GROUND-WATER FLOW AND QUALITY NEAR CANON CITY, COLORADO

By Glenn A. Hearne and David W. Litke

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DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
Water Resources Division
Box 25046, Mail Stop 415
Denver Federal Center
Denver, CO 80225

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CONVERSION FACTORS

For the convenience of readers who may prefer to use metric (International System) units, rather then the inch-pound units used in this report, values may be converted by using the following factors:

Multiply inch-pound unit	*By*	*To obtain metric unit*
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch (in.)	25.40	millimeter (mm)
mile (mi)	1.609	kilometer (km)

Temperatures are given in degree Celsius. To convert degree Celsius (°C) to degree Fahrenheit (°F) use the following formula:

$$°F=9/5\ °C+32$$

The following terms and abbreviations also are used in this report: atm, atmosphere; μS/cm, microsiemens per centimeter at 25 °Celsius; mg/L, milligram per liter; μg/L, microgram per liter; pCi/L, picocurie per liter; μs/ft, microsecond per foot.

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

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ABSTRACT

Water in aquifers that underlie the Lincoln Park area near Canon City, Colorado, contains measurable concentrations of chemical consitituents that are similar to those in raffinate (liquid waste) produced by a nearby uranium-ore processing mill. The objective of this study was to expand the existing geohydrologic data base by collecting additional geohydrologic and water-quality data, in order to refine the description of the geohydrologic and geochemical systems in the study area. Geohydrologic data were collected from nine test wells drilled in the area between the U.S. Soil Conservation Service dam and Lincoln Park. Lithologic and geophysical logs of these wells indicated that the section of Vermejo Formation penetrated consisted of interbedded sandstone and shale. The sandstone beds had a small porosity and small hydraulic conductivity. The alluvium penetrated south of the De Weese Dye Ditch was not saturated in February 1985 when the test wells were drilled, indicating that the alluvium was not saturated where the Vermejo Formation subcrop is topographically high. Ground-water flow from the U.S. Soil Conservation Service dam to Lincoln Park seemed to be along an alluvium-filled channel in the irregular and relatively undescribed topography of the Vermejo Formation subcrop. North of the De Weese Dye Ditch, the alluvium becomes saturated and ground water generally flows to the northeast.

Water samples from 28 sites were collected and analyzed for major ions and trace elements; selected water samples also were analyzed for stable isotopes. Collection and analysis of these samples were carefully documented. Samples were collected from wells near the uranium-ore processing mill, from privately owned wells in Lincoln Park, and from the test wells drilled in the intervening area. Results from the quality-assurance samples indicate that cross-contamination between samples from different wells was avoided and that the data are reliable.

Water in the alluvial aquifer underlying Lincoln Park is mainly a calcium bicarbonate type with small variation in composition; the water is chemically distinct from water from other aquifers in the study area. The chemical composition of water in the alluvial aquifer appears to result from reaction of water leaking from the De Weese Dye Ditch with alluvial material. Upward leakage from underlying aquifers does not seem to be significant in determining the chemical composition of water in the alluvial aquifer.

Water from the Poison Canyon Formation is either a calcium sulfate or a sodium sulfate type. Water from the Vermejo Formation is either a sodium sulfate or a sodium bicarbonate type. These variations in composition can be explained by reaction of the water with the different lithologies present in these formations.

The most raffinate-affected ground water has the following chemical characteristics: (1) Substantial ionic strength; (2) predominance of sodium and sulfate ions; (3) large concentrations of molybdenum, selenium,and uranium; (4) a delta deuterium to delta oxygen-18 ratio indicative of an evaporative history; (5) large tritium concentration; (6) a median delta carbon-13 value of -8.5 per mil; and (7) a median delta sulfur-34 value of -2.6 per mil. All raffinate-affected water seems to have mixed to some degree with water from the Poison Canyon Formation. Raffinate-affected water yielded by wells completed in the alluvial aquifer underlying Lincoln Park probably is a mixture of water from the alluvium and raffinate-affected water from the Poison Canyon Formation.

INTRODUCTION

An active uranium-ore processing mill owned by the Cotter Corp.[1] (hereinafter called the mill) and accompanying tailings ponds are located south of Canon City, Colo. (fig. 1). Lincoln Park, a suburban community north of this mill and south of the Arkansas River, consists mostly of small farms and ranches, orchards, and single-family housing with small acreage. A U.S. Soil Conservation Service dam (hereinafter called the SCS dam) is located on Sand Creek, where Sand Creek crosses a breach in a ridge formed by an outcrop of the Raton and Vermejo Formations. The ridge lies between the mill area and the Lincoln Park area.

Water in aquifers that underlie the Lincoln Park area near Canon City contains measurable concentrations of chemical constituents (molybdenum, selenium, and uranium) that occur in large concentrations in raffinate (liquid waste) from the mill (U.S. Environmental Protection Agency, written commun., 1985). The site has been investigated under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 and has been included in the National Priority List of hazardous-waste sites (U.S. Environmental Protection Agency, 1984). The U.S. Environmental Protection Agency determined that additional information was required for their evaluation of the site. Inadequacies identified in the existing data were: (1) Lack of quality-assurance and quality-control documentation for sampling and analysis; (2) lack of data on variation in hydraulic head and water quality in the Vermejo Formation, a potential "deep migration path" for contaminants; and (3) few geohydrologic data between the SCS dam and Lincoln Park, a potential "shallow migration path" for contaminants (U.S. Environmental Protection Agency, written commun., 1985). Much of the available data are in unpublished reports prepared by

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

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contractors for the Colorado Department of Health, for the Cotter Corp., or for the U.S. Environmental Protection Agency. In this report, references to these unpublished reports are cited as a 1985 written communication from the U.S. Environmental Protection Agency.

The objective of this study was to supplement information available from previous investigations and refine the description of the geohydrologic and geochemical systems in the study area. This objective was achieved by expanding the data base describing ground-water conditions by: (1) Documenting quality-assurance procedures and results for sampling and analysis; (2) providing measurements of hydraulic head and water quality at selected points in the Vermejo Formation; and (3) providing additional data on lithology, hydraulic head, and water quality between the SCS dam and Lincoln Park.

Purpose and Scope

The purpose of this report is to present and interpret geohydrologic and geochemical data collected in the study area. Data include water levels and analyses of water samples collected in 1985 by the U.S. Geological Survey, and selected analyses of water samples collected by the Cotter Corp. in 1981.

On the basis of these data, this report describes: (1) Hydraulic conductivity and hydraulic head in the Vermejo Formation between the SCS dam and Lincoln Park; (2) hydraulic head and ground-water flow in the alluvial aquifer underlying Lincoln Park; (3) major-ion and trace-element characteristics of water from the Poison Canyon Formation, the Vermejo Formation, and the alluvial aquifer underlying Lincoln Park; (4) isotope characteristics of water from the Poison Canyon Formation and Vermejo Formation; and (5) major-ion, trace-element, and isotope characteristics, and distribution of raffinate in water from the Poison Canyon Formation and the alluvial aquifer underlying Lincoln Park.

History of the Study Area

Coal was mined in the Canon City area from 1860 through the mid-1950's. Beneath the present site of the mill, coal was mined from a depth of about 1,000 ft until 1934. At the other mines in the area (fig. 2), mining started in the outcrop area of the Vermejo Formation and progressed down the dip of the mined bed.

The mill has been in operation since 1958. No uranium mining was done at this site; ore was transported to the mill for processing. Water obtained by Canon City from the Arkansas River was used for process water. The liquid wastes (raffinate), characterized by large values of specific conductance, and large concentrations of molybdenum, selenium, and uranium, were discharged into unlined tailings ponds in the Sand Creek basin (U.S. Environmental Protection Agency, written commun., 1985). Under these conditions, potential routes for migration of chemical constituents from the mill area toward Lincoln Park included airborne transport and surface-water transport by storm flow in Sand Creek in addition to transport by ground water.

Large concentrations of molybdenum, selenium, and uranium have been analyzed in water from wells in Lincoln Park since 1962 (U.S. Environmental Protection Agency, written commun., 1985). Documentation of those concentrations and evaluation of their potential sources had engaged several researchers in data collection and analysis since 1962. An assessment of the data base was prepared in 1983, and an interpretive report was written in 1985 (U.S. Environmental Protection Agency, written commun., 1985).

A flood-control dam was constructed by the U.S. Soil Conservation Service in 1970. No streamflow in Sand Creek between the mill area and Lincoln Park has been reported since construction of the dam.

The Littell shaft of the Littell (Wolf Park) Mine was filled and plugged in 1978. The source of the fill material and the method of plugging were not investigated as part of this study.

After 1979, tailing and raffinate were discharged into a large lined pond. The old unlined ponds were dredged, and the dredgings were placed in the new pond.

Data-Collection Sites

Data from 54 sites (table 1, fig. 2) are used in this report to describe the hydraulic head and chemical characteristics of water from the alluvial aquifer underlying Lincoln Park, from the Poison Canyon Formation, and from the Vermejo Formation. Of the 54 sites, 9 are test wells that were completed by the U.S. Geological Survey (wells with the prefix LP85); 18 are privately owned wells that are, or have been, part of the monitoring program of the Cotter Corp. (wells C-106 through C-144); 1 is the flowing air shaft of the Chandler Mine (shaft C-153); 10 are wells on the Cotter Corp. property that are, or have been, part of the corporation's monitoring program (wells C-312 through C-337); 3 are surface-water sites that are, or have been, part of the corporation's monitoring program (sites C-505, C-520, and C-531); 2 are seeps from the alluvium (seeps A and J); and 11 are privately owned wells that have not been part of the corporation's monitoring program (wells B, C, D, E, F, G, H, I, K, L, and M).

To describe the chemical characteristics of water from the alluvial aquifer in Lincoln Park, existing wells were selected that were: (1) Small in diameter, to facilitate flushing of at least three well-volumes of water prior to sample collection, and to minimize introduction of extraneous material from the land surface; and (2) less than 60 ft in depth, and therefore, presumed to be completed only in the alluvial aquifer. An additional requirement was that a workable pump already be emplaced to avoid cross-contamination between wells. Nine wells (wells C-129, D, E, G, H, I, K, L, and M) were selected in the study area that met these qualifications. Two seeps, representative of alluvial water also were selected for analysis: (1) Sand Creek seep (seep J), at the location where water first appeared in the dry channel downstream from the SCS dam at the time of sampling (February 1985); and (2) Cedar Road seep (seep A) about 2 mi east of where Sand Creek crosses Cedar Avenue.

Table 1.--*Data-collection sites and types of data available*

[Dashes indicate that the specified type of data was not collected at the site; USGS, U.S. Geological Survey sample; Cotter, Cotter Corp. sample]

Site identification[1]	Type of site[2] and source of water	Water-quality sample						Water level[4]
		Selected ions[3]	Isotopic composition					
			Stable isotope ratio					
			Carbon-13/ carbon 12	Hydrogen-2/ hydrogen-1	Oxygen-18/ oxygen-16	Sulfur-34/ sulfur-32	Tritium	
LP85-1S	Alluvium	--	--	--	--	--	--	October 1985
LP85-1D	Vermejo	USGS	Yes	Yes	Yes	Yes	Yes	Yes
LP85-2S	Vermejo	USGS	Yes	Yes	Yes	Yes	Yes	Yes
LP85-2D1	Vermejo	USGS	Yes	Yes	Yes	Yes	--	Yes
LP85-2D4	Vermejo	USGS	Yes	Yes	Yes	Yes	Yes	Yes
LP85-3	Alluvium	--	--	--	--	--	--	October 1985
LP85-4	Vermejo	USGS	Yes	Yes	Yes	Yes	Yes	Yes
LP85-6D1	Vermejo	USGS	Yes	Yes	Yes	--	--	Yes
LP85-6D4	Vermejo	USGS	Yes	Yes	Yes	Yes	Yes	Yes
C-106	Vermejo[5]	Cotter	--	--	--	--	--	--
C-111	Vermejo[5]	Cotter	--	--	--	--	--	--
C-114	Alluvium[6]	Cotter	--	--	--	--	--	--
C-117	Alluvium[7]	Cotter	--	--	--	--	--	--
C-119	Alluvium[6]	Cotter	--	--	--	--	--	Yes
C-120	Alluvium[6]	Cotter	--	--	--	--	--	--
C-122	Alluvium[8]	Cotter	--	--	--	--	--	--
C-123	Alluvium[9]	Cotter	--	--	--	--	--	--
C-124	Alluvium and Vermejo[10]	Cotter	--	--	--	--	--	--
C-129	Alluvium[6]	USGS	--	--	--	--	--	Yes
C-135	Poison Canyon[11]	Cotter	--	--	--	--	--	--
C-137	Alluvium[12]	Cotter	--	--	--	--	--	Yes
C-138	Alluvium[13]	Cotter	--	--	--	--	--	Yes
C-139	Alluvium[6]	Cotter	--	--	--	--	--	Yes
C-140	Alluvium[6]	Cotter	--	--	--	--	--	Yes
C-141	Vermejo[5]	Cotter	--	--	--	--	--	--
C-142	Vermejo[14]	Cotter	--	--	--	--	--	--
C-144	Alluvium[6]	Cotter	--	--	--	--	--	Yes
C-153	Mine shaft[15]	USGS	--	--	--	--	--	--
C-312	Poison Canyon[11]	USGS	--	--	--	--	--	--
C-313	Poison Canyon[11]	USGS	Yes	Yes	Yes	Yes	Yes	--
C-314	Poison Canyon[11]	USGS	Yes	Yes	Yes	Yes	Yes	--
C-317	Vermejo[16]	USGS	Yes	Yes	Yes	Yes	Yes	--
C-328	Vermejo[16]	Cotter	--	--	--	--	--	--
C-329	Alluvium and Vermejo[17]	USGS	Yes	Yes	Yes	Yes	Yes	--
C-330	Alluvium and Vermejo[17]	USGS	Yes	Yes	Yes	Yes	Yes	--
C-331	Alluvium and Vermejo[17]	USGS	Yes	Yes	Yes	Yes	Yes	--
C-333	Poison Canyon[18]	USGS	Yes	Yes	Yes	Yes	Yes	--
C-337	Poison Canyon[18]	Cotter	--	--	--	--	--	--
C-505	Surface water	Cotter	--	--	--	--	--	--
C-520	Surface water	Cotter	--	--	--	--	--	--
C-531	Surface water	USGS	--	--	--	--	--	--
A	Seep from alluvium[19]	USGS	--	--	--	--	--	--
B	Alluvium[20]	--	--	--	--	--	--	Yes
C	Alluvium[20]	--	--	--	--	--	--	Yes
D	Alluvium[20]	USGS	--	--	--	--	--	--
E	Alluvium[20]	USGS	--	--	--	--	--	Yes
F	Alluvium[20]	--	--	--	--	--	--	Yes
G	Alluvium[20]	USGS	--	--	--	--	--	Yes
H	Alluvium[20]	USGS	--	--	--	--	--	Yes
I	Alluvium[20]	USGS	--	--	--	--	--	Yes
J	Seep from alluvium[19]	USGS	--	--	--	--	--	--
K	Alluvium[20]	USGS	--	--	--	--	--	Yes
L	Alluvium[20]	USGS	--	--	--	--	--	Yes
M	Alluvium[20]	USGS	--	--	--	--	--	--

Table 1.--*Data-collection sites and types of data available*--Continued

Source of data	Source of water	Water-quality sample						Water level
		Selected ions	Isotopic composition					
			Stable isotope ratio				Tritium	
			Carbon-13/ carbon 12	Hydrogen-2/ hydrogen-1	Oxygen-18/ oxygen-16	Sulfur-34/ sulfur-32		
Totals for USGS	Alluvium	11	0	0	0	0	0	16
	Alluvium and Vermejo	3	3	3	3	3	3	0
	Vermejo	9	8	8	8	7	6	7
	Poison Canyon	4	3	3	3	3	3	0
	Streams and pond	1	0	0	0	0	0	0
	Total	28	14	14	14	13	12	23
Totals for Cotter	Alluvium	11	0	0	0	0	0	0
	Alluvium and Vermejo	1	0	0	0	0	0	0
	Vermejo	5	0	0	0	0	0	0
	Poison Canyon	2	0	0	0	0	0	0
	Streams and pond	2	0	0	0	0	0	0
	Total	21	0	0	0	0	0	0

[1] Location shown in figure 2. Sites with the prefix "LP85" were test wells drilled during 1985 by the U.S. Geological Survey as part of this study. Sites with the prefix "C" are or have been included in the monitoring program of the Cotter Corp.

[2] Unless otherwise indicated, the site is a well completed in the indicated formation.

[3] "USGS" indicates that water-quality samples were collected during 1985 as part of this study. "Cotter" indicates that water-quality samples were collected (generally during 1981) as part of the monitoring program of the Cotter Corp.

[4] Unless otherwise indicated, the water level was measured during April 25-26, 1985. Water levels measured in October 1985 are indicated in the table, but not included in the totals.

[5] Well identified as monitoring the Vermejo Formation (U.S. Environmental Protection Agency, written commun., 1985).

[6] Well identified as monitoring alluvium (U.S. Environmental Protection Agency, written commun., 1985). Depth of well is less than 60 feet.

[7] Water sample identified as being from alluvium based on major-ion concentrations. Well is 79 feet deep, and may produce water from the Vermejo Formation as well as from the alluvium.

[8] Well identified as monitoring alluvium (U.S. Environmental Protection Agency, written commun., 1985), although the depth of well is given as 80 feet.

[9] Well identified as monitoring alluvium (U.S. Environmental Protection Agency, written commun., 1985), although the depth of well is not given.

[10] Well identified as monitoring both alluvium and the the Vermejo Formation (U.S. Environmental Protection Agency, written commun., 1985). Depth of the well is given as 124 feet.

[11] Well identified as monitoring Poison Canyon Formation (U.S. Environmental Protection Agency, written commun., 1985).

[12] Water sample associated with alluvium because of shallow depth, 41 feet.

[13] Well identified as monitoring alluvium (with a query) (U.S. Environmental Protection Agency, written commun., 1985). Well is 48 feet deep, and may bottom in the Vermejo Formation.

[14] Well identified as monitoring the Vermejo Formation (U.S. Environmental Protection Agency, written commun., 1985). However, the well is cased to 60 feet and may have caved below this depth. Water may be produced from the alluvium as well as the Vermejo Formation.

[15] Water sample was associated with the Vermejo Formation because the shaft was constructed to the Vermejo Formation. However, the present condition of the shaft is unknown, and water from the Poison Canyon or Raton Formations may be entering the shaft.

[16] Well identified as being completed in the Vermejo Formation at the approximate location of the Wolf Park coal seam (U.S. Environmental Protection Agency, written commun., 1985).

[17] This well penetrates both alluvium and Vermejo Formation. Water may be produced from the alluvium or the Vermejo Formation or both. Depth is 46 feet or less.

[18] This well is completed in the Poison Canyon Formation (U.S. Environmental Protection Agency, written commun., 1985).

[19] Seeps issue from the alluvium. Major-ion composition is similar to that of samples from wells completed in the alluvial aquifer.

[20] Well is less than 60 feet deep and assumed to be completed in the alluvial aquifer.

Previous reports had indicated that considerable variation in water quality occurred annually from some sites in the alluvial aquifer, primarily because of the diluting effects of water leaking from the De Weese Dye Ditch, an irrigation-water supply ditch, and from applied irrigation water percolating down into the alluvial aquifer. Because of time limitations for this study, this source of variance was eliminated by completing the sampling before the irrigation season began in 1985.

Base flow in West Fork Sand Creek at Alkali Gap (site C-531) was sampled to describe water quality in the Sand Creek drainage. This site is upstream from the mill and tailings ponds. Base flow was presumed to be representative of surface water available for recharge to aquifers in the Poison Canyon and Vermejo Formations.

Data were collected by the U.S. Geological Survey from the test wells and from existing wells to describe the chemical characteristics of water from the Poison Canyon and Vermejo Formations. Four wells (wells C-312, C-313, C-314, and C-333) are completed in the Poison Canyon Formation. Eleven wells (wells LP85-1D, LP85-2S, LP85-2D1, LP85-2D4, LP85-4, LP85-6D1, LP85-6D4, C-317, C-329, C-330, and C-331) and one flowing mine shaft (shaft C-153, Chandler Mine) were sampled to describe the chemical characteristics of water from the Vermejo Formation. Eight of these wells (wells C-312, C-313, C-314, C-317, C-329, C-330, C-331, and C-333) and the mine shaft were part of the Cotter Corp. monitoring network. Seven of these wells are test wells (wells LP85-1D, LP85-2S, LP85-2D1, LP85-2D4, LP85-4, LP85-6D1, LP85-6D4) that were drilled by the U.S. Geological Survey between the SCS dam and Lincoln Park as part of this project. Of the 11 wells completed in the Vermejo Formation, 3 (wells C-329, C-330, and C-331) are shallow (maximum depth is 46 ft) wells that penetrate both alluvium and the Vermejo Formation. Samples from these wells may contain water from the alluvium or the Vermejo Formation or both.

Nine test wells were completed by the U.S. Geological Survey to obtain geohydrologic and water-quality data for the area between the SCS dam and Lincoln Park. These test wells provide two data-collection sites in alluvium and seven in the Vermejo Formation for water-level and water-quality data. The two test wells completed in alluvium (wells LP85-1S and LP85-3) were dry prior to the irrigation season. No water-level measurements or water-quality samples were collected from these two shallow wells as part of this study. Water-level measurements and water-quality samples for selected ions and isotopic composition were collected from the seven test wells completed in the Vermejo Formation. Altitude of the top of the casing was established for each test well. Geophysical logs were run on the three deepest test wells (wells LP85-1D, LP85-2D4, and LP85-6D4) to obtain qualitative data on lithology and aquifer characteristics.

Water-quality data from 19 wells and 2 surface-water sites previously analyzed by the Cotter Corp. (U.S. Environmental Protection Agency, written commun., 1985) were used to supplement the water-quality data collected during this project. Analyses from early 1981 were selected because complete analyses were available that represented conditions before the irrigation season started, the same time of year as the present study.

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Water levels were measured in 16 wells to contour part of the water table in the alluvial aquifer in Lincoln Park. Altitude of the reference point (commonly the top of casing) above sea level was established at wells that had not been previously surveyed.

Geohydrologic Setting of the Study Area

The geology of the study area (fig. 1) was mapped by Scott (1977). The dominant geologic structure is the Chandler syncline (fig. 1). The mill, near the Littell shaft (fig. 2), straddles the axis of the syncline (figs. 1 and 3). The southwestern flank of the syncline forms a hogback consisting of steeply dipping beds of the Raton and Vermejo Formations. The northeastern flank extends to the Lincoln Park area where most of the Vermejo Formation, the Trinidad Sandstone, and the Pierre Shale subcrop beneath alluvium of the Arkansas River terrace. The Raton and Vermejo Formations form a ridge, which is less prominant than the hogback, that separates the mill area from Lincoln Park. The Pierre Shale (3,900 ft thick) was assumed to be an efficient hydrologic barrier; no formations below the Pierre Shale are described.

Above the Upper Cretaceous Pierre Shale, the formations through which ground water flows, in ascending order, are: (1) The Trinidad Sandstone, (2) the Vermejo Formation, (3) the Raton Formation, (4) the Poison Canyon Formation, and (5) Quaternary alluvium, undifferentiated. The Upper Cretaceous Trinidad Sandstone (40 to 90 ft thick) is a medium-grained sandstone interlayered with carbonaceous shale. The Upper Cretaceous Vermejo Formation (150 to 750 ft thick) is a fine- to medium-grained sandstone (and shaly sandstone) interlayered with shale. Some shale beds contain large quantities of organic material. As many as 16 coal seams occur in the Vermejo Formation. The three coal seams that have been mined in the study area are, in ascending order, the Rockvale, Chandler, and Brookside. The Upper Cretaceous and Paleocene Raton Formation (240 to 500 ft thick) is a medium- to coarse-grained sandstone with thin carbonaceous layers in the upper part. The Paleocene Poison Canyon Formation (as much as 840 ft thick) consists of interbedded claystone, siltstone, sandstone, and conglomerate. Quaternary alluvium (about 20 to 60 ft thick) covers much of the northeastern flank of the Chandler syncline northeast of the ridge.

The Vermejo Formation crops out in the steeply dipping (as much as 71°; Scott, 1977) hogback to the southwest of the syncline axis. The altitude of the hogback ranges from about 5,800 to 6,000 ft. Near the axis of the Chandler syncline, the top of the Vermejo Formation is about 1,000 ft below land surface. On the gently dipping (in places less than 5°; Scott, 1977) northeastern flank of the syncline, the Vermejo Formation crops out along the ridge and subcrops beneath the alluvium to the northeast. Alluvium along Sand Creek was not shown on the geologic map (fig. 1) (Scott, 1977) but was penetrated in wells LP85-2S, LP85-2D4, LP85-3, and LP85-4 (fig. 2). Land-surface altitude along Sand Creek northeast of the ridge ranges from about 5,370 to 5,450 ft.

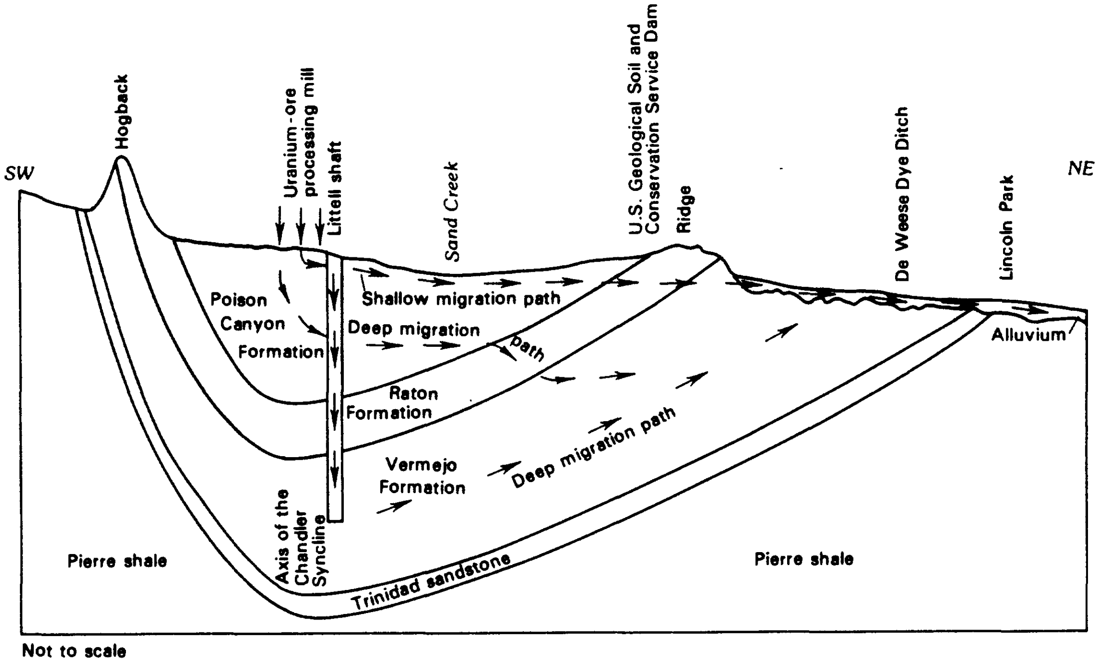


Figure 3.--Generalized geologic section normal to the Chandler syncline showing potential ground-water migration paths from the uranium-ore processing mill to Lincoln Park.

The Vermejo Formation contains aquifers--beds or lenses of rock with sufficient saturated material to yield significant quantities of water to wells and springs. The Vermejo Formation also contains confining units--beds or lenses of relatively impermeable rock that do not transmit water rapidly enough to supply a well or spring, but function as an upper or lower boundary of an aquifer. Although this heterogeneous body of intercalated permeable and less-permeable material could be called an aquifer system, nothing is gained by the terminology, because data are not available to identify individual aquifers and confining units. The complex nature of the Vermejo Formation is important because hydraulic head at a site may vary appreciably with depth. To evaluate directions of ground-water flow from measured hydraulic head within the Vermejo Formation, the three-dimensional character of the flow field needs to be considered.

Because the available geohydrologic data base is not commensurate with the complexity of the system, the direction of ground-water flow through the Vermejo Formation is uncertain. In a homogeneous, isotropic material, ground water flows from areas of high hydraulic head to areas of low hydraulic head. However, through beds or lenses of permeable and less-permeable material, flow tends to follow the permeable beds or lenses. Without data describing hydraulic head and hydraulic conductivity for several strata, the following general comments are offered. Commonly, hydraulic head in outcrop areas is a subdued expression of the topography. Assuming this to be true for the Vermejo Formation, ground water probably flows from recharge areas along the hogback to discharge areas northeast of the ridge. The lowest altitude of Vermejo Formation outcrop is about 3 mi east of the SCS dam where the Vermejo Formation contacts alluvium adjacent to the Arkansas River. In outcrop areas, discharge may be to springs. In subcrop areas, discharge may be to the overlying alluvium, and not be obvious at the land surface. Flow also may occur between the Vermejo Formation and adjacent formations. Superimposed on this regional flow system may be numerous local flow systems that may transport more water than the regional system.

Before extensive coal mining, springs were reported in the outcrop areas near Brookside (Cresto, 1980, p. 30), about 2 mi east of the SCS dam, and further east along Chandler Creek (Cresto, 1980, p. 26). The source of water for these springs is unknown.

Operation of coal mines in the Vermejo Formation commonly required that the mines be dewatered. The Brookside Mine, closed by a labor strike in 1913, was not reopened because of water which had accumulated during the strike (Cresto, 1980, p. 34). Cresto reported (1980, p. 39) that in the Wolf Park Mine, "...the floor of the upper level broke into an underground body of water, flooding the lower level and killing three men...," indicating that hydraulic conductivity in the Vermejo Formation is variable. This and other incidents of flooding (Cresto, 1980, p. 27) when water, "...broke through and flooded the mine..." may indicate that the more permeable beds or lenses are adjacent to the coalbed, rather than the coal itself. The effect of mine dewatering on flow paths in the Vermejo Formation is not known.

Although the direction of flow in the Vermejo Formation is not known, a "deep migration path" (fig. 3) has been postulated as a possible path for the transport of chemical constituents in raffinates from the mill area to Lincoln Park through aquifers in the Vermejo Formation. Two possible routes have been suggested that may have introduced raffinates into the Vermejo Formation. First, the Littell shaft may provide a conduit for raffinate to move from the land surface down to an aquifer in the Vermejo Formation. Alternatively, the route may be through the Poison Canyon and Raton Formations. In 1984 (U.S. Environmental Protection Agency, written commun., 1985), an argument was presented for substantial primary permeability in the deeper parts of the Poison Canyon Formation and substantial secondary permeability (fractures) in the Raton Formation. It was also then postulated that the flow of water was to the northeast in the Poison Canyon Formation, and then down through the Raton Formation to the Vermejo Formation.

For this study, water samples collected from the shaft at the Chandler Mine (shaft C-153), well C-317, and seven of the U.S. Geological Survey test wells (wells LP85-1D, LP85-2S, LP85-2D1, LP85-2D4, LP85-4, LP85-6D1, and LP85-6D4) were assumed to be representative of the Vermejo Formation. Well C-314 is completed in the Poison Canyon Formation at depths from 55 to 97 ft. Water samples from this well were assumed representative of water in stratigraphically lower beds of the Poison Canyon Formation.

The ridge separates two shallow aquifers; one southwest of the ridge, near the mill, and the other northeast of the ridge, near Lincoln Park. In the following discussion, the shallow aquifer southwest of the ridge is called the shallow aquifer near the mill; the shallow aquifer northeast of the ridge is called the alluvial aquifer near Lincoln Park.

Near the mill, water flows through the shallow aquifer of alluvium and possibly the upper part of weathered or fractured Poison Canyon Formation. Along the ridge, this water may flow through alluvium and possibly fractured beds of the Raton and Vermejo Formations. Flow may be greatest where the ridge has been breached, as by the channel of Sand Creek. In 1978 (U.S. Environmental Protection Agency, written commun., 1985), it was suggested that flow in this shallow aquifer followed a complex path from the tailings ponds near the mill to the SCS reservoir and beyond, and that the presence of raffinate in water at the SCS reservoir was indisputable. Wells C-312, C-313, and C-333 are completed in the Poison Canyon Formation at depths of 20 to 60 ft. These wells are included in the present monitoring program of the Cotter Corp.; they were selected for this study as representative of the shallow aquifer southwest of the ridge. Water samples from these wells were assumed representative of water from the Poison Canyon Formation mixed with raffinate.

Northeast of the ridge, the shallow aquifer consists of alluvium and possibly the upper part of weathered or fractured bedrock of either the Vermejo Formation, Trinidad Sandstone, or Pierre Shale, whichever underlies the alluvium. The base of this shallow aquifer is the irregular surface within the bedrock where it changes from weathered and fractured rock to unweathered and unfractured rock. Southwest of the De Weese Dye Ditch, there is no significant irrigation and consequently no recharge from irrigation. Sources of recharge are percolation of precipitation, leakage from intermittent streams (including Sand Creek prior to the SCS dam), flow beneath the ridge, and flow from the bedrock. The alluvium may be saturated only in areas where the base of the aquifer is topographically low. The direction of flow will follow the line of least resistance as determined by the unknown subsurface topography of the base of weathered and fractured Vermejo Formation.

Wells C-329, C-330, and C-331 are completed north of the SCS dam in the Vermejo Formation at depths of 32 to 46 ft, after penetrating 17 to 26 ft of alluvium. Well-completion data indicate no seal in the well bore between alluvium and the Vermejo Formation (U.S. Environmental Protection Agency, written commun., 1985). Water from these wells contains large concentrations of raffinate components and were assumed representative of water flowing past the ridge.

Irrigation with surface water is practiced northeast of the De Weese Dye Ditch. Leakage from the ditch and excess water from irrigation is a large source of recharge for the shallow aquifer in this area. A 1983 report (U.S. Environmental Protection Agency, written commun., 1985) concluded that ground water generally flows to the northeast. Discharge is to pumping wells and seeps and springs, including those in the downstream reaches of Sand Creek. Most of the privately owned wells in Lincoln Park are completed in this aquifer. For this study, samples collected from nine wells (wells C-129, D, E, G, H, I, K, L, and M) and two seeps (seeps A and J) were assumed to be representative of this shallow aquifer in Lincoln Park.

TEST-WELL CONSTRUCTION AND COMPLETION

The nine test wells drilled in the area between the SCS dam and Lincoln Park (fig. 2) were completed to observe hydraulic head and water quality at five selected locations. At each location, one to three test wells were completed at selected depths in the alluvium and the underlying Vermejo Formation. Each test well was screened to a selected interval and isolated from overlying and underlying strata.

The initial plan was to complete four test wells in alluvium. In previous studies (U.S. Environmental Protection Agency, written commun., 1985), a plume of raffinate-affected ground water was mapped on the basis of water-quality samples collected from the three monitoring wells (wells C-329, C-330, and C-331) just downgradient from the SCS dam and from privately owned wells in Lincoln Park. The maximum extent of each mapped plume usually extended to a privately owned well (well C-138) that had yielded water with larger concentrations of raffinate components compared to water from other privately owned wells. The shallow test wells were to be located to better document the change in concentration of raffinate components and to define the extent of the plume along this shallow flow path. Test well LP85-2S, located between the SCS dam and well C-138, was expected to yield water with intermediate concentrations of raffinate components. Test well LP85-4, located west of Sand Creek, was expected to help define the width of the plume. Test well LP85-1S, located 40 ft west of well C-138, was expected to yield water similar in quality to that yielded by well C-138. Test well LP85-3, located near Sand Creek and north of the De Weese Dye Ditch, was expected to help define the width of the plume. It was further expected that continued data collection at this well (not planned as part of this study) may provide insight into the effect of leakage from the ditch on water quality in the alluvium.

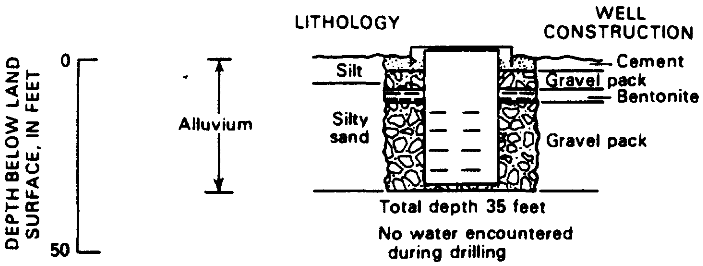
This plan was modified, because no saturated alluvium was penetrated at any site. The two test wells near the De Weese Dye Ditch (wells LP85-1S and LP85-3) were completed in alluvium. These test wells may yield water when water levels rise during the irrigation season; they were not sampled as part of this study. The two test wells further south (wells LP85-2S and LP85-4) were drilled deeper and completed in the Vermejo Formation. Both of these test wells are too far from the De Weese Dye Ditch to expect a significant change in water level resulting from irrigation.

The initial plan was to complete three test wells in the Vermejo Formation. Previous studies (U.S. Environmental Protection Agency, written commun., 1985) have postulated flow from the Vermejo Formation to the alluvium of Lincoln Park as part of the "deep migration path" for raffinate components. These studies also have postulated that raffinate enters the Vermejo Formation through the Littell shaft or through the Poison Canyon and Raton Formations. The postulated "deep migration path" for raffinate components includes the mined seam and stratigraphically higher beds. Well C-328, perforated at altitudes from about 5,201 to 5,211 ft, may yield water from the coal seam, which is the deepest coal seam mined in the Littell (Wolf Park) Mine (U.S. Environmental Protection Agency, written commun., 1985). Although the association between well C-328 and the coal seam is uncertain, an altitude of 5,200 ft was selected as a reasonable altitude for completion of the deepest test wells. The test wells were expected to provide hydraulic-head measurements and water-quality samples from the Vermejo Formation at a site beneath the shallow plume (well LP85-2D) and a site outside the shallow plume (well LP85-6D). Test well LP85-1D, located 165 ft south of well C-138, was completed at a shallower depth to identify the quality of water that may reach well C-138 from the Vermejo Formation.

This plan was modified to obtain as much information as possible from the test wells. The two deepest holes each were completed to two intervals using 4-in.-diameter and 1-in.-diameter PVC casing. Test well LP85-2D4 was slotted at altitudes of about 5,196 to 5,236 ft with 4-in.-diameter PVC casing, and test well LP85-2D1 was slotted at altitudes of about 5,319 to 5,339 ft with 1-in.-diameter PVC casing. Test well LP85-6D4 was slotted at altitudes of about 5,200 to 5,240 ft with 4-in.-diameter PVC casing and test well LP85-6D1 was slotted at altitudes of about 5,324 to 5,344 ft with 1-in.-diameter PVC casing. Therefore, a total of seven test wells were completed in the Vermejo Formation--three at one nest (wells LP85-2S, LP85-2D1, and LP85-2D4), two at another nest (wells LP85-6D1 and LP85-6D4), one near well C-138 (well LP85-1D), and one away from the irrigated area (well LP85-4).

Well construction and completion for each of these nine test wells is given in this section. This documentation is part of the quality assurance provided for the sampling and interpretation presented in this report.

Test well LP85-1S (fig. 4) was drilled with air through 35 ft of sand adjacent to well C-138 where large concentrations of chemical constituents associated with raffinate have been reported. The well penetrated no saturated alluvium and was not drilled deep enough to penetrate the Vermejo Formation. The well was dry when completed (February 27, 1985) and prior to extensive irrigation (April 26, 1985). During the irrigation season, the water level in the aquifer rose enough so that the well contained water. On October 11, 1985, the water level was 30 ft below land surface. This well was not sampled as part of this study, because it was dry when the other water samples were collected. If it were to be sampled, differences in the chemical characteristics of water from this well, well C-138, and test well LP85-1D may provide insight into the source of water yielded by well C-138.



DRILLING

Drilling was by U.S. Geological Survey personnel

Drill pipe was lubricated with Wooley Booger drill pipe compound (a mixture of grease, oil, graphite, and lead) from Chromalloy-Wooley, Odessa, Texas

The drilling fluid was air

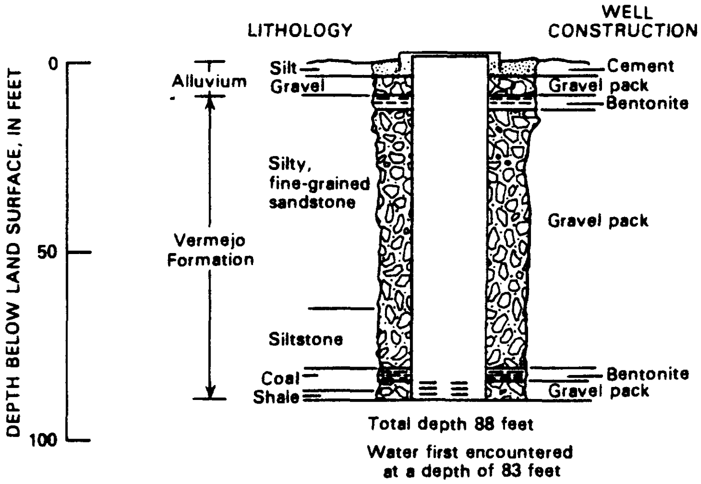
CASING

6-inch-diameter steel casing (5 feet long) set in cement to 3 feet. Locking cap for controlled access

4-inch-diameter PVC casing set to 34 feet. Box threaded with flush inside and outside diameters. Factory slotted from 14 to 34 feet with three vertical rows of horizontal slots; 1 slot every inch

Figure 4.--Lithology, construction, and completion of test well LP85-1S.

Test well LP85-1D (fig. 5) was drilled with air through 10 ft of unsaturated alluvium and 78 ft into the Vermejo Formation (total depth 88 ft), encountering water under artesian pressure in a coal seam at a depth of 83 ft. The test well is 165 ft south of well C-138. Assuming an eastward strike and a dip of about 5° south, the coal penetrated by test well LP85-1D would be near the bottom of well C-138. To minimize caving in the hole before casing, geophysical logs on this hole (natural gamma and gamma gamma) were run through the casing. The water yield was adequate to evacuate the casing, allow overnight recovery, and collect a sample for chemical analysis. Test well LP85-1D was pumped dry three times before a water sample was collected with a bailer. The water from this test well may represent water reaching well C-138 from this coalbed of the Vermejo Formation.



DRILLING

Drilling was by U.S. Geological Survey personnel

Drill pipe was lubricated with Wooley Booger drill pipe compound (a mixture of grease, oil, graphite, and lead) from Chromalloy-Wooley, Odessa, Texas

The drilling fluid was air

CASING

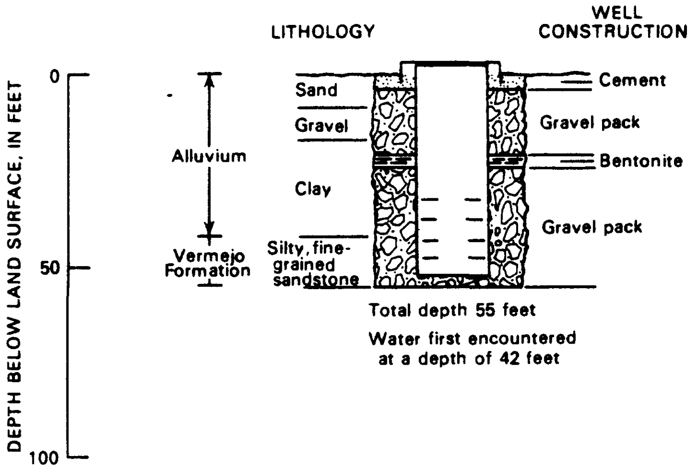
8-inch-diameter PVC casing set to 5 feet as temporary surface casing. Removed after drilling

6-inch-diameter steel casing (5 feet long) set in cement to 3 feet. Locking cap for controlled access

4-inch-diameter PVC casing set to 88 feet. Box threaded with flush inside and ouside diameters. Factory slotted from 83 to 88 feet with three vertical rows of horizontal slots; 1 slot every inch

Figure 5.--Lithology, construction, and completion of test well LP85-1D.

Test well LP85-2S (fig. 6) was drilled with air through 42 ft of unsaturated alluvium and 13 ft into the Vermejo Formation (total depth 55 ft), encountering water under artesian pressure in a silty, fine-grained sandstone at a depth of 42 ft. A natural-gamma log was run through the casing on this hole. The water yield was adequate to sustain a pumping rate of about 7 gal/min. The test well was pumped long enough to evacuate the casing more than three times before a water sample was collected for chemical analysis. Data from this well provided information on the area between the SCS dam and Lincoln Park, where available data are few. In combination with data from test wells LP85-2D1 and LP85-2D4, these data provide information on vertical variations in hydraulic head and water quality.



DRILLING

Drilling was by U.S. Geological Survey personnel

Drill pipe was lubricated with Wooley Booger drill pipe compound (a mixture of grease, oil, graphite, and lead) from Chromalloy-Wooley, Odessa, Texas

The drilling fluid was air

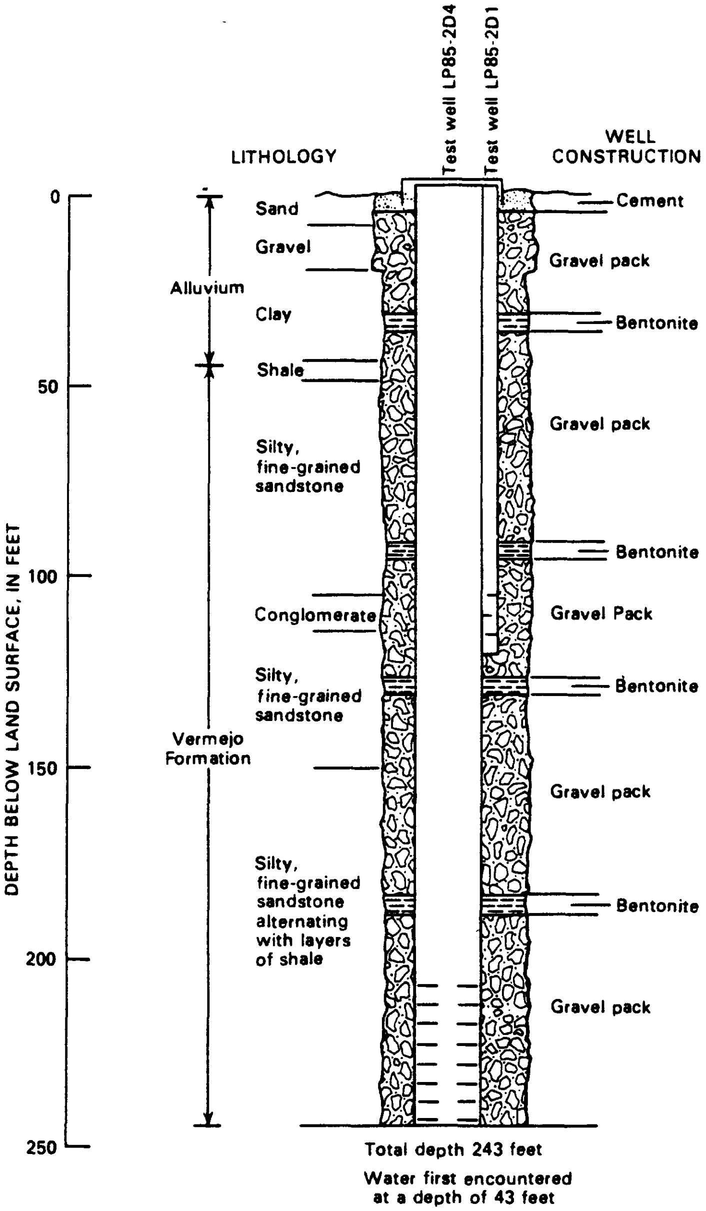
CASING

6-inch-diameter steel casing (5 feet long) set in cement to 3 feet. Locking cap for controlled access

4-inch-diameter PVC casing set to 52 feet. Box threaded with flush inside and outside diameters. Factory slotted from 32 to 52 feet with three vertical rows of horizontal slots; 1 slot every inch

Figure 6.--Lithology, construction, and completion of test well LP85-2S.

Test wells LP85-2D1 and LP85-2D4 (fig. 7) were completed in the same hole using 1-in.-diameter and 4-in.-diameter PVC casing. The hole was drilled through 43 ft of unsaturated alluvium and 200 ft into the Vermejo Formation (total depth 243 ft), encounting water in a shale at a depth of 43 ft. The hole was drilled with air to a depth of about 110 ft. Foam and water were used as the drilling fluid below a depth of about 110 ft. Geophysical logs for this hole include several run in the open hole (natural gamma, resistivity, neutron, density, acoustic velocity, caliper, and televiewer) and through the casing (natural gamma, gamma gamma, and neutron); they constitute the most complete set of logs of any of the test wells. Test well LP85-2D1 was completed with 1-in.-diameter PVC casing slotted between altitudes of 5,319 and 5,339 ft. Test well LP85-2D4 was completed with 4-in.-diameter PVC casing slotted between altitudes of 5,196 and 5,236 ft. A few days after completion, the water level was higher in the shallow test well (well LP85-2D1) than in the deep test well (well LP85-2D4). However, this difference was reversed less than 2 months later. The water yield to both wells was adequate to evacuate the casing, allow overnight recovery, and collect a water sample for chemical analysis. Test well LP85-2D1 was jetted dry with air twice, before a



DRILLING

Drilling was by U.S. Geological Survey personnel

Drill pipe was lubricated with Wooley Booger drill pipe compound (a mixture of grease, oil, graphite, and leed) from Chromalloy-Wooley, Odessa, Texas

Above 110 feet the drilling fluid was air

Below 110 feet the drilling fluid was versafoam (American Colloid Company, Skokie, Illinois) and water (Canon City Water Department)

CASING

8-inch-diameter PVC casing set to 10 feet as temporary surface casing. Removed after drilling

6-inch-diameter steel casing (5 feet long) set in cement to 3 feet. Locking cap for controlled access

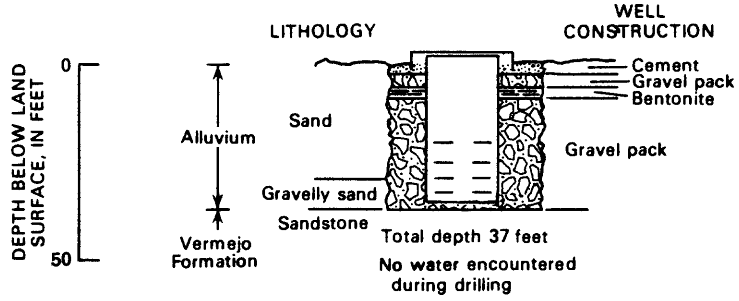
1-inch-diameter PVC casing set to 120 feet. 20-foot lengths glued together. Slotted from 100 to 120 feet with horizontal hacksaw cuts in a vertical spiral; 1 slot about every 2 inches

4-inch-diameter PVC casing set to 243 feet. Box threaded with flush inside and outside diameters. Factory slotted from 203 to 243 feet with three vertical rows of horizontel slots; 1 slot every inch

Figure 7.--Lithology, construction, and completion of test wells LP85-2D1 and LP85-2D4.

water sample was collected by jetting with air. Test well LP85-2D4 was pumped dry three times, before a water sample was collected with a bailer. These wells provide lithologic, hydraulic-head, and water-quality information for selected beds in the Vermejo Formation.

Test well LP85-3 (fig. 8) was drilled with air through 37 ft of unsaturated alluvium. Drilling was stopped when the Vermejo Formation was reached. Because of caving, foam and water were used as the drilling fluid to get the drill stem out of the hole. This test well is near Sand Creek and north of the De Weese Dye Ditch. The test well was dry when drilled (February 28, 1985) and prior to extensive irrigation (April 26, 1985). During the irrigation season, the water level in the aquifer rose enough so that the test well contained water. On October 11, 1985, the water level was 16.7 ft below land surface. This test well was not sampled as part of this study, because it was dry when the other water samples were collected. If it were to be sampled, chemical characteristics of water from this test well may provide insight into the effect of leakage from the De Weese Dye Ditch on the quality of water in the alluvial aquifer.



DRILLING

Drilling was by U.S. Geological Survey personnel

Drill pipe was lubricated with Wooley-Booger drill pipe compound (a mixture of grease, oil, graphite, and lead) from Chromalloy-Wooley, Odessa, Texas

The drilling fluid was air. Versafoam (American Colloid Company, Skokie, Illinois) and water (Canon City Water Department) was used as the drilling fluid to get the drill string out of the hole

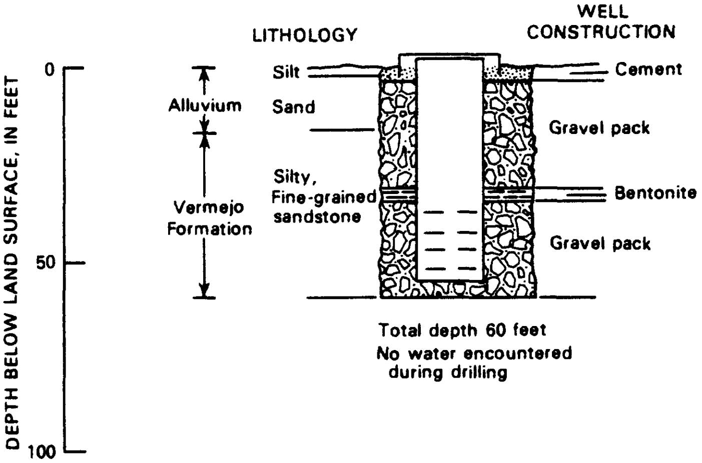
CASING

6-inch-diameter steel casing (5 feet long) set in cement to 3 feet. Locking cap for controlled access

4-inch-diameter PVC casing set to 36 feet. Box threaded with flush inside and outside diameters. Factory slotted from 16 to 36 feet with three three vertical rows of horizontal slots; 1 slot every inch

Figure 8.--Lithology, construction, and completion of test well LP85-3.

Test well LP85-4 (fig. 9) was drilled with air through 16 ft of unsaturated alluvium and 44 ft into the Vermejo Formation (total depth 60 ft). The test well was dry when drilled (February 25, 1985), and remained dry several days later (March 1, 1985). The water level in the well rose 11.6 ft from 28.8 to 17.2 ft below land surface between April 26 and October 11, 1985. Test well LP85-4 is about 500 ft south of the De Weese Dye Ditch, and the altitude of the base of the alluvium at the well is only about 7 ft below the altitude of the bottom of the ditch. Therefore, this change in water level does not seem to be related to leakage from the ditch during the irrigation season. A water sample for chemical analysis was collected on March 20, 1985. The casing was not evacuated before a water sample was collected with a bailer. The water from this test well may represent water from selected beds of the Vermejo Formation.



DRILLING

Drilling was by U.S. Geological Survey personnel

Drill pipe was lubricated with Wooley Booger drill pipe compound (A mixture of grease, oil, graphite, and lead) from Chromalloy-Wooley, Odessa, Texas

The drilling fluid was air

CASING

6-inch-diameter steel casing (5 feet long) set in cement to 3 feet. Locking cap for controlled access

4-inch-diameter PVC casing set to 55 feet. Box threaded with flush inside and outside diameters. Factory slotted from 35 to 55 feet with three vertical rows of horizontal slots; 1 slot every inch

Figure 9.--Lithology, construction, and completion of test well LP85-4.

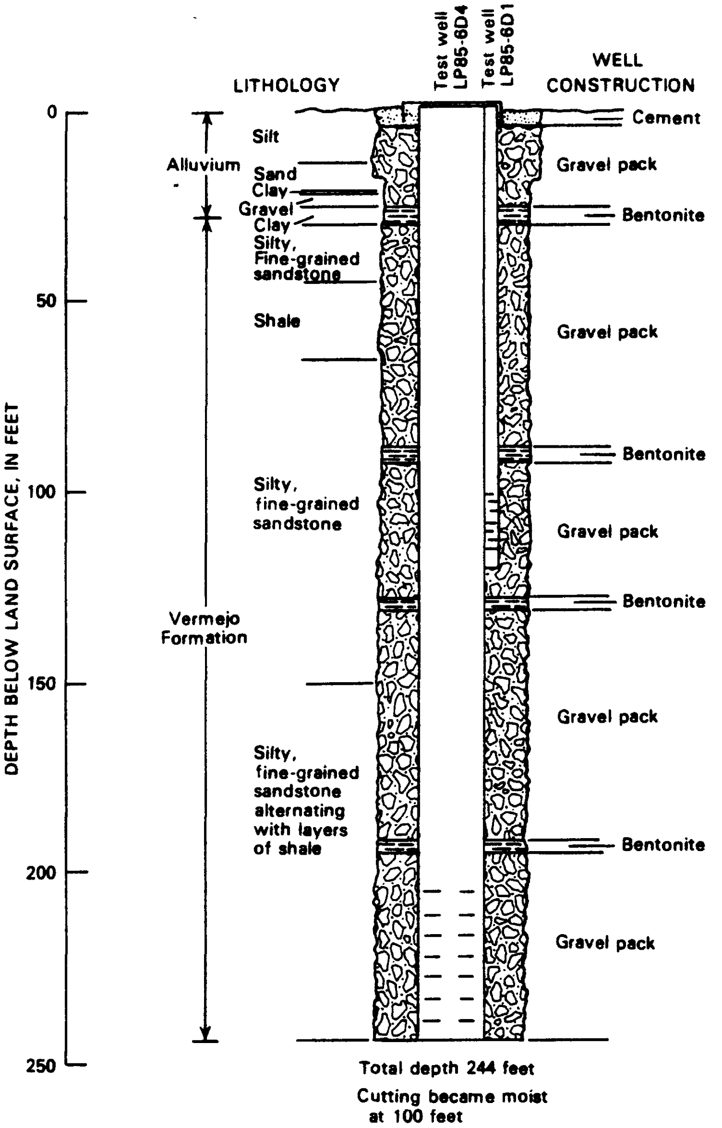
Test wells LP85-6D1 and LP85-6D4 (fig. 10) were completed in the same hole, using 1-in.-diameter and 4-in.-diameter PVC casing. The hole was drilled through 29 ft of unsaturated alluvium and 215 ft into the Vermejo Formation (total depth 244 ft). The hole was drilled with air to a depth of about 115 ft, producing cuttings ranging from dry to moist. At a depth of 115 ft, moist samples were clogging in the hole. Foam and water were used as the drilling fluid below a depth of about 115 ft. Geophysical logs for this hole include only caliper and nuclear logs (natural gamma, neutron, dual density, gamma in cased hole, and gamma gamma in cased hole), because the depth to water in the open hole was about 200 ft below land surface. Test well LP85-6D1 was completed using 1-in.-diameter PVC casing slotted between altitudes of 5,324 and 5,344 ft; test well LP85-6D4 was completed using 4-in.-diameter PVC casing slotted between altitudes of 5,200 and 5,240 ft. Seven hours after completion, water in the casing rose about 5 ft in the shallow test well (well LP85-6D1) and about 44 ft in the deep test well (well LP85-6D4). After they stabilized, the water level was higher in the shallow test well (well LP85-6D1) than in the deep test well (well LP85-6D4). The water yield to both test wells was adequate to evacuate the casing, allow overnight recovery, and collect a water sample for chemical analysis. Test well LP85-6D1 was jetted dry with air twice, before a water sample was collected by jetting with air. Test well LP85-6D4 was pumped dry three times, before a water sample was collected with a bailer. These test wells provide lithologic, hydraulic-head, and water-quality information for selected beds in the Vermejo Formation.

GROUND-WATER FLOW

The direction of ground-water flow is a function of the three-dimensional character of hydraulic conductivity and hydraulic head. Ground-water flow in the Vermejo Formation is described by examining water levels, lithologic logs, and geophysical logs collected during this study for implications about hydraulic conductivity and hydraulic head. Ground-water flow in the alluvial aquifer underlying Lincoln Park is described by examining hydraulic heads measured during this study. No data were collected relating to the hydraulic conductivity of the alluvial aquifer in Lincoln Park.

Hydraulic Conductivity of the Vermejo Formation

The ability of an aquifer to transmit water can be described by its hydraulic conductivity; the volume of water that will flow in unit time through a unit area under a unit hydraulic gradient. The hydraulic gradient is the change in hydraulic head per unit of distance, in a given direction. In aquifers composed of interbedded permeable and less-permeable materials, the hydraulic conductivity commonly is an anisotropic property; that is, the value of hydraulic conductivity is not the same in all directions. Commonly, in unfractured media, the hydraulic conductivity parallel to the bedding is greater than that normal to the bedding.



DRILLING

Drilling was by U.S. Geological Survey personnel

Drill pipe was lubricated with Wooley Booger drill pipe compound (a mixture of grease, oil, graphite, and lead) from Chromalloy-Wooley, Odessa, Texas

Above 115 feet the drilling fluid was air

Below 115 feet the drilling fluid was Versafoam (American Colloid Company, Skokie, Illinois) and water (Canon City Water Department)

CASING

8-inch-diameter PVC casing set to 5 feet as temporary surface casing. Removed after drilling

6-inch-diameter steel casing (5 feet long) set in cement to 3 feet. Locking cap for controlled access.

1-inch-diameter PVC casing set to 120 feet. 20-foot lengths glued together. Slotted from 100 to 120 feet with horizontal hacksaw cuts in a vertical spiral; 1 slot every 2 inches

4-inch-diameter PVC casing set to 244 feet. Box threaded with flush inside and outside diameters. Factory slotted from 204 to 244 feet with three vertical rows of horizontal slots; 1 slot every inch

Figure 10.--Lithology, construction, and completion of test wells LP85-6D1 and LP85-6D4.

Commonly, hydraulic conductivity is estimated using an aquifer test: a controlled onsite experiment made by observing ground-water flow that is produced by a known boundary condition, such as a pumping well. No aquifer tests were planned or conducted as part of this study. However, a few tentative implications can be derived. For the Vermejo Formation, implications about hydraulic conductivity were inferred from water levels, from lithologic logs, and from geophysical logs for the wells drilled as part of this study (test wells with the prefix LP85 in table 1).

Implications about Hydraulic Conductivity from Water Levels

Although no aquifer tests were conducted, some tentative implications about hydraulic conductivity were derived from the water levels measured in test wells that penetrated some beds of the Vermejo Formation. All test wells were drilled during the week ending March 1, 1985. The slow rate of water seepage into test wells and the slow rise in water levels in some wells indicated that the hydraulic conductivity of beds yielding water to the wells is minimal. The minimal hydraulic conductivity of some beds is indicated best by the history of water levels in test well LP85-4. This test well was dry when drilled (February 25, 1985); however, about 2 months later the water level had risen at least 26 ft (April 26, 1985). Test wells LP85-6D1 and LP85-6D4 penetrated beds with larger gradients toward the well, or greater hydraulic conductivity, or both. These wells were not dry when drilled; 7 hours after the wells were completed, the casing in well LP85-6D1 had accumulated about 4 ft of water, and the casing in well LP85-6D4 had accumulated about 43 ft of water. These water-level measurements were not representative of the undisturbed hydraulic head in the corresponding beds of the Vermejo Formation, as evidenced by measurements during April and October 1985 (table 2). The rise of water levels after March 1, 1985, also was large in test wells LP85-1D and LP85-2D4. Only in test wells LP85-2S and LP85-2D1 were the water levels on March 1, 1985, within 5 ft of those measured during April and October. Hydraulic conductivity in the Vermejo Formation is variable from one bed to another; hydraulic conductivity seems to be larger in the beds penetrated by test wells LP85-2S and LP85-2D1 and smaller in the beds penetrated by test wells LP85-1D, LP85-2D4, LP85-4, LP85-6D1, and LP85-6D4.

Response of the test wells to pumping prior to collecting a water sample was consistent with the previous observations. Test well LP85-2S yielded enough water to sustain a pumping rate of about 7 gal/min. In each of the other 4-in.-diameter test wells (wells LP85-1D, LP85-2D4, and LP85-6D4), the water yield was such that pumping evacuated the casing; the well was allowed to recover overnight before either pumping another casing volume or collecting a water sample.

Table 2.--*Water levels in test wells*

Test well number (see fig. 2)	Altitude, in feet above sea level				
	Top of casing	Bottom of slotted casing	Water level measured on		
			3-1-85	4-26-85	10-11-85
LP85-1S	5,439.7	5,403	(1)	(1)	5,407.0
LP85-1D	5,448.1	5,357	5,392.3	5,412.8	5,407.1
LP85-2S	5,441.9	5,388	5,415.8	5,417.6	5,418.9
LP85-2D1	5,442.1	5,319	5,412.3	5,415.3	5,416.6
LP85-2D4	5,442.1	5,196	5,409.2	5,417.4	5,417.7
LP85-3	5,425.2	5,387	(1)	(1)	5,406.2
LP85-4	5,435.4	5,379	(1)	5,405.1	5,416.7
LP85-6D1	5,447.5	5,324	[2]5,328.8	5,406.3	[3]5,405.6
LP85-6D4	5,447.5	5,200	[2]5,243.6	5,386.8	[3]5,385.3

[1] Dry.

[2] Water level not recovered from well development, which was completed about 7 hours before measurement. The measured altitude of water level was not representative of undisturbed hydraulic head in the Vermejo Formation.

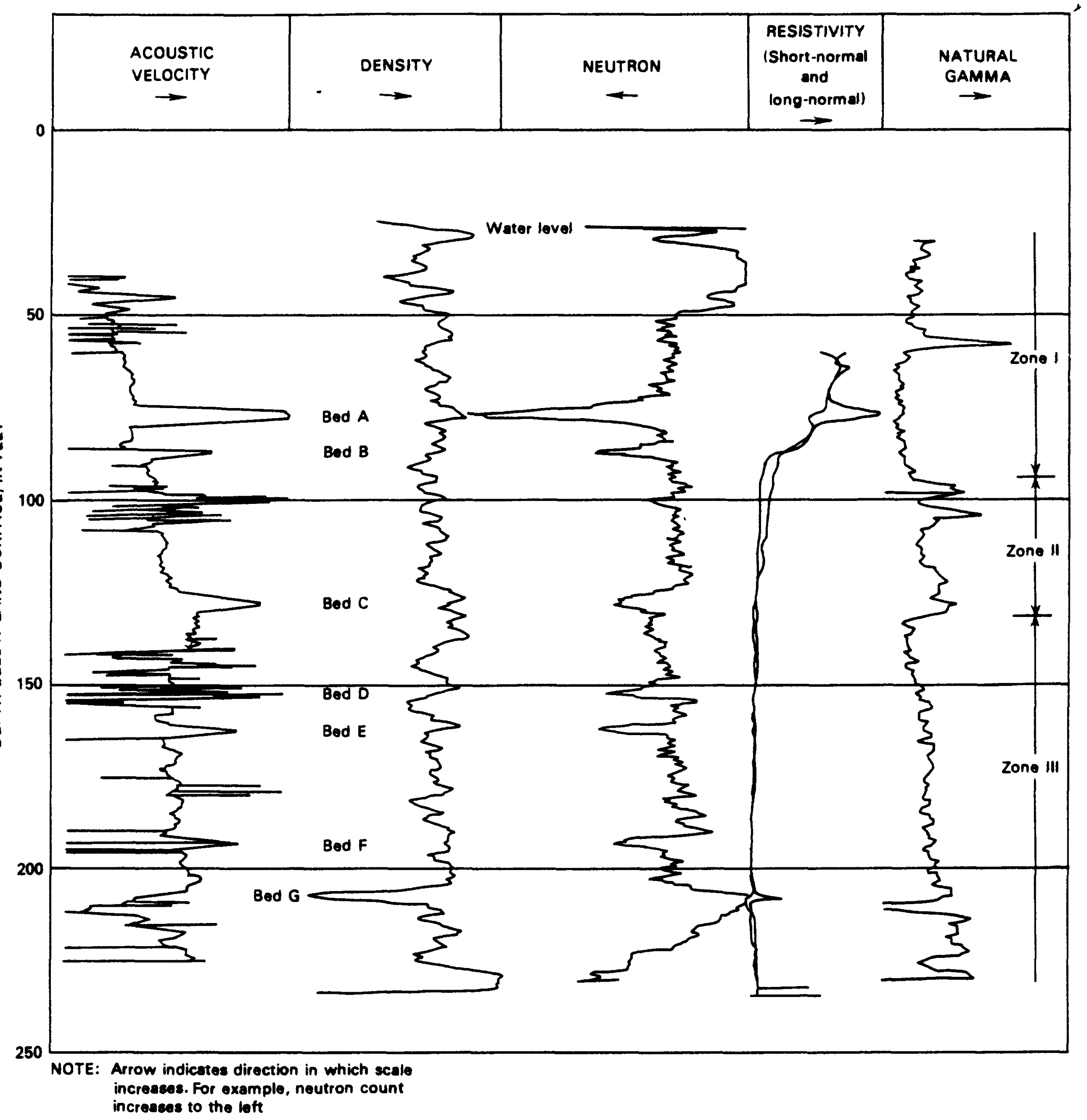
[3] Measurement made on October 22, 1985.

Implications about Hydraulic Conductivity from Lithologic and Geophysical Logs

Lithologic and geophysical logs of the test wells provided a qualitative description of aquifer characteristics in the Vermejo Formation. Lithologic logs completed during drilling described the Vermejo Formation as interbedded sandstone and shale. Coal was identified only in the cuttings from test well LP85-1D. Geophysical logs were all consistent with interbedded sandstone and shale, in which many of the beds were so thin that they were not resolved into individual beds on the logs (Frederick Paillet, U.S. Geological Survey, written commun., 1985).

For test well LP85-2D4, the geophysical logs indicate a few relatively clean, well-cemented sandstone beds within a section of shaly sandstone or siltstone beds. These relatively clean sandstone beds seem to have (fig. 11, beds A-F) faster acoustic velocities (shorter travel times) and smaller porosities (larger neutron counts).

Commonly, a natural-gamma log is used to indicate the relative clay or shale content of sedimentary strata. Natural-gamma activity of clay- or shale-bearing sediments is greater than that of quartz sands. For test well LP85-2D4 the natural-gamma log (fig. 11) does not provide good resolution of individual sandstone beds. This lack of good resolution may be the combined result of at least three factors: (1) Individual beds may be thin and never completely fill the volume affecting the log; (2) shale may occur in the sandstone bed [a signal from a shaly sandstone bed may be similar to that from a shale bed (Keys and MacCary, 1971, p. 65)]; and (3) the presence of uranium or its decay products in the cement of the sandstone bed or in the ground water in the sandstone bed may result in a signal from a sandstone bed similar to



NOTE: Arrow indicates direction in which scale increases. For example, neutron count increases to the left

Figure 11.--Selected geophysical logs for test well LP85-2D4.

that from a shale bed. For test well LP85-2D4, the natural-gamma log was used to divide the lithology into three zones: zone II is a zone of relatively more shaly sandstone beds (fig. 11) separating zones I and III that are zones of relatively less shaly sandstone beds.

For test well LP85-2D4, the resistivity log responded to the shallow sandstone bed (fig. 11, bed A) but did not respond to sandstone beds at greater depth (fig. 11, beds B-F), possibly because some of the beds, being thinner, were not recognized as individual beds. For thicker beds (fig. 11, bed C), the lack of response on the resistivity log may be the result of more shale in the lower sandstone bed (fig. 11, bed C) than in the upper sandstone bed (fig. 11, bed A). The trend of the resistivity log to the right at the upper part may indicate a grounding problem with the logging system.

The beds penetrated by test well LP85-2D4 do not seem to be fractured. Most of the spikes (cycle skips) on the acoustic-velocity log probably are the result of greater attenuation in shale beds rather than fractures.

The response (large resistivity, small density, small neutron, and small natural gamma) at about 210 ft in test well LP85-2D4 (fig. 11, bed G) is consistent with this being a coalbed. However, no coal was noted in the lithologic log.

Although sandstone beds penetrated by test well LP85-2D4 may be primary ground-water conduits, the acoustic-velocity and porosity (neutron) logs indicate that the porosity is small (larger neutron count). For the identified sandstone beds (fig. 11, beds A-F) the acoustic travel time (inverse of velocity) ranges from about 60 µs/ft (fig. 11, bed A) to 90 µs/ft (fig. 11, bed B). Assuming travel times of 55.6 and 218 µs/ft for sandstone and water, the calculated (Dresser Atlas, 1982) porosity ranges from 0.03 (fig. 11, bed A) to 0.21 (fig. 11, bed B). Larger porosity values may result from the sandstone beds being shaly rather than clean, which would be consistent with the large porosity of shale (commonly 0.20-0.35) and the lack of response in the resistivity log. Empirical relations have been developed between porosity and hydraulic conductivity for specific sandstone beds (Bredehoeft, 1964). However, data are not available to establish a similar relation for sandstone beds in the Vermejo Formation. The hydraulic conductivity of the sandstone beds penetrated by test well LP85-2D4 probably is minimal, but values of hydraulic conductivity cannot be reliably quantified from geophysical logs.

For test well LP85-6D4, fewer geophysical logs were obtained than for test well LP85-2D4, because the open hole contained water only in the bottom 40 ft. Comparisons between the beds penetrated by these two test wells is impaired by the lack of acoustic-velocity and resistivity logs for test well LP85-6D4.

Results are inconclusive on whether these two test wells have penetrated beds at the same position in a vertical profile or not. At test well LP85-6D4 (fig. 12) the response (small density, small neutron, and small natural gamma) at the bottom of the well is consistent with this being a coalbed. However, this may or may not be the same coalbed penetrated by test well LP85-2D4 (fig. 11, bed G). The same zones have been indicated in the gamma log for test well LP85-6D4 (fig. 12) as were identified in the gamma log for test well LP85-2D4 (fig. 11). However, the zones are not as well defined at test well LP85-6D4. Although these two characteristics of the geophysical logs may indicate that similar lithologies have been penetrated, none of the relatively clean sandstone beds identified on logs from test well LP85-2D4 (fig. 11, beds A-F) are obvious on logs from test well LP85-6D4 (fig. 12). This may indicate that individual beds are not continuous between the sites, or that hydraulic properties of the beds are heterogeneous.

In summary, lithologic and geophysical logs of the test wells are consistent with the general description of the Vermejo Formation as sandstone beds and shaly sandstone beds interlayered with shale beds. The beds do not seem to be fractured. Hydraulic conductivity of the few relatively clean, well-cemented sandstone beds probably is minimal. These sandstone beds are interbedded with less-permeable shale beds and shaly sandstone beds to form an anisotropic system, in which flow will tend to follow the bedding. Individual beds may terminate or have a substantial change in hydraulic conductivity within a short distance.

Hydraulic Head in the Vermejo Formation

Because of the three-dimensional character of hydraulic conductivity, a difference between hydraulic heads in the Vermejo Formation does not necessarily indicate a component of flow in the direction of decreasing hydraulic head. For example, hydraulic head in test well LP85-2D4 was about 30 ft higher than that in test well LP85-6D4 (table 2); commonly, this difference in hydraulic head would be assumed to indicate a component of flow toward the lower hydraulic head. However, water-level measurements made in these wells may not represent hydraulic heads in the same beds. Changes in hydraulic head with depth could account for all or part of the difference between measured hydraulic heads. In addition, the two hydraulic heads may be affected by separate local flow systems. Data available from the test wells are not adequate to determine the magnitude or direction of flow in the beds of the Vermejo Formation.

Hydraulic heads (table 2) measured in the clusters of test wells at various depths at site 2 (wells LP85-2S, LP85-2D1, and LP85-2D4) and site 6 (wells LP85-6D1 and LP85-6D4) provide information on the variation of hydraulic head with depth in the Vermejo Formation. At site 6, hydraulic heads decrease with depth; the hydraulic head at about the 100-ft depth (test well LP85-6D1) is 20 ft higher than the hydraulic head at about the 200-ft depth (test well LP85-6D4). At site 2, the hydraulic head at the 50-ft depth (test well LP85-2S) is higher than that at the 100-ft depth (test well LP85-2D1) or the 200-ft depth (test well LP85-2D4). However, the lowest hydraulic head was measured at the 100-ft depth (test well LP85-2D1), not in the deepest test well at the site (well LP85-2D4). Except for the anomalous lower hydraulic head at test well LP85-2D1, hydraulic heads decrease with depth.

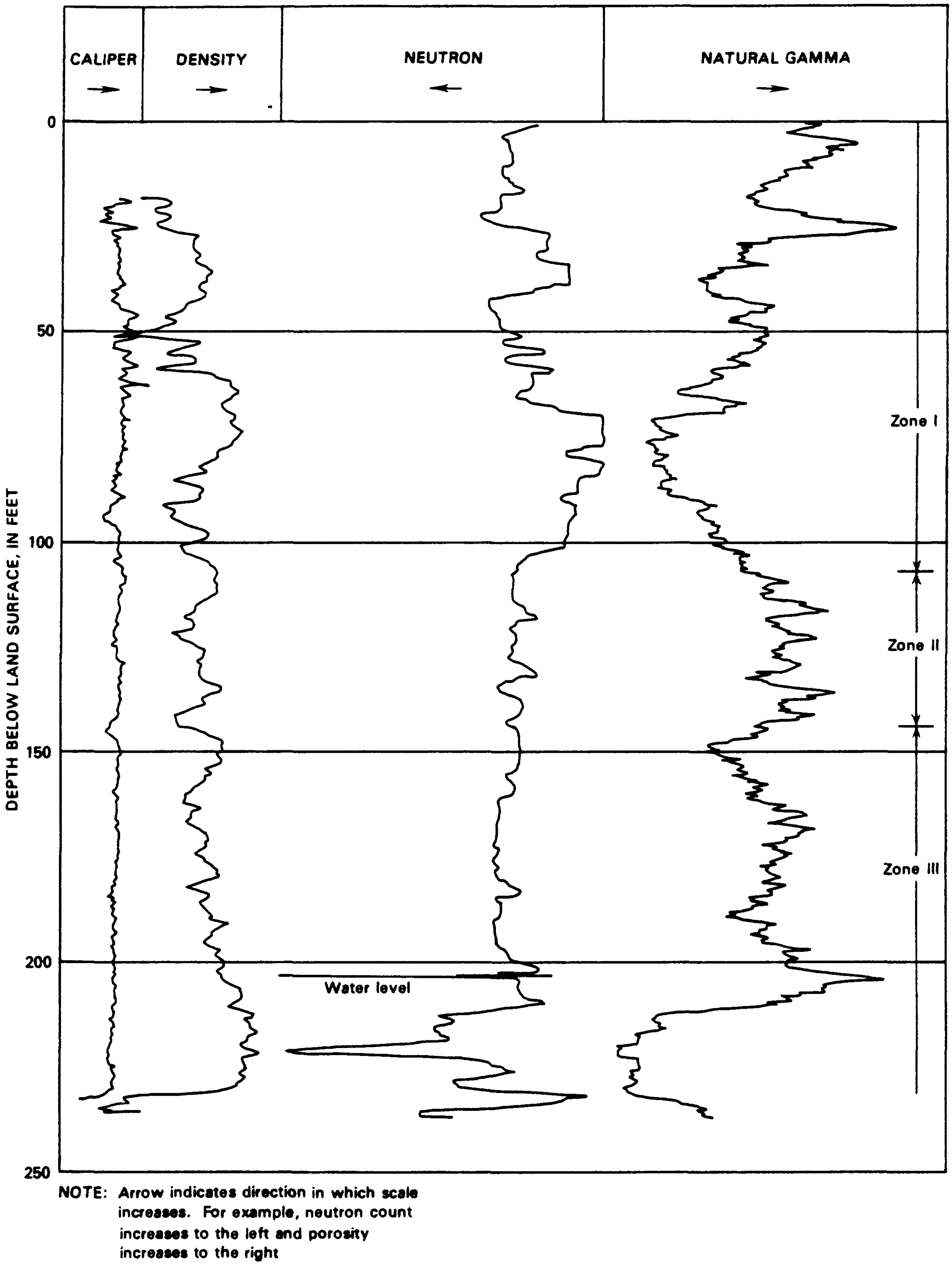


Figure 12.--Selected geophysical logs for test well LP85-6D4.

Decreasing hydraulic head with depth commonly is associated with a downward flow component, and it generally is assumed to indicate a recharge area rather than a discharge area. However, for dipping anisotropic beds, a vertical component of hydraulic-head gradient does not necessarily indicate a vertical component of flow; a vertical component of hydraulic-head gradient is necessary to maintain horizontal flow across the dipping anisotropic beds. To evaluate the direction of ground-water flow from measured hydraulic heads within the Vermejo Formation, it is necessary to consider the three-dimensional character of the hydraulic conductivity. Data available from test wells are not adequate to determine the magnitude or direction of the vertical component of flow.

Hydraulic Head in the Alluvial Aquifer

Water levels in selected shallow wells in Lincoln Park (table 1) were used to contour the water level in the alluvial aquifer (fig. 13). The base of the aquifer seems to form an irregular surface. For example, the top of the Vermejo Formation was at an altitude of about 5,435 ft in test well LP85-1D, but it was below 5,402 ft at nearby test well LP85-1S. Most of the water levels are north of the De Weese Dye Ditch, where the aquifer seems to be saturated. Because this aquifer is assumed to be almost isotropic, ground-water flow is approximately normal to the water-level contours. The contours indicate that flow in this area generally is to the northeast. In contrast, no saturated alluvium was penetrated in the test wells south of the De Weese Dye Ditch. The alluvium may be saturated only where the Vermejo Formation subcrop is topographically low. Ground-water flow may be restricted to a channel or channels in the irregular and relatively undescribed topography of the Vermejo Formation subcrop. Contours were not extended into this area.

GROUND-WATER QUALITY

Properties of the water-quality samples--specific conductance, pH, temperature, dissolved oxygen (or total sulfide), and alkalinity--were measured prior to analysis of the samples. All water-quality samples were analyzed for major ions and trace elements. Major ions consisted of calcium, magnesium, sodium, potassium, sulfate, chloride, fluoride, and silica. Trace elements analyzed include those in the U.S. Environmental Protection Agency's Task I and II inorganic analyses: aluminum, antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, nickel, selenium, silver, thallium, tin, vanadium, and zinc. All samples also were analyzed for one additional trace element--molybdenum--and for radiochemicals--radium-226 and uranium. Selected samples were analyzed for isotopic composition. Isotope analyses consisted of the stable-isotope ratios of carbon-13 to carbon-12, hydrogen-2 to hydrogen-1, oxygen-18 to oxygen-16, and sulfur-34 to sulfur-32, and the radioactive isotope tritium.

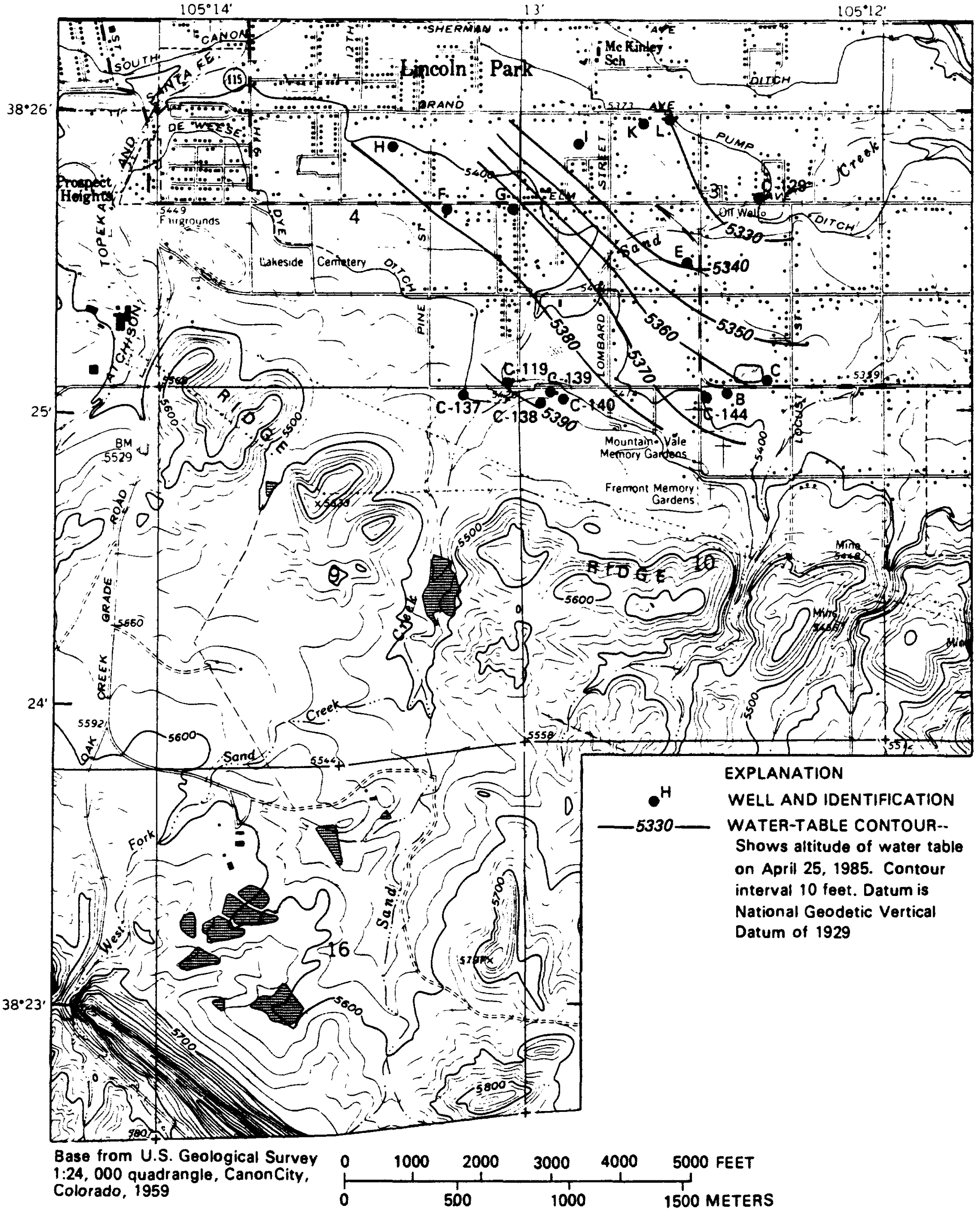


Figure 13.--Water level in the unconfined alluvial aquifer on April 25, 1985.

Sample Collection

The interpretation of laboratory analyses of ground water presumes that the concentrations reported by the laboratory accurately describe the characteristics of water from a definable part of the aquifer. Potential changes in water chemistry resulting from drilling, well completion, sample collection, and sample processing need to be evaluated and minimized.

Precautions were taken to minimize the introduction of extraneous substances, including water, during drilling and well completion. For some wells (test wells LP85-2D1, LP85-2D4, LP85-3, LP85-6D1, LP85-6D4), foam was required as the drilling fluid because air was not adequate to remove the cuttings. The foam was a mixture of water from the public supply of Canon City and Versafoam, a biodegradable product of American Colloid Company. Samples of both liquids were collected and submitted to the U.S. Geological Survey laboratory for analysis. During well completion, the 4-in.-diameter wells were cased with threaded PVC pipe, and no cement was used. The PVC pipe was washed with public-supply water before use. The 1-in.-diameter wells (test wells LP85-2D1 and LP85-6D1) were cased with PVC pipe cemented together. The casing and cement were assumed to add no chemical constituents to the water samples. During well completion, the production zone of 4-in.-diameter wells was jetted, using the drill stem. Sections of drill stem were connected using Wooley Booger Drill Pipe Compound, a mixture of grease, oil, graphite, and lead produced by Chromalloy-Wooley, as a lubricant. Cement, bentonite pellets, and pea gravel placed in the annulus also were assumed to add no chemical constituents to the water samples.

Sample collection included preliminary pumping designed to ensure that the collected sample was representative of water in the aquifer (see section entitled "Well construction and completion" for pumping information specific to each well). For those wells drilled as part of this project, an effort was made to prevent contamination between wells. Sampling procedures for 4-in.-diameter wells included using new plastic hose, electrical cable, and nylon rope at each well. After use, the hose, electrical cable, and nylon rope from each well were stored in plastic for reuse only on that well. After use, the pump was disassembled, washed in soapy water, rinsed in public-supply water, and rinsed three times in deionized water before being reassembled for use at the next well.

Sampling procedures for 1-in.-diameter wells included using a new PVC faucet and air hose at each well. After use, both were labeled and stored in a plastic bag for future use only on the designated well. Water was collected from these wells (test wells LP85-6D1, LP85-2D1) by introducing compressed air into the bottom of the well that subsequently lifted the sample to the land surface. These wells, which had small water yields, were dewatered twice on succeeding days prior to sample collection. The sample then collected was the first water received at the land surface after the well was allowed to recover overnight. Water-quality possibly could have been affected by this method of sample collection.

For private wells, only wells equipped with pumps were sampled. No pumping equipment was moved from well to well. Any chemicals added during well drilling and completion were assumed to have been removed by previous pumping. The volume of water in the casing of each well was calculated, and each well was pumped prior to sampling long enough to ensure removal of at least three casing volumes of water. Then, monitoring began of specific conductance, pH, and water temperature, and samples were not collected until these measurements stabilized.

For wells on the Cotter Corp. property, the sample-collection methods were determined by Cotter Corp. personnel. Any chemicals added during well drilling and completion were assumed to have been removed by previous pumping. The samples from wells on Cotter Corp. property analyzed in this study were obtained as a split from samples collected by Cotter Corp. personnel.

In all cases, samples were collected at a point as near as possible to the well head. Water was discharged through plastic hosing either directly into plastic or glass sample bottles (for unfiltered samples), or into a plastic collection vessel (for water to be filtered). Water propelled by a peristaltic pump was filtered through a 0.45-micrometer filter. Samples were preserved and processed according to documented U.S. Environmental Protection Agency guidelines (U.S. Environmental Protection Agency, 1984b). Samples were transported to appropriate laboratories following the chain-of-custody procedures of the U.S. Environmental Protection Agency (U.S. Environmental Protection Agency, written commun., 1985).

Discharge, specific conductance, pH, water temperature, dissolved oxygen, and alkalinity were determined onsite. Well discharge was estimated by volumetric methods. Specific conductance was measured with a meter equipped with two different range probes. The meter was calibrated daily, and was determined to be accurate within 5 percent. The meter used to measure pH was calibrated daily, and was found to be accurate within 0.02 pH units. Water temperature was measured to the nearest 0.5 °C. Dissolved oxygen was measured with a field meter; the probe was air calibrated within a 10-liter measurement vessel, and dissolved oxygen was measured as water continually flowed through the vessel. Values were read when the meter stabilized. Meter accuracy was judged to be about 0.2 mg/L, based on duplicate analyses at the same site. Dissolved oxygen was not measured at wells where water was collected by air lifting, nor at test well LP85-4, where there was insufficient water for analysis. Also, the dissolved-oxygen concentration was assumed to be zero at shaft C-153, where water smelled like hydrogen sulfide. Here, sulfide was determined onsite by the iodine titrimetric method. Alkalinity was determined by titration curve.

All samples were collected during two field trips. Samples from background wells and springs were collected during February 19-21, 1985. Cotter Corp. wells and new U.S. Geological Survey test wells were sampled during March 19-21, 1985. Weather during these trips was hot and dry, with no snow on the ground, and minimum soil moisture.

Quality-Assurance Results

Internal quality control on each analytical method was done by the U.S. Environmental Protection Agency contract laboratories according to U.S. Environmental Protection Agency requirements. These methods included duplicate analysis done on laboratory splits, standard-reference-sample analysis, interference-check samples, and spiked-sample analysis. The laboratory quality-assurance procedures were reviewed by the U.S. Environmental Protection Agency before the data were accepted.

Accuracy of laboratory analyses was evaluated by submitting duplicate samples and samples of known uranium concentration. To detect any systematic contamination, four blanks were submitted. The blanks consisted of ultrapure deionized water that was run through the same processing steps, including filtration, that were done for each water sample. A sample of public-supply water and a sample of distilled water mixed with drilling soap also were submitted. These analyses are shown in table 3.

Chemical constituents of the blanks were determined to be less than detection limits in almost all instances. In a few instances, trace elements were detected at concentrations greater than detection limits, but less than concentrations considered as significant contamination.

Duplicate analyses generally agreed within 10 percent of each other. The largest disagreement was determined for concentrations of sodium, iron, and zinc. At two wells, both filtered and unfiltered samples were analyzed for delta deuterium and delta oxygen-18; these results agreed within 3 percent. Two uranium standards (concentration of 10 μg/L) were analyzed by the laboratory and were reported to contain 11 and 12 μg/L.

Public-supply water mixed with Versafoam was used as a drilling fluid in several wells. Mixed together at a 1:200 dilution, the resulting water was a calcium chloride type with some sodium and sulfate; the specific conductance of this drilling fluid was about 350 μS/cm. The laboratory detected no concentrations of raffinate components in the public-supply water or in the drilling fluid; iron, probably from rust in the tanks used to haul the public-supply water to the site, was the only trace element found in significant concentration (1,100 μg/L). No evidence existed for contamination from drilling fluid in water from any of the wells where drilling fluid was used.

Accuracy of major-ion analyses was evaluated by calculating the cation-anion balance. Analyses of water from the first sampling trip balanced within 3 percent. Water sampled during the second trip was of greater ionic strength and analyses did not balance as well. However, analyses of water of greater ionic strength commonly show poorer chemical balances because the laboratory dilutions necessary for the analyses compound the imprecision of the analytical methods. These analyses balanced within 8 percent, except for samples from wells C-314, C-317, C-329, and C-330, and from test wells LP85-6D1 and LP85-6D4, all of which had imbalances in the range of 9 to 20 percent.

Table 3.--*Quality-assurance results for duplicate samples, public-supply water, drilling fluid, blanks, and uranium standards*

[µS/cm, microsiemens per centimeter at 25 °Celsius; °C, degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picocuries per liter; dashes indicate no data; DUP, duplicate; <, less than]

Sample	Date of sample	Temperature (°C)	Specific conductance (µS/cm)	Oxygen, dissolved (mg/L)	pH (standard units)	Alkalinity, field (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)
LP85-1D	03-21-85	14.0	3,210	2.8	7.5	239	140	32	520	5.5	1,300	53
LP85-1D-DUP	03-21-85	--	--	--	--	--	140	33	500	5.7	1,300	58
C-314	03-19-85	13.0	1,450	.9	7.9	195	42	6.6	260	2.8	600	28
C-314-DUP	03-19-85	--	--	--	--	--	42	6.6	260	3.0	600	28
H	02-19-85	14.5	720	7.1	7.4	355	83	33	24	3.0	40	8.0
H-DUP	02-19-85	--	--	--	--	--	85	33	19	3.0	36	8.0
K	02-22-85	14.5	700	6.8	7.5	323	70	29	42	<2.0	68	8.0
K-DUP	02-22-85	--	--	--	--	--	71	28	36	<2.0	65	9.0
Public-supply water.	03-01-85	--	224	--	8.4	66	27	6.2	8.0	3.6	29	6.6
Drilling fluid[1].	03-01-85	--	440	--	6.5	5	2.0	<.01	17	1.7	13	32
Blank	02-19-85	--	--	--	--	--	<1.0	<2.0	7.0	<2.0	<10	<2
Blank	02-21-85	--	--	--	--	--	<1.0	<2.0	<5.0	<2.0	<10	<2
Blank	03-19-85	--	--	--	--	--	.109	.011	.52	.4	<2	<1
Blank	03-21-85	--	--	--	--	--	.027	.002	.12	<.4	<2	<1
Uranium standard.	02-21-85	--	--	--	--	--	--	--	--	--	--	--
Uranium standard.	03-21-85	--	--	--	--	--	--	--	--	--	--	--

Table 3.--*Quality-assurance results for duplicate samples, public-supply*

Sample	Date of sample	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Aluminum, dissolved (µg/L as Al)	Antimony, dissolved (µg/L as Sb)	Arsenic, dissolved (µg/L as AS)	Barium, dissolved (µg/L as Ba)	Beryllium, dissolved (µg/L as Be)	Cadmium, dissolved (µg/L as Cd)	Chromium, dissolved (µg/L as Cr)	Cobalt, dissolved (µg/L as Co)	Copper, dissolved (µg/L as Cu)
LP85-1D	03-21-85	0.92	12	<20	<240	<10	43	<1.0	<5	<3	<4	<2
LP85-1D-DUP	03-21-85	.90	12	18	<240	<10	46	<1.0	<5	<3	<4	<2
C-314	03-19-85	.51	13	<20	<24	<10	21	<1.0	<5	<3	<4	<2
C-314-DUP	03-19-85	.51	13	<18	<240	<10	20	<1.0	<5	<3	<4	<2
H	02-19-85	.80	15	<200	<60	<20	<200	<3.0	<2	<10	<30	<10
H-DUP	02-19-85	.80	16	<200	<60	<20	<200	<3.0	<2	<10	<30	<10
K	02-22-85	1.0	15	<200	<60	<20	<200	<3.0	<2	<10	<30	<10
K-DUP	02-22-85	1.1	16	<200	<60	<20	<200	<3.0	<2	<10	<30	<10
Public-supply water.	03-01-85	.4	8.8	--	--	<1	--	--	--	--	--	--
Drilling fluid.	03-01-85	<.1	.4	--	--	<1	--	--	--	--	--	--
Blank	02-19-85	<.1	<1	<200	<60	<20	<200	<3.0	<2	<10	<30	<10
Blank	02-21-85	<.1	1	<200	<60	<20	<200	<3.0	<2	<10	<30	<10
Blank	03-19-85	<.2	<2	27	<24	<10	4	<1.0	<5	<3	<4	2.4
Blank	03-21-85	<.2	<2	<20	<24	<10	<1.0	<1.0	<5	<3	<4	<2
Uranium standard.	02-21-85	--	--	--	--	--	--	--	--	--	--	--
Uranium standard.	03-21-85	--	--	--	--	--	--	--	--	--	--	--

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[1] Drilling fluid (Versafoam) was mixed in distilled water at a 1:200 dilution.

[2] Number in parenthesis is actual concentration of standard.

water, drilling fluid, blanks, and uranium standards--Continued

Iron, dissolved (µg/L as Fe)	Lead, dissolved (µg/L as Pb)	Manganese, dissolved (µg/L as Mn)	Mercury, dissolved (µg/L as Hg)	Molybdenum, dissolved (µg/L as Mo)	Nickel, dissolved (µg/L as Ni)	Selenium, dissolved (µg/L as Se)	Silver, dissolved (µg/L as Ag)	Thallium, dissolved (µg/L as Tl)	Tin, dissolved (µg/L as Sn)	Vanadium, dissolved (µg/L as V)	Zinc, dissolved (µg/L as Zn	Radium-226, dissolved (pCi/L)	Uranium, dissolved (µg/L as U)
86	<25	250	<0.2	830	<10	<25	<3	<10	<100	<30	3	0.5	3.2
114	<25	260	<.2	830	<10	<5	<3	<10	<130	<30	5	.4	3.0
6	<50	11	<.2	<500	<10	<25	<3	<10	<200	<3	14	1.2	2.6
4	6	11	<.2	<500	<10	6	<3	<10	<130	<3	9.6	1.2	3.2
<100	<4	<15	<.2	<200	<20	<6	<10	<14	<40	<10	40	.0	15
<100	<4	<15	<.2	<200	<20	<6	<10	<14	<40	<10	30	.1	15
<100	<4	<15	<.2	<200	<20	<6	<10	<14	<40	<10	<20	.1	28
<100	<4	<15	<.2	<200	<20	<6	<10	<14	<40	40	<20	.1	22
1,100	--	29	--	3	--	<1	--	--	--	<1	--	--	--
52	--	2	--	<1	--	<1	--	--	--	2.5	--	--	--
<100	<4	<15	<.2	<200	<20	<6	<10	<14	<40	<10	<20	.03	.2
<100	<4	<15	<.2	<200	<20	<6	<10	<14	<40	<10	<20	.01	.2
11	<5	<2	<.2	<500	<10	<5	<3	<10	19	<3	<3	.02	.1
6	5	<2	<.2	<500	<10	<5	<3	<10	<13	<3	<3	.01	.2
--	--	--	--	--	--	--	--	--	--	--	--	--	^{2}11 (10)
--	--	--	--	--	--	--	--	--	--	--	--	--	^{2}12 (10)

Major Ions and Trace Elements

Water-quality data for the study sites are listed in table 4. Detection limits vary from sample to sample, because two different laboratories were used to analyze the samples for the two sampling trips, and these two laboratories used different detection limits. Also, when dilutions were used during sample analysis, the reported detection limit was a multiple of the base detection limit. For example, selenium in samples from the first sampling trip was reported with a detection limit of 6 µg/L, and from the second sampling trip with a detection limit of 5 µg/L if not diluted and 25 µg/L if diluted. The data are available from the U.S. Geological Survey's Water Data Storage and Retrieval System (WATSTORE) (Hutchinson, 1975), along with data concerning the wells from which the samples were collected.

Recommended water-quality limits for various constituents are listed in table 5. The Colorado State drinking-water standards were not exceeded in water samples from private wells for any of the analyzed constituents. Trace-element concentrations in water samples from private wells were small. Some zinc was detected that probably originated from metal well casings. Water from one private well (well C-129) contained a detectable concentration of molybdenum and also contained the largest concentration (58 µg/L) of uranium in samples from private wells.

Some water from the Vermejo Formation, as represented by samples collected from U.S. Geological Survey test wells, exceeded drinking-water standards for pH, sulfate, chloride, fluoride, dissolved solids, iron, manganese, and selenium. However, water from the Vermejo Formation is variable in its quality, and samples from individual wells need to be evaluated individually. Large concentrations of fluoride were present in samples from test wells LP85-6D4 and LP85-4. Water from aquifers in the Vermejo Formation in the Raton basin (located in Huerfano and Las Animas Counties in Colorado about 50 mi from the study area) also has been determined to contain large concentrations of fluoride (Howard, 1980, p. 56). Fluoride is most soluble in water having larger pH values, when calcium concentrations are small; samples with these characteristics were collected from the two wells yielding water with large concentrations of fluoride.

Chemical composition of water from site C-531 was relatively unique among the water sampled; the source of this water might have been from aquifers outside the study area which are stratigraphically deeper than those examined in this study. The chemical composition might have been affected by industrial operations occurring within the drainage of upper West Fork Sand Creek. The sample was of interest because it had a uranium concentration of 100 µg/L. However, analysis of this site is beyond the scope of this study.

Water analyses discussed in the following sections are divided into groups, based on whether the samples are raffinate-affected or not, and on source aquifer. In previous studies, sulfate, molybdenum, selenium, and uranium have been recognized as mobile raffinate components (U.S. Environmental Protection Agency, written commun., 1985). For this study, uranium concentrations did correlate well with sulfate (r=0.79), molybdenum (r=0.89), and selenium (r=0.94) concentrations. Samples from wells C-312, C-313, C-329, C-330, C-331, and C-333 clearly were raffinate-affected, based on their greater concentrations of sulfate, molybdenum, selenium, and uranium.

The major-ion composition of sampled water indicated distinct groupings. Stiff diagrams of relative proportions of major ions in sampled water (fig. 14) display these differences in graphical form. Potassium does not occur in proportionately substantial concentrations in any of the water. Chloride does occur in proportionately substantial concentrations only in water from test well LP85-6D4. Calcium bicarbonate water has a distinctively shaped stiff diagram that predominates in the northern part of the study area; this water comes from the alluvial aquifer underlying Lincoln Park. Sodium sulfate type water has a different distinctively shaped stiff diagram that predominates in the southern part of the study area. Samples that have this shape include some that are raffinate-affected (for example, wells C-312 and C-313); some from aquifers in the Vermejo Formation (for example, well C-317 and test well LP85-6D1); and one from an aquifer in the Poison Canyon Formation (well C-314). A third shape of stiff diagram, representative of sodium bicarbonate sulfate water, occurs for a cluster of four test wells (wells LP85-2S, LP85-2D1, LP85-2D4, and LP85-4) just north of the SCS reservoir (fig. 14). All these wells are completed in the Vermejo Formation. The unique and localized major-ion pattern for these wells indicates that they are representative of a localized ground-water flow system.

The groupings of major-ion composition were further analyzed using trilinear diagrams (figs. 15-18). Analyses of water from each aquifer were plotted on separate diagrams. To extend the data base, major-ion composition of some water previously analyzed by the Cotter Corp. (U.S. Environmental Protection Agency, written commun., 1985) also is plotted in these figures. In general, the Cotter Corp. data for 1981 are comparable to recent Cotter Corp. data except that a decreasing trend of raffinate-component concentrations has been detected in water from most wells (U.S. Environmental Protection Agency, written commun., 1985). The Cotter Corp. analyses are listed in table 6. Analyses grouped by source aquifer are discussed in the following sections.

Table 4.--*Water-quality analyses of*

[µS/cm, microsiemens per centimeter at 25 °Celsius; °C, degrees Celsius; mg/L, milligrams per liter; dashes indicate no data;

Site identification (See fig. 2)	Date of sample	Temperature (°C)	Specific conductance (µs/cm)	Solids, sum of constituents, dissolved (mg/L)	Oxygen, dissolved (mg/L)	pH (standard units)	Alkalinity, field (mg/L as $CaCO_3$)	Alkalinity, lab (mg/L as $CaCO_3$)	Sulfide, total (mg/L as S)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)
LP85-1D	03-21-85	14.0	3,210	2,200	2.8	7.5	239	250	--	140	32	520
LP85-2S	03-20-85	15.0	760	490	2.2	7.7	164	168	--	28	7.5	120
LP85-2D1	03-20-85	16.0	690	420	--	8.5	160	167	--	13	3.9	130
LP85-2D4	03-21-85	15.5	820	430	4.1	9.0	194	158	--	1.9	.45	140
LP85-4	03-20-85	15.5	1,100	660	--	8.5	217	212	--	14	4.5	200
LP85-6D1	03-20-85	15.0	3,670	3,400	--	8.3	396	409	--	120	29	770
LP85-6D4	03-21-85	14.0	2,170	1,700	2.0	8.5	325	336	--	13	2.2	480
C-129	02-20-85	14.5	670	360	6.4	7.4	283	272	--	70	20	32
C-153	02-21-85	20.0	5,300	3,000	--	6.8	2,840	2,800	0.7	26	<2.0	1,200
C-312	03-19-85	15.0	7,700	6,800	--	7.9	538	554	--	170	110	1,800
C-313	03-19-85	12.0	7,630	7,300	--	7.7	520	537	--	140	80	2,000
C-314	03-19-85	13.0	1,450	1,300	.9	7.9	195	202	--	42	6.6	260
C-317	03-19-85	13.5	4,620	4,000	--	9.6	285	261	--	5.3	7.1	1,100
C-329	03-20-85	13.5	3,100	2,900	8.7	7.3	216	228	--	280	75	380
C-330	03-19-85	11.5	6,710	5,700	6.2	7.3	503	516	--	260	110	1,200
C-331	03-20-85	15.0	5,990	4,900	--	7.6	439	461	--	240	110	1,200
C-333	03-19-85	14.0	3,910	4,000	8.0	7.4	415	440	--	280	130	780
C-531	02-20-85	8.5	2,700	1,900	11.5	7.9	401	376	--	120	66	430
A	02-20-85	11.0	950	590	7.1	7.5	387	382	--	90	42	60
D	02-21-85	14.0	750	440	5.4	7.3	328	308	--	73	31	51
E	02-21-85	15.5	580	300	5.1	7.3	285	268	--	64	23	24
G	02-19-85	14.0	600	350	6.9	7.4	290	236	--	68	29	18
H	02-19-85	14.5	720	420	7.1	7.4	355	320	--	83	33	24
I	02-21-85	15.0	710	420	7.3	7.3	300	295	--	68	28	44
J	02-20-85	13.5	660	370	6.7	7.4	286	306	--	81	22	20
K	02-22-85	14.5	700	430	6.8	7.5	323	310	--	70	29	42
L	02-21-85	14.5	700	410	7.0	7.3	312	260	--	77	29	35
M	02-19-85	12.5	720	430	6.5	7.3	307	316	--	110	25	10

samples collected from study sites

μg/L, micrograms per liter; pCi/L, picocuries per liter; per mil, parts per thousand; TU, tritium units; <, less than; E, estimated]

Potassium, dissolved (mg/L as K)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Aluminum, dissolved (μg/L as Al)	Antimony, dissolved (μg/L as Sb)	Arsenic, dissolved (μg/L as As)	Barium, dissolved (μg/L as Ba)	Beryllium, dissolved (μg/L as Be)	Cadmium, dissolved (μg/L as Cd)	Chromium, dissolved (μg/L as Cr)	Cobalt, dissolved (μg/L as Co)
5.5	1,300	53	0.92	12	<20	<240	<10	43	<1.0	<5	<3	<4
1.7	200	12	1.4	17	40	<24	<10	37	<1.0	<5	<3	<4
.56	150	9.8	1.5	12	60	<24	<10	19	<1.0	<5	<3	<4
.89	140	11	1.7	14	450	<24	<10	18	<1.0	<5	<3	<4
1.7	290	6.6	4.9	7.1	60	<24	<10	17	<1.0	<5	<3	<4
5.4	2,200	45	1.4	9.3	<20	<24	<10	67	<1.0	<5	<3	<4
1.8	780	250	4.8	11	60	<24	<10	42	<1.0	<5	<3	<4
<2.0	43	8.0	.70	12	<200	<60	<20	<200	<3.0	<2	<10	<30
4.0	17	13	.60	9.0	<200	<60	<20	600	<3.0	<2	<10	<30
1.7	4,100	250	1.1	17	180	<240	<100	14	<10	<5	10	<40
2.4	4,500	240	1.6	15	170	<240	<100	15	<1.0	<5	10	<40
2.8	830	9.4	.51	12	<20	<24	<10	21	<1.0	<5	<3	<4
5.0	2,700	14	.88	<2.1	20	<24	<10	14	<1.0	<5	<3	<4
3.0	1,900	140	2.4	18	20	<24	<10	36	<1.0	<5	<3	<4
5.8	3,600	200	1.7	24	120	240	<10	10	<1.0	<5	8	<40
4.3	2,800	190	2.8	15	210	<240	<10	17	1.4	<5	4	<40
4.7	2,300	200	2.3	21	190	<240	<10	14	<1.0	5	9	<40
3.0	910	92	5.4	7.0	<200	<60	<20	<200	<3.0	<2	<10	<30
3.0	130	17	1.3	14	<200	<60	<20	<200	<3.0	<2	<10	<30
<2.0	65	11	1.2	14	<200	<60	<20	<200	<3.0	<2	<10	<30
<2.0	<10	4.0	1.0	15	<200	<60	<20	<200	<3.0	<2	<10	<30
<2.0	41	5.0	1.1	16	<200	<60	<20	<200	<3.0	<2	<10	<30
3.0	40	8.0	.80	15	<200	<60	<20	<200	<3.0	<2	<10	<30
<2.0	71	8.0	1.0	15	<200	<60	<20	<200	<3.0	<2	<10	<30
<2.0	55	8.0	.70	13	<200	<60	<20	<200	<3.0	<2	<10	<30
<2.0	68	8.0	1.0	15	<200	<60	<20	<200	<3.0	<2	<10	<30
<2.0	59	9.0	1.0	16	<200	<60	<20	<200	<3.0	<2	<10	<30
<2.0	85	6.0	.70	12	<200	<60	<20	<200	<3.0	<2	<10	<30

Table 4.--*Water-quality analyses of samples*

Site identification (See fig. 2)	Date of sample	Copper, dissolved (µg/L as Cu)	Iron, dissolved (µg/L as Fe)	Lead, dissolved (µg/L as Pb)	Manganese, dissolved (µg/L as Mn)	Mercury, dissolved (µg/L as Hg)	Molybdenum, dissolved (µg/L as Mo)	Nickel, dissolved (µg/L as Ni)	Selenium, dissolved (µg/L as Se)	Silver, dissolved (µg/L as Ag)	Thallium, dissolved (µg/L as Tl)	Tin, dissolved (µg/L as Sn)
LP85-1D	03-21-85	<2	86	<25	250	<0.2	830	<10	<25	<3	<10	<130
LP85-2S	03-20-85	3	56	<5	100	<.2	<500	<10	<25	<3	<10	<13
LP85-2D1	03-20-85	3	50	<5	12	<.2	<500	<10	<5	<3	<10	<13
LP85-2D4	03-21-85	9	350	<5	5	<.2	<500	<10	<5	<3	<10	<13
LP85-4	03-20-85	7	25	<5	3	<.2	<500	<10	E24	<3	<10	<13
LP85-6D1	03-20-85	<2	12	<25	8	<.2	<500	<10	E5	<3	<10	<130
LP85-6D4	03-21-85	2	36	<25	18	<.2	<500	<10	<5	<3	<10	<130
C-129	02-20-85	<10	<100	<4	<15	<.2	500	<20	<6	<10	<14	<40
C-153	02-21-85	<10	700	<4	100	<.2	<200	<20	<6	<10	<14	<40
C-312	03-19-85	6	9	<50	3	<.2	26,200	<10	E130	<3	<10	<130
C-313	03-19-85	6	5	<50	2	<.2	27,800	15	E81	<3	<10	<130
C-314	03-19-85	<2	6	<50	11	<.2	<500	<10	<25	<3	<10	<174
C-317	03-19-85	<2	9	<50	6	<.2	<500	17	<25	<3	<10	<130
C-329	03-20-85	4	9	<25	10	<.2	<500	<10	<25	<3	<10	<130
C-330	03-19-85	<2	6	<25	4	<.2	18,800	<10	<25	<3	<10	<130
C-331	03-20-85	13	<3	<25	53	<.2	21,000	<10	E62	<3	<10	<130
C-333	03-19-85	<2	13	<50	3	<.2	9,800	<10	E94	E4	<10	<130
C-531	02-20-85	<10	<100	<4	20	<.2	<200	<20	6	<10	<14	<40
A	02-20-85	<10	<100	<4	<15	<.2	<200	<20	<6	<10	<14	<40
D	02-21-85	<10	<100	<4	<15	<.2	<200	<20	<6	<10	<14	<40
E	02-21-85	<10	<100	<4	<15	<.2	<200	<20	<6	<10	<14	<40
G	02-19-85	<10	<100	<4	<15	<.2	<200	<20	<6	<10	<14	<40
H	02-19-85	<10	<100	<4	<15	<.2	<200	<20	<6	<10	<14	<40
I	02-21-85	<10	<100	<4	<15	<.2	<200	<20	<6	<10	<14	<40
J	02-20-85	<10	<100	<4	<15	<.2	<200	<20	<6	<10	<14	<40
K	02-22-85	<10	<100	<4	<15	<.2	<200	<20	<6	<10	<14	<40
L	02-21-85	<10	<100	<4	<15	<.2	<200	<20	<6	<10	<14	<40
M	02-19-85	<10	<100	<4	<15	<.2	<200	<20	<6	<10	<14	<40

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[1] A synonym for this term is "delta carbon-13." The standard reference material for this analysis is

[2] A synonym for this term is "delta deuterium." The standard reference material for this analysis is

[3] A synonym for this term is "delta oxygen-18." The standard reference material for this analysis is

[4] A synonym for this term is "delta sulfur-34." The standard reference material for this analysis is

collected from study sites--Continued

Vanadium, dissolved (µg/L as V)	Zinc, dissolved (µg/L as Zn)	Radium-226 dissolved (pCi/L)	Uranium, dissolved (µg/L as U)	Carbon-13/ carbon-12 stable-isotope ratio[1] (per mil)	Hydrogen-2/ hydrogen-1 stable-isotope ratio[2] (per mil)	Oxygen-18/ oxygen-16 stable-isotope ratio[3] (per mil)	Sulfur-34/ sulfur-32 stable-isotope ratio[4] (per mil)	Tritium (TU)
<30	3	0.5	3.2	-14.1	-78.5	-10.5	-2.6	1±4
<3	3	.1	.4	-11.7	-73.5	-10.0	-2.2	-2±4
4	7	.08	2.5	-11.1	-73.5	-9.9	-4.4	--
7	6	.04	5.5	-12.7	-74.0	-9.9	-5.8	-2±4
5	4	.05	40	-12.0	-71.5	-9.9	-9.1	3±4
<3	9	.2	30	-8.2	-77.0	-10.3	--	--
3	4	.07	10	-6.1	-84.5	-11.1	-6.6	0±5
<10	<20	.05	58	--	--	--	--	--
<10	<20	.3	1.3	--	--	--	--	--
<30	19	.2	5,500	--	--	--	--	--
<30	45	.2	5,500	-8.4	-80.0	-10.0	-2.6	46±5
<3	14	1.2	3.2	-11.7	-84.0	-11.4	-5.0	5±4
<3	<3	1.4	8.6	-15.6	-86.5	-11.4	9.7	3±4
<3	21	1.6	330	-8.9	-81.5	-10.7	-3.7	26±5
<30	21	.08	3,900	-10.8	-79.5	-9.6	-3.2	75±6
<30	19	.5	2,900	-8.1	-83.0	-10.2	-1.5	64±5
<30	<3	.2	5,700	-8.5	-95.5	-12.1	-1.3	41±6
<10	<20	.1	100	--	--	--	--	--
<10	<20	.05	25	--	--	--	--	--
<10	<20	.1	27	--	--	--	--	--
<10	40	.1	27	--	--	--	--	--
<10	<20	.07	20	--	--	--	--	--
<10	40	.09	15	--	--	--	--	--
<10	<20	.08	40	--	--	--	--	--
<10	<20	.08	18	--	--	--	--	--
<10	<20	.1	28	--	--	--	--	--
<10	40	.09	25	--	--	--	--	--
<10	<20	.1	12	--	--	--	--	--

PDB (Peedee belemnite).
V-SMOW (Vienna-Standard Mean Ocean Water).
V-SMOW (Vienna-Standard Mean Ocean Water).
triolite from the Canyon Diablo meteorite.

Table 5.--*Water-quality standards for Colorado*

(modified from Wentz and Steele, 1980)

[°C, degree Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picocuries per liter; dashes indicate no water-quality standards; value given is the maximum allowed, unless otherwise specified]

Water-quality variable	National and proposed Colorado drinking-water regulations (U.S. Environmental Protection Agency, 1976a, 1976b, 1977; Colorado Department of Health, 1977)	Colorado water-quality standards (Colorado Department of Health, 1979)		
		Water supply[1]	Aquatic life[2]	Agriculture[3]
	Physiochemical variables			
Temperature (°C)	-----------	-----------	[4]20	-----
pH (standard units)	[5]$6.5 \leq \text{pH} \leq 8.5$	[6]$5.0 \leq \text{pH} \leq 9.0$	$6.5 \leq \text{pH} \leq 9.0$	-----
Dissolved oxygen (mg/L)	-----------	-----------	[7]6.0	-----
	Major inorganic constituents (mg/L)			
Sulfate	[5]250	250	----------	-----
Chloride	[5]250	250	----------	-----
Fluoride	[9]4.0	[9]4.0	----------	-----
Dissolved solids	[5]500	-----------	----------	-----
	Trace elements (µg/L)			
Aluminum	-----------	-----------	[10]100	-----
Arsenic	[8]50	50	50	100
Barium	[8]1,000	1,000	----------	-----
Beryllium	-----------	-----------	10	100
Cadmium	[8]10	10	.4	10
Chromium	[8]50	50	100	100
Copper	[5]1,000	1,000	10	200
Iron	[5]300	[10]300	[11]1,000	-----
Lead	[8]50	50	4	100
Manganese	[5]50	[10]50	1,000	200
Mercury	[8]2	2	.05	-----
Molybdenum	-----------	-----------	----------	150
Nickel	-----------	-----------	50	200
Selenium	[8]10	10	50	20
Silver	[8]50	50	.1	-----
Thallium	-----------	-----------	15	-----
Uranium	-----------	-----------	30	-----
Zinc	[5]5,000	5,000	50	2,000
	Radiological variables (pCi/L)			
Radium 226 and 228	[8]5	[12]5	[12]5	[12]5
Uranium	-----------	[13]40	----------	-----

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[1] Includes uncontaminated ground water and ground and surface water requiring disinfection or standard treatment (raw water).

[2] Includes cold-water biota (inhabitants, including trout, of waters where temperatures do not normally exceed 20 °C) and warm-water biota (inhabitants of waters where temperatures normally exceed 20 °C). Trace-element standards apply to waters having total hardness from 0 to 100 mg/L as calcium carbonate; standards for waters of greater hardness may be equal or greater. Total trace-element concentrations are given, unless otherwise specified.

[3] Includes irrigation and stock watering.

[4] Applies only to cold-water biota; standard for warm-water biota is 30 °C. In addition, a maximum 3 °C increase over a minimum 4-hour period lasting for 12 hours maximum from naturally occurring temperatures shall be allowed.

[5] Secondary maximum contaminant level. These "*** are not Federally enforceable and are intended as guidelines for the States ***" (U.S. Environmental Protection Agency, 1977).

[6] Applies only to ground and surface water requiring disinfection or standard treatment (raw water).

[7] Minimum allowed concentration. Applies only to cold-water biota; standard for warm-water biota is 5.0 mg/L. In addition, a 7.0 mg/L standard during periods of spawning of cold-water fish may be set on a case-by-case basis.

[8] Interim primary maximum contaminant level. Applies to all systems providing piped water for human consumption, "*** if such system has at least fifteen service connections or regularly serves at least twenty-five individuals." (U.S. Environmental Protection Agency, 1976a; 1976b). Proposed primary drinking-water regulations (Colorado Department of Health, 1977).

[9] New standard in effect April 1986.

[10] Refers to soluble form.

[11] Refers to total concentration.

[12] Including naturally occurring or background contributions.

[13] A standard of 40 pCi/L (approximately equal to 59 µg/L uranium) has been adapted for waters in the Arkansas River basin (Colorado Department of Health, 1982).

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Table 6.--*Water-quality analyses of samples*

[μS/cm, microsiemens per centimeter at 25 °Celsius; °C, degrees Celsius; mg/L, milligrams per liter;

Site identification (see fig. 2)	Date of sample	Temperature (°C)	Specific conductance (μS/cm)	pH (standard units)	Alkalinity, field (mg/L as $CaCO_3$)	Calcium dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Sulfate dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Aluminum, dissolved (μg/L as Al)
C-106	02-26-81	16.5	3,030	6.2	736	218	47	610	7.0	1,294	61	<50
C-111	03-19-81	18.6	1,340	6.9	516	82	23	290	4.7	286	30	<200
C-114	02-21-81	14.7	572	6.9	326	82	31	26	3.6	51	11	400
C-117	04-21-81	15.9	856	7.1	268	106	23	72	2.1	232	21	400
C-119	02-18-81	14.1	2,140	8.3	254	145	42	310	3.4	760	48	<100
C-120	02-18-81	15.3	661	8.0	280	71	17	31	4.2	138	14	<100
C-122	02-13-81	13.9	822	7.3	312	78	19	89	2.4	114	14	<100
C-123	02-13-81	15.4	970	7.2	267	101	43	57	2.5	192	49	<100
C-124	02-13-81	14.9	786	7.5	310	79	19	78	2.9	94	16	<100
C-135	02-24-81	14.5	4,090	7.3	423	181	38	920	7.0	2,087	138	<100
C-137	02-13-81	13.3	766	7.4	315	108	19	44	2.3	92	31	<100
C-138	02-16-81	13.4	3,660	7.6	255	339	106	660	5.0	2,169	137	<100
C-139	02-16-81	13.7	2,520	7.6	255	225	65	390	3.6	1,293	101	<100
C-140	02-16-81	13.6	2,150	7.4	288	191	56	315	3.3	1,060	72	<100
C-141	02-16-81	14.7	1,765	7.6	640	46	8	375	4.5	438	52	<100
C-142	02-23-81	13.5	1,345	7.7	261	85	31	170	2.1	506	51	<100
C-144	02-12-81	12.5	720	7.4	347	92	35	66	1.9	122	14	<100
C-328	02-25-81	13.6	1,088	9.1	811	4	0	290	1.0	7	71	<100
C-337	02-20-81	14.6	3,150	7.0	133	534	155	200	7.0	2,068	175	<100
C-505	02-02-81	14.2	4,150	8.0	358	236	101	960	4.9	2,117	210	<100
C-520	09-06-84	13.5	250	8.2	160	45	11	13	1.8	40	<10	--

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[1] U.S. Environmental Protection Agency, written commun., 1985.

collected from Cotter Corp. monitoring sites[1]

μg/L, micrograms per liter; pCi/L, picocuries per liter; <, less than; dashes indicate no data]

Arsenic, dissolved (μg/L as As)	Cadmium, dissolved (μg/L as Cd)	Copper, dissolved (μg/L as Cu)	Iron, dissolved (μg/L as Fe)	Lead, dissolved (μg/L as Pb)	Manganese, dissolved (μg/L as Mn)	Mercury, dissolved (μg/L as Hg)	Molybdenum, dissolved (μg/L as Mo)	Nickel, dissolved (μg/L as Ni)	Selenium, dissolved (μg/L as Se)	Vanadium, dissolved (μg/L as V)	Zinc, dissolved (μg/L as Zn)	Radium-226, dissolved (pCi/L)	Uranium, dissolved (μg/L as U)
<5	<50	10	490	60	720	<0.1	20	80	<5	<50	<10	0.8	<50
<5	<50	<10	5,900	<50	190	.1	30	20	<5	<50	<20	3.4	<50
<5	<50	10	<50	<50	<10	<.1	<20	40	<5	<50	20	.5	<50
<5	<50	10	<50	--	<10	<.1	430	40	<5	<50	560	.2	100
<5	<50	<10	<50	<50	<10	<.1	5,530	50	11	<50	30	.3	820
<5	<50	<10	<50	<50	30	<.1	400	30	<5	<50	90	.6	80
<5	<50	<10	160	160	<10	<.1	980	20	<5	<50	60	.6	230
5	<50	<10	60	<50	<10	<.1	550	40	9	<50	70	.8	110
<5	<50	<10	<50	<50	<10	<.1	860	30	<5	<50	110	.9	230
<5	<50	10	230	<50	150	<.1	60	60	<5	<50	20	.9	<50
<5	<50	<10	<50	<50	60	<.1	20	30	<5	<50	200	.3	40
<5	<50	<10	<50	<50	20	<.1	10,800	60	20	<50	40	.6	1,670
<5	<50	<10	70	<50	<10	<.1	5,800	50	17	<50	110	.2	810
<5	<50	<10	50	<50	<10	<.2	5,200	50	10	<50	50	.8	760
<5	<50	<10	3,160	<50	<10	<.1	160	40	<5	<50	20	.9	<50
<5	<50	<10	100	<50	<10	<.1	3,070	50	<5	<50	80	1.0	350
<5	<50	40	70	<50	<10	.4	590	30	<5	<50	30	3.0	90
<5	<50	<10	60	<50	<10	<.1	50	40	<5	<50	60	.2	<50
<5	<50	30	<50	110	40	<.2	30	110	96	<50	70	.7	<50
<5	<50	80	80	80	450	<.1	7,000	80	107	<50	70	.5	3,600
--	<5	<20	50	<5	20	.0	<5	<50	<5	<50	31	--	1

Characterization of Water from the Vermejo Formation

The major-ion composition of water from the Vermejo Formation is shown in figure 15. None of the water analyses plotted in this figure contained any significant concentrations of raffinate components other than sulfate. The analyses all have sodium as the major cation, but vary considerably in relative proportions of sulfate and bicarbonate.

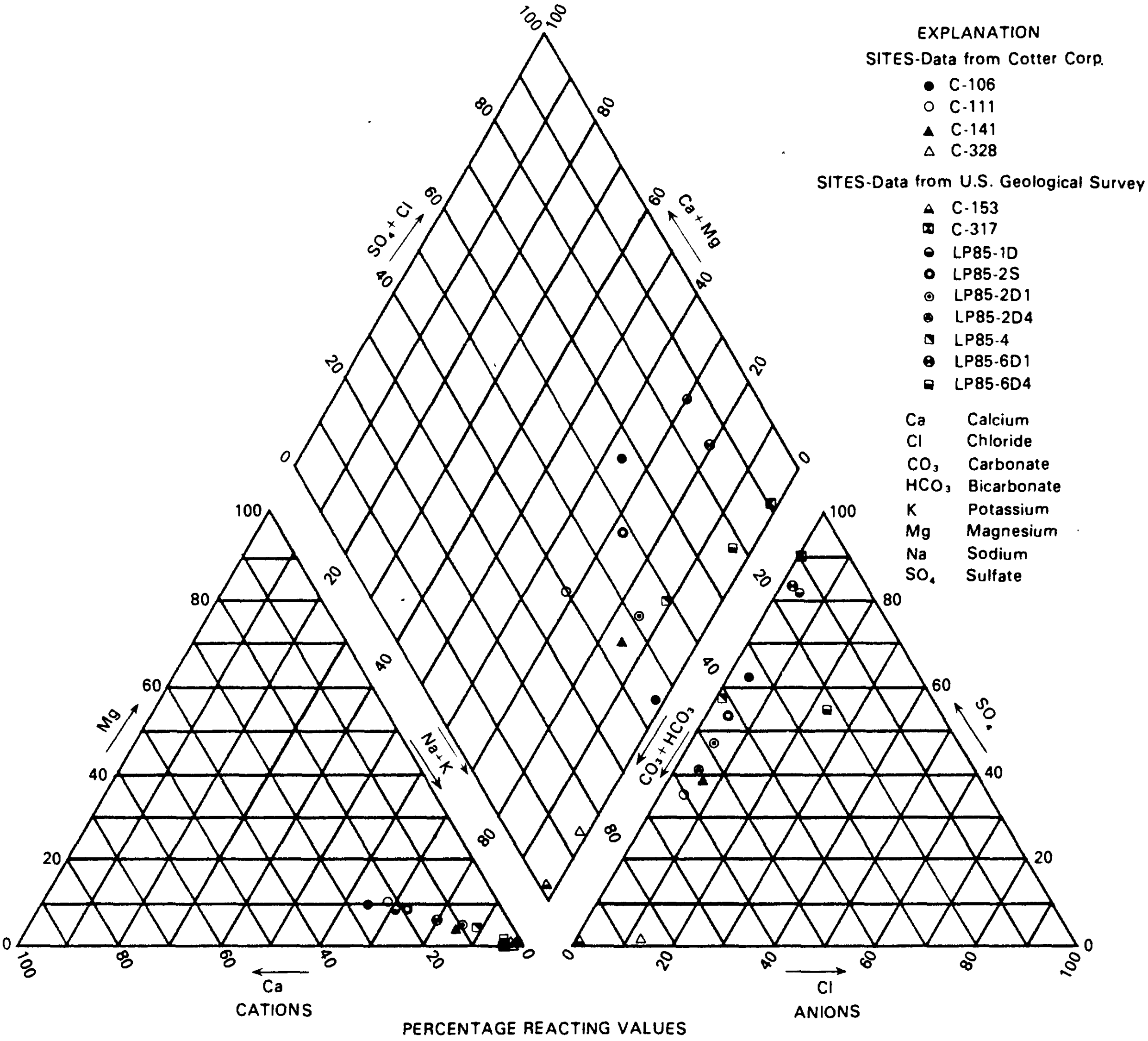

Figure 15.--Major-ion composition of water from the Vermejo Formation.

Lithologic variability is common within the Vermejo Formation. Lithologic logs from the wells drilled for this project established that organic material is heterogeneously distributed throughout the formation. A qualitative mineralogic analysis done for this study of four rock samples indicated substantial variability of rock composition. Quartz, clay, and feldspar were the major constituents. Clay minerals varied in relative abundance (from 15 to 50 percent) and in type of clay mineral present; clays with substantial exchange capacity occurred in varying abundances. Calcite, dolomite, gypsum, and pyrite each were found in some samples but were absent in others.

A large range in geochemical environments also is indicated by the water samples from the Vermejo Formation. Measured pH ranged from 7.5 to 9.6, and Eh, as calculated by the computer code WATEQF (Plummer and others, 1976), ranged from -0.187 to 0.793 volts, which corresponds to a large range of oxidation-reduction conditions.

This variability of aquifer conditions probably can account for the water-quality variation depicted in figure 15. Recharge water first entering the Vermejo Formation would be a calcium bicarbonate type; however, no recharge areas of the Vermejo Formation were sampled for this study, and no analyses plot in the calcium bicarbonate area on the trilinear diagram. Given the lithologic and geochemical conditions discussed in the previous paragraphs, several mechanisms exist by which a calcium bicarbonate recharge water could evolve to the sodium sulfate and sodium bicarbonate water plotted in the trilinear diagram. Sulfate could be added to the recharge water through dissolution of gypsum. Sulfate also could be added by oxidation of organic material or pyrite. Clays with substantial exchange capacity are common in the Vermejo Formation, so cation exchange probably is important in removing calcium from the water and replacing it with sodium. These processes would result in a sodium sulfate type water. Where reducing conditions and organic material are present, sulfate can be reduced, producing a sodium bicarbonate type water.

Characterization of Water from the Poison Canyon Formation

Only three samples (fig. 16) seem to represent water from the Poison Canyon Formation that is unaffected by raffinate components . Two of these samples (from wells C-135 and C-314) are sodium sulfate type water and are similar in relative major-ion composition. Water from well C-337 is a calcium sulfate type. Howard (1980, p. 60) described water in the Poison Canyon Formation from the Raton basin that varied from a calcium bicarbonate type in recharge areas to a calcium sulfate or a sodium sulfate type farther down the flow path. Among the three analyses presented here, none are likely to be representative of water recharging the Poison Canyon Formation. Water from well C-337 probably is representative of a chemically evolving water in the Poison Canyon Formation; water from wells C-135 and C-314 probably is representative of a mature water in the Poison Canyon Formation.

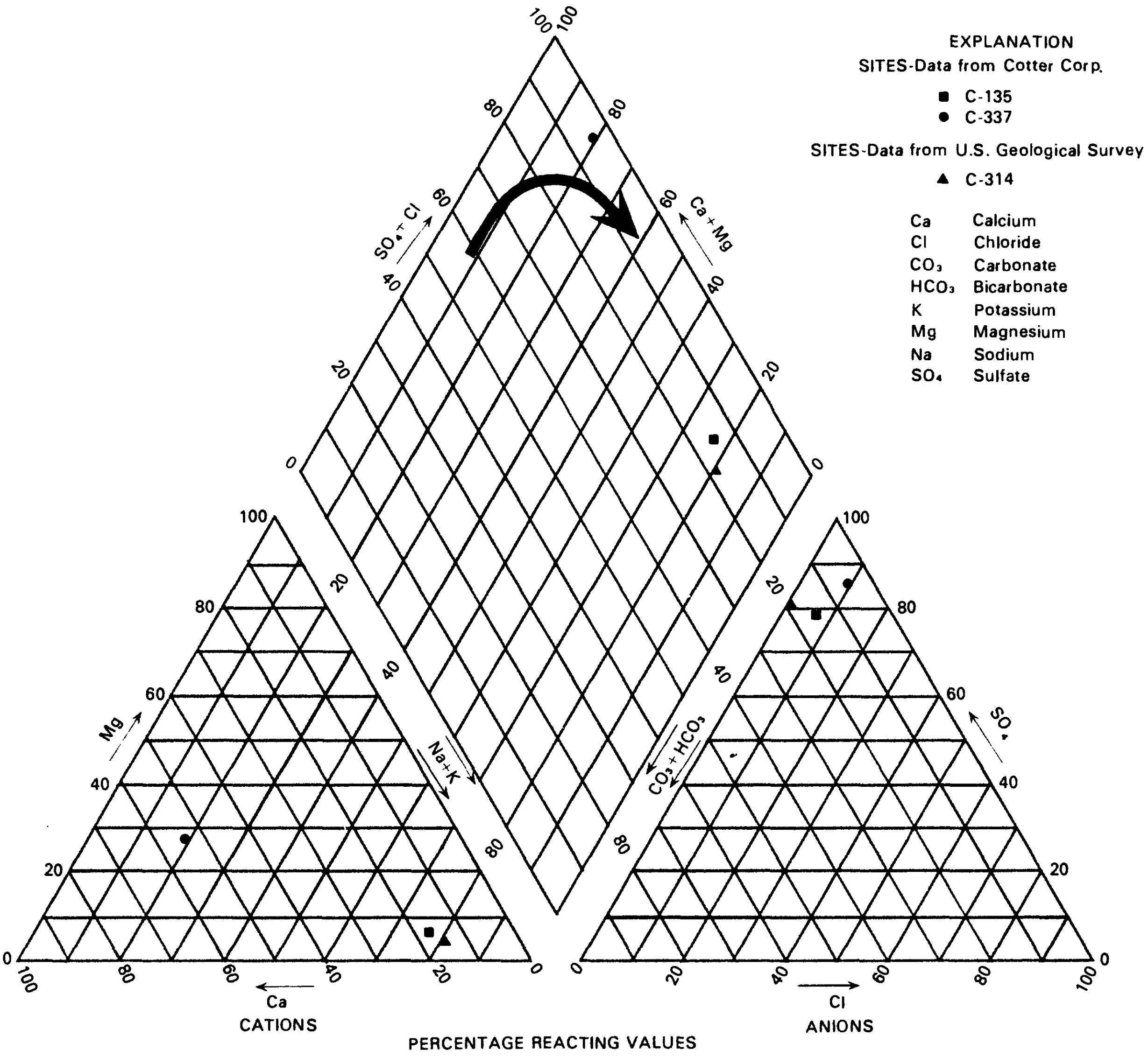

Figure 16.--Major-ion composition of water from the Poison Canyon Formation. (Arrow indicates chemical evolution of water in the Poison Canyon Formation reported by Howard, 1980.)

Characterization of Water from Alluvium

Fourteen analyses of water from alluvium in Lincoln Park were available (fig. 17). Statistics for these water analyses are presented in table 7. Cotter Corp. analyses for wells C-114 and C-137 and site C-520 are shown in figure 17; however, these older data are not included in the statistical analysis presented in this report. Specific conductance and alkalinity have the smallest coefficient of variation. Other variables have larger coefficients of variation, probably because of nonhomogeneity in the mineralogic composition of the alluvium.

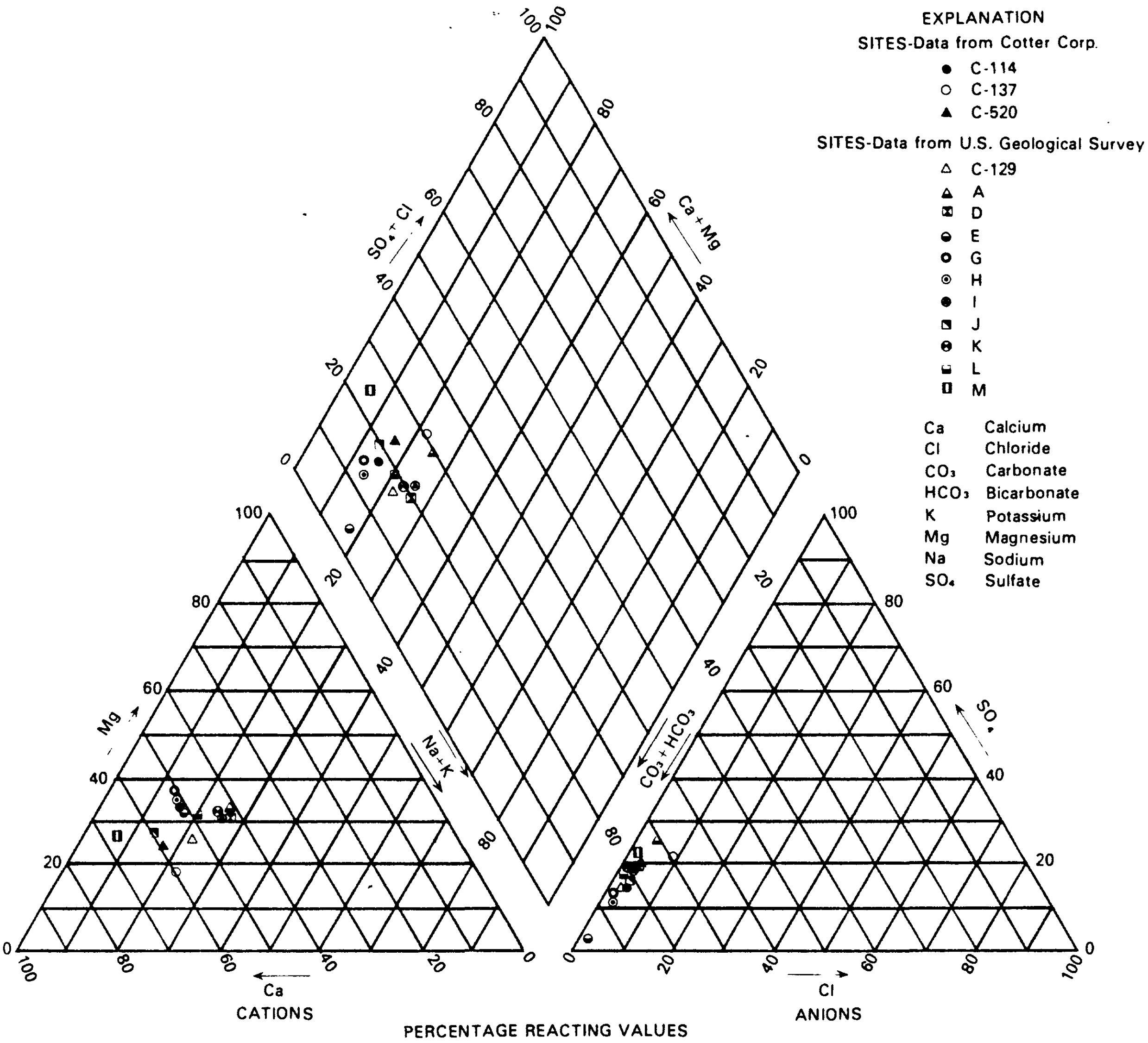

Figure 17.--Major-ion composition of water from the alluvium in Lincoln Park.

The water-quality variables listed in table 7 generally are distributed with a well-defined central tendency. Exceptions are silica and radium, which have a uniform distribution. However, because no single distribution fits all the water-quality variables, because no theoretical basis exists for assigning a particular distribution, and because the sample size is small, nonparametric statistical methods were useful in analyzing these data. Therefore median values, interquartile ranges, and far outside values, if any, also are listed in table 7. A large far outside value is defined as a value that is larger than the third quartile by more than three times the interquartile range. It is probable that a far outside value is nonrepresentative of the statistical sample. Three far outside values were identified: specific conductance and chloride concentration at seep A and uranium concentration at well C-129. Descriptive statistics with these values removed from the sample also are presented in table 7.

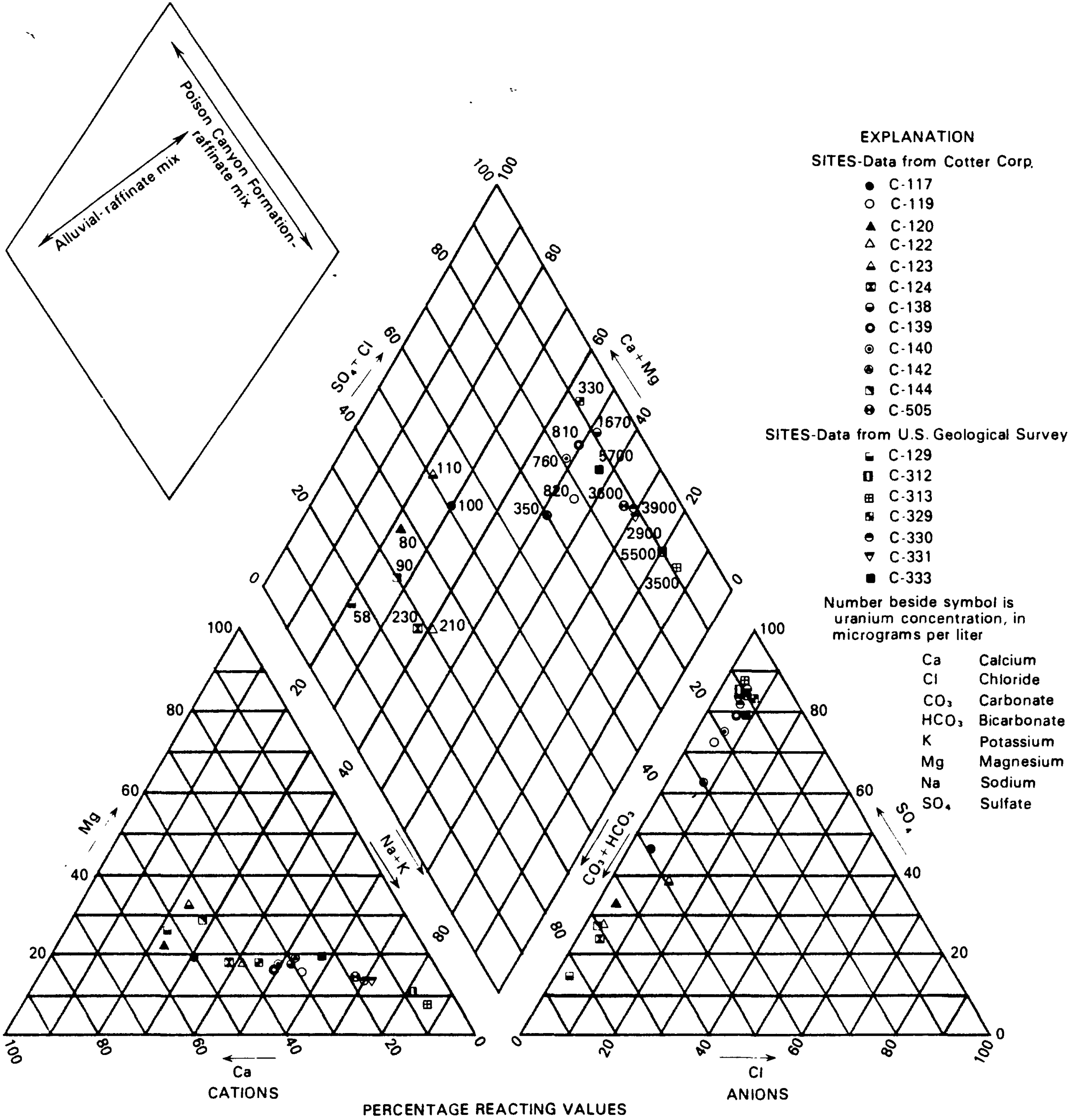

Figure 18.--Major-ion composition and uranium concentrations in raffinate-affected ground and surface water. (Small schematic diagram shows hypothesized mixing lines.)

The predominant lithology of material yielding water to these wells is identified in the drillers' logs as "sand and boulders." Some wells penetrate weathered or fractured bedrock (notably wells H, I, K, and L, where gray clay and shaly weathered detritus of the Pierre Shale are penetrated); however, the bedrock does not seem to yield substantial quantities of water, because there is no variation in water composition relative to differences in subcrop formation, and because the water-quality variables have no tendency toward bimodal distributions. Therefore, the water quality probably is primarily dependent on surface recharge to the alluvium, and on chemical reactions between this recharge and the alluvium. Such recharge is primarily water from the De Weese Dye Ditch. Recharge by precipitation is small because annual mean precipitation is 13 in., whereas potential evapotranspiration is 33 in.

Table 7.--*Descriptive statistics for water-quality analyses of samples collected from alluvium*

[μS/cm, microsiemens per centimeter at 25 °Celsius; mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; μg/L, micrograms per liter; pCi/L, picocuries per liter; information in parentheses in the far outside values column is the seep or well at which the far outside value occurs; dashes indicate no statistics calculated]

Variable	Mean	Standard deviation	Coefficient of variation	Median	Interquartile range	Third quartile	Far outside values
Specific conductance, μS/cm (full data set).	705	96.2	13.6	700	55.0	720	950 (seep A)
Specific conductance, μs/cm (far outside value deleted).	681	54.5	8.0	700	60.0	720	None
Alkalinity, mg/L as $CaCO_3$.	314	32.7	10.4	307	38.0	326	None
Calcium, mg/L	77.6	13.2	17.0	73.0	13.0	82.0	None
Magnesium, mg/L	28.3	6.05	21.4	29.0	6.0	30.0	None
Sodium, mg/L	32.7	15.3	46.8	32.0	21.0	43.0	None
Potassium[1], mg/L	3.0	--	--	--	--	--	None
Sulfate, mg/L	59.7	32.3	54.1	59.0	27.5	69.5	None
Chloride, mg/L (full data set).	8.36	3.44	41.1	8.0	1.50	8.5	17 (seep A)
Chloride, mg/L (far outside value deleted).	7.50	2.01	26.8	8.0	1.00	8.0	None
Molybdenum[2], μg/L	500	--	--	--	--	--	--
Selenium[3], μg/L	--	--	--	--	--	--	--
Radium-226, pCi/L	.083	.019	23.0	.090	.025	100	None
Uranium, μg/L (full data set).	26.8	12.8	47.7	25.0	8.50	27.5	58 (well C-129)
Uranium, μg/L (far outside value deleted).	23.7	7.94	33.5	25.0	9.00	27.0	None

[1] Potassium detected at only two sites; detection limit is 2 mg/L.
[2] Molybdenum detected at only one site; detection limit is 200 μg/L.
[3] Selenium detected at no sites; detection limit is 6 μg/L.

Samples of water from the De Weese Dye Ditch have been collected from two locations by the Cotter Corp. since 1981. Monthly variation of the composition of this water is relatively small. A representative analysis is listed in table 6 (site C-520). This water is a calcium bicarbonate type similar to water in the alluvium, but with a smaller specific conductance.

The computer code WATEQF (Plummer and others, 1976) was used to evaluate the chemistry of water in the alluvium and to determine if surface recharge, as opposed to recharge from underlying aquifers, could be the source of this water. This computer program uses thermodynamic data to calculate concentrations of aqueous species present in a water under equilibrium conditions and then determines the state of saturation of the water relative to various minerals. Saturation indices for calcite and dolomite for these samples, as calculated by WATEQF, are listed in table 8. Saturation indices of about zero indicate saturation; indices less than zero (negative values) indicate undersaturation; indices greater than zero indicate supersaturation. All water samples from the alluvium are almost saturated with respect to calcite and dolomite, indicating that the dissolution of calcite and dolomite is a principal reaction in the genesis of the water. The partial pressure of carbon dioxide in equilibrium with these samples, as calculated by WATEQF, also is listed in table 8. The partial pressure of carbon dioxide in the air is 0.0003 atm; the partial pressure of carbon dioxide of the air in soil is about 10 to 100 times larger (Hem, 1970, p. 136). The partial pressure of carbon dioxide calculated for these samples is similar to that found in soil air, which is consistent with a genetic model where surface water percolates through unsaturated soil and alluvium, dissolving calcite and dolomite along the way. Finally, equivalence ratios of calcium plus magnesium to bicarbonate are listed in table 8. This ratio is close to unity for these samples. This ratio also is supportive of a calcite- and dolomite-dissolution model, because these dissolution reactions are congruent, producing equivalent proportions of calcium plus magnesium relative to bicarbonate. In summary, these relations indicate that dissolution of calcite and dolomite during percolation of surface recharge through unsaturated soil and alluvium is sufficient to produce the major-ion composition determined for the water samples from the alluvium.

Water from the De Weese Dye Ditch contains less than 10 μg/L uranium according to Cotter Corp. analyses of August and September 1984 (U.S. Environmental Protection Agency, written commun., 1985). The water from alluvium sampled for this study had a median uranium concentration of 25 μg/L. If the water from alluvium sampled for this study has water from the De Weese Dye Ditch as its primary source, then the uranium in the water must be coming from an additional source. Historical, natural background concentrations of uranium in ground water of Lincoln Park do not seem to have been determined. The uranium in the water from alluvium sampled for this study might originate from natural sources or sources on the Cotter Corp. site. Possible natural sources might be minerals in the alluvium, or upward leakage from uranium-bearing waters from bedrock aquifers. Possible sources on the Cotter Corp. site might be wind-blown dust or contaminated surface-water sediments.

Table 8.--*Selected geochemical characteristics of water from alluvium*

[SI_{cc}, saturation index for calcite; SI_{dl}, saturation index for dolomite; P_{CO_2}, partial pressure of carbon dioxide in atmospheres; $\frac{Ca + Mg}{HCO_3}$, ratio of concentrations (expressed in milliequivalents) of calcium plus magnesium, relative to bicarbonate]

Site identification (see fig. 2)	SI_{cc}	SI_{dl}	P_{CO_2}	$\frac{Ca + Mg}{HCO_3}$
C-129	0.140	-0.059	-0.011	0.909
A	.362	.543	.011	1.03
D	.088	.002	.016	.945
E	.038	-.151	.015	.894
G	.128	.082	.011	.996
H	.290	.384	.014	.966
I	.040	-.090	.015	.950
J	.185	-.008	.011	1.02
K	.273	.369	.010	.910
L	.104	-.011	.016	1.00
M	.208	-.054	.015	1.23

Characterization of Raffinate-Affected Ground Water

Both acid leaching and sodium carbonate leaching have been used at the uranium-ore precessing mill to extract uranium from ores (U.S. Environmental Protection Agency, written commun., 1985). Analyses of raffinate in tailings ponds indicate dissolved-solids concentrations as large as 100,000 mg/L; the analyses also indicate varying compositions of raffinate in different ponds, apparently dependent on the mix of process liquors that the ponds received. As raffinate migrates into the ground-water system, it is changed by reaction with earth materials, by mixing among various types of raffinate, and by dilution with native ground water. Gerlitz (1982) studied migration of acidic raffinate through rock cores from the Poison Canyon Formation; she determined that raffinate acidity was neutralized through reaction with calcite in these rocks, thereby adding calcium and bicarbonate to the percolating waters. Little attenuation of magnesium, potassium, sodium, chloride, or sulfate occurred.

Water in the shallow aquifer in the Sand Creek basin, south of the SCS dam, flows from the vicinity of the old tailings ponds in a northeasterly direction toward the SCS dam (U.S. Environmental Protection Agency, written commun., 1985). Wells sampled for this study, that lie within this shallow flow route, are wells C-333, C-312, and C-313. Wells C-329, C-330, and C-331 are located just north of the SCS dam. Selected water-quality variables for samples collected from these wells are listed in table 9. As discussed earlier, water from all these wells can be categorized as raffinate affected, according to the greater concentrations of sulfate, molybdenum, selenium, and uranium. Water from wells C-312 and C-313 has the largest concentrations of raffinate components among samples collected for this study, and is the most representative of raffinate-affected ground water. This water is a sodium sulfate type (as shown in fig. 18); presumably the sulfate came from sulfuric acid used in the acid-leaching process, and the sodium came from sodium carbonate used in the carbonate-leaching process. Water from wells C-329, C-330, C-331, and C-333 is similar to water from wells C-312 and C-313, but is more dilute with respect to raffinate components. Water from these wells contains a larger proportion of calcium, but a similar anionic composition as that in water from wells C-312 and C-313, indicating that the raffinate-affected sodium sulfate water has been mixed with a calcium sulfate type water.

Isotopic analyses also were made on these raffinate-affected waters; results are listed in table 9. These isotopic variables, discussed in the following sections in the order of their importance to the study, provide an additional means of identification of raffinate-affected water.

Isotopes

The existence of sodium sulfate type water in both the Vermejo and Poison Canyon Formations sometimes obscures the identification of raffinate presence, because raffinate-affected water also is commonly a sodium sulfate type. However, isotopic analysis can aid in identification of raffinate-affected water. Isotopic analysis was done on 14 water samples suspected to be raffinate affected; the analyses are listed in table 4.

Table 9.--*Selected water-quality variables for raffinate-affected ground water*

[μS/cm, microsiemens per centimeter at 25 °Celsius; mg/L, milligrams per liter; μg/L, micrograms per liter; per mil, parts per thousand; TU, tritium units; E, estimated; dashes indicate no data; <, less than]

Site identification (see fig. 2)	Specific conductance (μS/cm)	Sulfate, dissolved (mg/L as SO_4)	Molybdenum, dissolved (μg/L as Mo)	Selenium, dissolved (μg/L as Se)	Uranium, dissolved (μg/L as U)	Carbon-13/carbon-12 stable-isotope ratio[1] (per mil)	Sulfur-34/sulfur-32 stable-isotope ratio[2] (per mil)	Tritium (TU)
C-312	7,700	4,100	26,200	E130	5,500	--	--	--
C-313	7,630	4,500	27,800	E81	5,500	-8.4	-2.6	46±5
C-329	3,100	1,900	<500	<25	330	-8.9	-3.7	26±5
C-330	6,710	3,600	18,800	<25	3,900	-10.8	-3.2	75±6
C-331	5,990	2,800	21,000	E62	2,900	-8.1	-1.5	64±5
C-333	3,910	2,300	9,800	E94	5,700	-8.5	-1.3	41±6

[1] A synonym for this term is "delta carbon-13." The standard reference material for this analysis is PDB (Peedee belemnite).

[2] A synonym for this term is "delta sulfur-34." The standard reference material for this analysis is triolite from the Canyon Diablo meteorite.

Tritium

Tritium is the radioactive isotope of hydrogen; natural tritium concentrations generally are small, but a large concentration of tritium was added to the hydrologic cycle from 1952 to the mid-1960's by the testing of thermonuclear weapons in the atmosphere. Tritium concentrations are reported in tritium units (TU); 1 TU is 1 atom of tritium in 10^{18} atoms of hydrogen. Water with tritium concentrations of about zero usually contain no post-1952 water, whereas water with large tritium concentrations (greater than 50 TU) usually contain significant proportions of post-1952 water (Coplen, 1985).

Samples affected by raffinate all have large tritium concentrations (table 9), as would be expected, because the source of water in the tailings pond was the Arkansas River. The variability in tritium concentrations among these samples indicates that they are representative of different mixes of source water.

Water from wells that tap only the Vermejo Formation (test wells LP85-1D, LP85-2S, LP85-2D4, LP85-4, and LP85-6D4; and well C-317) had small tritium concentrations; therefore the water contained no significant proportion of post-1952 water, which indicates that the Vermejo Formation is not a principal route of raffinate movement in the areas of the sampled wells. The fact that the sampled water from the Vermejo Formation contained no post-1952 water, however, does not rule out the possibility that, although contaminated post-1952 water has not yet reached the sampled wells, it might still be present in the Vermejo Formation upgradient from the sampled wells.

Oxygen-18 and Deuterium

Oxygen-18 is the heavy stable isotope of oxygen; and deuterium is the heavy stable isotope of hydrogen. Concentrations of isotopes are reported in delta notation, which is a comparison of the heavy-to-light isotope ratio (that is, oxygen-18 to oxygen-16 ratio) of the sample with the heavy-to-light isotope ratio of a standard-reference material. The reporting unit is "per mil," which is this ratio expressed in thousandths. A delta value of zero per mil means that the sample has the same ratio of heavy-to-light isotopes as the standard. Negative delta values indicate that the sample is depleted in the heavy isotope--it is "light"; positive values indicate that the sample is enriched in comparison with the standard--it is "heavy."

Because hydrogen and oxygen compose the water molecule, every water sample has a unique and constant delta deuterium to delta oxygen-18 ratio, provided that no gross reactions involving hydrogen or oxygen occur. Isotopes in precipitation under current climatological conditions are related along the "global meteoric water line," which is a relation represented by the equation (Craig, 1961):

$$\delta D=8\delta^{18}O+10, \tag{1}$$

where δD = delta deuterium, and
$\delta^{18}O$ = delta oxygen-18.

The delta deuterium to delta oxygen-18 relation for ground water in the study area is shown in figure 19. Water that does not contain raffinate plots on a single best fit line (slope of 8.6, intercept of 11.7, r=0.98). This indicates that these waters have a genetic similarity.

Water that contains raffinate plots to the right of the local genetic line. This shift is indicative of evaporation, which is a nonequilibrium process that enriches water in deuterium and oxygen-18 such that the slope of the delta deuterium to delta oxygen-18 ratio is between 3 and 6 (Coplen, 1985). This process is likely to have occurred with raffinate water, as it passed through evaporation ponds.

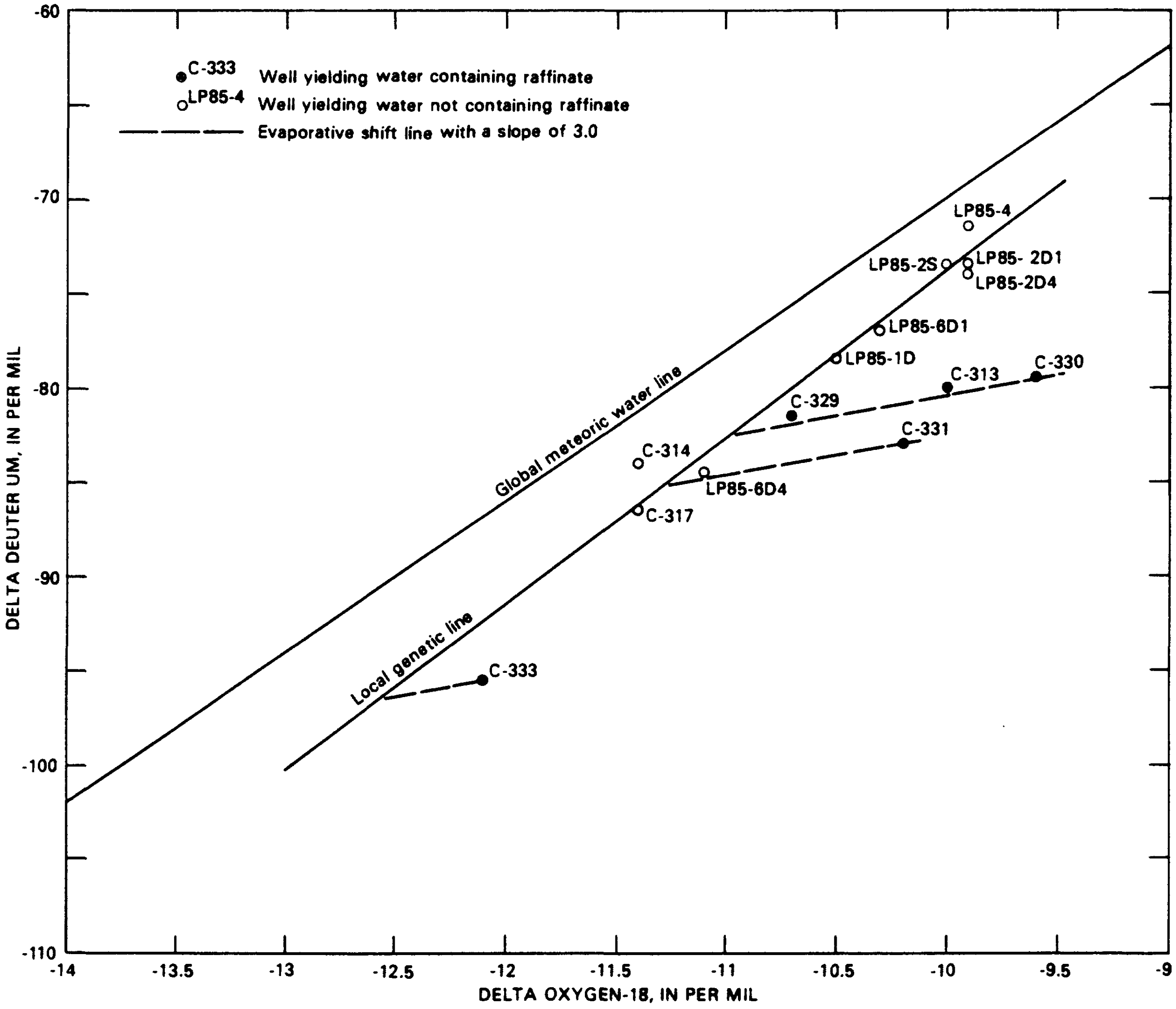

Figure 19.--Relation of delta deuterium to delta oxygen-18.

Carbon-13

The carbon-isotopic composition of water is dependent on the source of the carbon. Carbon from dissolution of marine carbonate rocks has a delta value of about 0 per mil (Mook, 1980). Organic debris can be expected to have a delta value of about -23 per mil or less, whereas carbon derived from carbon dioxide in the soil zone can be expected to have a delta value of about -25 per mil (Coplen, 1985). For this study, delta carbon-13 values were measured for two rock samples from the Vermejo Formation. A coal sample from a depth of 85 ft in test well LP85-1D had a delta carbon-13 value of -26.92 per mil for organic carbon. A tan shale from a depth of 240 ft in test well LP85-2D had a delta carbon-13 value of -26.36 per mil for organic carbon and a delta carbon-13 value of -10.74 per mil for inorganic carbon. These values for organic carbon-13 were in the expected range. The value for inorganic carbon was somewhat lighter than expected for marine carbonate rocks and probably reflects the presence of secondary carbonate cement. Nevertheless, the difference in carbon-13 ratios between organic and inorganic carbon is helpful in understanding the genesis of water from the Vermejo Formation.

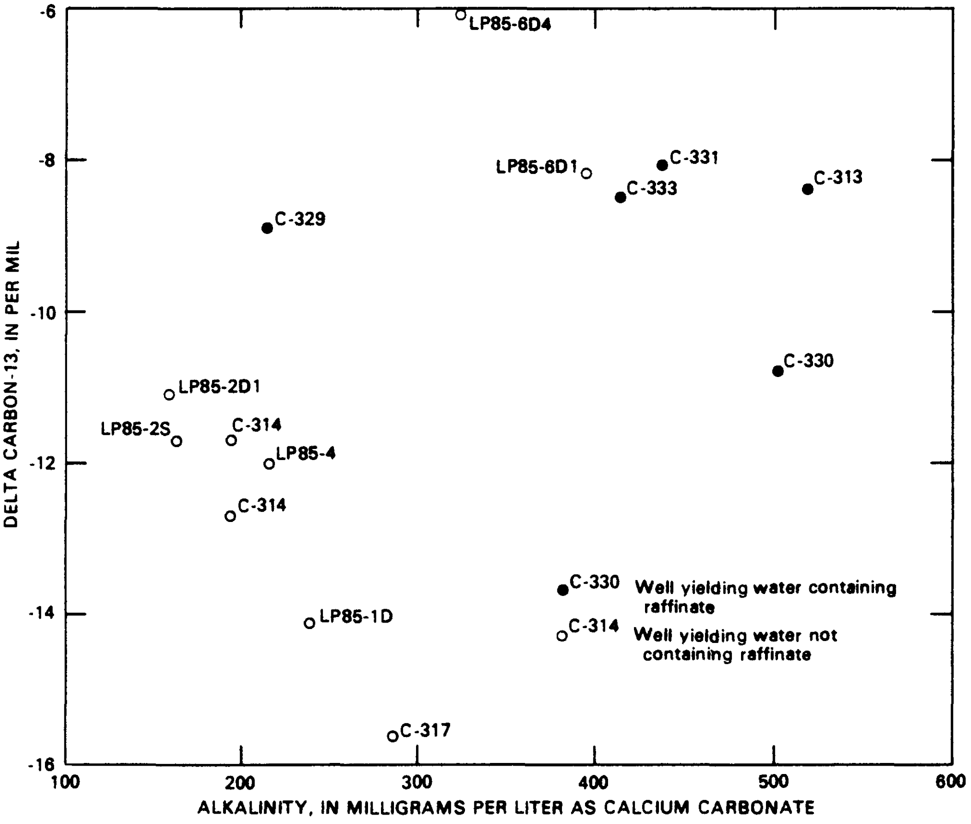

Figure 20.--Relation of delta carbon-13 to alkalinity.

A plot of alkalinity and delta carbon-13 (alkalinity is a measure of total carbon concentration) for selected water samples indicates that several processes are occurring (fig. 20). A large grouping of samples occurs for alkalinity values from 160 to 220 mg/L and for corresponding delta carbon-13 values of -11 to -13 per mil. This grouping most likely represents recharge water that has been modified by dissolution of carbonate cement within the Vermejo Formation. Samples from test wells LP85-6D1 and LP85-6D4 completed in the Vermejo Formation have increased alkalinity and heavier carbon; these samples probably are representative of a more advanced stage of dissolution of the carbonate cement. However, mixing with a small proportion of raffinate water also could result in heavier carbon in the water from these two wells.

A second type of reaction within Vermejo Formation aquifers shows increased alkalinity while producing lighter carbon; samples from test well LP85-1D and well C-317 are representative of this process. These wells are completed in coal seams where reducing conditions are likely. Under these conditions, bacterially mediated sulfate reduction can add organically derived carbon to solution, thereby increasing alkalinity while producing a water lighter in carbon-13.

Raffinate-affected water has a median delta carbon-13 value of -8.5 per mil that varies little with alkalinity. This lack of variation implies a single source of carbon, which is consistent with carbonate acquisition by acidic raffinate as it dissolves carbonate rocks. A delta carbon-13 value of about -8.5 per mil is representative of raffinate-affected water and can be used as supporting evidence in identifying water that has been affected by raffinate.

Sulfur-34

A plot of sulfate concentration and delta sulfur-34 for sampled water (fig. 21) indicates that several sulfate sources or processes are involved; natural sources might include dissolution of sulfate minerals and oxidation of sulfide minerals or organic sulfides. Water samples containing raffinate cluster around a median delta value of -2.6 per mil; the source of this sulfur presumably is sulfuric acid used in the acid leaching process. Water from well C-317 has a delta sulfur-34 value of 9.7 per mil, a value apart from the others; the reason for this is not known. The remaining water samples range around a median delta value of -5.0 per mil. The variability might be related to relative bacterial activity, because sulfur-isotopic composition is dependent on kinetic-isotope fractionation by bacteria (Coplen, 1985). Relative bacterial activity in this water is not known. The mean values for delta sulfur-34 for the raffinate-affected water (-2.46 per mil) and nonraffinate-affected water (-5.10 per mil) are statistically different at the 0.044 significance level; therefore, sulfur-34 content can be used as supportive evidence in identifying the presence of raffinate in water.

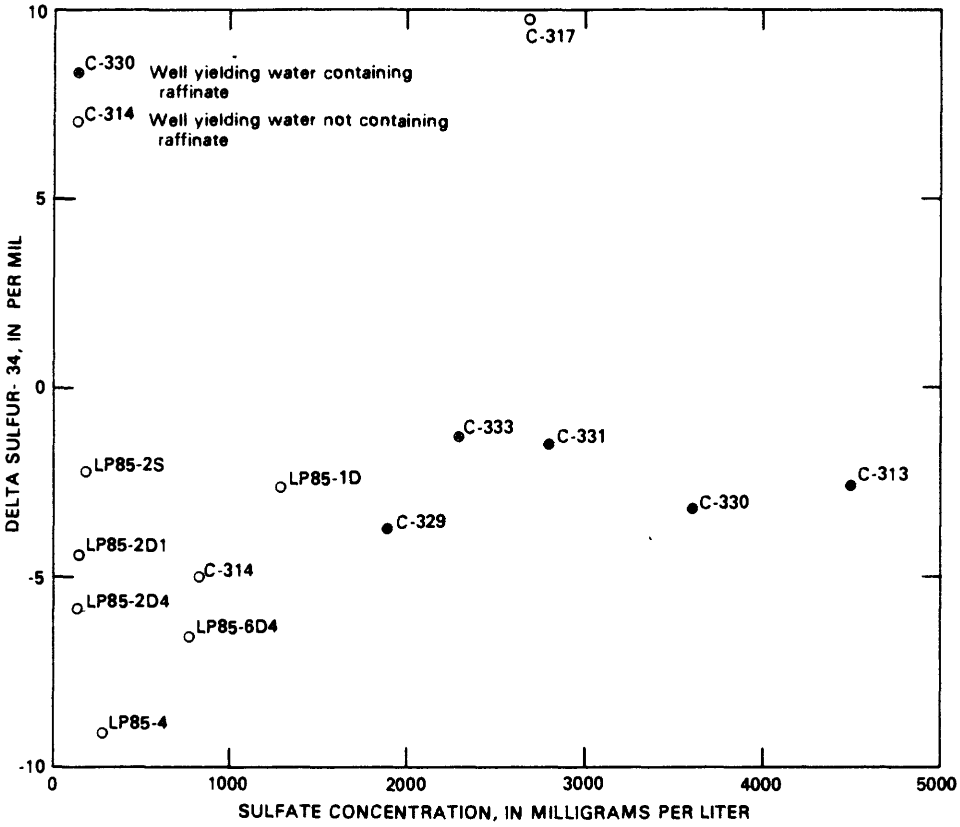

Figure 21.--Relation of delta sulfur-34 to sulfate concentration.

Mixing of Waters

On a trilinear diagram, mixtures of two water types plot on the straight line connecting the two; this is called a mixing line. The major-ion composition of water from the sampled wells (figs. 15-18) indicates several mixing relations. Water from wells C-312 and C-313 is representative of the most concentrated raffinate sampled. Water from wells C-333, C-329, C-330, and C-331 also contains a substantial proportion of raffinate components; in this water, sulfate is still the predominant anion, but calcium is present in larger proportions relative to sodium. Generally, as raffinate components and other dissolved solids decrease in concentration, the proportion of calcium increases. This change indicates mixing with a calcium sulfate water from the Poison Canyon Formation; the mixing line is shown in figure 18.

Examination of uranium concentrations relative to major-ion composition (fig. 18) indicates an additional mixing mechanism. The principal mixing line runs between water from alluvium and mixed raffinate-affected water from the Poison Canyon Formation. Water from well C-129 has a uranium concentration only slightly larger than nonraffinate-affected water from wells completed in the alluvium, and insufficient mixing has occurred to noticeably shift the major-ion composition away from the plotting area for water from alluvium. Samples from wells C-120 and C-144 have somewhat larger concentrations of uranium and show a major-ion shift towards the sulfate axis. Further along the mixing line, with still larger concentrations of uranium, are samples from wells C-123 and C-117. Finally, samples from wells C-142, C-119, C-140, C-139, and C-138 have the largest measured uranium concentrations among wells in Lincoln Park and are shifted most toward the major-ion composition field occupied by mixed raffinate-affected water from the Poison Canyon Formation.

It is believed that all these wells are completed only in the alluvium, except for well C-142. This well has been reported to penetrate the Vermejo Formation, but the well appears to have caved in at depth, and it is suspected that the alluvium provides much of the water in this well.

Water from wells C-122 and C-124 has a composition that indicates mixing of water from alluvium with a concentrated raffinate water, such as that present at wells C-312 and C-313. Alternatively, water from wells C-122 and C-124 might result from a mix of raffinate-containing water from the Poison Canyon Formation with water from the Vermejo Formation. These two wells are at least 80 ft deep, and possibly are completed in both aquifers in the alluvium and Vermejo Formation (U.S. Environmental Protection Agency, written commun., 1985). However, no examples of direct mixing between water from the Vermejo Formation and raffinate appear to exist.

Distribution of Raffinate

The areal distribution of molybdenum, selenium, and uranium in water from U.S. Geological Survey test wells and for selected Cotter Corp. data sites is shown in figures 22-24. Molybdenum and uranium have similar distribution patterns. Distribution of selenium is similar to the distribution of molybdenum and uranium in water from sites south of the SCS dam; however, comparison of distributions in water from wells and seeps north of the SCS dam is hampered by the variable detection limits used for analyses of selenium. The distribution maps show large raffinate-component concentrations in water from wells between the uranium-ore processing mill and the SCS dam. North of this area, increased concentrations are not encountered until the vicinity of the intersection of Sand Creek with the De Weese Dye Ditch. Here, a cluster of wells with water containing increased concentrations occurs; however, water from several nearby wells do not seem to be affected. Generally, the remaining affected wells are located within 1,000 ft of the channel of Sand Creek, as far downstream as the point where Sand Creek intersects Elm Avenue. Two wells contradict this pattern: water from well C-144, located 3,000 ft east of Sand Creek, contains increased concentrations of uranium, whereas water from well E, located only 500 ft from Sand Creek, seems to be unaffected.

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The distribution pattern indicates several conclusions relative to the route of raffinate movement. Water from shallow wells between the uranium-ore processing mill and the SCS dam is affected by raffinate, indicating a shallow route through this area; water from deep wells did not seem to be affected by raffinate. Between the SCS dam and the De Weese Dye Ditch, water from deep wells did not seem to be affected by raffinate; shallow wells contained no water. Therefore, the route of raffinate movement through this area cannot be defined, based on our data. North of the De Weese Dye Ditch, wells with water affected by raffinate are mostly in the vicinity of the Sand Creek channel. However, this pattern is not always consistent, and, in at least one location, water from adjacent wells had different characteristics, which indicates that the route through Lincoln Park is complex, and perhaps is related only indirectly to the present-day channel of Sand Creek.

SUMMARY AND CONCLUSIONS

The purpose of this study was to supplement information available from previous investigations and to refine the description of the geohydrologic and geochemical systems in the study area. Data from this improved data base were used to describe: (1) Hydraulic conductivity and hydraulic head in the Vermejo Formation between the SCS dam and Lincoln Park; (2) hydraulic head and ground-water flow in the alluvial aquifer underlying Lincoln Park; (3) major-ion and trace-element characteristics of water from the Poison Canyon Formation, the Vermejo Formation, and the alluvial aquifer underlying Lincoln Park; (4) isotope characteristics of water from the Poison Canyon Formation and Vermejo Formation; and (5) major-ion, trace-element, and isotope characteristics, and distribution of raffinate in water from the Poison Canyon Formation and the alluvial aquifer underlying Lincoln Park. The following conclusions emphasize the significance of this information relative to the concerns of the U.S. Environmental Protection Agency about the potential migration of raffinates from the uranium-ore processing mill to Lincoln Park.

The following conclusions are supported by the interpretations presented in this report: (1) The "deep migration path" probably is less important than the "shallow migration path" in providing a route for the migration of raffinate-affected water; (2) between the ridge and the De Weese Dye Ditch, the "shallow migration path" may be along a channel or channels in the subsurface topography of the Vermejo Formation; (3) concentrated raffinate-affected ground water has distinctive chemical characteristics; and (4) the concentrated raffinate-affected ground water seems to be diluted by mixing with native ground water from the Poison Canyon Formation in the area south of the SCS dam, and further diluted by mixing with water in the alluvium in Lincoln Park.

The "deep migration path" probably is less important than the "shallow migration path" in providing a route for the migration of raffinate-affected water. Three interpretations presented in this report support this hypothesis. First, none of the samples from deep wells contained significantly large concentrations of raffinate components. South of the ridge, samples from the Vermejo Formation (well C-317) and from deeper beds of the Poison Canyon

Formation (well C-314) did not contain large concentrations of raffinate components like those measured in samples from shallow beds of the Poison Canyon Formation (wells C-312 and C-313) at the same location. North of the ridge, none of the samples from the new test wells completed in the Vermejo Formation (wells LP85-1D, LP85-2S, LP85-2D1, LP85-2D4, LP85-4, LP85-6D1, and LP85-6D4) contained significantly large concentrations of raffinate components. For example, the concentration of uranium was not significantly different from that measured in samples from the alluvial aquifer (table 4). Also, none of the samples from these wells were post-1952 water; whereas, the raffinate-affected water principally consists of post-1952 water. Although this water possibly contains some raffinate-affected water, or some raffinate components may have been removed by geochemical controls, no evidence occurs of large concentrations of raffinate components moving through the Vermejo Formation to become dilute as they mix with water from the alluvial aquifer in Lincoln Park.

Second, beds of the Vermejo Formation penetrated by the test wells do not seem to be very transmissive. Lithologic and geophysical logs indicated that the section of Vermejo Formation penetrated by the test wells consisted of interbedded sandstone, shaly sandstone, and shale. The sandstone beds that are relatively clean (less shaly) have minimal porosity and minimal hydraulic conductivity. The slow rate of water seepage into some of the test wells also indicated a small hydraulic-conductivity value for the beds of the Vermejo Formation to which the well was completed.

Third, the major-ion composition of water from the study area does not indicate substantial flow from the Vermejo Formation to the alluvial aquifer in Lincoln Park. Water from the Vermejo Formation is a variable sodium sulfate to sodium bicarbonate type. The differences in composition may result from reactions within the different geochemical environments present in the Vermejo Formation. Water from the alluvial aquifer in Lincoln Park is a calcium bicarbonate type with small variation in composition, distinct from water from other aquifers in the study area. Geochemical analysis of this water indicates that it could result from reaction of water from the De Weese Dye Ditch with alluvial material. Leakage from the underlying Vermejo Formation does not seem to be significant in determining the chemical composition of this water.

Although these data support the conclusion that a "deep migration path" within the Vermejo Formation probably is less important than a "shallow migration path" in providing a route for the migration of raffinate-affected water, this conclusion remains tentative. Raffinate-affected water may be migrating along a "deep migration path" that does not pass the sites where data were collected. Raffinate-affected water may be migrating toward the sampled sites but may not yet have reached the wells. If raffinate-affected water is migrating along a "deep migration path," the direction and distance of migration remain unknown.

Between the ridge and the De Weese Dye Ditch, flow in the "shallow migration path" may be restricted to a channel or channels. The base of the alluvial aquifer, unweathered and unfractured Vermejo Formation, seems to form an irregular surface. North of the De Weese Dye Ditch, the alluvial aquifer seems to be saturated and water flows generally to the northeast. In contrast, no saturated alluvium was penetrated south of the De Weese Dye Ditch, which is consistent with the hypothesis that the alluvium is saturated only where the Vermejo Formation subcrop is topographically low. From the ridge to Lincoln Park, flow may be along a channel or channels in the irregular and relatively undescribed topography of the Vermejo Formation. Migration of raffinate-affected water may follow a narrow and tortuous path among these channels.

Water analyses from wells that contain the most concentrated raffinate-affected water have distinctive chemical characteristics. This water has substantial ionic strength and is a sodium sulfate type. Molybdenum, selenium, and uranium are present in large concentrations. The water has a delta deuterium to delta oxygen-18 ratio indicative of an evaporative history. It has a large tritium concentration indicative of post-1952 water. For the samples tested, the median delta carbon-13 value was -8.5 per mil, and the median delta sulfur-34 value was -2.6 per mil. This combination of characteristics is sufficient to identify concentrated raffinate-affected water.

Concentrated raffinate-affected ground water seems to be diluted through mixing with native ground waters. South of the SCS dam, calcium sulfate type water from the Poison Canyon Formation mixes with raffinate-affected water producing a sodium calcium sulfate water; raffinate components, such as molybdenum and uranium are diluted.

One water sample from the alluvial aquifer in Lincoln Park contained measurable concentrations of uranium. Nonparametric statistical analysis identified water from well C-129 as having an anomalously large uranium concentration; that is, water from this well may be a mixture of water in the alluvium and raffinate-affected water. Cotter Corp. data from 1981 indicate that water in the alluvium mixes with water from the Poison Canyon Formation and raffinate-affected water along a fairly continuous mixing line. The raffinate characteristics become faint as dilution progresses, and geochemical controls also can selectively modify raffinate-component concentrations.

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