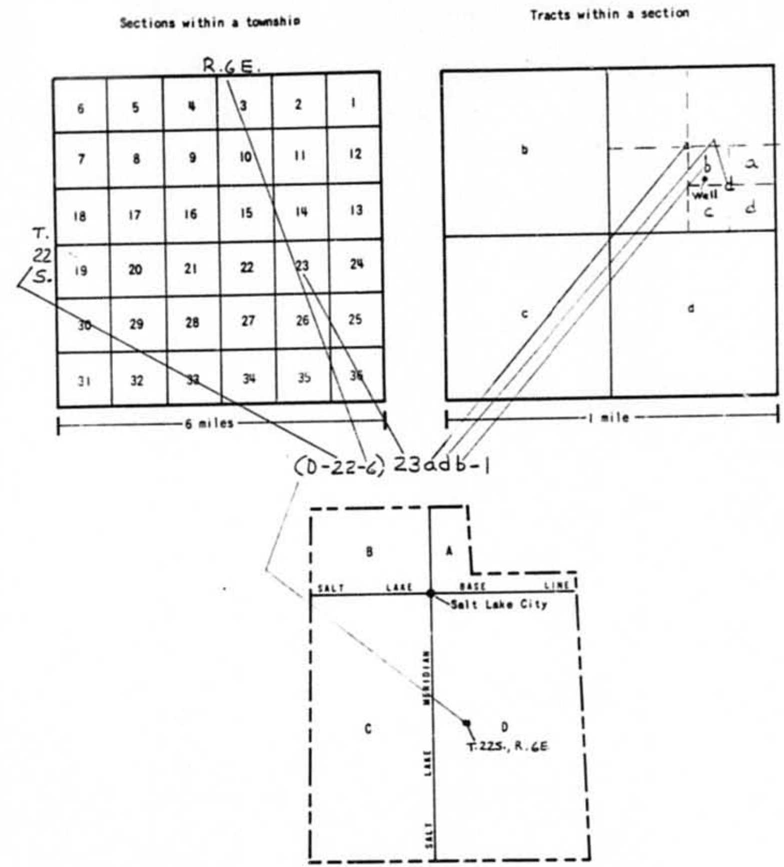

Figure 3.-- Well-, spring-, and site-numbering system used in Utah.

STRATIGRAPHY

The Ferron Sandstone Member of the Mancos Shale, the coal-bearing unit in the Emery Coal Field, is exposed in a series of prominent cliffs in the southern part of Castle Valley. The escarpment produced by the Ferron defines the eastern limit of Castle Valley. The Ferron cliffs attain their maximum development between the town of Moore and the southern end of Castle Valley. The thickness of the Ferron generally increases southward from about 300 feet near Moore to about 850 feet near the southern end of Castle Valley. (See fig. 4.) The Ferron dips 2° to 10° to the northwest beneath the surface of Castle Valley. The altitude of the top of the Ferron is shown in figure 5.

Figures 4 and 5 (captions on next page) near here

In the area between Moore and the southern end of Castle Valley, the Ferron consists of massive beds of very fine to medium-grained, delta-front sandstone, prodelta mudstones, and a wide variety of delta-plain rock types (mainly carbonaceous shale, coal, mudstone, siltstone, and thin-bedded, rippled, very fine grained sandstone). The Ferron outcrop along Quitchupah Creek near Emery is shown in figure 6.

Figure 6 (caption on next page) near here

Figure 4.--Map showing the thickness of the Ferron Sandstone Member of the Mancos Shale in Castle Valley, Utah.

Figure 5.--Map showing the altitude of the top of the Ferron Sandstone Member of the Mancos Shale in Castle Valley, Utah.

Figure 6.--Outcrop of the Ferron Sandstone Member of the Mancos Shale along Quitchupah Creek near Emery. View facing north.

Figure 6.--The outcrop of the Ferron Sandstone Member of the Mancos Shale along Quitchupah Creek near Emery.

North of Moore, the Ferron escarpment gradually becomes more subdued until, at the latitude of Castle Dale, the Ferron is represented by a pair of units of very fine grained, silty sandstone each about 50 feet thick. The upper unit of this pair, shown in figure 7, crops out continuously along the east side of

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Castle Valley from about Emery to as far as Wellington at the northern end of Castle Valley. The lower unit pinches out northward near the town of Cleveland. One or more ledge-forming units of very fine grained sandstone and sandy siltstone occur at the stratigraphic level of the Ferron between Wellington and the Utah-Colorado State line, and these are mapped collectively as Ferron Sandstone Member on the geologic map of Utah (Stokes, 1964).

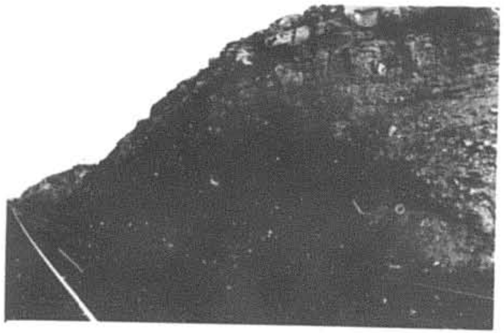

Figure 7.--Outcrop of the Washboard Unit of Cotter (1975a) of the Ferron Sandstone Member of the Mancos Shale along U.S. Highway 6 southeast of Wellington.

The first, and still the most comprehensive study of the geology and mineral resources of the Ferron Sandstone Member was conducted by Lupton (1916). Minor modification and updating of Lupton's coal-resource calculations were made by Doelling (1972). Lupton (1916, p. 31) named the Ferron Sandstone Member for exposures "in the vicinity of Ferron and Emery." Though he cited no type locality for the member, a section along Ivie Creek, about 8 miles south of Emery, was presented as representative. It is clear from Lupton's description of the stratigraphy of the Ferron (1916, p. 31-33) that he considered the pair of very fine grained sandstones in the northern part of Castle Valley to be a northward extension of the thicker, coal-bearing sequence of strata exposed near Emery. Later work by Katich (1951, 1953, and 1954), Davis (1954), and Cotter (1975 a h and 1976) demonstrate that this is not the case. The pair of Ferron units of northern Castle Valley are about 100 feet stratigraphically lower than the lowest delta-front sandstone of the Ferron Sandstone Member that crops out south of Emery, and they pinch out toward the south into the marine shale of the Tununk Member of the Mancos. (See fig. 8.) The two Ferron units of northern Castle

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Valley were informally named, in ascending stratigraphic order, the Clawson and Washboard units of the Ferron Sandstone Member by Cotter (1975a). Cotter's informal names are used in this report.

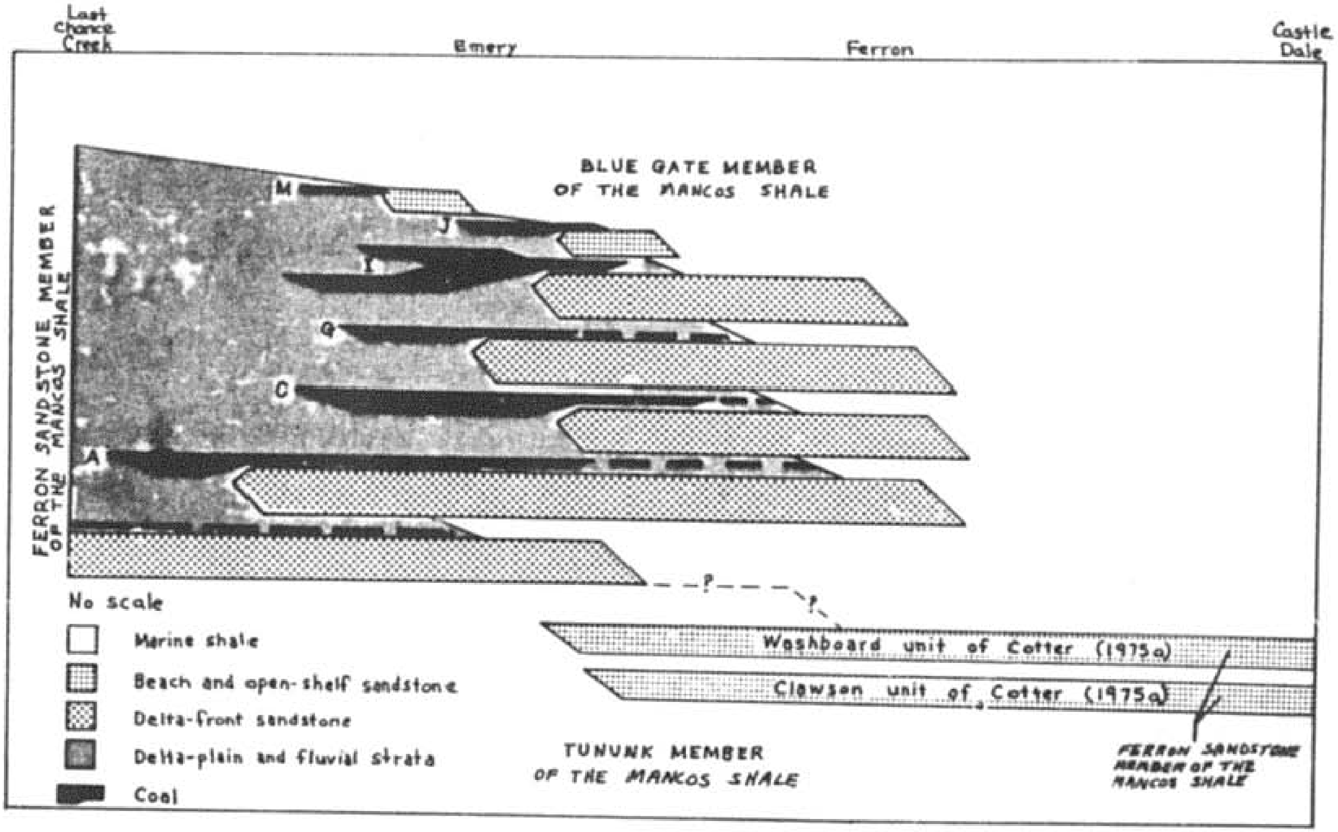


Figure 8.-- Diagrammatic southwest-northeast section showing stratigraphic relationships of the various units of the Ferron Sandstone Member and the Tununk and Blue Gate Members of the Mancos Shale in Castle Valley. Major coal beds carry the letter designations of Lupton (1916).

The Ferron Sandstone Member in Castle Valley, then, contains two parts that are stratigraphically distinct and of different origin. The older, stratigraphically lower part of the Ferron consists of a pair of units of very fine grained, silty sandstone that accumulated in a shallow, open-marine environment situated well offshore. These units are the Clawson and Washboard units of Cotter (1975a). They are separated from the younger, upper part of the Ferron by as much as 100 feet of marine shale. The upper part of the Ferron, the product of deposition in a delta system, is characterized by massive beds of very fine to medium-grained sandstone and beds of coal. The upper part of the Ferron thins to the north, interfingers with marine shale of the Blue Gate Member of the Mancos Shale, and finally pinches out between Ferron and Castle Dale. The two parts of the Ferron are not differentiated on the thickness and structure contour maps (figs. 4 and 5). The outcrop areas of the Ferron Sandstone Member and other geologic units in the Emery area are shown in figure 9.

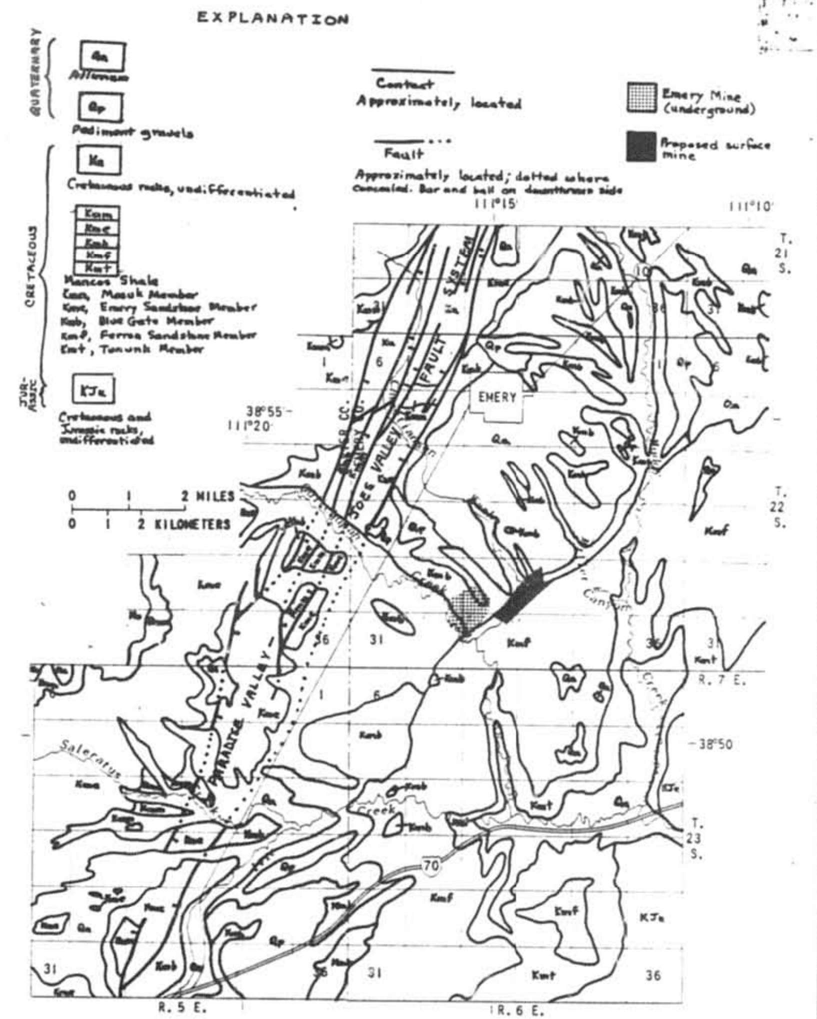
Figure 9 (caption on next page) near here

FERRON SANDSTONE AQUIFER

Aquifer characteristics

Thickness

The Ferron sandstone aquifer in Castle Valley consists of the whole thickness of the Ferron Sandstone Member. The thickness of the Ferron varies considerably in the study area (fig. 4). Along the outcrop, the Ferron thickness varies from about 80 feet in the northern part of Castle Valley near Mounds to 850 feet in the southern part along Last Chance Creek (Lupton, 1916, pl. IV). The Ferron also generally thickens in the subsurface downdip from the outcrop area.



Geology from Williams and Hackman (1971); modified by G.C. Lines, 1980.

Figure 9.-- Geology of the Emery area.

Records from wells and test holes indicate that a short distance from the outcrop area, the complete thickness of the Ferron is usually saturated with water. In the area of the proposed surface coal mine near Emery, the saturated thickness of the Ferron is about 450 feet. In the outcrop area, not all the Ferron is saturated with water; and at the higher altitudes along the outcrop, much of it is unsaturated.

Hydraulic conductivity[1]

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[1] The hydraulic conductivity of a water-bearing material is the volume of water that will move through a unit cross section of the material in unit time under a unit hydraulic gradient. The units for hydraulic conductivity are cubic feet per day per square foot $[(ft^3/d)/ft^2]$, which reduces to ft/d. The term hydraulic conductivity replaces the term field coefficient of permeability, which was formerly used by the Geological Survey and which was reported in units of gallons per day per square foot. To convert a value of field coefficient of permeability to the equivalent value of hydraulic conductivity, divide by 7.48; to convert from hydraulic conductivity to coefficient of permeability, multiply by 7.48.

Hydraulic conductivity was determined in the laboratory for 17 rock samples from the Ferron Sandstone Member obtained from core holes in the Emery area. Hydraulic conductivity was determined in horizontal and vertical directions for 15 of the samples, porosity was determined for all but one sample, and grain size was determined for 10 sandstone samples.

Results of the laboratory determinations are summarized in table 1. The

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data indicate a large variation in the porosity and hydraulic conductivity of the sandstone. This may be due to differences in cementation and compaction between samples. Unconsolidated sand, similar in size and sorting, would have a porosity of about 40 percent (Johnson, 1967, fig. 3) as compared to the average of 16 percent for the sandstone in the Ferron.

In all the sandstone samples, the difference between horizontal and vertical hydraulic conductivities was less than one order of magnitude. The average hydraulic conductivity of delta-front sandstone samples was 1.0×10^{-1} ft/d in the horizontal direction and 9.1×10^{-2} ft/d in the vertical. Similarly, hydraulic conductivity of the fluviatile sandstone samples averaged 1.5×10^{-1} ft/d in the horizontal direction and 9.9×10^{-2} ft/d in the vertical. Hydraulic conductivity of the shale and siltstone samples was much less than that of most of the sandstones, and it averaged 3.8×10^{-4} ft/d in the horizontal direction and 1.3×10^{-5} ft/d in the vertical.

Transmissivity_/

_/Transmissivity is the rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient. The units for transmissivity are cubic feet per day per foot [$(ft^3/d)/ft$], which reduces to ft^2/d. The term transmissivity replaces the term coefficient of transmissibility, which was formerly used by the Geological Survey and which was reported in units of gallons per day per foot. To convert a value for coefficient of transmissibility to the equivalent value of transmissivity, divide by 7.48; to convert from transmissivity to coefficient of transmissibility, multiply by 7.48.

Nine aquifer tests were conducted on the Ferron sandstone aquifer in the Emery area, and the results are summarized in table 2. Considering the thickness and

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lithology of the aquifer tapped by the discharging well at each test site, some transmissivity values calculated from the te[illegible] gree fairly well with what would be expected from the hydraulic conductivities determined in the laboratory. In some cases, particularly at test sites near the Paradise Valley-Joes Valley fault system, the computed transmissivities of several hundred feet squared per day are larger than would be expected from the laboratory data. This is believed to be due to secondary permeability in the form of fractures.

None of the test wells fully penetrate the Ferron sandstone aquifer. However, where the Ferron is extensively fractured, thus increasing hydraulic connection in the aquifer, the computed transmissivities of several hundred feet squared per day fairly accurately represent the transmissivity of the full thickness of the aquifer. Tests that were conducted more than about 2 miles from the Paradise Valley-Joes Valley fault system usually indicated transmissivities of 100 ft^2/d or less. Computed transmissivities from these tests probably most accurately represent the transmissivity of only a partial thickness of the aquifer because hydraulic connection is not as great as along the fault system.

Test results in the Emery area indicate that transmissivity of the Ferron sandstone aquifer ranges from about 200 to 700 ft^2/d downdip from the Ferron outcrop. (Compare figs. 9 and 10.) Transmissivity is less than 200 ft^2/d in

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the outcrop area of the Ferron. The decrease in transmissivity in the outcrop area is due mainly to the decrease in the saturated thickness of the aquifer rather than a decrease in hydraulic conductivity.

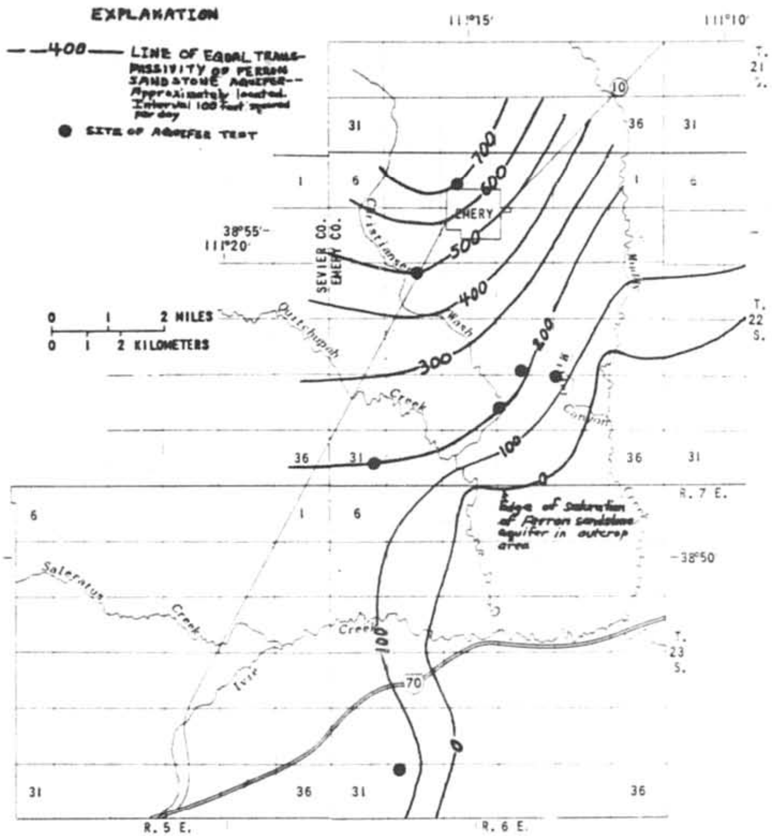

Figure 10.--Transmissivity of the Ferron sandstone aquifer in the Emery area.

The transmissivity values in figure 10 were based on data from aquifer tests, lithologic information, and estimates of saturated thickness in the outcrop area. Because of secondary permeability and the nonhomogeneous nature of the aquifer, the lines of equal transmissivity are considered to be approximate. Figure 10 is presented only to depict the general pattern of increasing transmissivity from the outcrop area toward the Paradise Valley-Joes Valley fault system. Calibration of a three-dimensional digital-computer model of the Ferron sandstone aquifer indicated that the aquifer was simulated most accurately when transmissivity values north of about the 200-ft^2/d line in figure 10 were reduced by 10-30 percent. The model is discussed in a following section of this report and is documented by Morrissey, Lines, and Bartholoma (1980).

Storage

Water in the Ferron sandstone aquifer is confined, except for possibly a few areas in the outcrop and in the upper part of the aquifer near the Emery Mine. The water is confined under pressure between shale and siltstone beds within the aquifer and between the enclosing shales in the Blue Gate and Tununk Members of the Mancos Shale. Where a well taps the confined aquifer, water is released from storage mainly by compression of the sandstone and less permeable confining beds as pressure in the aquifer declines. The quantity of water that can be released from storage from the Ferron sandstone aquifer is dependent upon the storage coefficient_/, which ranges from about 3×10^{-6} to 2×10^{-3} in the confined parts of the aquifer (table 2).

_/The storage coefficient of an aquifer is the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in head. Storage coefficient is a dimensionless number. Under confined conditions, the storage coefficient is typically small, generally between 10^{-5} and 10^{-3}. Under unconfined conditions, it is much larger, typically between 5×10^{-2} and 3×10^{-1}.

Where a well taps the unconfined aquifer, water is released from storage mainly by gravity drainage; and the storage coefficient is virtually equal to the specific yield. Aquifer tests were not conducted in an unconfined part of the Ferron sandstone aquifer. However, other studies (Johnson, 1967) have found that specific yield varies from about 0.01 in shales to about 0.1 in sandstones that are similar to those in the Ferron. Because the Ferron consists of both sandstone and shale, storage coefficient in the unconfined parts of the aquifer probably averages about 0.05.

Potentiometric surfaces

The potentiometric surface (the level to which water rises in tightly cased wells) varies appreciably with depth in the Ferron sandstone aquifer. Where data permit, more than one potentiometric surface is defined in order to describe the distribution of head_/ in the aquifer.

_/Head is defined by Lohman and others (1972, p. 7) as "the height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point." The head is the sum of the elevation head and the pressure head. Under conditions to which Darcy's law may be applied, the velocity of ground water is so small that the velocity head is negligible.

Except for the Emery area, data are lacking in Castle Valley to define the distribution of head in the Ferron sandstone aquifer and surrounding rocks. On a regional scale, however, the distribution of head in the Ferron may be similar to that in the Emery area. Petroleum-test hole (D-17-7)25ddc-1 penetrated the Ferron in the northern part of Castle Valley about 9 miles from the outcrop area; and water reportedly flowed from the hole at land surface, which was at an altitude of 7,040 feet. (See table 5.) The water level in well (D-17-10)16dda-1, which penetrates the Ferron only about 1 mile from the outcrop area, was within a few feet of land surface during 1979 at an altitude of about 5,670 feet. Information from these two sites indicates that head in the Ferron increases downdip from the outcrop area. This is consistent with head distribution observed near Emery, which is discussed in detail in the following sections of the report.

In the Emery area, downdip from the outcrop of the Ferron, head in the Ferron sandstone aquifer generally increases with depth. In most of this area, head in the Ferron is above the water table in overlying rocks. In the outcrop area of the Ferron, where there is a small amount of recharge from precipitation and where water from the Ferron leaks downward into the underlying Tununk Member, head in the aquifer decreases with depth.

Basal section

Figure 11 shows the configuration of the potentiometric surface of the basal

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Figure 11 (caption on next page) near here

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section of the Ferron sandstone aquifer (below the A-coal seam) in the Emery area. The contours are based on measurements of different accuracy. The potentiometric surface was determined accurately at 11 sites--in tightly cased wells that tap only the basal section and in uncased test holes drilled for the Geological Survey where an expandable packer was used to isolate the basal section.

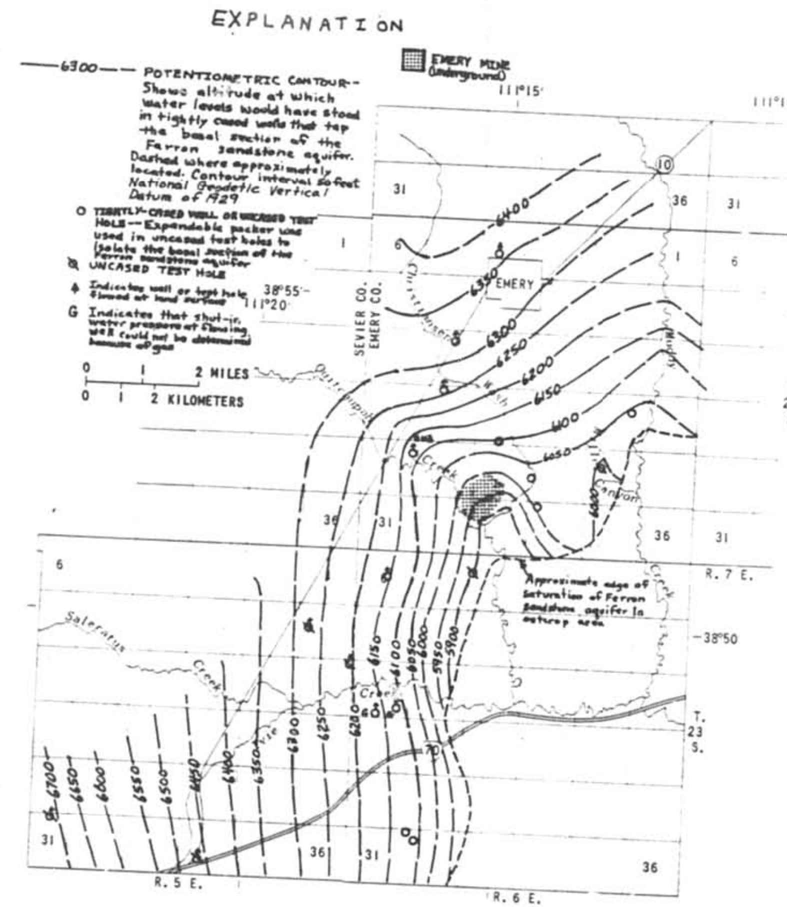

Figure 11.--Potentiometric surface of the basal section of the Ferron sandstone aquifer in the Emery area, 1979.

Data from six other uncased test holes that penetrated the basal section also were considered in drawing the potentiometric contours. Downdip from the outcrop of the Ferron, four of the test holes flowed at land surface. Because the holes were uncased, no shut-in pressures were measured. Thus, the only thing known of the potentiometric surface was that it was at a higher altitude than land surface. Water levels also were measured, or obtained from an electric log, in two nonflowing test holes that penetrated the basal section. Because the holes were not cased through the upper coal-bearing section of the Ferron Sandstone Member and the Blue Gate Members, water levels in the holes probably did not accurately represent the altitude of the potentiometric surface of the basal section of the Ferron sandstone aquifer. In most areas, except on the outcrop of the Ferron, the potentiometric surface of the basal section was probably at significantly higher altitudes (as much as 150 feet at one packer-test site) than the water levels in the uncased holes. Nevertheless, the water-level data from the six uncased test holes were useful in drawing the potentiometric contours, as the water levels in most cases represented the minimum altitudes to which water would have risen had the test holes been tightly cased.

Upper section

Configuration of the potentiometric surface of the upper section of the Ferron sandstone aquifer (above the base of the I-coal seam) is shown in figure 12. Near the Emery Mine, many coal-test holes have been cased and are open only

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to the upper section. In addition, packer tests were conducted in two Geological Survey uncased test holes to determine the potentiometric surface of the upper section.

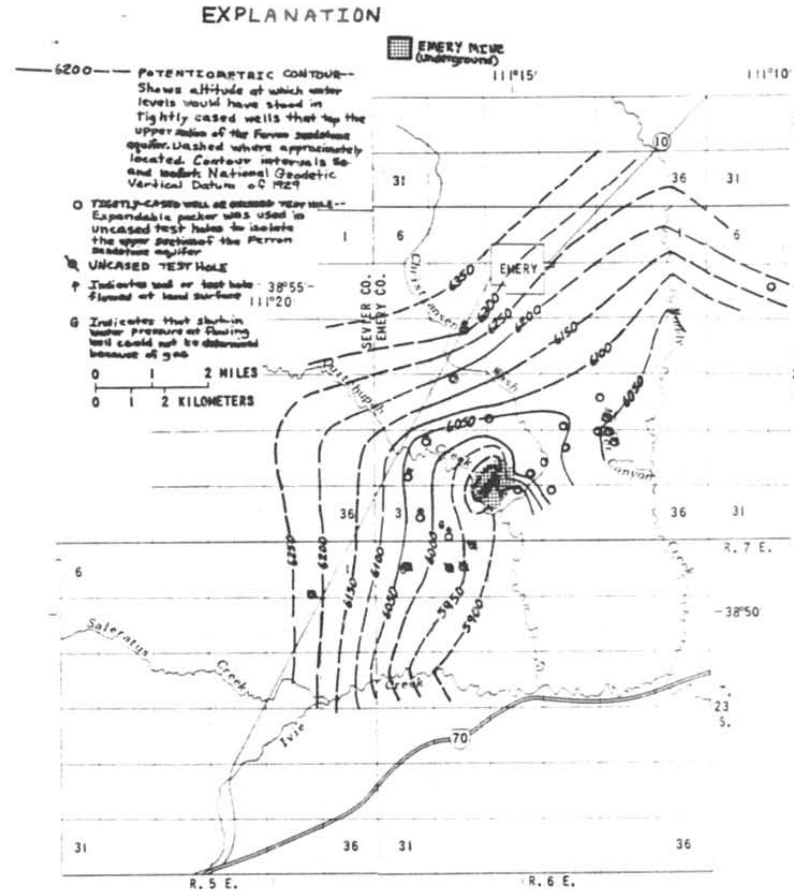

Figure 12.-- Potentiometric surface of the upper section of the Ferron sandstone aquifer in the Emery area, 1979.

In addition to water levels measured in wells and test holes, the altitude of the I-coal seam in the Emery Mine was also considered in drawing potentiometric contours for the upper section. Observations in the mine indicate that the aquifer has been dewatered above much of the I-seam. Water production in the mine during 1979 was concentrated in those areas farthest downdip, near the working faces at the I-seam. Much of the old mine workings produced no water.

Most of the water-level data from which the potentiometric-surface maps in figures 11 and 12 were derived were collected during 1979. However, some of the data from coal-test holes are 4 to 5 years older. Even though these earlier data were used to compile the maps, the configurations of the potentiometric surfaces should fairly well represent conditions that existed in 1979.

It should be noted that the Ferron sandstone aquifer has yielded hydrogen sulfide gas and occasionally methane or carbon dioxide gas to some wells in the Emery area. When the wells flowed at the land surface, it was not possible to accurately determine shut-in pressures because of the gas.

Adjacent water-bearing zones

The approximate configuration of the water table (the level at which pressure is atmospheric) in rocks that overlie the Ferron sandstone aquifer in the Emery area is shown in figure 13. The altitude of the water table in rocks that overlie

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Figure 13 (caption on next page) near here

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the Ferron is defined in order to determine the direction of vertical movement of water. During the summer of 1979, the water table in many areas was in the Blue Gate Member; but on the benches north of Quitchupah Creek, the water table was commonly in pediment gravels and alluvium. Water-level data were available from 11 wells and test holes to define the water table. Along perennial streams and irrigation canals and at springs that issue from the Blue Gate and pediment gravels, the water table was assumed to be at the altitude of land surface. Along ephemeral streams, the water-table contours were drawn at an altitude below land surface. The water table was assumed to be within 50 feet of land surface in areas with phreatophytic growth.

No data are available to define the distribution of head in the Tununk Member which underlies the Ferron sandstone aquifer. It is believed that in those areas where head in the overlying Ferron increases with depth, head in the Tununk also increases with depth. In most areas, the potentiometric surface of the upper part of the Tununk is probably at a slightly higher altitude than the potentiometric surface of the basal Ferron. In the Ferron outcrop area, head in the aquifer decreases with depth and is probably a few feet higher than the potentiometric surface of the upper part of Tununk.

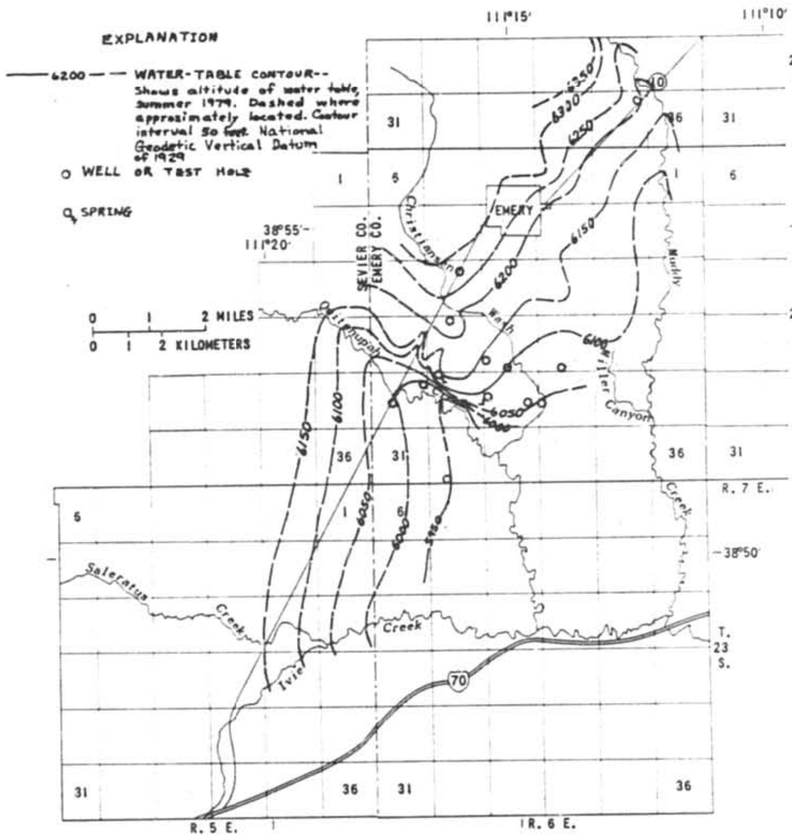

Figure 13.--Configuration of the water table in rocks that overlie the Ferron sandstone aquifer in the Emery area, 1979.

Water-level changes

Monitoring of water levels in the Emery area started in 1975. During the course of this study, additional observation wells were constructed, and water levels or shut-in pressures were measured monthly in 18 wells. Little water-level data exist for the years prior to 1975; thus, an evaluation of long-term changes is not possible.

Water-level hydrographs for four representative wells in the Emery area are shown in figure 14. Well (D-22-6)17abc-1 is unused, and it taps the basal

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section of the Ferron sandstone aquifer. The well is about 2 miles from the Emery public-supply well, which also taps the basal section. Except for seasonal fluctuations, water pressure at the well declined from mid-1975 through 1979, with a net decline of 7 feet. When the well was drilled in May 1973, water pressure was reported as 74 feet above land surface, as contrasted to a measured water pressure of 41 feet above land surface in December 1979.

Well (D-22-6)23bcc-1 bottoms in the basal section approximately 2.5 miles from the Emery Mine. Casing perforations in the well are below the Blue Gate Member, and the well taps both the basal and upper sections of the Ferron sandstone aquifer. The net water-level decline was about 16 feet from mid-1975 through 1979.

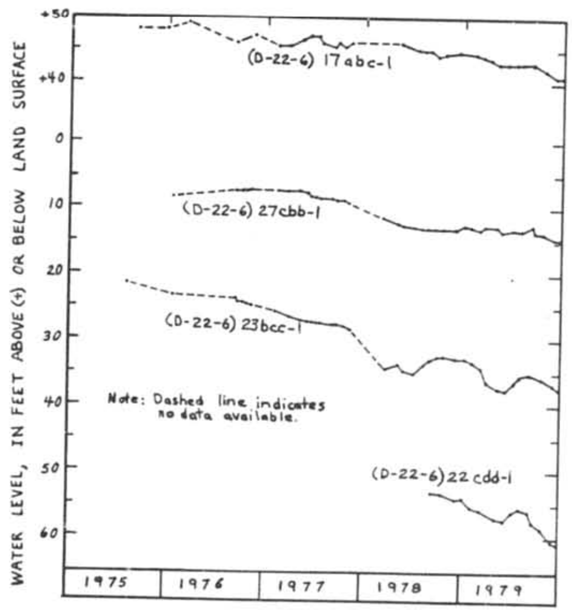

Figure 14.--Water-level changes in four wells that tap the Ferron sandstone aquifer in the Emery area.

Well (D-22-6)27cbb-1 also bottoms in the basal section, but the top perforations in the well casing are opposite the Blue Gate Member. The well is in the proposed surface-mine area about 1 mile from the Emery Mine. Water levels in nearby wells that were constructed during this study indicate that the water level in well (D-22-6)27cbb-1 closely approximates the altitude of the water table in the Blue Gate. From early 1976 through 1979 the water level in the well has dropped about 5 feet.

Well (D-22-6)22cdd-1 is a[illegible] mile from the northwestern edge of the proposed surface mine. The w[illegible] in a shale immediately below the I-coal seam at a depth of 275 feet. The upper 100 feet of the hole was cemented around the casing to seal off water in the Blue Gate, and the water level in the well represents the potentiometric surface of the upper section of the Ferron sandstone aquifer. The water level in the well declined about 8 feet from the date of its construction in the summer of 1978 through 1979.

Precipitation at long-term U.S. Oceanic and Atmospheric Administration stations in and near Castle Valley and at rain gages installed for this study indicate that precipitation in the area between 1975 and 1979 was about 90 percent of normal and averaged about 7 inches per year in the Emery area. Below-average precipitation in the area can explain some of the declines in water levels, but most of the declines probably are due to manmade withdrawals of water from the Ferron sandstone aquifer.

Movement and age of water

Water moves laterally through the Ferron sandstone aquifer downgradient at approximately right angles to the potentiometric contours shown in figures 11 and 12. On a regional scale, the strike and dip of beds in the aquifer have little effect on the movement of water. Movement of water is governed instead by the location and altitude of sources of recharge and discharge. In the Emery area, water moves through the aquifer from areas of subsurface recharge in the west and northwest toward areas of manmade discharge and toward areas of natural discharge along the Ferron outcrop.

The rate at which water moves laterally through the aquifer can be estimated from the following equation (Lohman, 1972, p. 10):

$$V = \frac{KI}{\theta}$$

where V = velocity, in feet per day,

K = hydraulic conductivity, in feet per day,

I = hydraulic gradient, a decimal fraction, and

θ = effective porosity, a decimal fraction.

Assuming a hydraulic conductivity of 1 ft/d, a hydraulic gradient of 50 ft/mi or 0.0095, and an effective porosity of 5 percent, then

$$V = \frac{(1 \text{ ft/d})(0.0095)}{0.05}$$

$$V = 0.2 \text{ ft/d (rounded)}$$

It should be stressed that 0.2 ft/d would be the average fluid velocity through the aquifer at the assumed conditions. It does not necessarily equal the actual velocity between any two points in the aquifer, which would depend on the flow path followed. Water moving along an open fracture would move much faster than water moving through pore spaces between sand grains.

Water samples from the basal section of the Ferron sandstone aquifer were obtained from well (D-22-6)17abc-1 and Geological Survey test hole (D-23-6)6acc-1, and carbon-14 dating of the two samples indicated ages of 28,000 and 31,000 years. Between the recharge area and sampling points, solution of carbonate rocks is a possible source of error in the dating technique. Carbonate dissolved from rocks would be depleted of the carbon-14 radioisotope. The degree to which this process is taking place is unknown, but it is safe to assume that the dating indicates the maximum possible age.

In addition to lateral flow through the Ferron sandstone aquifer, potentiometric-surface data also indicate that significant vertical components of flow exist. Along the outcrop of the Ferron, where a small amount of recharge from precipitation occurs, water moves downward through the aquifer and some water leaks into the underlying Tununk Member. In most areas downdip from the outcrop, head in the aquifer increases with depth, and water moves upward into the Blue Gate Member.

Dewatering of the Emery Mine (the largest manmade discharge from the Ferron sandstone aquifer) has induced movement of water toward the mine from all sections of the aquifer. Most water produced from the mine has come from the upper section of the aquifer, but the potentiometric surface of the basal section also has been affected.

Two water samples were collected from seepage areas in the roof of the Emery Mine and were analyzed for concentrations of tritium (a radioisotope of hydrogen with an atomic weight of 3). Both samples contained detectable concentrations of tritium--12 and 21 picocuries per liter (Teledyne Isotopes, written commun., November 2, 1979). Prior to testing of nuclear weapons in the early 1950's, natural tritium levels were about 26 picocuries per liter. Tritium levels reached a peak in the Northern Hemisphere in 1963 when concentrations in the atmosphere exceeded the natural level by approximately three orders of magnitude (Thatcher and others, 1977, p. 8). Because tritium has a half-life of only 12.33 years, some of the mine water must have been recharged to the aquifer since the early 1950's. A number of possible sources of recharge water are Quitchupah Creek and Christiansen Wash, irrigation water applied to land overlying the mine, and precipitation on land overlying the mine.

The concentration of tritium was also determined in a water sample from well (D-22-6)31dab-1, a flowing well about 1 mile southwest of the Emery Mine. The well taps the upper section of the Ferron sandstone aquifer, and potentiometric contours (fig. 12) indicate that the well is upgradient from the mine. As might be expected, tritium concentration in the water was less than the detectable limits of 6 picocuries per liter (Teledyne Isotopes, written commun., November 2, 1979).

Recharge and discharge

Sources of recharge to and discharge from the Ferron sandstone aquifer in the Emery area during 1979 are shown diagrammatically in figure 15. The estimate

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of recharge and discharge shown in figure 15 indicate that discharge exceeded recharge by about 0.1 ft^3/s; however, they are only order-of-magnitude estimates. Water-level declines in observation wells in the Emery area during 1979 indicate that the amount of storage in the aquifer declined, but the degree of imbalance between recharge and discharge is not known precisely.

Subsurface inflow

The largest source of recharge to the Ferron sandstone aquifer in the Emery area is subsurface flow, probably from the Wasatch Plateau. Most of the water in the aquifer in the Emery area probably originates as precipitation on the plateau, and most, if not all, is transmitted into the area along the highly permeable zone along the Paradise Valley-Joes Valley fault system. Previously described carbon-14 dating indicates that movement of water from the original recharge areas to the Emery area probably takes thousands of years.

A reasonable estimate can be made of the amount of subsurface inflow to the aquifer from the west in the Emery area. Using potentiometric-surface maps (figs. 11 and 12) to determine hydraulic gradients, transmissivity developed from calibration of the computer model (Morrissey and others, 1980, fig. 5) and Darcy's law (Lohman, 1972, p. 10), subsurface inflow to the Emery area is estimated to have averaged 2.4 ft^3/s during 1979 or about 1,700 acre-feet per year. Data are lacking to accurately estimate subsurface inflow to the Ferron in other areas of Castle Valley.

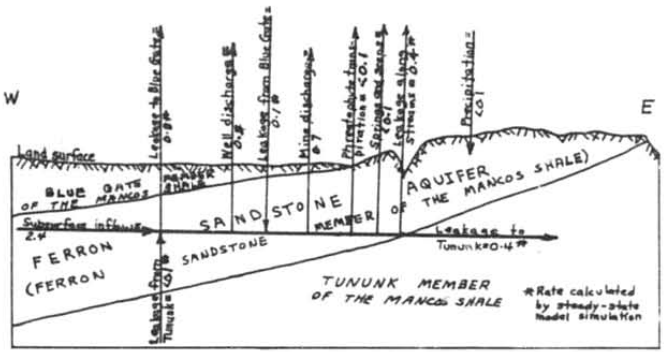

Figure 15.-- Diagrammatic section showing sources of recharge to and discharge from the Ferron sandstone aquifer in the Emery area, 1979. Recharge and discharge values are in cubic feet per second.

Precipitation on outcrop area

Annual precipitation on the 100 mi^2 outcrop of the Ferron Sandstone Member in Castle Valley averages about 8 inches (U.S. Weather Bureau, 1963). Precipitation occurs about equally as rain from thunderstorms and as snow. Thunderstorms contribute little recharge because the slopes on the Ferron outcrop are usually steep, there is little or no soil cover in most of the area, and runoff is rapid. Most of what little recharge occurs on the outcrop area probably takes place during the spring when snow melts slowly.

In those areas of the lower Dirty Devil River basin where annual precipitation averages less than 12 inches, Hood and Danielson (1979, table 4) estimate that recharge to bedrock aquifers averages, at most, 0.5 percent of precipitation. This is also probably the maximum amount that could be recharged on the Ferron outcrop, and it amounts to only about 200 acre-feet per year for the entire 100 mi^2 of outcrop area in Castle Valley.

The Ferron outcrop, particularly in the southern part of Castle Valley, is deeply cut by stream channels as shown in figure 6. Much of the water that recharges the aquifer in the outcrop is discharged close to the recharge areas by leakage to the underlying Tununk Member and by leakage to alluvium along streams. In most areas, little or no recharge from the outcrop area reaches the main body of the aquifer downdip from the outcrop.

The Ferron sandstone aquifer in the Cleveland, Elmo, and Wellington areas (the Clawson and Washboard units of Cotter) is separated from the main body of the Ferron that underlies the Wasatch Plateau and Castle Valley to the south. (See fig. 8.) Unlike the Emery area, recharge to the aquifer in these areas may be limited to a small amount of recharge on the narrow strip of Ferron outcrop.

Leakage

The Ferron sandstone aquifer lies between relatively impermeable shales in the Blue Gate and Tununk Members, but there is some movement of water between these three zones. In most of the Emery area downdip from the Ferron outcrop, heads in the aquifer are usually higher than the water table in overlying rocks, and there is upward leakage of water into the Blue Gate. Much of the water in the overlying Blue Gate is consumed by greasewood (*Sarcobatus vermiculatus*), a phreatophyte. Computations using the three-dimensional digital-computer model of the Ferron sandstone aquifer indicate that upward leakage from the Ferron into the Blue Gate averaged about 0.8 ft^3/s during 1979, or about 600 acre-feet per year in the Emery area (Morrissey and others, 1980, fig. 2).

It should be noted that records of many wells and test holes drilled in Castle Valley indicate that the shale in the Blue Gate Member is "dry." In most cases, the use of the term "dry" refers to the lack of water production when drilling and does not indicate that the shale was unsaturated. Test holes (D-22-6)27cbb-4 and 6 bottom in the Blue Gate in the proposed surface-mine area. Both holes were drilled with an air-rotary drilling rig, and shale cuttings appeared dry when drilling. The test holes contained no water between the time drilling ceased and the holes were cased, but over a period of several days both holes partly filled with water to the approximate level of the water table.

Near the Emery Mine, the potentiometric surface of the upper section of the Ferron sandstone aquifer has been lowered to a level below the water table in the Blue Gate Member by mine dewatering. This is the only area near Emery where water-level data indicate that water in the Blue Gate was leaking into the Ferron during 1979. Computations using the computer model indicate that leakage from the Blue Gate to the Ferron near the Emery Mine averaged about 0.1 ft^3/s during 1979, or about 70 acre-feet per year.

Along the Paradise Valley-Joes Valley fault system, hydraulic connection between the Blue Gate and Ferron sandstone aquifer probably has been increased by fracturing. Well (D-22-6)19cdb-1 bottoms in the Blue Gate approximately 300 feet above the Ferron, and the well had a sustained flow of 20 gal/min during the summer of 1979. The dissolved-solids concentration in the water was 808 mg/L (table 6) and was typical of water from the Ferron and not the Blue Gate. It is believed that when the well is allowed to flow, most of the water is actually derived from the Ferron, although it has probably moved freely through fractures into the Blue Gate.

Head in the underlying Tununk Member and the direction of water movement between the Tununk and Ferron sandstone aquifer are unknown. It is probably safe to assume that downdip from the Ferron outcrop and away from major manmade sources of discharge from the Ferron, the exchange of water between the two units is negligible. Computations using the computer model indicate that during 1979 in the Emery area less than 0.1 ft^3/s (less than 70 acre-feet) probably leaked upward into the Ferron from the Tununk, all in areas downdip from the Ferron outcrop.

In much of the outcrop area of the Ferron near Emery, heads in the Ferron sandstone aquifer decrease with depth. Water probably leaks from the Ferron into alluvium in the bottoms of the deeply incised stream canyons and into the underlying shales of the Tununk. Much of the water in the alluvium is consumed by phreatophytes, mainly greasewood. Most of the water that leaks into the Tununk evaporates on the barren shale slopes beneath the Ferron outcrop where salt accumulates through summer and fall. (See fig. 16.) Computations using

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Figure 16 (caption on next page) near here

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the computer model indicate that during 1979 in the Emery area leakage to alluvium along streams and leakage to the Tununk each probably averaged about 0.4 ft^3/s.

Transpiration of phreatophytes

Although many areas in Castle Valley support dense phreatophyte growth, few phreatophytes obtain water directly from the Ferron sandstone aquifer. Most phreatophytes in Castle Valley obtain water from alluvium along streams and from the shallow saturated zone in the Blue Gate Member. Phreatophyte growth on the Ferron outcrop is limited by the depth to water and poor soil conditions. The few phreatophytes (mainly greasewood) that obtain water from the Ferron grow along a narrow strip about 0.2 mile wide east of the contact between the Ferron and the Blue Gate. Depth to the saturated zone in this area is less than about 50 feet.

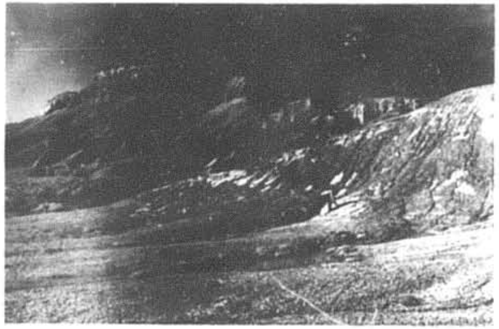

Figure 16.--Salt on the barren shale slopes of the Tununk Member of the Mancos Shale where ground water has evaporated. Overlying Ferron Sandstone Member of the Mancos Shale and Coal Cliffs in background.

Approximately 440 acres of sparse phreatophyte growth on the Ferron outcrop in the Emery area was mapped using aerial photographs. Using a method by Criddle, Harris, and Willardson (1962, p. 12 and 13), transpiration of water directly from the Ferron in the Emery area during 1979 is estimated to have averaged 0.04 ft^3/s (about 30 acre-feet per year).

Springs and seeps

Numerous seeps issue from the Ferron sandstone aquifer in Castle Valley, but only four springs were found with discernible flows. Springs (D-22-6)23dda-S1, (D-23-6)17dba-S1, and (D-24-5)13bcd-S1 all issue from the basal section of the Ferron near the contact with the Tununk Member along Muddy Creek, Ivie Creek, and Willow Springs Wash. The fourth spring, (D-22-6)23cdc-S1, issues from the upper section of the Ferron at the head of Miller Canyon near the contact with the Blue Gate Member. Records for these springs and chemical analyses of the water, where available, are listed in tables 5 and 6. Continuous-discharge records at springs are not available, and it is difficult to estimate the water discharged through the seeps. The discharge of springs and seeps issuing from the Ferron in Castle Valley, however, probably does not exceed 0.2 ft^3/s, or about 140 acre-feet per year. In the Emery area, the combined discharge of springs and seeps from the Ferron is probably about half this amount.

Lupton (1916, p. 16) described a spring that issued from the Ferron at the head of Short Canyon in the SW¼ sec. 24, T. 21 S., R. 7 E., and that supplied "sufficient excellent water for a few head of stock the year round." This site was visited in June 1978 and November 1979. An empty stock-watering tank was found, but no spring flow was observed.

Well discharges

During 1979 in Castle Valley, 18 wells tapped the Ferron sandstone aquifer for purposes other than hydrologic testing. Water from the Ferron was used for public supply in the town of Emery, coal washing, stock watering, a small amount of irrigation, and domestic supply at three ranches.

Records from a meter on the discharge line of the Emery municipal well, (D-22-6)4cab-1, indicate that the discharge averaged 0.2 ft^3/s during 1979. Three wells were used for coal washing at the Dog Valley Mine in T. 23 S., R. 6 E., and the total discharge averaged about 0.04 ft^3/s during 10 months of operation in 1979 (Western States Minerals Corp., written commun., February 14, 1980). Discharge from the remainder of the Ferron wells in Castle Valley averaged about 0.07 ft^3/s.

Mine dewatering

Dewatering of the underground Emery Mine was the largest source of manmade discharge from the Ferron sandstone aquifer in Castle Valley during 1979. From discharge measurements at the end of the mine-discharge line and pumping time furnished by Consolidation Coal Co., mine pumpage is estimated to have averaged 0.6 ft^3/s during 1979. An additional 0.1 ft^3/s is estimated to have been removed from the mine for showers and by evaporation.

Discharge from the mine increased during 1979. The discharge averaged about 0.5 ft^3/s during January 1-July 19, 0.6 ft^3/s during July 20-October 8, 0.8 ft^3/s during October 9-November 1, and 0.7 ft^3/s during the remainder of the year. As the underground mining progresses toward the Paradise Valley-Joes Valley fault system into areas with higher aquifer transmissivity, mine dewatering should increase.

Availability of water

The largest quantities of water are available from the Ferron sandstone aquifer within about 2 miles of the Paradise Valley-Joes Valley fault system in the Emery area. In this area, the aquifer transmissivity has been increased by fracturing, and several wells have been constructed that are capable of producing more than 100 gal/min. (See wells (D-22-6)4cab-1 and 2, 17abc-1, 30dcb-1, and 31dab-1 in table 5.) Most of the wells in this area flow naturally at land surface at rates less than 100 gal/min, but discharges could be increased by pumping. Wells that fully penetrate the aquifer in this area could be expected to produce 100 to 500 gal/min if pumped.

Elsewhere in the Emery area and farther south in Castle Valley, individual wells could be expected to produce 10 to 50 gal/min from the Ferron sandstone aquifer. Yields would be greatest from fully penetrating wells in areas with the greatest saturated thickness and transmissivity. Saturated thickness and transmissivity decrease in the outcrop area of the Ferron. Wells within about 1 mile of the contact with the underlying Tununk Member probably would yield less than 10 gal/min.

In the northern two-thirds of Castle Valley, several miles from major faulting and where the Ferron is less than 300 feet thick, yields of individual wells that tap the Ferron probably would not exceed 10 gal/min. As pointed out earlier, the Ferron sandstone aquifer in the Cleveland, Elmo, and Wellington areas is separated from the main body of the Ferron that underlies the Wasatch Plateau and Castle Valley to the south. Unlike the Emery area, recharge to the aquifer in the northern part of Castle Valley may be limited to a small amount of recharge from precipitation on the narrow strip of Ferron outcrop. Well (D-17-10)4bba-1 reportedly penetrates the Ferron about 0.5 mile south of Elmo, and the driller reported that no water was encountered. About 3 miles farther south, well (D-17-10)16dda-1 taps the Ferron and produces enough water for one household.

Quality of water

Chemical analyses of water from wells, test holes, springs and the Emery Mine in Castle Valley, are listed in table 6.

As shown in figures 17 and 18, the concentration of dissolved solids in

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Figures 17 and 18 (captions on next page) near here

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water from the Ferron sandstone aquifer in the Emery area increases eastward from the Paradise Valley-Joes Valley fault system toward the Ferron outcrop. Comparison of figures 17 and 18 indicates that in most areas dissolved-solids concentrations also increase upward in the aquifer.

In the Emery area, deterioration of water quality in the Ferron sandstone aquifer usually is due to increased concentrations of dissolved sodium and sulfate. Shales in the Mancos Shale contain large quantities of soluble sodium-sulfate minerals such as mirabilite ($Na_2SO_4 \cdot 10H_2O$) and thenardite (Na_2SO_4) (Waddell and others, 1979). Dissolved-solids concentrations generally increase with increased time that water is in storage in the aquifer and in contact with the shales.

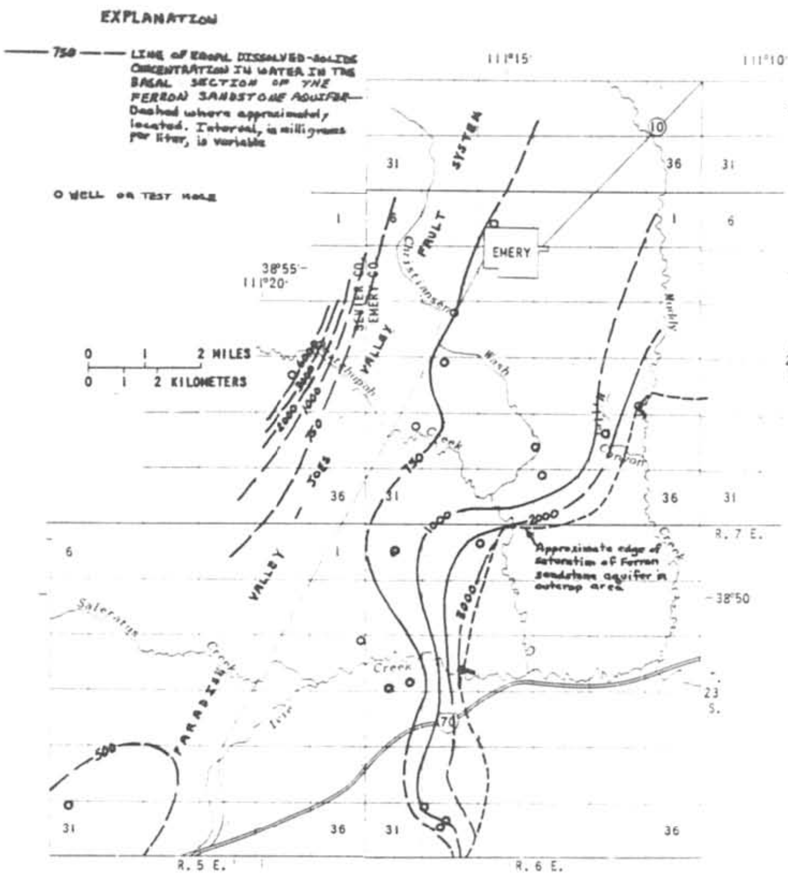

Figure 17.-- Concentration of dissolved solids in water in the basal section of the Ferron sandstone aquifer in the Emery area, 1979.

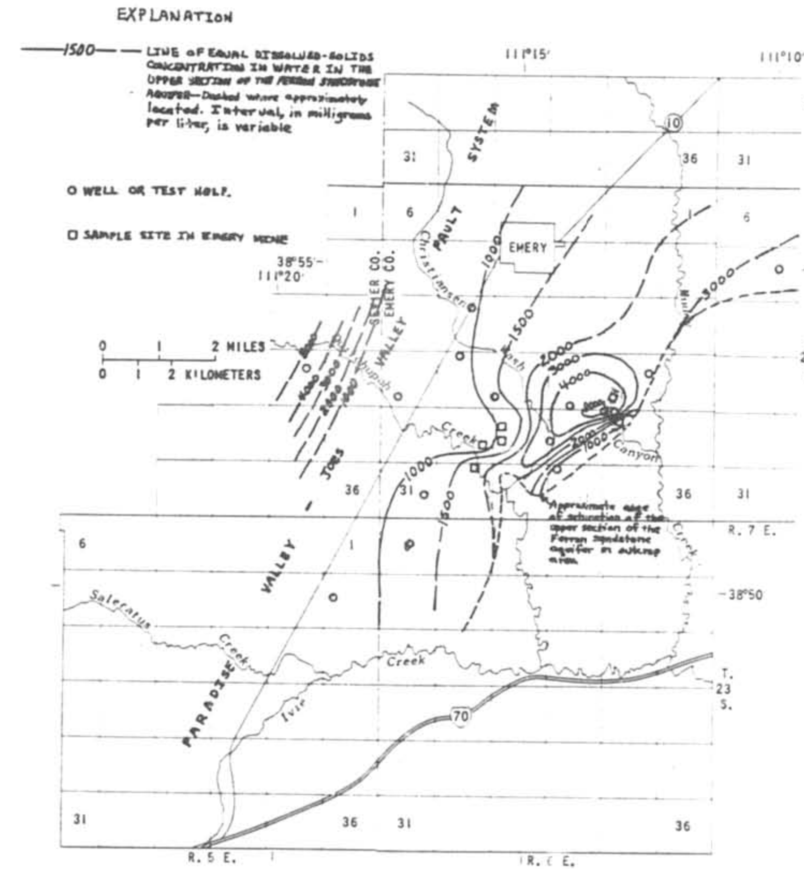

Figure 18.-- Concentration of dissolved solids in water in the upper section of the Ferron sandstone aquifer in the Emery area, 1979.

The largest observed concentration of dissolved solids in the upper section of the Ferron sandstone aquifer east of the Paradise Valley-Joes Valley fault system were in an area near the proposed surface mine, between the Emery Mine and the head of Miller Canyon. During 1979 in this area, the water table in the Blue Gate Member was at a higher altitude than the potentiometric surface of the upper section of the Ferron. Water in the Blue Gate, which contained about 20,000 mg/L of dissolved solids, was leaking downward into the Ferron. The downward leakage of saline water from the Blue Gate in this area could be induced by natural discharge from the aquifer at the head of Miller Canyon, or it could be due to dewatering of the Emery Mine.

From the configuration of the contours in figure 18, it can be inferred that the removal of large quantities of water from the Emery Mine has improved water quality in the upper section of the Ferron between the mine and the fault system to the west. Dewatering of the mine has accelerated the rate of water movement toward the mine from all directions. The increased movement of less saline water from the west through the upper section of the aquifer, however, has more than offset any deterioration of water quality that may have been caused by increased downward leakage from the Blue Gate. Improvement in the quality of water entering the mine also may be indicated by changes in dissolved-solids concentrations in water pumped from the mine. Water collected in 1975 at the end of the mine discharge line contained 5,100 mg/L of dissolved solids (Waddell and others, 1978, p. 15). Samples collected in February and September 1979 contained 4,780 and 3,040 mg/L of dissolved solids.

Data are lacking to define water quality in the Ferron sandstone aquifer in most areas west of the Paradise Valley-Joes Valley fault system. However, large dissolved-solids concentrations in water from test hole (D-22-5)23aca-1 indicate that water quality in the Ferron deteriorates, at least in some areas, a short distance west of the fault system. This is consistent with the hypothesis that most, if not all, of the water moving from the Wasatch Plateau to the Ferron in the Emery area is transmitted along the highly permeable zone created by faulting.

The few chemical analyses of water from the Ferron in the northern two-thirds of Castle Valley and adjacent Wasatch Plateau (table 6) indicate that water is generally of poorer quality than in most of the Emery area. This is probably due to the increased distance from recharge areas and the increased time water is in contact with the rocks. Dissolved-solids concentrations in water in the Ferron in the northern two-thirds of Castle Valley usually exceed 3,000 mg/L. Several water samples obtained from test holes and gas wells in the Ferron contained more than 10,000 mg/L of chloride and more than 20,000 mg/L of dissolved solids.

SURFACE WATER

The northern and central parts of Castle Valley are drained by the Price and San Rafael Rivers, both of which are tributaries to the Green River. Three major tributaries to the San Rafael River (Huntington, Ferron, and Cottonwood Creeks) originate on the central Wasatch Plateau and cross Castle Valley and the outcrop of the Ferron Sandstone Member. The flows of these streams are diverted in Castle Valley for irrigation or municipal supply.

The southern part of Castle Valley is drained by tributaries to the Dirty Devil River, which is a tributary to the Colorado River. Three major tributaries to the Dirty Devil River that originate on the Wasatch Plateau and that cross the outcrop of the Ferron Sandstone Member are Muddy, Quitchupah, and Ivie Creeks.

Quitchupah Creek and its tributary Christiansen Wash are treated in detail in this report because they are near the proposed surface mine. Figure 19 shows

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Figure 19 (caption on next page) near here

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data-collection sites on these streams during 1978-79. For information on other surface waters in the area, the reader is referred to Mundorff (1972 and 1979) and Waddell, Contratto, Sumsion, and Butler (1979).

Quantity

Quitchupah Creek has a drainage area of 104 mi^2 at gaging station 09331900 near the Emery Mine. The average daily discharge for water year 1979, the first complete year of operation, was 6.7 ft^3/s, ranging from a low of 1.1 ft^3/s on October 28-30, 1978, to a high of 45 ft^3/s on November 2, 1978 (U.S. Geological Survey, 1980, p. 290). During the summer months, flow at the station consists mainly of water pumped from the Emery Mine and return flow of irrigation water.

Christiansen Wash was gaged at station 09331950 during the 1979 water year. The drainage area at this station, a short distance downstream from the proposed surface mine, is 13.6 mi^2. Daily discharge at the station averaged 2.8 ft^3/s during water year 1979, ranging from 0.43 ft^3/s on January 7, 1979, to 20 ft^3/s on May 6 and 20, 1979 (U.S. Geological Survey, 1980, p. 294). The flow in Christiansen Wash is perennial at the gaging station, and streamflow is due mainly to return flow of irrigation water originally diverted from Muddy Creek. The upper reaches of Christiansen Wash, upstream from irrigated areas, flow only in response to snowmelt or thunderstorms.

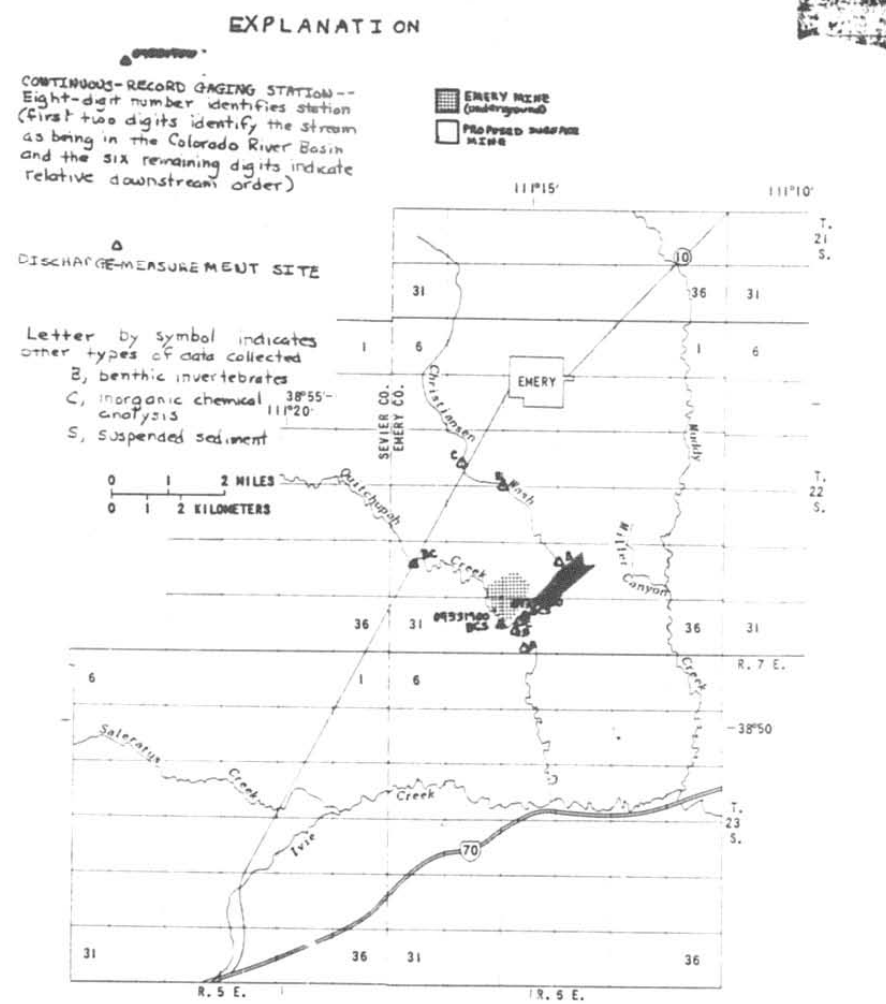

Figure 19.--Location of data-collection sites on Quitchupah Creek and Christiansen Wash in the Emery area 1978-79.

Quality

Inorganic dissolved solids

Most surface waters in Castle Valley deteriorate in chemical quality as they cross shales in the Blue Gate Member (Mundorff, 1979, p. 34). As previously, mentioned, the shales contain large quantities of soluble sodium and sulfate minerals. These minerals are subject to solution by surface runoff and ground water.

Water in Quitchupah Creek deteriorates in chemical quality between State Highway 10 and the confluence with Christiansen Wash. At State Highway 10, during 1975-76, the average concentration of dissolved solids in six water samples was 950 mg/L. The average concentration in six samples collected concurrently from Quitchupah Creek just above the confluence with Christiansen Wash was 2,270 mg/L (Mundorff, 1979, table 6). This increase in dissolved-solids concentration is due to increased concentrations of all the major cations and anions but mostly to an increase in sodium and sulfate. Inflow between the two sites mainly consisted of pumpage from the Emery Mine and return flow of irrigation water.

Seasonal variation in the concentration of dissolved solids at the gaging station on Quitchupah Creek during the 1979 water year is illustrated in figure 20.

Figure 20 (caption on next page) near here

Observed extremes of dissolved-solids concentrations were 696 mg/L on May 8, 1979, and 3,960 mg/L on November 19, 1978 (U.S. Geological Survey, 1980, p. 292). The trend during the 1979 water year was from greater discharge and lesser concentration of dissolved solids during the spring-runoff period (April-June) to lesser discharge and greater concentration of dissolved solids during the summer and fall (July-November). During the winter (December-March), discharge and concentration of dissolved solids generally were intermediate to those observed during the spring and summer.

Areal variation in the concentration of dissolved solids along Christiansen Wash is slightly different than along Quitchupah Creek. The average concentration of dissolved solids in six sets of samples collected during 1975-76 at State Highway 10 and at the mouth of Christiansen Wash were 3,470 and 2,610 mg/L (Mundorff, 1978, table 6), indicating a downstream decrease in the concentration of dissolved solids. Flow in Christiansen Wash at State Highway 10 is intermittent and, with the exception of periods during thunderstorms and snowmelt, consists of seepage of irrigation water that contains large concentrations of dissolved solids. A part of the flow of Christiansen Wash at the mouth also consists of irrigation water returned by ground-water seepage, but the flow is also sustained by overland flow of irrigation water and water discharged from the Ferron sandstone aquifer. The major part of the flow at the mouth probably represents overland flow of irrigation water, which generally contains smaller concentrations of dissolved solids than does ground water that seeps into the Wash.

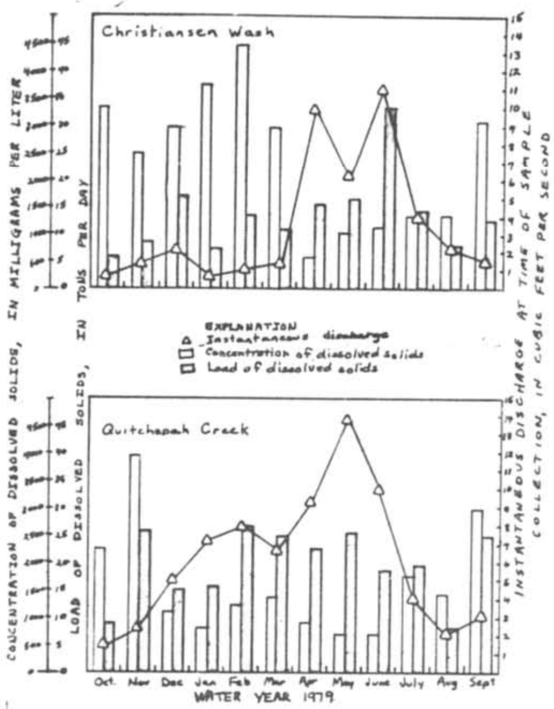

Figure 20.-- Monthly variation in the concentration and load of dissolved solids at gaging stations 09331900 and 09331950 on Quitchupah Creek and Christiansen Wash in the Emery area, water year 1979.

The average concentration of dissolved solids of 12 monthly samples collected at the gaging station on Christiansen Wash during the 1979 water year was 2,380 mg/L. Observed extremes of dissolved solids were 582 mg/L on April 18, 1979, and 4,470 mg/L on February 18, 1979 (U.S. Geological Survey, 1980, p. 296). The predominant cation and anion in the water were sodium and sulfate, and the pH ranged from 8.1 to 8.5.

Seasonal variations of discharge and concentration of dissolved solids in Christiansen Wash also are shown in figure 20. During winter when there is no irrigation, discharge decreases, and the streamflow is supported mainly by ground-water seepage, which has a relatively large concentration of dissolved solids. During spring and early summer, discharge increases and concentrations of dissolved solids are smallest.

Suspended sediment

Suspended-sediment samples were collected at the gaging stations on Christiansen Wash and Quitchupah Creek by the equal-discharge increment and equal-width increment methods (Guy and others, 1977, chap. 3). During August 2, 1978, to September 17, 1979, the observed suspended-sediment concentration at the gaging station on Quitchupah Creek ranged from 111 to 30,200 mg/L. The relationship between suspended-sediment concentration and stream discharge at the Quitchupah station is shown in figure 21. As discharge increased, the

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concentration of suspended sediment also increased. It is interesting to note that there is less scatter from the regression line at discharges above 5 ft^3/s. The correlation coefficient_/ for the regression line in figure 21 is 0.88.

_/Correlation coefficient is an estimate of the degree of interrelation between variables and is expressed in dimensionless units. A correlation of +1 indicates a perfect direct relationship between two variables; a correlation of -1 indicates that one variable changes inversely with relation to the other. Between the two extremes is a spectrum of less-than-perfect relationships, including zero, which indicates the lack of any sort of linear relationship.

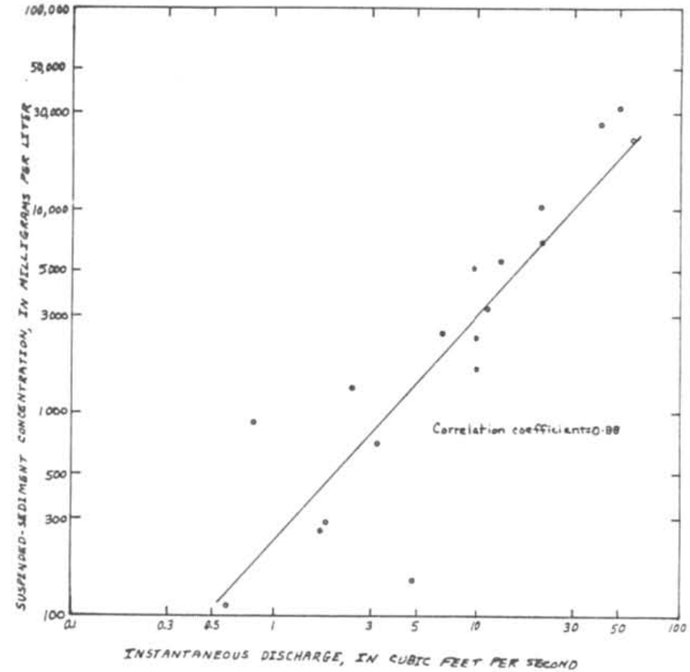

Figure 21.-- Relationship between suspended-sediment concentration and stream discharge at gaging station 09331900 on Quitchupah Creek in the Emery area, August 1978 – September 1979

During May 25, 1978, to September 17, 1979, the observed suspended-sediment concentration at the gaging station on Christiansen Wash ranged from 3 to 4,870 mg/L. The relationship between suspended-sediment concentration and discharge at the Christiansen Wash station for discharges greater than 1 ft^3/s is shown in figure 22. This relationship is not as well defined as at Quitchupah Creek. The

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Figure 22 (caption on next page) near here

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regression line in figure 22, which applies to observed discharges that were greater than 1 ft^3/s, has a correlation coefficient of 0.72. The regression lines in figures 21 and 22 should not be used to estimate suspended-sediment concentrations for discharges outside the ranges that were sampled.

Sediment data at the gages on Christiansen Wash and Quitchupah Creek are insufficient to determine sediment yields from the basins. King and Mace (1953, p. 18) studied sedimentation in a number of small reservoirs in Castle Valley, and they found that the average annual sediment production varied from 0.3 acre-ft/mi^2 in areas underlain by resistant sandstones like those in the Ferron Sandstone Member to about 2.6 acre-ft/mi^2 in areas underlain by shales like those in the Blue Gate Member.

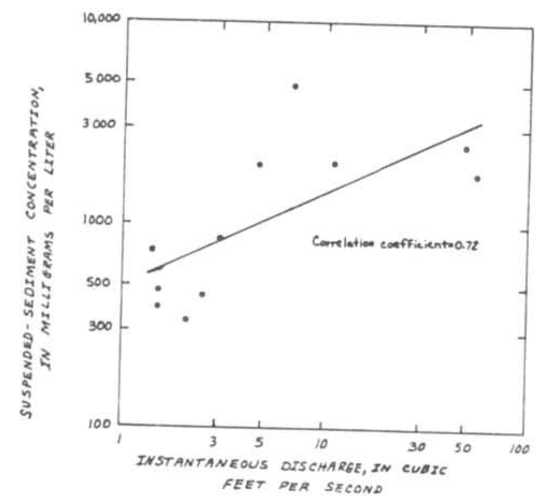

Figure 22.--Relationship between suspended-sediment concentration and stream discharge at gaging station 09331950 on Christiansen Wash in the Emery area, May 1978 - September 1979.

Benthic invertebrates

To determine baseline conditions before surface mining occurs, benthic invertebrates were sampled in Christiansen Wash and Quitchupah Creek at the eight locations shown in figure 19. Samples were taken in the summer and fall of 1978 and in the spring, summer, and fall of 1979. The samples were collected using a Surber sampler according to methods outlined by Greeson and others (1977, p. 171). Each sample represents those organisms collected from 3 ft^2 of stream bottom in riffle areas. Table 7 is a listing of organisms identified by phylogenetic order or family, the diversity index_/ by order, and the total wet

_/According to Lium (1974, p. 382) "Diversity, or the evenness of distribution of insects, gives some indication of the environmental condition of a stream." Diversity was computed for each sample by order using the Shannon-Weiner approximation:

$$\text{Diversity index} = -\sum PI \log_2 PI$$

where PI is the probability of occurrence of the I^{th} order. The probability (PI) is equal to NI/NS, where NI is the number of individuals in each order and NS is the total number of individuals in all orders.

weight of organisms in each sample.

At the sites in Christiansen Wash, there were large seasonal and areal variations in the benthic-invertebrate population. However, 94 percent of all organisms collected were from the order Diptera (true flies), 4 percent from the order Trichoptera (caddis flies), with the remaining 2 percent composed of nine other orders. Of all organisms collected in Christiansen Wash, the families Chironomidae (midges) and Simuliidae (black flies) represented 89 percent. This dominance of the benthic-invertebrate population by two families indicates an environment that does not support a varied population of organisms.

As in Christiansen Wash, there were also large seasonal and areal variations in the benthic-invertebrate population in Quitchupah Creek. For all samples collected on Quitchupah Creek, the order Diptera (true flies) comprised 45 percent, Trichoptera (caddis flies) 30 percent, Ephemeroptera (mayflies) 13 percent, and Basommatophora (snails) 9 percent. The remaining 4 percent of the organisms were in an unknown order of aquatic worms and the orders Odonata (dragonflies), Hemiptera (true bugs), and Acarina (water mites).

The population of organisms in Quitchupah Creek was more diverse than the population in Christiansen Wash. However, the total number of organisms collected in Quitchupah Creek in 11 samples was 1,291 compared to 18,026 organisms collected in 13 samples from Christiansen Wash. The reason for the differences in diversity of organisms may be that a more varied habitat (pools, riffles, and variety of substrate material) exists in Quitchupah Creek. However, the greater sediment loads and scouring from spring floods prevents large numbers of organisms from becoming established in Quitchupah Creek. Christiansen Wash has a less varied habitat, but more stable overall conditions allow certain groups of organisms to become well established.

Benthic invertebrates collected during 1978-79 indicate that there are large seasonal variations in diversity and numbers of individual organisms in Christiansen Wash and Quitchupah Creek. Additional samples are needed (particularly at the gaging station on Christiansen Wash downstream from the proposed surface mine) to further define the natural seasonal variability and to detect changes in the benthic-invertebrate population that may occur because of surface mining. Members of the orders Ephemeroptera, Plecoptera, and Trichoptera are especially susceptible to damage from increased sediment (R. H. Fuller, U.S. Geological Survey, written commun., 1980). Changes in pH and dissolved solids (including dissolved trace metals) associated with mining activities also have been shown to affect benthic invertebrates (Fuller and others, 1978, p. 22-27; Herricks and Cairns, 1973, p. 103).

COMPUTER MODEL

A three-dimensional digital-computer model was used to simulate ground-water flow in the Ferron sandstone aquifer in the Emery area. Approximately 60 mi^2 of the aquifer were modeled and the modeled area and grid used are shown in figure 23.

Figure 23 (caption on next page) near here

The model also was used to predict the effects of dewatering the proposed surface mine on potentiometric surfaces and the base flow of streams. The model used for this study is documented by Trescott (1975) and Trescott and Larson (1976). Changes were made to the original Trescott-Larson three-dimensional model to allow simulation of leakage along streams from all layers of the model. The design, construction, and calibration of the model are discussed in detail by Morrissey, Lines, and Bartholoma (1980).

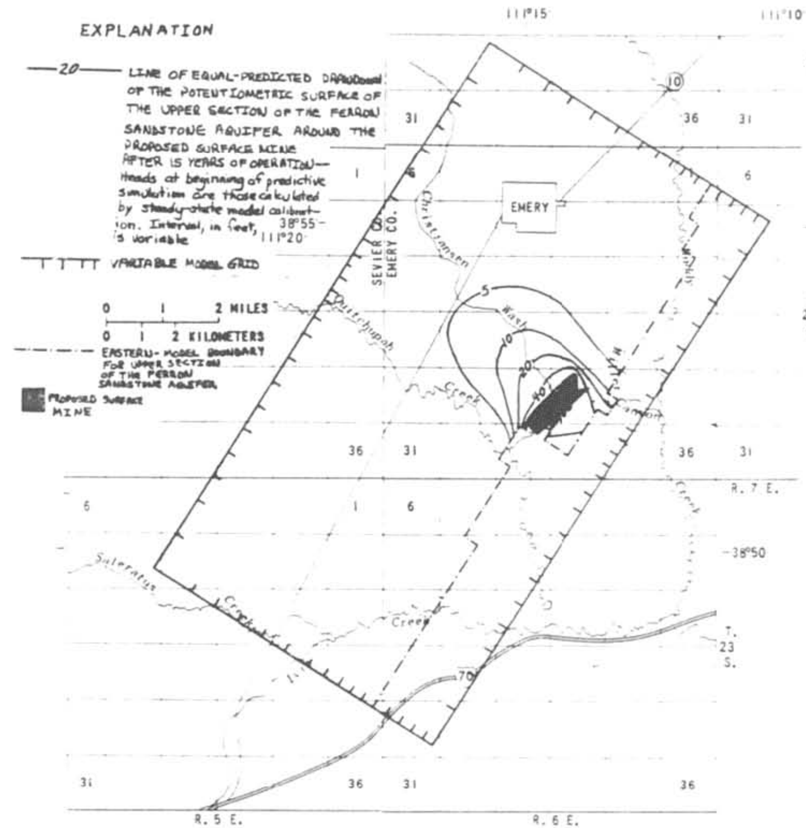

Figure 23.--Variable grid used in the three-dimensional digital-computer model and the predicted drawdown of the potentiometric surface of the upper section of the Ferron sandstone aquifer around the proposed surface mine after 15 years of operation.

Assumptions and accuracy

Predictions made with the model are considered to be semiquantitative for three reasons. The first reason is a lack of historical ground-water data in the modeled area, which results in an inability to verify the model with historical data for aquifer response to manmade discharge. The second reason is the assumption made in calibration of the model that the Ferron sandstone aquifer was in a steady-state condition during 1979. Although the aquifer was not in a true steady-state condition, the assumption of steady state is reasonable as water-level changes were only a few feet in most wells during 1979. The third reason involves an assumption inherent in the model that flow in the aquifer is through pore spaces. Although in some areas fractures are the major conduits through which water flows through the Ferron, the aquifer can be modeled because on a large scale the system probably acts as a porous medium.

Despite these limiting assumptions, the model provides the most realistic available method to analyze the effects of mine dewatering on the aquifer. The alternative approach, using an analytical method of analysis, would require more simplifying assumptions than those associated with the model. Thus, results of an analytical method could be used with less confidence than those obtained with the model.

Prediction

The calibrated model was used to predict the effects of dewatering the proposed surface mine on 1979 ground-water conditions. Transient and steady-state simulations of the proposed surface mine were made with the model. In simulating the surface mine, it was assumed that the pit would be dewatered, and this was simulated by constant-head nodes for layer [illegible] the model (the upper section of the Ferron Sandstone aquifer) in the mine area. The constant-head nodes were held at the altitude of the base of the coal seam to be mined. Grid spacing did not permit a precise simulation of the "moving" pit, and an average mine location was simulated. Constant-head nodes also were used to simulate the underground Emery Mine during the predictive simulations.

Aquifer tests of confined parts of the Ferron sandstone aquifer indicate that the storage coefficient ranges from about 3×10^{-6} to 2×10^{-3}. During the transient-predictive simulation, a storage coefficient of 1×10^{-4} was assigned to all layers of the Ferron where they were confined either by overlying shale or another layer of the Ferron. In areas where the aquifer was unconfined, a value of 5×10^{-2} was assigned. Storage coefficients for layers 1 and 5 (the shales in the Tununk and Blue Gate Members) were not needed because these layers were simulated by constant-head nodes.

To check the sensitivity of the model to variations in storage coefficient, two additional simulations were made. In one simulation, the storage coefficients in confined areas were set at 1×10^{-5} and in unconfined areas at 1×10^{-2}. In the second simulation, storage coefficients were set at 1×10^{-3} in confined areas and at 1×10^{-1} in unconfined areas. The results of these two simulations, as compared with results of the transient-predictive simulation, show that variations in storage do not seriously affect model predictions. Differences in calculated drawdowns at most nodes near the surface mine were less than 1 foot when using the different storage coefficients.

Results of predictive model simulations indicate that dewatering of the proposed surface mine will affect potentiometric surfaces of all layers of the Ferron sandstone aquifer, however, predicted drawdowns along model boundaries would be less than 4 feet. The predicted drawdowns in potentiometric surfaces and the effects on the base flow of streams are discussed in detail in following sections of this report.

EFFECTS OF PROPOSED SURFACE MINING

Mining plans

In March 1976, application was filed with the Oil, Gas and Mining Division of the Utah Department of Natural Resources for a surface-coal mine in the Emery Coal Field. The proposed surface mine would be in the drainage of Christiansen Wash (fig. 23) near the existing underground Emery Mine. Approximately 430 acres would be directly disturbed by the mining operation. Coal would be mined from the I- and J-coal seams in the Ferron Sandstone Member. Surface mining would begin along Christiansen Wash in the area shown in figure 24, where the coal is at the surface. The mining would proceed in

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strips to the northwest until an uneconomical depth was reached, about 120 feet according to the mining application. Mining would terminate on the Blue Gate Member in areas like that shown in figure 25. The mine would have a life

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of about 15 years. There has been no surface mining in the Emery Coal Field through 1980.

Figure 24.--Area of proposed surface mine along Christiansen Wash. Ferron Sandstone Member of the Mancos Shale crops out along edges of floodplain; greasewood grows on alluvium along stream.

Figure 25.--Sparsely vegetated surface of the Blue Gate Member of the Mancos Shale that is typical of area where proposed surface mining will terminate. Christiansen Wash and outcrop of the Ferron Sandstone Member of the Mancos Shale in background.

The proposed mining sequence is as follows: (1) construction of mine access roads and surface facilities, (2) removal and storage of surface material (soil), (3) drilling and blasting of overburden, (4) removal of overburden, (5) removal of coal, (6) grading of spoil overburden, (7) replacement of soil, and (8) revegetation.

Overburden from each successive mine cut would be placed in the previously mined cut or on adjacent land not to be mined. Grading of the spoil overburden, replacement of soils, and revegetation would occur simultaneously with the mining operation. Maximum slope of land surface in the reclaimed mine area would be 18 percent and would occur along the final mine highwall.

According to the mining application, Christiansen Wash would be diverted around the northwest side of the mine. A diversion ditch also would be installed along the southeast side of the mine area to intercept and divert surface runoff from the Ferron outcrop into Christiansen Wash below the mine.

Mine dewatering

Effects on ground water

The three-dimensional digital-computer model of the Ferron sandstone aquifer was used to evaluate the effects of dewatering the proposed surface mine on the aquifer. As pointed out earlier, predictions made with the model are considered to be semiquantitative.

Discharge from the surface mine is predicted to average about 0.3 ft^3/s during the proposed 15 years of operation. Model calculations indicate that water discharged from the surface mine would be balanced by a decrease in storage in the Ferron sandstone aquifer, by a decrease in water entering the underground Emery Mine, by a decrease in natural leakage from the aquifer, and by an increase in leakage to the aquifer from the Blue Gate Member.

The predicted drawdown in the potentiometric surface of the upper section of the Ferron sandstone aquifer (the section in which surface mining is proposed) after 15 years of mine dewatering is shown in figure 23. It is predicted that drawdowns greater than 5 feet in the upper section of the aquifer would extend about 2.5 miles from the mine. Other sections of the Ferron sandstone aquifer also would be affected, but drawdowns would not be as great. In the basal section of the aquifer, it is predicted that drawdowns greater than 5 feet would extend about 2 miles from the proposed mine, and drawdowns greater than 10 feet would extend about 0.25 mile from the mine.

Model calculations indicate that dewatering of the surface mine would increase downward leakage into the Ferron sandstone aquifer from the Blue Gate Member by about 0.05 ft^3/s; practically all (98 percent) of this increase would occur within the area of drawdown greater than 5 feet shown in figure 23. Water in the Blue Gate contained about 20,000 mg/L dissolved solids, and the dissolved-solids concentration of water in the upper section of the Ferron ranged from about 1,000 to 8,000 mg/L in the affected area during 1979. Thus, the additional downward leakage of water from the Blue Gate might cause deterioration of water quality in the upper section of the Ferron in some areas.

As discussed earlier, dewatering of the underground Emery Mine might have caused deterioration of water quality in the upper section of the Ferron sandstone aquifer in the area between the mine and the head of Miller Canyon. Dewatering of the surface mine might further deteriorate water quality in the upper section of the aquifer in the area between the surface mine and the canyon. However, as near the underground mine, water quality in the upper section of the aquifer might not deteriorate in other areas. The increased movement of less saline water through the aquifer toward the surface mine from the west might more than offset any deterioration that would be caused by increased leakage from the overlying Blue Gate Member west of the mine.

The predicted effects of dewatering of the surface mine on potentiometric surfaces and water quality in the Ferron are based upon conditions that existed in 1979. Ground-water conditions in the Ferron could be changed, however, by increased withdrawals from wells and from the underground Emery Mine. If ground-water conditions were significantly different during the surface mining, the effects of mining on the ground-water system would be different than those predicted.

Effects on surface water

Modeling results indicate that, except for Christiansen Wash, the dewatering of the proposed surface mine would not affect the base flow of streams. If water from the mine were discharged into Christiansen Wash, streamflow would increase accordingly. The predicted mine discharge (0.3 ft^3/s) would be almost equal to the minimum observed discharge on Christiansen Wash during the 1979 water year.

Dissolved-solids concentrations in water in the upper section of the Ferron sandstone aquifer ranged from about 1,000 to 8,000 mg/L in the surface-mine area during 1979, and water in the Blue Gate Member contained about 20,000 mg/L of dissolved solids. The water entering the surface mine would be a mixture of these two waters and water that would drain from the disturbed overburden. Chemical quality of the mine water would vary with time and would probably have a dissolved-solids concentration within a range of 2,000 to 10,000 mg/L. The average dissolved-solids concentration of 12 monthly samples taken at the gaging station on Christiansen Wash below the mine area during the 1979 water year was 2,380 mg/L, and the concentration ranged from 582 to 4,470 mg/L. Thus, at least during some periods, the dissolved-solids concentration of water in Christiansen Wash would be increased if mine water were discharged into the stream.

Leaching of overburden

In the process of mining at the proposed 430-acre surface site, approximately 25,800 acre-feet (41,600,000 cubic yards) of overburden would be displaced, based on an average overburden thickness of 60 feet. The overburden would be highly fractured during the mining process: thus, it would be a readily available source of material that could be leached by surface water, ground water, and precipitation. In order to estimate the possible effects of leaching of overburden during the mining operation, laboratory leaching studies were carried out.

Cores of representative overburden were obtained from test holes. In the laboratory experiments, 100 grams of core material (table 3), which had been

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crushed to less than 0.25 inch in size, were placed in a 1-liter erlenmeyer flask with 750 milliliters of deionized water (similiar to rainfall and snowmelt) and shaken at room temperature. Samples were shaken from 12 to 26 weeks until the pH and specific conductance of the solution remained constant. Core material within the flasks had abraded to sand and clay sizes by the end of the equilibration period. These equilibration experiments showed the composition of leachate under oxidizing conditions (table 4). No attempt was made to simulate leaching under

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reducing conditions.

The results of the equilibration experiments (table 4) indicate water of better chemical quality than had been expected, especially when compared with many of the ground-water analyses reported in table 6. The dissolved solids of the equilibrated samples ranged from 539 to 2,556 mg/L, with a mean concentration of 1,160 mg/L. The equilibrated samples were of the calcium sulfate water type, with the exception of samples 4A-6, 4A-7, and 5-11, which were mixed calcium and magnesium sulfate waters, and sample 3-10, which was a sodium sulfate water. The major constituents found in the equilibration leachate are attributed to the alteration and solution of soluble salts such as mirabilite ($Na_2SO_4 \cdot 10H_2O$), thenardite (Na_2SO_4), and gypsum ($CaSO_4 \cdot 2H_2O$), which have been reported to be in large quantities in the Mancos Shale (Waddell and others, 1979, p. 17). These minerals and pyrite and calcite all were common in the core samples. These minerals, with the exception of pyrite, are of a sodium or calcium sulfate composition; and this is reflected in the composition of the leachate. A detailed study of the chemical composition of the Ferron Sandstone Member and associated coal beds in the study area is given by Affolter, Hatch, and Ryer (1979).

The leachates contained relatively low concentrations of trace elements (table 4). Iron concentrations were unusually high in samples 3-2 and 4A-6, however, with concentrations of 61,000 and 7,000 μg/L. This is attributed to the pyrite that was noted in both samples and was reflected in pH values of 4.0 and 3.8. Mixing pyritic material with calcareous material in mine-spoil placement would reduce iron mobilization and acid production. Aside from the two samples with large iron concentrations, trace elements in the leachates were found in quantities that would not be considered toxic to man, animals, or plants.

The concentration of dissolved solids in the leachates were considerably lower than in many of the ground-water samples taken during the course of the study. Three possible reasons for this are:

1. The short period of contact time (12 to 26 weeks) in the case of the equilibrated samples compared to years in the case of much of the ground water.
2. Some minerals, especially halite (NaCl), are found in the Mancos Shale but were not present in appreciable quantities in the cores. Halite may account for much of the sodium and chloride found in some of the ground-water samples.
3. The equilibration experiments did not attempt to simulate reducing conditions or bacterial activity which undoubtedly have a significant influence on the solution of some minerals, especially pyrite and some of the sulfate minerals.

The equilibration studies indicate that the water in the mine spoil would be of a chemical quality that is better than much of the ground water in the mine area and about the same quality as water in Christiansen Wash. This would be the case if the water table were below the base of the spoil and if precipitation were the only water allowed to infiltrate the spoil. If surface or ground water is allowed to infiltrate the spoil, the resulting water quality would be worse than indicated by the equilibration studies because minerals dissolved from the spoil would add to the original concentrations in the infiltrating water.

Erosion of overburden

Weather conditions during and after surface mining would influence both the success of land reclamation and the amount of sediment eroded from the disturbed area. It is not possible to predict the weather with sufficient precision to predict sediment yield from the proposed mine area. However, it is possible to identify those elements of mining and reclamation operations that are most likely to affect sediment yield and to identify environmental safeguards most likely to minimize the impact.

There are many environmental safeguards in regulations implementing Public Law 95-87, the Surface Mining Control and Reclamation Act of 1977 (U.S. Office of Surface Mining Reclamation and Enforcement, 1979). Many of the safeguards are designed to prevent additional contributions of sediment to streams outside the mine area. The regulations require that the smallest possible area at any one time be disturbed by mining operations and that there be progressive backfilling, grading, and prompt revegetation.

Probably the most important safeguard to minimize sediment loads downstream from the disturbed area is the use of sediment ponds. The ponds are required to be as near as possible downstream from the disturbed area, and they must be able to store the runoff resulting from the 10-year maximum 24-hour precipitation. Ponds must retain this flow for at least 10 hours. In the Emery area, the 10-year maximum 24-hour precipitation is about 1.7 inches (Miller and others, 1973, p. 37). The ponds also are required to store at a minimum the sediment that accumulates in 3 years from the drainage area, or a minimum of 0.035 acre-foot of sediment for each acre of disturbed area.

King and Mace (1953, table 6) found that basins in Castle Valley, which are sparsely vegetated and are underlain by shale and sandstone like those in the proposed surface-mine area, have annual sediment yields that normally range from 0.3 to 2.5 acre-ft/mi^2. Sediment loads of streams downstream from the mine area would not increase significantly if slopes were graded to the least possible angle, if revegetation were prompt so as to stabilize the stockpiled topsoil and backfilled overburden, and if runoff were channeled from the disturbed area through the sediment ponds. The long-term sediment yield from the disturbed area could actually decrease if vegetative cover were improved from premining conditions and sediment ponds were properly maintained.

Long-term sediment yields could also be minimized by permanently diverting Christiansen Wash and runoff from slopes southeast of the mine around the reclaimed area. Regulations for Public Law 95-87 require that natural riparian vegetation be enhanced or maintained along a permanent diversion and that the natural meandering shape and an acceptable gradient be established. Aquatic habitats, such as a pattern of riffles, pools, and drops, that approximate premining characteristics could also be established along the diversion of Christiansen Wash. However, until vegetation is established along diversions and until diversion channels have stabilized, erosion along the diversion channels would probably greatly increase sediment yield. Erosion along the freshly cut channels could be minimized by channel lining. Here again, impact on streams downstream from the mine area could be held to a minimum by channeling the diverted waters to properly constructed and maintained sediment ponds.

NEED FOR FUTURE STUDY

An observation-well network needs to be established in the Emery area for the semiannual measurement of water levels in three or four wells that tap each section of the Ferron sandstone aquifer and the overlying Blue Gate Member. The wells also need to be sampled annually to detect possible changes in water quality. Discharge from the Emery municipal well, the underground Emery Mine, and the surface mine (when operational) needs to be monitored. After approximately 5 years, the additional data can be used to recalibrate and verify the three-dimensional digital-computer model of the aquifer.

SUMMARY

The largest quantities of water are available from the Ferron sandstone aquifer in the Emery area within about 2 miles of the Paradise Valley-Joes Valley fault system. Wells that fully penetrate the aquifer in this area could be expected to produce 100 to 500 gal/min if pumped. Elsewhere the availability of water from the Ferron is not as great, and in the northern two-thirds of Castle Valley the aquifer probably would not yield more than about 10 gal/min to individual wells. The chemical quality of water in the Ferron varies both with depth in the aquifer and areally. Fully penetrating wells near the fault system in the Emery area would yield water with concentrations of dissolved solids less than 1,000 mg/L. In the northern part of Castle Valley, the concentration of dissolved solids in water from the Ferron probably would exceed 3,000 mg/L and could exceed 20,000 mg/L.

Simulations using the model of the Ferron sandstone aquifer in the Emery area indicate that dewatering of the proposed surface mine would average about 0.3 ft^3/s during the 15 years of operation. Dewatering of the mine would affect the potentiometric surfaces of all sections of the aquifer. The maximum drawdown would occur in the upper section of the aquifer, and drawdowns greater than 5 feet would extend about 2.5 miles from the mine. Downward leakage of poor quality water from the shale in the Blue Gate Member would be induced near the mine, and water quality in the upper section of the Ferron could deteriorate in some areas.

Except for Christiansen Wash, dewatering of the surface mine would not affect the base flow of streams. If water from the mine were discharged into Christiansen Wash, the streamflow would increase accordingly. Chemical analyses of ground water in the mine area and leaching experiments indicate that the chemical quality of water produced in the mine would vary. Concentrations of dissolved solids in the mine water should range from 2,000 to 10,000 mg/L. If the mine water is discharged into Christiansen Wash, the dissolved solids in the stream water would be increased above premining concentrations, at least during some periods.

With proper reclamation practices and the use and maintenance of sediment ponds downstream from the mine area, there should be no significant increase in the sediment load of Christiansen Wash. Long-term sediment yield from the disturbed area could decrease if vegetative cover on reclaimed lands is improved from premining conditions and Christiansen Wash is permanently diverted around the mine area.

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Table 1.--Laboratory determinations of porosity, hydraulic conductivity, and grain size of rock samples from the Ferron Sandstone Member of the Mancos Shale. (Determinations by Core Laboratories, Inc., Dallas, Texas).

Lithology: S, sandstone; SH, shale; SLT, siltstone; a, altered by coal burn; d, delta-front; f, fluviatile; m, marine; w, weathered.

Sorting coefficient: $\sqrt{Q_3/Q_1}$, where Q_3 is the size where 25 percent of the grains are larger and 75 percent are smaller, and Q_1 is the size where 75 percent are larger and 25 percent are smaller (Pettijohn, 1957, p. 37).

Test hole	Lithology	Depth (feet below land surface)	Porosity (percent)	Hydraulic conductivity (feet per day)		Mean grain size (inches)	Sorting coefficient
				Horizontal	Vertical		
(D-22-6) 22 cdd-1	S,d	182	19	8.0×10^{-2}	1.1×10^{-1}	1.2×10^{-2}	1.28
	S,d	202	18	9.8×10^{-2}	9.5×10^{-2}	1.0×10^{-2}	1.22
34 cacl	S,d	84	17	2.5×10^{-1}	2.1×10^{-1}	8.5×10^{-2}	1.23
	S,f	125	18	4.9×10^{-3}	5.1×10^{-3}	6.6×10^{-2}	1.43
	S,d	169	10	2.4×10^{-3}	2.3×10^{-3}	6.4×10^{-2}	1.50
	S,d	181	13	5.6×10^{-2}	4.1×10^{-2}	1.0×10^{-2}	1.68
	SH,m	200	–	–	5.5×10^{-6}	–	–
(D-23-6) 3 ddc-1	S,f,w	9	20	7.7×10^{-1}	3.2×10^{-1}	1.2×10^{-2}	1.18
	S,f,w	34	18	1.1×10^{-2}	2.9×10^{-3}	–	–
	S,f,a	54	14	7.3×10^{-4}	–	–	–
	S,f	164	17	2.7×10^{-2}	6.8×10^{-3}	1.3×10^{-2}	1.45
	S,d	224	12	7.3×10^{-4}	2.9×10^{-3}	–	–
	S,d	283	20	3.2×10^{-1}	2.6×10^{-1}	6.3×10^{-2}	1.44
(D-24-6) 5 abb-1	S,f	42	20	8.8×10^{-2}	1.6×10^{-1}	1.2×10^{-2}	1.21
	SLT,m	92	11	3.2×10^{-5}	2.9×10^{-6}	–	–
	SLT,m	151	16	7.3×10^{-4}	3.2×10^{-5}	–	–
	S,d	342	15	9.8×10^{-3}	4.6×10^{-3}	–	–

Table 2.--Summary of aquifer tests conducted on the Ferron sandstone aquifer in the Emery area, 1978-9.

Method of test analysis: C, constant drawdown (Lohman, 1972, p. 23-26); L, Hantush modified method for leaky confined aquifer (Lohman, 1972, p. 32-34); R, straight-line recovery method (Lohman, 1972, p. 26 and 27).

Location	Time-weighted average discharge (gallons per minute)	Duration of test (minutes)	Depth of well (feet)	Depth to first opening in well (feet below land surface)	Distance to observation well from discharging well (feet) and direction	Transmissivity (feet squared per day)	Storage coefficient	Method of test analysis	Remarks
(D-22-6) 4cab-1	51	150	1,614	1,586	-	800 600	[1]	C R	Open hole below 1,586 ft in basal section of Ferron sandstone aquifer
17abc-1	176	310	1,543	1,368	-	400 600	[1]	C R	Taps basal section of Ferron sandstone aquifer
17abc-2	3	120	1,100	1,040	-	30	-	R	Expandable packer set at 1,040 ft; open hole below in upper section of Ferron sandstone aquifer
22cdd-1	10	1,500	275	100	-	10	-	R	Both wells tap upper coal-bearing section of Ferron sandstone aquifer
22cdd-2			270	230	375, northwest	20	2×10^{-3}	L	
26bbb-1	8	1,500	349	40	174, south	100	7×10^{-4}	L	Both wells tap entire upper section and part of basal section of Ferron sandstone aquifer
27cbb-2	4	40	380	310	-	100	-	R	Open hole below 310 ft in basal section of Ferron sandstone aquifer
27cbb-5	3	1,500	158	118	-	40	-	R	Both wells tap upper section of Ferron sandstone aquifer
27cbb-3			150	75	206, north	100	8×10^{-4}	L	
31dab-1	13	3,065	406	360	-	200	-	R	Taps upper section of Ferron sandstone aquifer
(D-23-6) 32bbb-2	16	1,540	280	225	-	100	-	R	All wells tap basal section of Ferron sandstone aquifer
32bbb-3			280	-	480, north	50	1×10^{-5}	L	
32bbb-1			282	160	695, northwest	400	1×10^{-5}	L	
32bda-1			240	200	480, southeast	90	3×10^{-6}	L	
32bcb-1			245	205	890, southwest	60	3×10^{-5}	L	

Table 5.--Records of selected wells, test holes, and springs in the Castle Valley area.

Location: See description of well- and spring-numbering system.

Owner, user, or name: BLM, U.S. Bureau of Land Management; Consol, Consolidation Coal Company; USGS, U.S. Geological Survey.

Casing: Depth--depth to top of perforations or first opening; P, depth to bottom of expandable packer.

Water-bearing zone(s): Age--Q, Quaternary; K, Cretaceous. Mappable unit--a, alluvium; p, pediment gravel; me, Emery Sandstone Member of Mancos Shale; mb, Blue Gate Member of Mancos Shale; mf, Ferron Sandstone Member of Mancos Shale; mt, Tununk Member of Mancos Shale.

Altitude of land-surface datum: Interpolated from topographic map.

Water level: Measured except as indicated by R, reported; F, flows at land surface; E, determined from electric log.

Discharge: Measured except as indicated by R, reported. Method of discharge--A, air line used to lift water to surface; F, natural flow; P, pumped.

Use of water, well, test hole, or spring: C, coal test; D, domestic; G, geophysical test; I, irrigation; M, municipal public supply; N, industrial; O, observation; P, petroleum or natural gas; S, stock watering; T, aquifer test; U, unused.

Remarks and other data available: A, aquifer-test data in files of U.S. Geological Survey, Salt Lake City, Utah; C, chemical analysis of water in table 4. Top of Ferron Sandstone Member in feet below land surface.

Location	Owner, user, or name	Year constructed	Depth of well or test hole (feet)	Casing: Diameter (inches)	Casing: Depth (feet)	Water-bearing zone(s)	Altitude of land-surface datum above mean sea level (feet)	Water level above(+) or below land-surface datum (feet)	Discharge (gallons per minute)	Date of water-level and discharge measurements	Use of water, well, test hole, or spring	Remarks and other data available
(D-13-7) 15cda-1	Stanolind Oil and Gas Co. (No. 1)	1954	6,502	-	-	Kmf	9,200	-	-	-	P	Abandoned gas test. Top of Ferron Sandstone Member at 6,121 ft. C
32dbd-1	Mountain Fuel Supply Co. (No. 3)	1952	4,564	-	-	Kmf	8,450	F	<1F	11-5-64	P	Producing gas well. Top of Ferron Sandstone Member at 4,564 ft. C
(D-13-9) 25add-1	G. Haslam	1971	210	4	120	Kmb	5,775	6.63	-	9-18-75	U	C
25dcc-1	V. Sacco	1956	31	6	-	Qa	5,725	7.20	-	9-18-75	D	C
(D-14-7) 30cad-1	Mountain Fuel Supply Co. (A-3)	1963	4,049	5	3,797	Kmf	8,200	-	-	-	P	Producing gas well. Top of Ferron Sandstone Member at 3,706 ft. C

Table 5.-- Records of selected wells, test holes, and springs -- Continued

Location	Owner, user, or name	Year constructed	Depth of well or test hole (feet)	Casing: Diameter (inches)	Casing: Depth (feet)	Water-bearing zone(s)	Altitude of land-surface datum above mean sea level (feet)	Water level, above (+) or below land-surface datum (feet)	Discharge (gallons per minute)	Date of water level and discharge measurements	Use of water, well, test hole, or spring	Remarks and other data available
(D-14-7) 24abd-1	Amerada Petroleum Co.	1962	4,215	-	-	Kmf	6,320	-	-	-	P	Abandoned gas test. Ferron Sandstone Member from 2,669 to 3,023 ft. Tununk Member also produced water. C
(D-15-11) 7aac-1	Carbon Dioxide and Chemical Co.	1953	46	8	33	Qa	5,390	15.15	-	9-27-79	N	C
(D-17-7) 25ddc-1	Utah Southern Oil Co.	1954	4,577	-	-	Kmf	7,040	F	-	3- -54	P	Abandoned gas test. Top of Ferron Sandstone Member at 3,577 ft. C
(D-17-9) 23acb-1	A. Christiansen	1979	200	4	[illegible]	Kmb	5,[illegible]	79.66	-	9-27-79	U	C
(D-17-10) 4bbc-1	M. Coonrod	1979	700	-	-	-	5,660	-	-	-	U	Driller reported no water encountered in Ferron Sandstone Member
16dda-1	L. Smith	1979	205	4	185	Kmf	5,680	7.60	-	10-30-79	D	C
(D-19-9) 31acb-S1	BLM	-	-	-	-	Kmb	5,650	-	<1 F	-	S	C
(D-20-7) 27cac-1	English Oil Co. (No. 23-27)	1962	983	4.5	804	Kmf	5,940	-	-	-	P	Producing gas well. Ferron Sandstone Member from 790 to 951 ft. C
(D-20-8) 3bbd-1	Pacific Western Exploration Co.	1978	105	-	-	Kmf	5,600	-	-	-	G	Plugged. C
4dbc-1	do.	1978	120	-	-	Kmf		-	-	-	G	Do.
21bda-1	do.	1978	100	-	-	Kmf	5,960	38.92	-	5-18-78	G	Do.
22caa-1	do	1978	100	-	-	Kmf	5,870	29.67	-	5-18-78	G	Plugged
29bba-1	do.	1978	100	-	-	Kmf	5,850	10.73	-	5-18-78	G	Plugged. C
(D-21-6) 35aac-1	USGS	1978	76	2	56	Kmb	6,260	53.10	-	5-10-78	O	Converted geophysical test hole. C
(D-21-7) 4aac-1	do.	1978	82	2	62	Kmb	6,250	44.34	-	5-10-78	O	Do.
(D-22-4) 17cbd-1	Mountain Fuel Supply Co. (No. 1)	1955	6,971	-	-	Kmf	8,155	-	-	-	P	Abandoned gas test. Ferron Sandstone Member from 4,727 to 5,340 ft. Several other zones produced water, see Peltis (1964, p. 76). C
(D-22-5) 23aca-1	K. D. Owen (No. 1)	1953	3,670	-	-	Kmf	6,220	F	-	1-19-53	P	Abandoned gas test. Ferron Sandstone Member from 1242 to 1,757 ft. C

Table 5.--Records of selected wells, test holes, and springs--Continued

Location	Owner, user, or name	Year constructed	Depth of well or test hole (ft)	Casing: Diameter (inches)	Casing: Depth (ft)	Water-bearing zone(s)	Altitude of land-surface datum (ft above mean sea level)	Water level above(+) or below land-surface datum (ft)	Discharge (gallons per minute)	Date of water level and discharge measurements	Use of water, well, test hole, or spring	Remarks and other data available
(D-22-5) 34dc	Skelly Oil Co. (No. 1)	1962	10,740	–	–	Kmf	6,350	F	76F	2-8-62	P	Ferron Sandstone Member from 1,170 to 1,710 ft. C
(D-22-6) 4cab-1	City of Emery	1966	1,614	5	1,586	Kmf	6,360	+27.48	51F	6-14-78	M	Open hole from 1,586 to 1,614 ft. Top of Ferron Sandstone Member at 1,265 ft; entire thickness not penetrated. A.C
4cab-2	do.	1979	2,535	10	1,250	Kmf	6,360	98.25	100P	10-27-79	M	Open hole from 1,565 to 1,900 ft; hole caved below. Ferron Sandstone Member from 1,250 to 1,710 ft. Specific conductance 1,500 micromhos and water temperature 25.0°C on 10-25-79
17abc-1	Kemmerer Coal Co.	1973	1,543	8	1,368	Kmf	6,285	+45	176F	7-10-79	O	Top of Ferron Sandstone Member at 1,053 ft; entire thickness not penetrated. A.C
17abc-2	USGS (No. 1-4)	1978	1,100	–	1,040P	Kmf	6,280	+26.80	2F	12-14-78	T	Plugged. Top of Ferron Sandstone Member at 1,043 ft; entire thickness not penetrated. Water table in Blue Gate Member, 16 ft below land surface on 12-14-78. A.C
19cdb-1	G. Olson (Consol FC 451)	1979	410	4	390	Kmb, Kmf	6,070	+20	20F	5-16-79	I	Converted coal-test hole. C
20baa-1	Consol (Piezometer site H)	1979	1,140	1	1,113	Kmf	6,250	+14	<1F	10-24-79	O	Top of Ferron Sandstone Member at 815 ft; entire thickness not penetrated. Cement grout around casing from 993 to 1,018 ft. C
20baa-2	do.	1979	995	1	969	Kmf	6,250	+27	<1	10-25-79	O	Cement grout around casing from 869 to 880 ft. C
20baa-3	do.	1979	869	1	840	Kmf	6,250	62.18	–	11-15-79	O	Cement grout around casing from 808 to 835 ft
20baa-4	do.	1979	808	1	40	Kmb	6,250	32.14	–	10-24-79	O	Cement grout around casing from surface to 17 ft
21ccb-1	USGS (No. 1-3)	1978	725	–	600P	Kmf	6,155	107.22	3A	12-1-78	T	Plugged. Top of Ferron Sandstone Member at 598 ft; entire thickness not penetrated. Water table in Blue Gate Member, 24 ft below land surface on 12-1-78. C

Table 5.--Records of selected wells, test holes, and springs--Continued

Location	Owner, user, or name	Year constructed	Depth of well or test hole (feet)	Casing: Diameter (inches)	Casing: Depth (feet)	Water-bearing zone(s)	Altitude of land surface datum (feet above mean sea level)	Water level above (+) or below land-surface datum (feet)	Discharge (gallons per minute)	Date of water level and discharge measurements	Use of water, well, test hole, or spring	Remarks and other data available
(D-22-6) 21cdd-1	Consol (Piezometer site I)	1979	728	1	695	Kmf	6,110	11.33	-	10-25-79	O	Top of Ferron Sandstone Member at 415 ft; entire thickness not penetrated. Cement grout around casing from 601 to 636 ft
21cdd-2	do.	1979	609	1	587	Kmf	6,110	62.25	-	10-25-79	O	Cement grout around casing from 475 to 508 ft
21cdd-3	do.	1979	475	1	441	Kmf	6,110	385.70	-	11-15-79	O	Cement grout around casing from 405 to 425 ft. Piezometer probably plugged and not open to aquifer
21cdd-4	do.	1979	544	1	63	Kmb	6,110	9.56	-	10-25-79	O	
22cdd-1	USGS (EMRIA 3)	1979	275	4	100	Kmf	6,100	58.90	10P	4-19-79	T,O	Top of Ferron Sandstone Member at 171 ft; entire thickness not penetrated. Cement grout around casing from surface to 90 ft. A,C
22cdd-2	USGS (EMRIA 3A)	1978	270	2	230	Kmf	6,090	44.02	-	9-22-78	T,O	Cement grout around casing from surface to 200 ft
22cdd-3	USGS (EMRIA 3B)	1978	40	6	20	Kmb	6,090	16.55	-	9-22-78	T,O	
23aac-1	USGS (EMRIA 1A)	1978	315	2	275	Kmf	6,190	149.14	-	10-27-78	T,O	Converted coal-test hole. C
23adb-1	USGS (EMRIA 1)	1978	305	4	20	Kmf	6,180	138.17	2P	10-25-78	T,O	Converted coal-test hole
23bcc-1	Consol (FC 346)	1974	355	3	149	Kmf	6,120	24.49	-	10-7-76	O	Plugged. C
23cca-1	Pacific Western Exploration Co.	1978	100	-	-	Kmf	6,100	32.23	-	5-31-78	G	
23cdc-S1	M. Christiansen	-	-	-	-	Kmf	6,050	-	6F	10-24-79	U	Specific conductance 4,500 micromhos and water temperature 9.5°C on 10-24-79
23dda-S1	BLM	-	-	-	-	Kmf	5,900	-	5F	4-4-79	U	C
26bac-1	Pacific Western Exploration Co.	1978	100	-	-	Kmf	6,010	7.71	-	5-31-78	G	Plugged. C
26bba-1	do.	1978	100	-	-	Kmf	6,040	28.95	-	5-31-78	G	Do.

Table 5.--Records of selected wells, test holes, and springs--Continued

Location	Owner, user, or name	Year constructed	Depth of well or test hole (feet)	Casing: Diameter (inches)	Casing: Depth (feet)	Water-bearing zone(s)	Altitude of land surface datum (feet above mean sea level)	Water level above (+) or below land-surface datum (feet)	Discharge (gallons per minute)	Date of water level and discharge measurements	Use of water, well, test hole, or spring	Remarks and other data available
(D-22-6) 26bbb	USGS (EMRIA 2)	1978	349	4	40	Kmf	6,080	26.52	9P	6-19-79	T,O	Converted coal-test hole. A.C
26bbb-2	USGS (EMRIA 2A)	1978	300	2	30	Kmf	6,080	33.50	—	10-27-78	T,O	
26bdb-1	R[illegible] Western Exploration Co.	1978	100	—	—	Kmf	6,000	7.89	—	5-31-78	G	Plugged. C
26dcb-1	do.	1978	100	—	—	Kmf	5,970	11.98	—	5-31-78	G	Do.
27bda-1	USGS (Muddy No. 4)	1979	113	2.5	93	Kmf	6,060	8.19	—	6-13-79	O	Converted coal-test hole
27cbb-1	Consol (FC 363)	1975	400	3	22	Kmb, Kmf	6,050	7.69	—	10-7-76	O	Do.
27cbb-2	USGS (No. 1-1)	1978	380	2	310	Kmf	6,060	42.65	3.1	11-17-78	T,O	Top of Ferron Sandstone Member at 73 ft; entire thickness not penetrated. Cement grout around casing from surface to 310 ft. C
27cbb-3	USGS (No. 1-2)	1978	150	2	75	Kmf	6,060	37.68	—	12-10-78	T,O	Cement grout around casing from surface to 75 ft; open hole below. C
27cbb-4	USGS (No. 3-1)	1979	71	2	51	Kmb	6,060	17.23	—	6-13-79	O	C
27cbb-5	USGS (Muddy No. 3)	1979	158	4	118	Kmb, Kmf	6,065	42.26	3P	8-22-79	T,O	Converted coal-test hole. A.C
27cbb-6	USGS (No. 4-1)	1979	30	2.5	10	Kmb	6,060	18.77	—	6-13-79	O	
28[illegible]-1	Cedar Ridge Land and Livestock Co.	—	—	—	—	Qp	6,030	—	1F	9-25-79	U	C
28[illegible]-1	Consol	1976	[illegible]	[illegible]	156	Kmb, Kmf	6,075	23.24	—	9-16-76	O	Top of Ferron Sandstone Member at 156 ft; entire thickness not penetrated
28dab-2	do. (FC 343)	1974	256	3	148	Kmb, Kmf	6,085	23.53	—	10-7-76	O	

Table 5.--Records of selected wells, test holes, and springs--Continued

Location	Owner, user, or name	Year constructed	Depth of well or test hole (feet)	Casing: Diameter (inches)	Casing: Depth (feet)	Water-bearing zone(s)	Altitude of land-surface datum (feet above mean sea level)	Water level above (+) or below land-surface datum (feet)	Discharge (gallons per minute)	Date of water level and discharge measurements	Use of water, well, test hole, or spring	Remarks and other data available
(D-22-6) 23314-1	USGS (Muddy No. 2)	1979	136	2.5	96	Kmf	6,045	44.18	–	6-13-79	O	Converted coal-test hole
29bba-S1	A. [illegible]	–	–	–	–	Qp	6,190	–	6F	11-15-79	U	C
30aad-1	Consol (Piezometer site K)	1979	884	1	838	Kmf	6,030	+83	–	12-4-79	O	Top of Ferron Sandstone Member at 581 ft; entire thickness not penetrated. Cement grout around casing from surface to 830 ft. C
30aad-2	do.	1979	825	1	718	Kmf	6,030	F	–	12-4-79	O	Cement grout around casing from 652 to 692 ft. Shut-in water pressure could not be determined because of gas
30aad-3	do.	1979	652	1	599	Kmf	6,030	+ .42	–	12-4-79	O	Cement grout around casing from 554 to 581 ft
30aad-4	do.	1979	554	1	105	Kmb	6,030	53.39	–	12-4-79	O	Cement grout around casing from surface to 11 ft
30bdd-1	USGS	1978	40	2	20	Kmt	6,020	837	–	11-7-78	O	Converted geophysical test hole
30dcb-1	J. Lewis	1979	608	4	590	Kmb, Kmf	6,030	+8.50	27F	10-18-79	I, S	Top of Ferron Sandstone Member at about 600 ft; entire thickness not penetrated. Cement grout around casing from about 540 to 590 ft. C
31dab-1	E. Bryant	1972	406	6	360	Kmf	6,020	+10.41	45F	7-6-78	I, S	Top of Ferron Sandstone Member at 365 ft; entire thickness not penetrated. A, C
32cdc-1	Consol (Piezometer site AA)	1979	490	1	420	Kmf	5,980	73.03	–	11-16-79	O	Top of Ferron Sandstone Member at 95 ft; entire thickness not penetrated. Cement grout around casing from 396 to 418 ft. Piezometer probably plugged and not open to aquifer
32cdc-2	do.	1979	396	1	336	Kmf	5,980	+1.79	–	11-16-79	O	Cement grout around casing from 215 to 232 ft
32cdc-3	do.	1979	212	1	168	Kmf	5,980	F	–	11-16-79	O	Cement grout around casing from 79 to 96 ft. Shut-in water pressure could not be determined because of gas
32cdc-4	do.	1979	79	1	61	Kmb	5,980	24.84	–	11-16-79	O	Cement grout around casing from surface to 17 ft

Table 5.--Records of selected wells, test holes, and springs--Continued

Location	Owner, user, or name	Year constructed	Depth of well or test hole (ft)	Casing: Diameter (inches)	Casing: Depth (ft)	Water-bearing zone(s)	Altitude of land-surface datum above mean sea level (ft)	Water level above (+) or below land-surface datum (ft)	Discharge (gallons per minute)	Date of water level and discharge measurements	Use of water, well, test hole, or spring	Remarks and other data available
(D-22-6) 33abb-1	USGS (Muddy No. 1)	1979	162	2.5	122	Kmf	6,090	141.08	—	7-2-79	O	Converted coal-test hole
33abb-2	Consol (Site 22)	1979	390	4	310	Kmf	6,090	145.16	—	9-28-79	O	Cement grout around casing from surface to 96 ft. C
34bba-1	USGS (No. 2-4)	1978	160	—	—	Kmf	6,110	86.29	3A	12-12-78	T	Plugged. C
			360	—	273P	Kmf		167.00	<1A	12-14-78		C
34cac-1	BLM (EMRIA 4A)	1977	200	—	—	Kmf	6,200	—	—	—	C	Plugged. Driller reported hole was dry
(D-22-7) 8bcd-1	Cedar Ridge Land and Livestock Co.	—	130	—	—	Kmf	6,260	77	—	10-26-78	D	C
(D-23-5) 2ddc-1	Emery Energy	1979	926	—	—	Kmf	6,340	149E	—	4-18-79	C	Plugged
12bcd-1	BLM (Consol No. 487)	1979	709	6	28	Kmf	6,190	F	3F	12-28-79	S	Specific conductance 950 micromhos and water temperature 17.0°C on 12-28-79
13aaa-1	Consol	1979	540	—	—	Kmf	6,020	P	—	8-1-78	C	Plugged. C
12cad-S1	R. Jensen	—	—	—	—	Kmf	6,280	—	5F	7-24-79	U	C
31aba-1	Johnson Land and Livestock Co.	1977	3,340	6	339	Kmf	6,720	+3	1F	8-31-78	S	Converted petroleum test. On 8-31-78 obstruction in hole at 504 ft. Ferron Sandstone Member from 6535 to 2,235 ft. C
						Kmf	6,580	—	—	—	C	Plugged. Driller reported hole was dry
(D-23-6) 3ddc-1	BLM (EMRIA 5)	1977	274	—	—	Kmf	6,180	288.99	<1A	11-30-78	T	Plugged. C
4bcb-1	USGS (No. 2-3)	1978	410	—	—							
6acc-1	USGS (No. 2-1)	1978	385	—	—	Kmf	6,040	1E 4	23A	11-21-78	T	Plugged. Top of Ferron Sandstone Member at 290 ft, entire thickness not penetrated. C
			720	—	665P	Kmf		+122	4F	11-28-78		A. C
17dba-S1	BLM	—	—	—	—	Kmf	5,830	—	1F	11-8-78	U	C
18bac-1	Hidden Valley Coal Co.	1977	439	2.75	165	Kmf	6,020	FR	17FR	8-14-78	U	Cement grout around casing from surface to 165 ft
18cbd-1	do.	1977	551	2.75	155	Kmf	6,060	FR	6FR	3-1-77	U	Cement grout around casing from surface to 155 ft

Table 5.--Records of selected wells, test holes, and springs--Continued

Location	Owner, user, or name	Year constructed	Depth of well or test hole (feet)	Casing: Diameter (inches)	Casing: Depth (feet)	Water-bearing zone(s)	Altitude of land-surface datum (feet above mean sea level)	Water level above (+) or below land-surface datum (feet)	Discharge (gallons per minute)	Date of water level and discharge measurements	Use of water, well, test hole, or spring	Remarks and other data available
(D-23-6) 18cdc-1	Hidden Valley Coal Co.	1979	600	6	300	Kmf	6,150	F	5F	8-3-79	U	Cement grout around casing from surface to 300 ft. Shut-in water pressure could not be determined because of gas. C
18ddb-1		1977	484	275	160	Kmf	6,120	F	50F	8-3-79	U	Cement grout around casing from surface to 85 ft. Shut-in water pressure could not be determined because of gas. C
32bbb-1	Western States Minerals Co.	1978	282	6	160	Kmf	6,220	93.49	—	9-20-78	N	
32bbb-2	do	1978	280	6	225	Kmf	6,230	119.90	16P	9-20-78	N	A.C
32bbb-3	do.	1978	280	—	—	Kmf	6,220	101.24	—	9-20-78	N	
32bbd-1	do.	1978	210	6	150	Kmf	6,250	137.98	—	9-20-78	N	
32bcb-1	do.	1978	245	6	205	Kmf	6,230	99.85	—	9-20-78	N	
32bda-1	do.	1976	240	4	200	Kmf	6,260	141R	10PR	6-5-78	D,N	C
32bdc-1	do.	1975	293	8	253	Kmf	6,250	—	10PR	6-5-78	D,N	C
(D-24-5) 1ccb-1	USGS (No. 22-WS)	1977	480	—	—	Kmf	6,470	175E	—	6-30-77	C	Plugged
1ccc-1	USGS (No. 15-WS)	1977	1,240	—	—	Kmb, Kmf	7,130	581E	—	7-15-77	C	Plugged. Top of Ferron Sandstone Member at 330 ft; entire thickness not penetrated
10acc-1	USGS (No. 21-WS)	1977	720	—	—	Kmb, Kmf	6,480	189E	—	7-16-77	C	Plugged. Top of Ferron Sandstone Member at 186 ft; entire thickness may not have been penetrated
11bda-1	USGS (No. 16-WS)	1977	695	—	—	Kmf	6,500	138E	—	6-17-77	C	Plugged. Ferron Sandstone Member from 65 to 586 ft
13bcd-S1	BLM (Willow Springs)	—	—	—	—	Kmf	6,210	—	15F	9-29-79	U	C
15adc-1	USGS (No. 17-WS)	1977	760	—	—	Kmb, Kmf	6,525	40R	—	6-19-77	C	Plugged. Ferron Sandstone Member from 18? to about 690 ft

Table 5.-- Records of selected wells, test holes, and springs -- Continued

Location	Owner, user, or name	Year constructed	Depth of well or test hole (ft)	Casing: Diameter (in)	Casing: Depth (ft)	Water-bearing zone(s)	Altitude of land surface datum above mean sea level (ft)	Water level above (+) or below land-surface datum (ft)	Discharge (gal per minute)	Date of water level and discharge measurements	Use of water, well, test hole, or spring	Remarks and other data available
(D-24-5) 22aac-1	USGS (No. 18-WS)	1977	780	—	—	Kmb, Kmf	6,665	90E	—	6-22-77	C	Plugged. Ferron Sandstone Member, from 170 to about 780 ft
28abc-1	USGS (No. 20-WS)	1977	1,480	—	—	Kmb, Kmf	7,480	617E	—	7-15-77	C	Plugged. Top of Ferron Sandstone Member at 970 ft; entire thickness not penetrated
28cdc-1	USGS (No. 19-WS)	1977	1,300	—	—	Kmb, Kmf	7,700	91E	—	7-7-77	C	Plugged. Top of Ferron Sandstone Member at about 1,035 ft; entire thickness not penetrated
(D-24-6) 5all-1	BLM (EMRIA 6)	1977	351	—	—	Kmf	6,520	—	—	—	C	Plugged.

Table 6.-- Chemical analyses of water from wells, test holes, springs, and the Emery Mine.

Location: See description of well- and spring-numbering system. Suffix M indicates sample collected in Emery Mine.

Water-bearing zone(s): Age-- Q, Quaternary ; K, Cretaceous. Mappable unit-- a, alluvium; p, pediment gravel; me, Emery Sandstone Member of Mancos Shale; mb, Blue Gate Member of Mancos Shale; Kmf, Ferron Sandstone Member of Mancos Shale; mt, Tununk Member of Mancos Shale; d, Dakota Sandstone.

Method of collection: A, air line used to lift water to surface; B, bailed; D, sample collected while drilling with air; DS, sample recovered from drill-stem test; F, natural flow; P, pumped.

pH: Field determination except L, determined in laboratory.

Dissolved solids: Calculated from sum of constituents.

Specific conductance: Field determination except L, determined in laboratory.

Source of analytical data: CGL, Chemical and Geological Laboratories, Casper, Wyoming; CL, Core Laboratories, Dallas, Texas; GS, U.S. Geological Survey.

Table 6.-- Chemical analyses of water from wells, test holes, springs, and the Emery Mine --Continued

Location	Water-bearing zone(s)	Interval sampled (feet below land surface)	Method of collection	Date of collection	Temperature (°C)	pH (units)	Milligrams per liter: Dissolved calcium (Ca)	Dissolved magnesium (Mg)	Dissolved sodium (Na)	Dissolved potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Dissolved sulfate (SO_4)	Dissolved chloride (Cl)	Dissolved bromide (Br)	Dissolved boron (B)	Dissolved silica (SiO_2)	Hardness as $CaCO_3$	Noncarbonate hardness as $CaCO_3$	Dissolved solids	Specific conductance (micromhos)	Source of analytical data
(D-13-7) 15cda-1	Kmf	6,195-97	–	12- -54	–	8.2L	14	[1]	1,344 [2]	–	1,960	74	16	859	–	–	–	–	–	3,272	–	CGL
	Kmf	6,472-6,502	DS	12- -54	–	8.3L	14	[1]	1,487 [2]	–	2,050	118	24	733	–	–	–	–	–	3,335	–	CGL
32dbd-1	Kmf	4,070-4,462	F	11-5-64	–	6.5L	6.4	5.8	239 [2]	–	274	0	11	230	–	–	1.6	40	0	629	–	GS
(D-13-9) 25add-1	Kmb	120-210	P	9-24-75	12.5	7.6	240	210	640	12	102	0	2,800	35	–	0.61	3.3	1,500	1,400	4,090	4,000	GS
25dcc-1	Qa	–	P	9-18-75	17.5	–	84	71	52	7.6	248	–	400	17	–	.21	15	500	300	778	1,270	GS
(D-14-7) 30cad-1	Kmf	3,797-4,049	–	4-30-63	–	7.9L	25	6	1,151	6	1,537	0	0	950	–	–	–	–	–	2,895	–	CGL
(D-14-9) 29abd-1	Kmf	At 2,756	D	12- -62	–	7.0L	320	24	19,978 [3]	–	488	144	40	30,956	–	–	–	–	–	51,950	–	CL
	Kmf	At 2,806	D	12- -62	–	8.0L	280	24	14,975 [3]	–	3,514	240	40	21,300	–	–	–	–	–	37,860	–	CL
	Kmt	At 3,064	D	12- -62	–	8.0L	120	24	6,537 [3]	–	1,220	336	40	2,840	–	–	–	–	–	11,117	–	CL
	Kmt	At 3,325	D	12- -62	–	8.0L	80	24	7519 [3]	–	1,464	96	40	2,840	–	–	–	–	–	12,093	–	CL
(D-15-11) 7aac-1	Qa	33-46	P	9-27-79	13.0	7.0	490	240	400	12	590 [4]	0	2,400	39	0.2	.71	18	2,100	1,600	3,850	4,400	GS
(D-17-7) 25ddc-1	Kmf	–	–	3- -54	–	8.5L	32	24	6,248 [3]	–	9,750	835	–	2,800	–	–	–	–	–	14,541	–	CGL
(D-17-9) 23acb-1	Kmb	120-200		9-27-79	12.0	7.5	160	81	9,000	26	400 [4]	0	38	13,000	130	.68	7.6	730	400	22,600	33,200	GS
(D-17-10) 16dda-1	Kmf	185-205		9-26-79	13.0	6.9	400	290	380	22	430 [4]	0	2,500	24	.2	.55	9.2	2,200	1,800	3,840	4,750	GS
(D-18-9) 31aba-S1	Kmb	–	F	5-10-78	15.5	7.1L	430	410	530	17	45	–	3,600	48	–	–	19	2,800	2,700	5,080	6,000	GS
(D-20-7) 27cac-1	Kmf	804-6	–	4- -62	–	8.2L	49	25	8,404 [3]	–	2,562	192	24	11,500	–	–	–	–	–	21,534	–	[4]
(D-20-8) 3bbd-1	Kmf	At 105	D	5-12-78	17.0	7.8L	40	25	3,200	15	1,050	–	91	4,200	20	.17	8.0	200	0	8,120	13,600	GS
4dbc-1	Kmf	At 120	D	5-12-78	16.5	7.8L	270	310	2,700	26	660	–	5,100	1,400	1.2	.48	10	2,000	1,400	10,100	12,500L	GS
21bda-1	Kmf	At 39	D	5-18-78	13.0	7.5L	310	300	1,400	13	300	–	4,300	390	3.0	.89	9.6	2,000	1,800	6,870	8,000L	GS
29bba-1	Kmf	At 11	D	5-18-78	12.5	7.8L	120	170	1,500	13	1,300	–	2,000	380	4.7	.65	9.2	1,000	0	5,340	7,940L	GS

Table 6.--Chemical analyses of water from wells, test holes, springs, and the Emery Mine--Continued

...ation	Water-bearing zone(s)	Interval sampled (feet below land surface)	Method of collection	Date of collection	Temperature (°C)	pH (units)	Milligrams per liter: Dissolved calcium (Ca)	Dissolved magnesium (Mg)	Dissolved sodium (Na)	Dissolved potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Dissolved sulfate (SO_4)	Dissolved chloride (Cl)	Dissolved bromide (Br)	Dissolved boron (B)	Dissolved silica (SiO_2)	Hardness as $CaCO_3$	Noncarbonate hardness as $CaCO_3$	Dissolved solids	Specific conductance (micromhos)	Source of analytical data
(D-21-6) 35aac-1	Kmb	56-76	B	8-10-78	13.5	7.1	90	190	7,600	29	750	0	7,000	4,100	17	1.5	12	1,000	390	19,400	31,000	GS
(D-21-7) 40ac-1	Kmb	62-82	G	8-10-78	13.0	7.6	29	15	2,200	12	540	0	3,000	910	13	.78	8.7	130	0	6,450	9,000	GS
(D-22-4) 17cbd-1	Kme	2,045-2,107	DS	12-5-53	—	7.7L	49	13	603[1]	—	980	—	597	44	—	—	—	—	—	1,793	—	CGL
	Kmf	4712-59	DS	1-23-56	—	7.0L	471	126	6,202[1]	—	1,035	—	10,176	2,660	—	—	—	—	—	20,145	—	CGL
	Kmf	4782-98	DS	1-24-56	—	6.8L	506	190	7981[1]	—	360	—	13,415	3,660	—	—	—	—	—	25,931	—	CGL
	Kmf	4,910-20	DS	1-27-56	—	7.5L	153	41	1,793[1]	—	1,560	—	2,263	580	—	—	—	—	—	5,598	—	CGL
	Kmf	5226-92	DS	2-10-56	—	6.5L	514	154	3,660[1]	—	610	—	8,473	400	—	—	—	—	—	13,501	—	CGL
	Kd	6,196-6,212	DS	2-24-56	—	6.5L	4,498	1,042	21,010[1]	—	645	—	41	43,000	—	—	—	—	—	69,909	—	CGL
(D-22-5) 23aaa-1	Kmf	1,305-19	F	1-19-53	—	—	109	32	2,317[1]	—	395	—	4,143	575	—	—	—	—	—	7,370	—	GS
	Kmf	1,395-1,408	DS	1-22-53	—	—	221	48	2,397[1]	—	452	—	4,424	703	—	—	—	—	—	8,015	—	GS
	Kmf	1,423-36	DS	1-24-53	—	—	209	40	2,492[1]	—	437	—	4,575	702	—	—	—	—	—	8,233	—	GS
	Kmf	1,520-30	DS	1-28-53	—	—	222	62	2077[1]	—	855	—	3,465	707	—	—	—	—	—	6,954	—	GS
34dc	Kmf	1,174-1,200	F	2-8-62	—	7.2L	489	24	2,600[1]	—	370	0	5,630	567	—	1.9	15	1,320	1,010	9,310	10,700L	GS
(D-22-6) 4aab-1	Kmf	1,586-1,614	F	2-5-79	26.0	7.9	31	19	180	4.1	280	0	350	20	.1	.22	15	160	0	757	1,180	GS
17abc-1	Kmf	1,368-1,[illegible]3	F	7-10-79	25.0	7.6L	29	19	200	4.4	300	—	300	32	.2	.23	16	150	0	749	1,150L	GS
17abc-2	Kmf	1,040-1,100	F	12-14-78	15.5	8.1	19	14	290	5.1	310	0	440	30	.2	.29	16	110	0	967	1,480	GS
19cdb-1	Kmb, Kmf	390-410	F	5-16-79	20.5	8.4L	36	19	220	4.4	300	—	340	28	.3	.25	12	170	0	808	1,250	GS
20baa-1	Kmf	1,018-1,140	F	10-24-79	12.5	8.2	7.5	40	300	5.0	470[1]	0	250	12	.1	.31	25	35	0	838	1,350	GS
20baa-2	Kmf	880-995	F	10-23-79	11.5	8.8	36	7.9	260	5.1	310[1]	—	420	23	.1	.28	22	120	0	931	1,400	GS
21ccb-1	Kmf	600-725	A	11-30-78	10.5	9.0	17	16	460	4.4	570	5	590	31	.2	.61	12	110	0	1,420	2,100	GS

Table 6.-- Chemical analyses of water from wells, test holes, springs, and the Emery Mine -- Continued

Location	Water-bearing zone(s)	Interval sampled (feet below land surface)	Method of collection	Date of collection	Temperature (°C)	pH (units)	Milligrams per liter: Dissolved calcium (Ca)	Dissolved magnesium (Mg)	Dissolved sodium (Na)	Dissolved potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Dissolved sulfate (SO_4)	Dissolved chloride (Cl)	Dissolved bromide (Br)	Dissolved boron (B)	Dissolved silica (SiO_2)	Hardness as $CaCO_3$	Noncarbonate hardness as $CaCO_3$	Dissolved solids	Specific conductance (micromhos)	Source of analytical data
(D-22-6)22cdd-1	Kmf	100-275	P	4-19-79	13.0	7.1	300	290	880	12	640	0	3,200	120	.5	.62	19	1,900	1,400	5,140	6,100	GS
23adb-1	Kmf	138-305	P	10-25-78	13.0	7.4L	130	23	640	6.1	580	–	1,300	35	.4	.89	16	420	0	2,440	3,400L	GS
23cca-1	Kmf	At 32	B	5-31-79	12.0	7.2L	470	400	320	16	510	–	2,900	96	.4	.59	13	2,800	2,400	4,470	4,780L	GS
23dda-S1	Kmf	–	F	4-4-78	10.0	7.5L	130	110	660	5.3	690	–	1,500	110	.5	.47	12	780	210	2,870	3,850L	GS
26bac-1	Kmf	At 8	B	5-31-78	12.0	7.5L	44	37	300	6.3	500	–	470	28	.1	.48	12	260	0	1,140	1,700	GS
26bba-1	Kmf	At 29	B	5-31-78	12.5	–	510	370	240	83	6	–	3,000	45	.3	2.6	18	2,800	2,800	4,200	4,500	GS
26bbb-1	Kmf	40-349	P	6-21-79	13.5	3.6L	110	930	940	10	0	0	5,900	140	1.0	.77	36	4,100	4,100	8,070	10,700	GS
26bdb-1	Kmf	At 8	B	5-31-78	11.0	7.5L	75	58	370	7.2	560	–	700	28	.1	.51	13	430	0	1,530	2,200	GS
26cbb-1	Kmf	At 12	B	5-31-78	13.0	7.1L	380	260	480	9.3	490	–	2,400	100	.5	1.1	11	2,000	1,600	3,880	4,100	GS
27cbb-2	Kmf	310-80	A	11-17-78	10.0	8.8L	4.5	2.2	310	5.0	620	–	170	19	4.6	.60	8.9	20	0	830	1,250	GS
27cbb-3	Kmf	75-150	A	11-17-78	8.5	7.4L	140	220	760	48	330	–	2,500	20	.5	.43	21	1,300	980	3,870	5,000	GS
27cbb-4	Kmb	51-71	B	5-31-79	11.0	7.9L	170	1,100	4,000	46	300	–	12,000	230	.8	1.1	69	5,000	4,700	17,700	20,000	GS
27cbb-5	Kmb, Kmf	118-58	P	8-22-79	11.5	7.4	2,000	200	5,000	67	560	0	15,000	640	3.1	.45	6.3	5,800	5,400	23,200	23,000	GS
28bca-M	Kmf	–	F	3-29-79	13.0	8.7	93	9.2	380	2.6	590	0	390	28	.2	.59	12	61	0	1,120	1,620	GS
28bcc-S1	Qp	–	F	9-25-79	21.0	8.5	72	58	94	4.1	420	–	250	6.0	.1	.22	13	420	69	718	1,180L	GS
28cba-M	Kmf	–	F	9-1-78	13.5	8.4	24	29	420	2.6	630[3]	–	520	28	.3	.58	13	180	0	1,350	2,040L	GS
				3-29-79	12.0	8.4	30	30	440	4.2	640	0	530	31	.2	.57	11	200	0	1,390	2,070L	GS
29bbc-S1	Qp	–	F	9-25-79	21.0	8.5	58	39	35	2.6	340[3]	–	75	6.7	.1	.14	14	310	25	399	720	GS
29dac-M	Kmf	–	F	9-1-78	13.0	9.5	.9	.6	320	1.9	670[3]	–	74	27	.3	.85	9.5	5	0	774	1,300	GS
				3-29-79	12.5	9.3	1.2	.6	290	1.1	580	14	92	29	.2	.77	9.3	5	0	724	1,290L	GS

Table 6.-- Chemical analyses of water from wells, test holes, springs, and the Emery Mine -- Continued

Location	Water-bearing zone(s)	Interval sampled (feet below land surface)	Method of collection	Date of collection	Temperature (°C)	pH (units)	Dissolved calcium (Ca)	Dissolved magnesium (Mg)	Dissolved sodium (Na)	Dissolved potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Dissolved sulfate (SO_4)	Dissolved chloride (Cl)	Dissolved bromide (Br)	Dissolved boron (B)	Dissolved silica (SiO_2)	Hardness as $CaCO_3$	Noncarbonate hardness as $CaCO_3$	Dissolved solids	Specific conductance (micromhos)	Source of analytical data
							Milligrams per liter															
(D-22-6) 30aad-1	Kmf	838-84	F	10-15-79	19.0	8.0	12	6.9	220	4.4	400[3]	0	180	16	.1	.35	14	58	0	652	1,100	GS
30dcb-1	Kmf	590-608	F	9-28-79	16.0	8.8	410	300	370	1.5	310[3]	–	2,700	24	.2	.55	93	2,300	2,000	3,970	4,540L	GS
31dab-1	Kmf	360-406	F	10-7-76	13.0	7.9	35	18	360	3.7	299	0	600	45	–	.28	14	160	0	1,230	1,800L	GS
32aba-M	Kmf	–	F	3-29-79	10.0	8.9	8.6	10	640	4.6	620	37	830	71	.3	.88	8.2	63	0	1,900	3,080	GS
33abb-2	Kmf	310-90	A	9-12-79	16.0	8.9	10	4.5	290	8.8	494	65	130	13	.1	.00	21	36	0	904	1,250	GS
34bba-1	Kmf	At 160	D	12-12-78	10.5	8.9	10	6.3	260	6.3	430	–	230	23	.1	.36	11	51	0	759	1,100	GS
	Kmf	273-360	A	12-14-78	9.0	9.1	14	7.4	300	5.2	700	17	140	21	.2	.47	39	65	0	854	1,320	GS
(D-22-7) 8bcd-1	Kmf	–	P	6-15-78	15.0	7.0L	420	310	140	5.8	600	–	2,000	46	.8	.23	25	2300	1,800	3,240	3,710L	GS
(D-23-5) 13aaa-1	Kmf	–	F	8-1-79	–	8.6L	14	8.2	220	2.8	370	–	230	15	.1	.35	14	69	0	687	1,010L	GS
16acd-S1	Kme	–	F	7-24-79	13.5	8.0L	45	27	290	5.5	480	0	300	48	.2	.36	9.8	220	0	1,160	1,700	GS
31aba-1	Kmf	–	F	8-31-78	13.0	8.8	1.7	.2	130	1.4	260	8	51	15	.2	.18	15	5	0	351	540	GS
(D-23-6) 4bcb-1	Kmf	At 440	D	11-30-78	14.0	8.4	110	45	600	8.4	320	0	1,400	83	.5	.67	83	460	200	2,410	3,400	GS
6acc-1	Kmf	At 385	D	11-21-78	12.5	8.2	35	19	370	4.1	280	0	660	49	.4	.30	15	176	0	1,290	1,980	GS
	Kmf	665-720	A	11-28-78	13.5	8.9	13	4.3	290	3.2	370	13	330	30	.2	.35	11	50	0	877	1,400	GS
17dba-S1	Kmf	–	F	11-8-78	13.0	7.4L	210	190	470	8.1	360	–	1,800	150	.6	.56	16	1,300	1,000	3,020	3,720L	GS
18cdc-1	Kmf	300-598	F	8-3-79	14.5	8.2L	27	19	180	4.3	290	–	290	13	.1	.17	16	150	0	693	975	GS
18ddb-1	Kmf	160-484	F	10-26-78	17.0	7.8	34	18	170	4.2	280	0	290	16	.2	.19	15	160	0	686	980	GS
32bbb-2	Kmf	225-80	P	9-22-78	13.5	8.7L	6.0	2.1	370	1.8	420	–	450	16	.4	.33	8.1	24	0	1,060	1,650	GS
32bda-1	Kmf	200-40	P	6-21-78	18.5	8.0L	30	20	330	2.7	410	–	440	13	.2	.25	11	160	0	1,050	1,600	GS
32bdc-1	Kmf	253-93	P	9-24-76	17.0	8.4	5.4	4.4	290	1.3	413	5	300	13	–	.21	8.3	32	0	834	1,250L	GS
(D-24-5) 13bcd-S1	Kmf	–	F	10-15-79	12.0	7.6	180	61	97	7.3	370[3]	0	410	17	.1	.11	20	500	190	899	1,200	GS

Table 6.-- Chemical analyses of water from wells, test holes, springs, and the Emery Mine-- Continued

1] Trace.
2] Sodium plus potassium.
3] Estimated from total laboratory alkalinity
4] Analysis supplied by Pacific Natural Gas Exploration Co.

Table 7. -- Benthic invertebrates collected from Christiansen Wash and Quitchupah Creek in the Emery area, 1978-79.

Location and station number: See explanation of data-site numbering system in text and on figure 19.
Wet weight: Weight of benthic invertebrates per unit area of stream bottom, in grams per square meter.
Diversity index: See text for explanation

Location or station number	Date	Number of organisms collected from 3 ft² of stream bottom; identified by phylogenetic order (common name in parenthesis) or family (indented)																																		Wet weight	Diversity index by Order
		Acarina (water mites)	Diptera (true flies)	Psychodidae	Culicidae	Simuliidae	Stratiomyidae	Tipulidae	Chironomidae	Ceratopogonidae	Empididae	Ephydridae	Syrphidae	Tabanidae	Muscidae	Rhagionidae	Trichoptera (caddis flies)	Ephemeroptera (mayflies)	Plecoptera (stoneflies)	Perlodidae	Collembola (springtails)	Lepidoptera (moths)	Coleoptera (beetles)	Dytiscidae	Haliplidae	Hydrophilidae	Elmidae	Odonata (dragonflies)	Libellulidae	Coenagrionidae	Aeschnidae	Gomphidae	Hemiptera (true bugs)	Basommatophora (snails)	Lymnaeidae	Unknown order (aquatic worms)		
CHRISTIANSEN WASH																																						
(D-22-6)16cec	7-13-78	2	-	-	79	419	8	-	285	62	-	17	1	1	19	-	-	1	-	-	1	-	-	10	-	14	-	-	-	-	-	-	-	-	-	-	17.0	0.1
Do.	5-31-79	-	-	-	95	-	-	-	187	103	-	1	-	-	-	-	-	2	-	-	-	-	-	1	-	8	-	-	-	-	-	-	-	-	-	5	.50	.3
Do.	8-22-79	-	-	-	6	11	1	1	420	-	-	-	-	-	-	-	13	4	-	-	-	-	-	4	1	3	-	-	-	-	49	1	1	-	-	55	2.12	.6
(D-22-6)27cab	7-13-78	-	-	-	7	166	-	1	501	44	-	3	-	-	1	-	-	1	-	-	13	-	-	1	-	-	-	-	-	-	-	-	1	-	-	-	1.78	.2
(D-22-6)27cba	7-12-75	-	-	1	2	192	1	-	427	4	-	-	-	-	-	-	-	-	-	-	3	-	-	-	-	-	-	-	-	-	-	1	1	-	-	-	3.33	.0

Table 9. -- Benthic invertebrates collected from Christiansen Wash and Quitchupah Creek in the Emery Area, 1978-79 -- Continued 3.

Location or Station number	Date	Numbers of organisms collected from 3 ft² of stream bottom																																		Wet weight	Diversity Index by Order
		Acarina (water mites)	Diptera (true flies)	Phoridae	Culicidae	Simuliidae	Stratiomyiidae	Tipulidae	Chironomidae	Ceratopogonidae	Empididae	Ephydridae	Syrphidae	Tabanidae	Muscidae	Rhagionidae	Trichoptera (caddis flies)	Ephemeroptera (mayflies)	Plecoptera (stoneflies)	Perlodidae	Collembola (spring tails)	Lepidoptera (butterflies)	Coleoptera (beetles)	Dytiscidae	Haliplidae	Hydrophilidae	Elmidae	Odonata (dragon flies)	Libellulidae	Coenagriidae	Aeschnidae	Gomphidae	Hemiptera (true bugs)	Basommatophora (snails)	Lymnaeidae	Unknown Order (aquatic worms)		
QUITCHUPAH CREEK																																					
(D-22-6)30bda	7-14-78	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	.004	1.6
Do	5-21-79	-	-	-	-	-	-	-	6	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.60	.6
Do	8-22-79	-	-	-	-	-	-	-	27	1	1	-	-	-	-	-	1	149	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.49	.7
09331900	7-14-78	-	-	-	1	3	-	-	13	12	-	1	-	-	-	1	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	77	-	1.12	1.1
Do	9-26-78	-	-	-	-	1	-	-	19	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	6	1	.09	1.1
Do	5-21-79	-	-	-	-	-	-	1	8	1	-	-	-	-	-	-	-	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.03	.8
Do	8-22-79	-	-	-	1	-	1	-	8	17	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	-	.11	.7
Do	9-11-79	2	-	-	-	2	-	-	176	10	10	-	-	-	-	-	358	-	-	-	-	-	-	-	-	-	-	-	-	2	-	8	-	-	-	-	9.84	1.1

Table 7.--Benthic invertebrates collected from Christiansen Wash and Quitchupah Creek in the Emery Area, 1978-79--Continued 2.

Location or Station number	Date	Numbers of organisms collected from 3 ft² of stream bottom																																	Wet weight	Diversity Index by Order
		Acarina (water mites)	Diptera (true flies)	Phoridae	Culicidae	Simuliidae	Stratiomyiidae	Tipulidae	Chironomidae	Ceratopogonidae	Empididae	Ephydridae	Syrphidae	Tabanidae	Muscidae	Rhagionidae	Trichoptera (caddis flies)	Ephemeroptera (mayflies)	Plecoptera (stone flies)	Perlodidae	Collembola (spring tails)	Lepidoptera (butterflies)	Coleoptera (beetles)	Dytiscidae	Haliplidae	Hydrophilidae	Elmidae	Odonata (dragon flies)	Libellulidae	Coenagriidae	Aeschnidae	Gomphidae	Hemiptera (true bugs)	Basommatophora (snails)	Lymnaeidae	Unknown Order (aquatic worms)		
(D-22-6)27cba	8-22-79	2	–	–	6	28	4	14	3964	–	–	–	–	–	–	–	164	2	–	–	–	–	–	–	–	–	–	–	–	–	12	–	–	–	2	–	7.44	0.6
09331950	7-18-78	–	–	–	–	32	–	–	1880	3	20	–	–	–	2	–	1	–	–	–	1	–	–	–	–	–	1	–	–	–	–	1	1	–	–	–	2.51	.0
Do.	9-27-78	16	–	–	–	3144	–	–	450	48	176	–	–	–	43	–	189	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	15.4	.2
Do.	3-15-79	2	–	–	–	6	–	–	91	3	7	–	–	–	–	–	5	–	–	–	–	–	–	–	–	–	–	–	–	5	–	–	–	–	–	6	.54	1.8
Do.	5-31-79	–	–	–	53	–	–	–	41	18	–	–	–	–	–	–	2	–	–	–	–	1	–	–	–	–	–	–	–	1	–	–	–	–	–	–	.32	.3
Do.	6-14-79	17	–	–	25	20	–	–	81	53	1	–	–	–	–	–	3	–	–	–	–	–	1	–	–	–	–	–	–	1	–	–	–	–	–	–	.27	.6
Do.	8-22-79	–	–	–	–	–	–	–	928	2	28	–	–	–	–	–	76	–	–	–	–	–	–	–	–	–	–	–	–	4	–	2	–	–	–	18	2.51	.6
Do.	9-13-79	–	–	–	–	3	–	–	451	–	1	–	–	–	–	–	368	–	–	–	–	–	–	–	–	–	–	–	–	–	2	–	–	–	–	–	3.42	1.0

Table 7. -- Benthic invertebrates collected from Christiansen Wash and Quitchupah Creek in the Emery Area, 1978-79 -- Continued

Numbers of organisms collected from 3 ft² of stream bottom

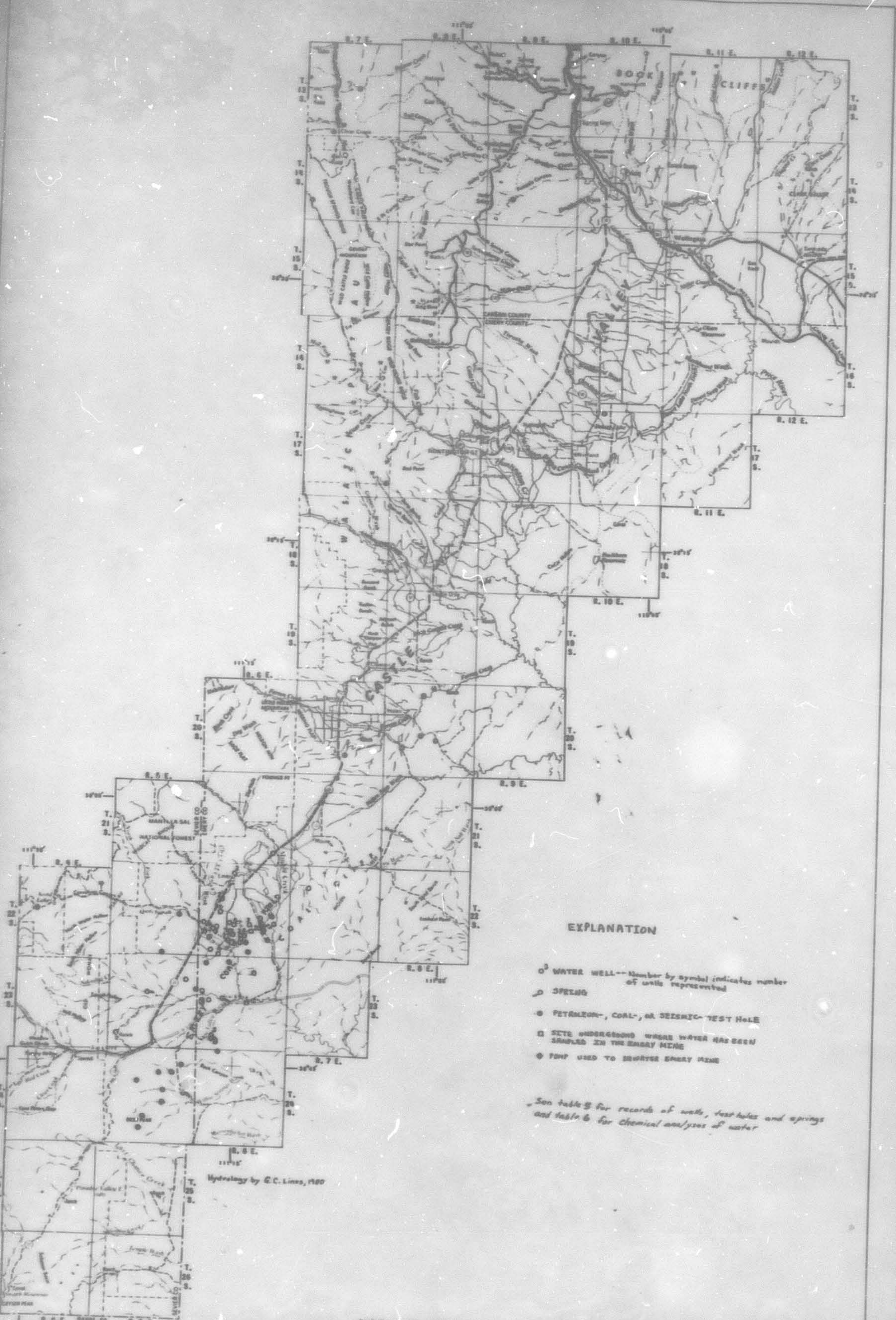
Location or station number	Date	Acarina (water mites)	Diptera (true flies)	Pheridae	Culicidae	Simuliidae	Stratiomyiidae	Tipulidae	Chironomidae	Ceratopogonidae	Empididae	Ephydridae	Syrphidae	Tabanidae	Muscidae	Rhagionidae	Trichoptera (caddis flies)	Ephemeroptera (may flies)	Plecoptera (stone flies)
(D-22-4)33cdd	7-14-78	-	-	-	-	-	-	-	1	1	1	-	-	-	-	-	3	-	1
(D-22-6)33cba	5-31-79	-	-	-	4	-	-	-	9	2	1	-	-	-	-	-	1	3	-
Do	8-22-79	1	-	-	-	1	1	1	216	3	1	-	-	-	-	-	21	9	-

Location or station number	Date	Acladidae	Collembola (spring tails)	Lepidoptera (butterflies)	Coleoptera (beetles)	Dytiscidae	Haliplidae	Hydrophilidae	Elmidae	Odonata (dragon flies)	Libellulidae	Coenagriidae	Aeschnidae	Gomphidae	Hemiptera (true bugs)	Basommatophora (snails)	Lymnaeidae	Unknown Order (aquatic worms)	Wet weight	Diversity Index by Order
(D-22-4)33cdd	7-14-78	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	37	-	1.36	1.0
(D-22-6)33cba	5-31-79	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	.09	.9
Do	8-22-79	-	-	-	-	-	-	-	-	-	3	-	-	-	-	-	-	4	.68	.8

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH THE
UNITED STATES BUREAU OF LAND MANAGEMENT

WATER-SUPPLY PAPER



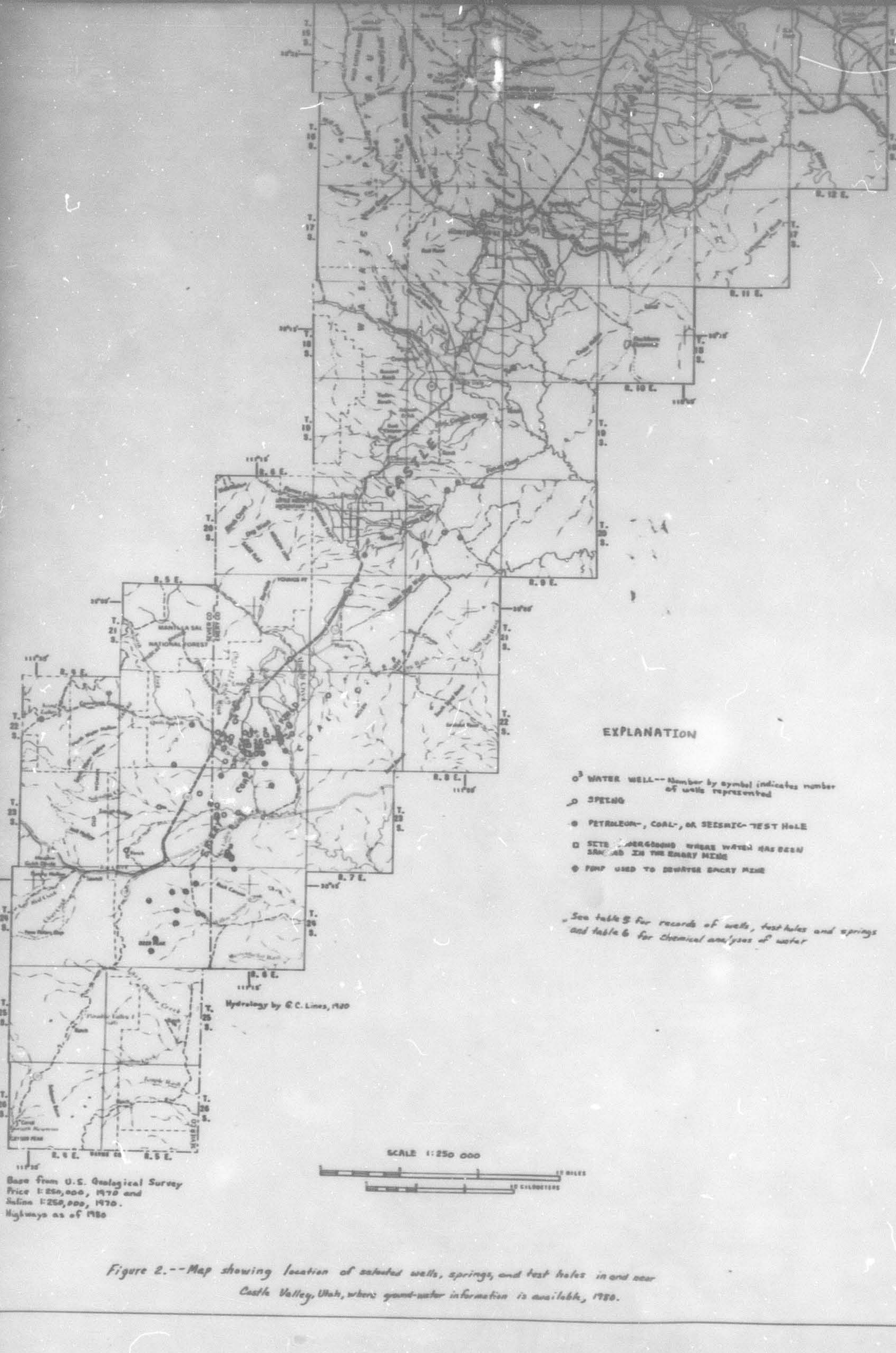
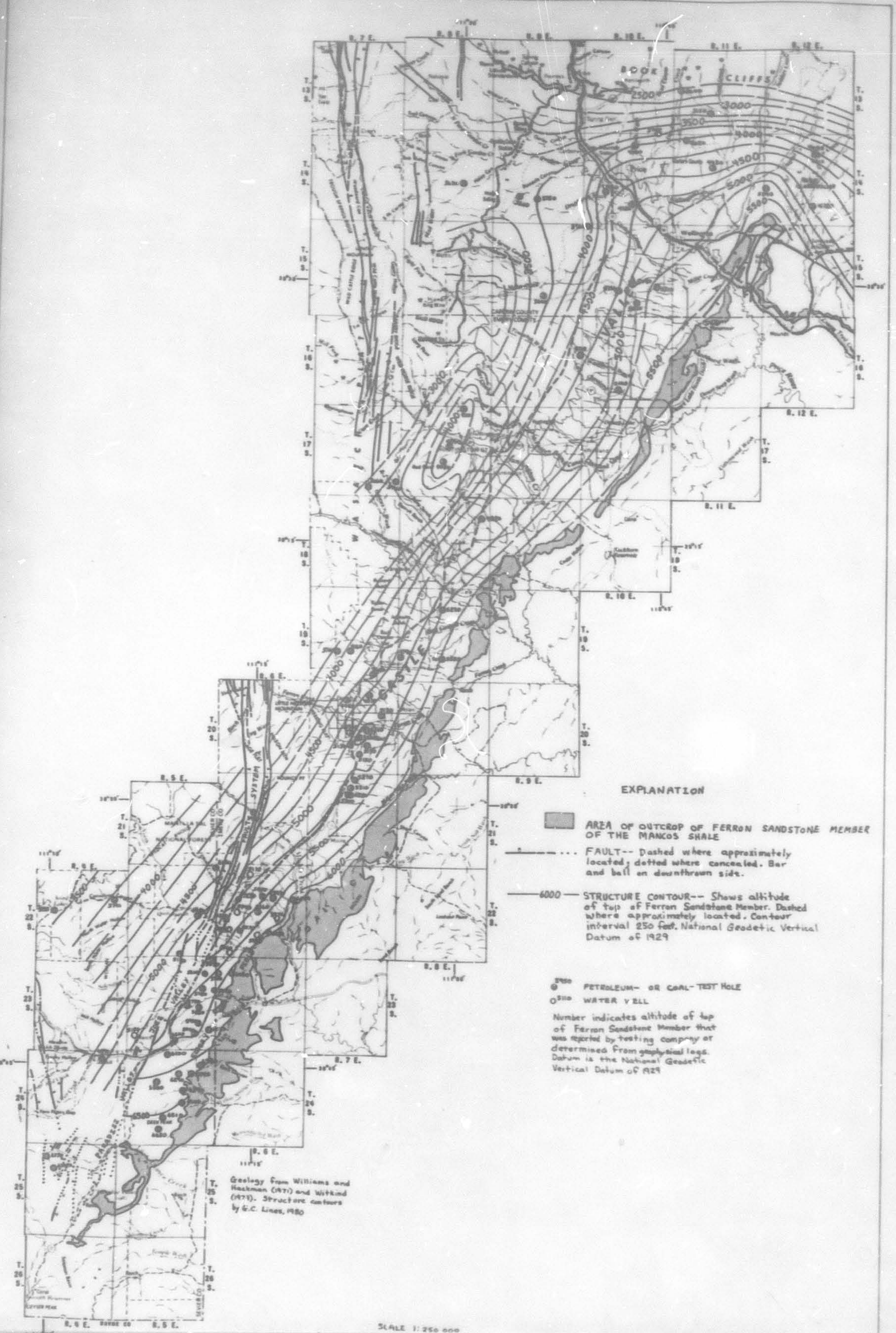


Figure 2.--Map showing location of selected wells, springs, and test holes in and near Castle Valley, Utah, where ground-water information is available, 1980.


BOOK CLIFFS
EXPLANATION
AREA OF OUTCROP OF FERRON SANDSTONE MEMBER OF THE MANCOS SHALE
FAULT-- Dashed where approximately located; dotted where concealed. Bar and ball on downthrown side.
6000 STRUCTURE CONTOUR-- Shows altitude of top of Ferron Sandstone Member. Dashed where approximately located. Contour interval 250 feet. National Geodetic Vertical Datum of 1929
PETROLEUM- OR COAL-TEST HOLE
WATER WELL
Number indicates altitude of top of Ferron Sandstone Member that was reported by testing company or determined from geophysical logs. Datum is the National Geodetic Vertical Datum of 1929
Geology from Williams and Hackman (1971) and Witkind (1971). Structure contours by G.C. Lines, 1980
SCALE 1:250 000

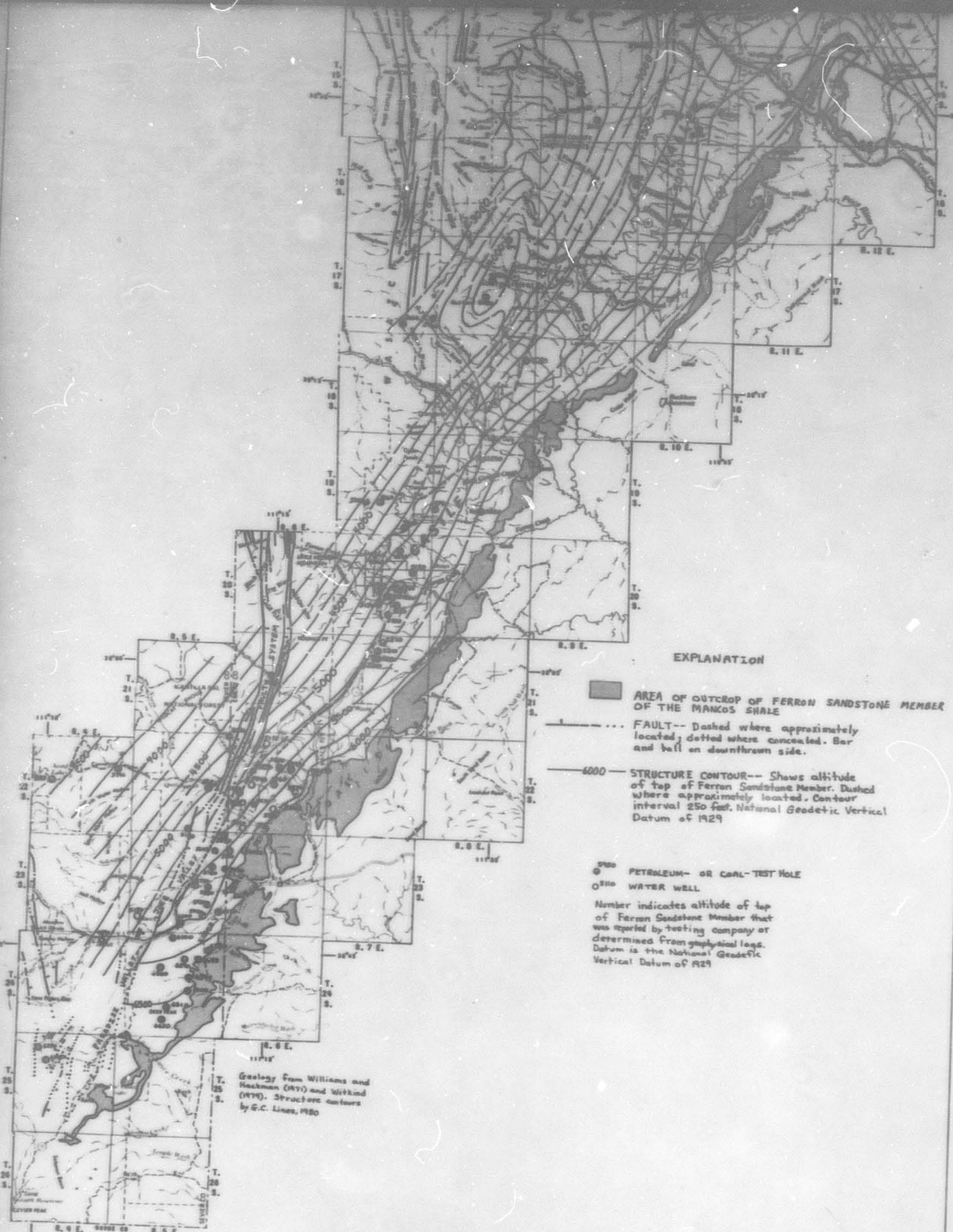
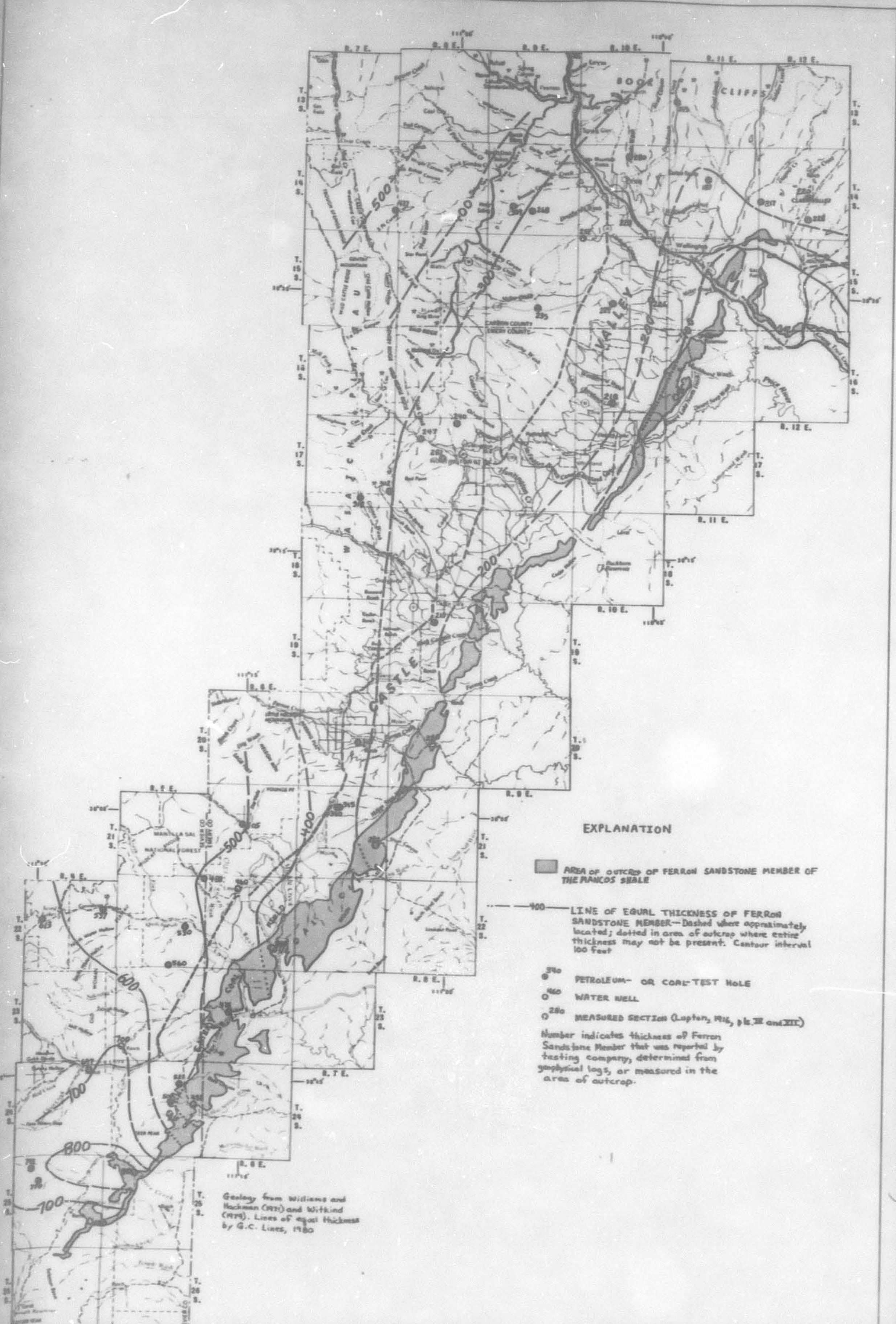


Figure 5.--Map showing altitude of the top of the Ferron Sandstone Member of the Mancos Shale in Castle Valley, Utah.


BOOK CLIFFS
CASTLE VALLEY
WASATCH PLATEAU
MANTI-LA SAL NATIONAL FOREST
CARBON COUNTY
EMERY COUNTY
EXPLANATION
AREA OF OUTCROP OF FERRON SANDSTONE MEMBER OF THE MANCOS SHALE
400 LINE OF EQUAL THICKNESS OF FERRON SANDSTONE MEMBER—Dashed where approximately located; dotted in area of outcrop where entire thickness may not be present. Contour interval 100 feet
340 PETROLEUM- OR COAL-TEST HOLE
460 WATER WELL
280 MEASURED SECTION (Lupton, 1916, pls. XI and XII)
Number indicates thickness of Ferron Sandstone Member that was reported by testing company, determined from geophysical logs, or measured in the area of outcrop.
Geology from Williams and Hackman (1971) and Witkind (1979). Lines of equal thickness by G.C. Lines, 1980

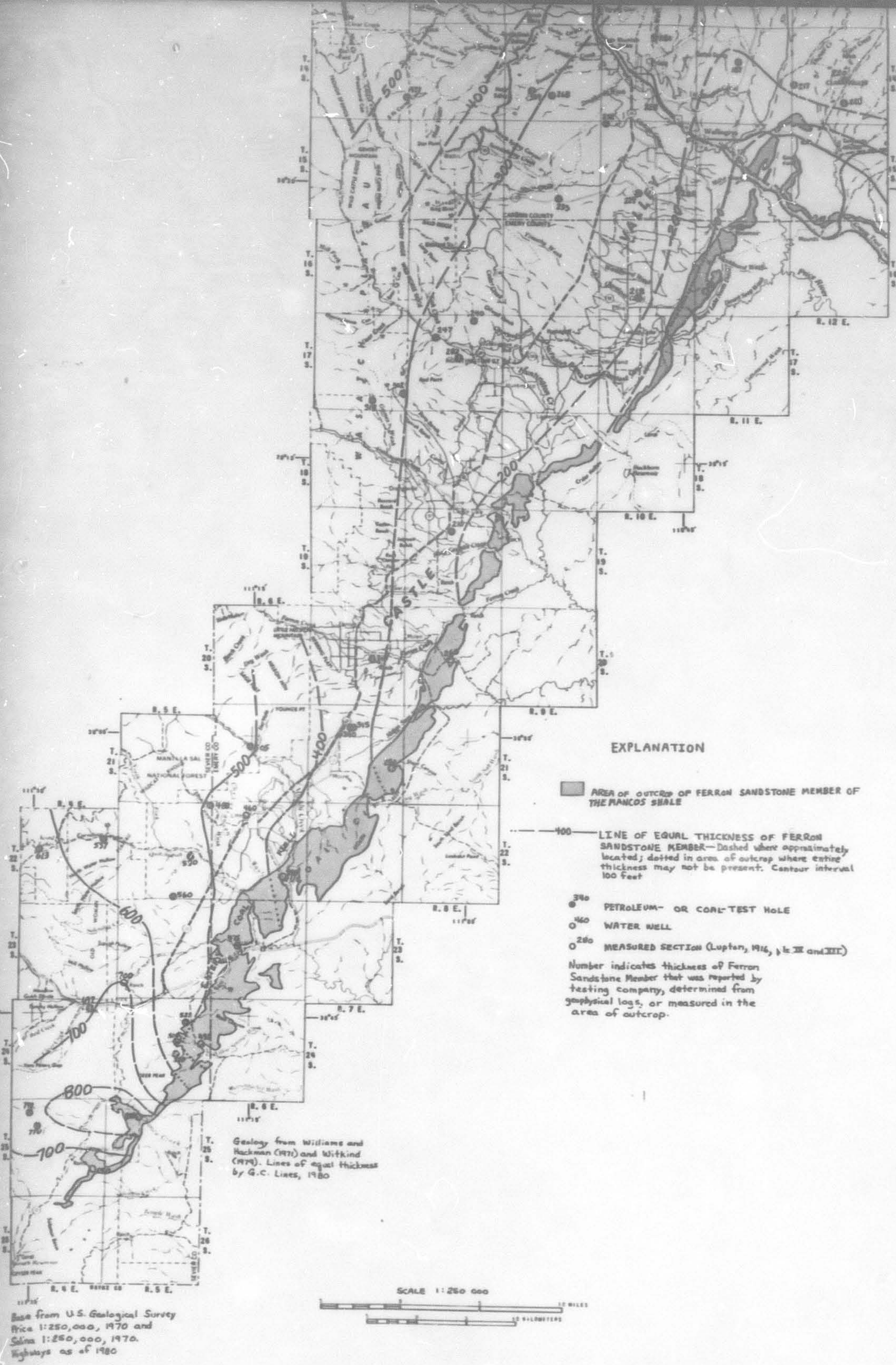


Figure 4.--Map showing thickness of the Ferron Sandstone Member of the Mancos Shale in Castle Valley, Utah.