Geologic Framework of the Regional Ground-Water Flow System in the Upper Deschutes Basin, Oregon

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY
Water-Resources Investigations
Report 02–4015

Prepared in cooperation with
OREGON WATER RESOURCES DEPARTMENT;
CITIES OF BEND, REDMOND, AND SISTERS;
DESCHUTES AND JEFFERSON COUNTIES;
THE CONFEDERATED TRIBES OF THE
WARM SPRINGS RESERVATION OF OREGON;
and U.S. ENVIRONMENTAL PROTECTION AGENCY

Cover photographs:

Top: Steelhead Falls on the Deschutes River near Crooked River Ranch, Oregon.

Middle: Crooked River Canyon at Crooked River Ranch, Oregon.

Bottom: North and Middle Sister with a wheel-line irrigation system in the foreground near Sisters, Oregon. (Photographs by Rodney R. Caldwell, U.S. Geological Survey.)

U.S. Department of the Interior
U.S. Geological Survey

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By KENNETH E. LITE JR. and MARSHALL W. GANNETT

Water-Resources Investigations Report 02–4015

Prepared in cooperation with Oregon Water Resources Department;
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and U.S. Environmental Protection Agency

Portland, Oregon
2002

U. S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	3.528×10^{-6}	meters per second (m/s)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	6.308×10^{-5}	cubic meters per second (m^3/s)

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

°C = (°F – 32) / 1.8

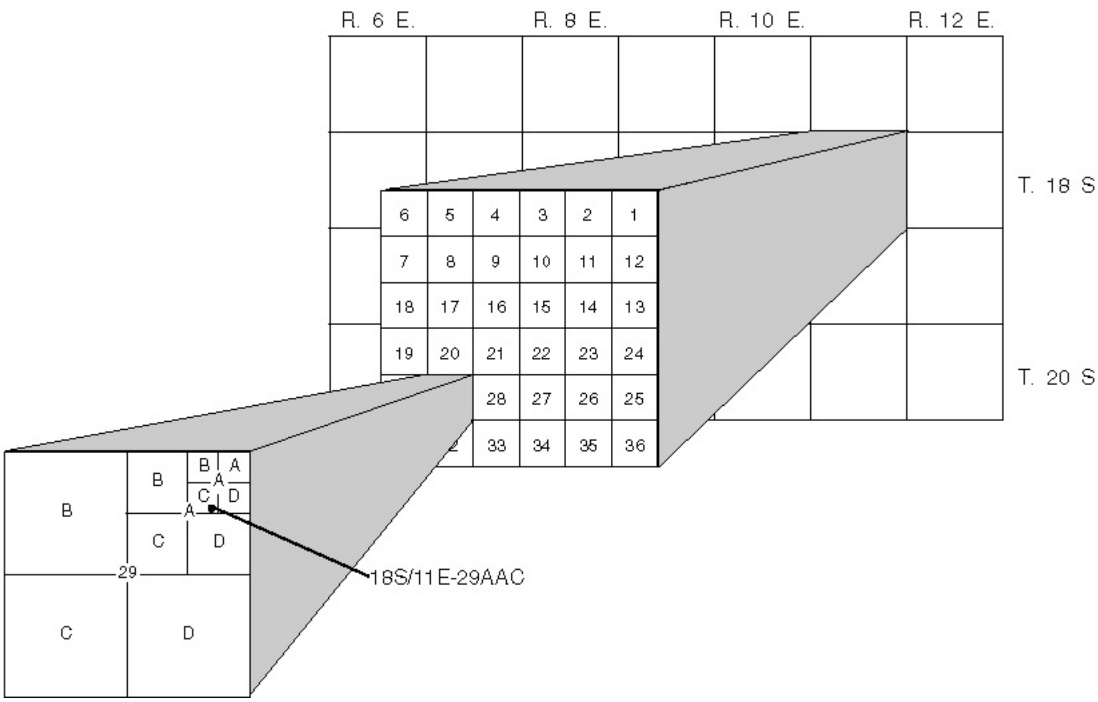
Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F = (1.8 × °C) + 32

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

LOCATION SYSTEM

The system used for locating wells, springs, and surface-water sites in this report is based on the rectangular system for subdivision of public land. The State of Oregon is divided into townships of 36 square miles numbered according to their location relative to the east-west Willamette baseline and a north-south Willamette meridian. The position of a township is given by its north-south “Township” position relative to the baseline and its east-west “Range” position relative to the meridian. Each township is divided into 36 one-square-mile (640-acre) sections numbered from 1 to 36. For example, a well designated as 18S/11E-29AAC is located in Township 18 south, Range 11 east, section 29. The letters following the section number correspond to the location within the section; the first letter (A) identifies the quarter section (160 acres); the second letter (A) identifies the quarter-quarter section (40 acres); and the third letter (C) identifies the quarter-quarter-quarter section (10 acres). Therefore, well 29AAC is located in the SW quarter of the NE quarter of the NE quarter of section 29. When more than one designated well occurs in the quarter-quarter-quarter section, a serial number is included.



Well- and spring-location system.

Each well is assigned a unique 8-digit identification number known as the log-id number. The first two digits of the log-id number indicate the county code from the Federal Information Processing Standards (FIPS) code file for the county in which the well exists. The FIPS codes for the counties in the study area are as follows: 13, Crook County; 17, Deschutes County; 31, Jefferson County; and 35, Klamath County. The last 6 digits of the number correspond to the State of Oregon well-log number (a unique number assigned by the Oregon Water Resources Department to the report filed by the well driller).

MAPPING SOURCES:

Base map modified from U.S. Geological Survey 1:500,000 State base map, 1982, with digital data from U.S. Bureau of the Census, TIGER/Line (R), 1990, and U.S. Geological Survey Digital Line Graphs published at 1:100,000.

Projection: Universal Transverse Mercator projection, Zone 10, 1927 North American Datum.

Acknowledgments

The authors wish to acknowledge the area residents, municipalities, private water companies, engineering companies, and well constructors who provided drill cutting samples, access to their property, and access to wells for geophysical logging. In particular we thank Doug Aiken, well constructor, who provided excellent quality samples from numerous wells throughout Deschutes County and Larry Carey, Oregon Water Resources Department, South Central Region Office, for organizing the drill cuttings sampling program and retrieving and labeling hundreds of samples. We also thank Pat Dorning, City of Redmond, and Bob MacRostie, Deschutes Valley Water Company, for providing drill cutting samples, geophysical logs, and hydrologic data from their newly constructed wells. Finally, we wish to thank the geologists that have collected much of the geologic information for the area and freely shared their insights with us. They include Dave Sherrod, U.S. Geological Survey; Rick Conrey, Washington State University; Mark Ferns, Oregon Department of Geology and Mineral Industries; Gary Smith, University of New Mexico; Ed Taylor, Oregon State University; and Larry Chitwood, Deschutes National Forest.

Geologic Framework of the Regional Ground-Water Flow System in the Upper Deschutes Basin, Oregon

By Kenneth E. Lite Jr. *and* Marshall W. Gannett

Abstract

Ground water is increasingly relied upon to satisfy the needs of a growing population in the upper Deschutes Basin, Oregon. Hydrogeologic studies are being undertaken to aid in management of the ground-water resource. An understanding of the geologic factors influencing ground-water flow is basic to those investigations. The geology of the area has a direct effect on the occurrence and movement of ground water. The permeability and storage properties of rock material are influenced by the proportion, size, and degree of interconnection of open spaces the rocks contain. These properties are the result of primary geologic processes such as volcanism and sedimentation, as well as subsequent processes such as faulting, weathering, or hydrothermal alteration. The geologic landscape in the study area evolved during about 30 million years of volcanic activity related to a north-south trending volcanic arc, the current manifestation of which are today's Cascade Range volcanoes.

The oldest rock unit in the upper Deschutes Basin study area, the John Day Formation, is a sequence of upper Eocene to lower Miocene volcanic and sedimentary rocks. Weathering and alteration of the rocks has resulted in very low permeability; consequently, the unit forms the hydrologic basement for the regional ground-water flow system throughout much of the area. The Deschutes Formation and age-equivalent deposits that overlie the John Day Formation, in contrast, are highly permeable and are the most widely used ground-water-bearing units in the study area. The Deschutes Formation consists of a variety of volcanic and sedimentary deposits ranging in age from late Miocene to Pliocene (approximately 7.5 to 4.0 million years). Three distinct depositional environments previously described for the formation provide useful hydrogeologic subdivisions. The ancestral Deschutes River deposits and some units within the arc-adjacent alluvial-plain region are among the highest yielding units within the Deschutes Formation, with some wells producing up to a few thousand gallons per minute. Opal Springs basalt, Pelton basalt, and the rhyodacite dome complex near Steelhead Falls are particularly productive subunits within the Deschutes Formation and provide tens to hundreds of cubic feet per second of ground-water discharge to the Deschutes and Crooked Rivers, upstream of Round Butte Dam.

Most ground-water recharge in the upper Deschutes Basin occurs in Quaternary deposits of the Cascade Range and Newberry Volcano. These deposits are highly permeable, and the fractured character of the lava flows facilitates rapid infiltration of precipitation and snowmelt, as well as movement of ground water to lower elevations. Additional recharge from canal leakage occurs along sections of unlined canals near Bend, constructed on lava flows from Newberry Volcano. Hydrothermal alteration and secondary mineralization at depth beneath the Cascade Range and Newberry Volcano has drastically reduced the permeability of the material in those regions, effectively restricting most ground water to the strata above the altered rocks. The top of the hydrothermally altered region is considered the base of the regional ground-water system beneath the Cascade Range and Newberry Volcano.

Structural features influence ground-water flow within the upper Deschutes Basin mainly by juxtaposing materials with contrasting permeability. This juxtaposition can be caused by fault movement or by the influence of a fault on subsequent deposition. Several depositional centers have formed along the base of fault-line scarps or in grabens within the study area, and the infilling sedimentary deposits have permeability that differs from the surrounding rocks. The effects of faults on ground-water flow may be masked in some areas.

For example, the water-table gradient changes slope in the vicinity of the Sisters fault zone, but the slope change also corresponds with a major precipitation gradient change; therefore, any influence of the fault zone is unclear.

Geologic units in the Deschutes Basin were divided into several distinct hydrogeologic units. In some instances the units correspond to existing stratigraphic divisions. In other instances, hydrogeologic units correspond to different facies within a single stratigraphic unit or formation. The hydrogeologic units include Quaternary sediment, deposits of the Cascade Range and Newberry Volcano, four zones within the Deschutes Formation and age-equivalent rocks that roughly correspond with depositional environments, and pre-Deschutes-age strata.

INTRODUCTION

Background

The population in the upper Deschutes Basin has grown rapidly during the past few decades. Deschutes County, the most populous county in the basin, experienced a population increase of from 30,442 in 1970 to 106,700 in 1999 (State of Oregon, 2001). This growth is expected to continue. Surface-water resources in the area have been virtually closed to additional appropriation for many years by the State of Oregon. Ground water, therefore, is increasingly relied upon to satisfy the needs of the growing population.

To provide information on the ground-water resources of the upper Deschutes Basin, the U.S. Geological Survey (USGS) began a cooperative study in 1993 with the Oregon Water Resources Department (OWRD); the Cities of Bend, Redmond, and Sisters; Deschutes and Jefferson Counties; The Confederated Tribes of the Warm Springs Reservation of Oregon; and the U.S. Environmental Protection Agency. The objectives of the study were to provide a quantitative assessment of the regional ground-water system and to provide the understanding and analytical tools for enabling State and local government agencies, as well as the general public, to make informed resource-management decisions. This report is one in a series that will present the results of the upper Deschutes Basin ground-water study.

Purpose and Scope

The purpose of this report is to describe the various geologic structures and stratigraphic units that form the framework for the ground-water flow system in the upper Deschutes Basin. The geology has a direct effect on the occurrence and movement of ground water. The proportion, size, and degree of interconnection of void spaces within a geologic material influence the water-bearing properties of that material. The proportion of void space and the degree of interconnection of geologic material are often the result of primary geologic processes, such as volcanic eruptions and sedimentation, as well as subsequent processes, such as faulting and weathering. Understanding the geologic framework of the area and ascertaining the relation between permeability and geologic processes is fundamental to understanding the ground-water flow system.

This report will present a context for relating site-specific geologic and hydrologic data to the regional geologic framework and, thus, the regional ground-water flow system. The report progresses from a description of the volcano-tectonic evolution of the study area, through a description of important water-bearing rock units, and concludes with a discussion of the division of the regional geology into hydrogeologic units.

Study Area Description

The upper Deschutes Basin study area encompasses approximately 4,500 mi^2 (square miles) of the Deschutes River drainage basin in central Oregon (fig. 1). The area is drained by the Deschutes River and its major tributaries: the Little Deschutes River, Tumalo and Squaw Creeks, and the Metolius River from the west, and the Crooked River from the east. The mean annual flow of the Deschutes River below the tributaries (near Madras) is 4,553 ft^3/s (cubic foot per second). Land-surface elevation ranges from less than 1,300 ft (feet) above sea level near Gateway in the northern part of the study area to 10,358 ft in the Cascade Range.

The study area boundaries were chosen to coincide as much as possible with natural hydrologic boundaries across which ground-water flow can be reasonably estimated or assumed to be negligible. The study area is bounded on the north by Jefferson Creek, the Metolius River, the Deschutes River, and Trout Creek; on the east by the generalized contact

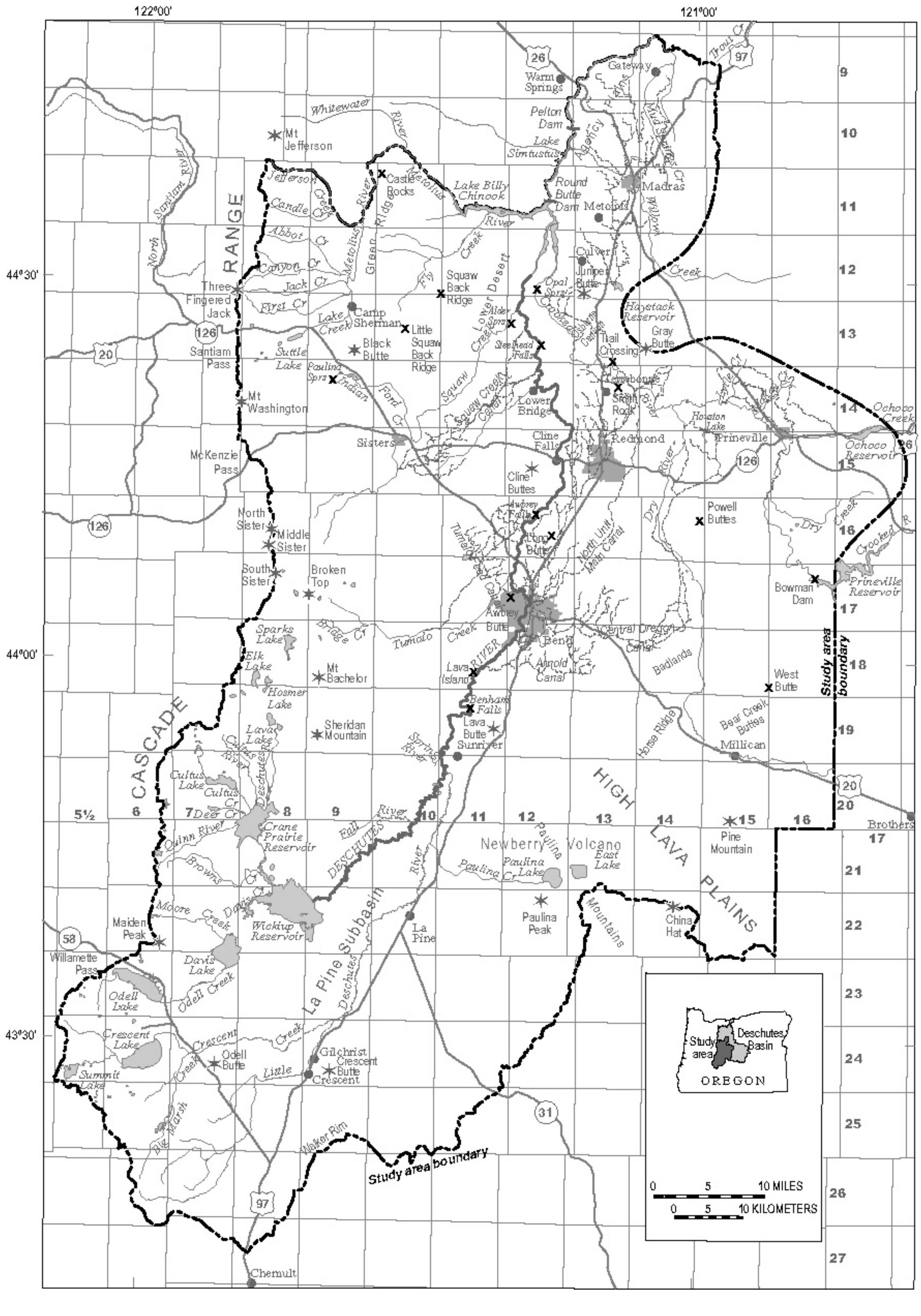


Figure 1. Location of the upper Deschutes Basin, Oregon, and major geographic and cultural features.

between the Deschutes Formation and the older, relatively impermeable John Day Formation; on the south by the drainage divide between the Deschutes Basin and the Fort Rock and Klamath Basins; and on the west by the Cascade Range crest.

The study area includes the major population centers in the basin, where ground-water development is most intense and resource-management questions are most urgent. The major communities include Bend, Redmond, Sisters, Madras, Prineville, and La Pine. Principal industries in the region are agriculture, forest products, tourism, and service industries.

Sixty-six percent of the 4,500 mi^2 upper Deschutes Basin is publicly owned (fig. 2). Approximately 2,230 mi^2 are under the jurisdiction of the U.S. Forest Service, 730 mi^2 are under the jurisdiction of the Bureau of Land Management, and about 20 mi^2 are under the stewardship of State or County agencies. The remaining 1,520 mi^2 are in private ownership.

The highest elevations in the upper Deschutes Basin are in the western and southern parts. These regions are covered by coniferous forests, most of which have been managed for timber production. The remaining parts of the basin, which are at lower elevation, are more arid and, where not cultivated, are dominated by grassland, sagebrush, and juniper. Most of the non-forest-related agriculture occurs in the central and northern parts of the upper Deschutes Basin.

There are approximately 164,000 acres (256 mi^2) of irrigated agricultural land in the study area. The largest source of irrigation water is the Deschutes River. Most water is diverted from the Deschutes River near Bend and distributed to areas to the north through several hundred miles of canals. Smaller amounts of irrigation water are diverted from Tumalo and Squaw Creeks, the Crooked River, and Ochoco Creek.

The climate in the upper Deschutes Basin is controlled primarily by air masses that move eastward from the Pacific Ocean, across western Oregon, and into central Oregon. The climate is moderate, with cool, wet winters and warm, dry summers. Orographic processes result in large amounts of precipitation in the Cascade Range in the western part of the basin, with precipitation locally exceeding 200 in/yr, mostly as snow during the winter (Taylor, 1993). Precipitation rates diminish rapidly toward the east to less than 10 in/yr (inches per year) in the central part of the basin. Temperatures also vary across the basin. Records from the Oregon Climate Service show that mean daily minimum and maximum temperatures at Santiam Pass in the Cascade Range (period of record 1961–85) range from 21 and 34°F (degrees Fahrenheit) in January to 43 and 73°F in July (Oregon Climate Service, 1999). Conditions are warmer at lower elevations in the central part of the basin. The mean daily minimum and maximum temperatures in Bend (period of record 1961 to 1999) range from 22 and 42°F in January to 45 and 81°F in July (Oregon Climate Service, 1999).

Methods

The observations and conclusions described in this report are based on preexisting data and analyses as well as new information. The preexisting information includes well reports for approximately 15,000 wells, geophysical logs for 15 wells, and numerous geologic studies by State, Federal, university, and private consulting geologists. The scope of these studies range from site-specific municipal well designs to regional geophysical studies and geologic mapping. Much of the original geologic mapping for the area has been incorporated in a few regional-scale geologic map compilations, which are the main source of the geologic mapping data shown on the geologic map in this report (plate 1).

Newly acquired data, much of it described herein, are from wells. Those data include material descriptions for 1,500 wells that were visited and documented during this study (fig. 2) (also, see Caldwell and Truini, 1997); tens of cross-sections constructed and analyzed, based on the visited-wells data; examination of well cuttings samples from 35 wells (fig. 3); down-hole geophysical logging of 35 wells (fig. 4); and geochemical analysis of 50 well cuttings samples. In addition, numerous ground traverses were made to examine exposures of geologic materials in many parts of the study area.

Wells where cuttings samples were collected, geophysical logs were made, or from which data were cited in this report are listed in table 1. Table 1 also includes well location, wellhead elevation, and well depth information. Each well is assigned a unique eight-digit identification number known as the “log-id” number. The first two digits of the log-id number indicate the county code from the Federal Information Processing Standards (FIPS) code file for the county in which the well exists. The FIPS codes for the study area are as follows: 13, Crook County; 17, Deschutes County; 31, Jefferson County; and 35, Klamath County. The last six digits of the number correspond to the State of Oregon well-log number (a unique number assigned by the OWRD to the report filed by the well driller).

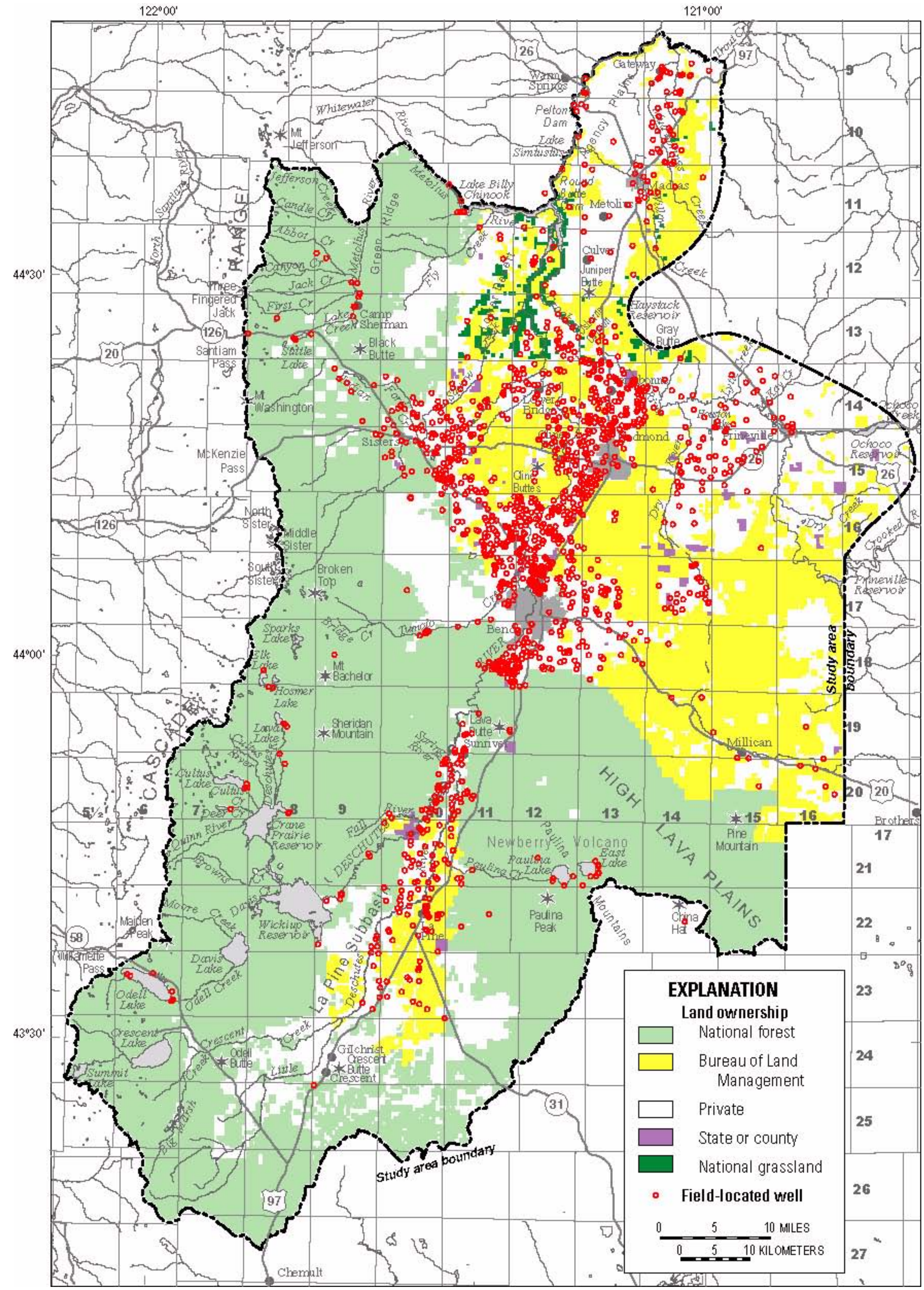


Figure 2. Location of field-located wells and land ownership in the upper Deschutes Basin, Oregon.

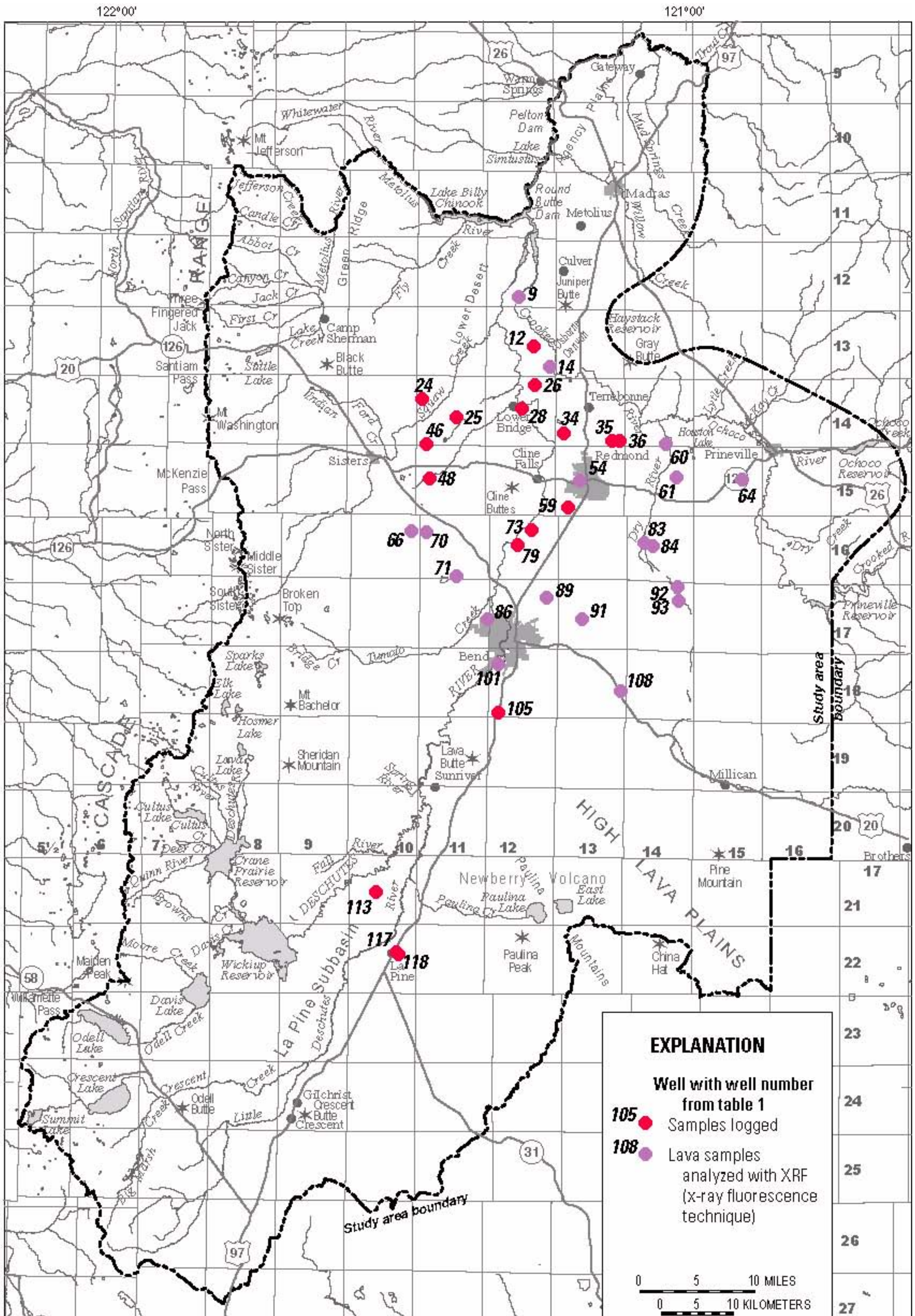


Figure 3. Location of wells with drill-cuttings samples.

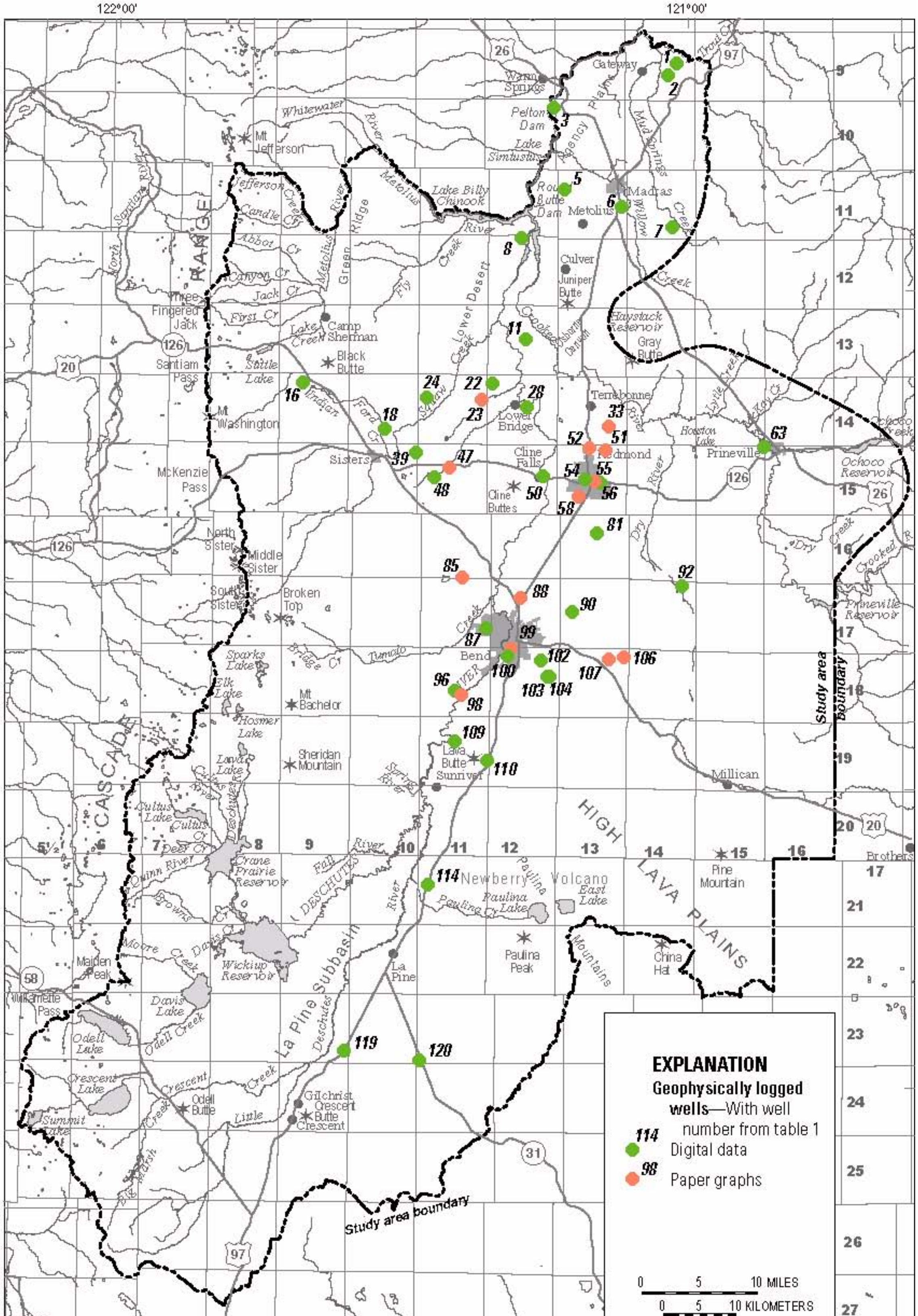


Figure 4. Location of geophysically logged wells.

Table 1. Data for selected wells in the upper Deschutes Basin, Oregon

Well location: Refer to "Well- and "Spring-Location System" for explanation. Log-ID number: Identification number permanently assigned to the well by the U.S. Geological Survey. Latitude/Longitude of well in °, degrees; ', minutes; ", seconds. Well elevation: Given in feet above sea level. Well depth: Depth of completed well, in feet below land surface. —, no sample or no data collected; X, sample collected.

Well number	Well location	Log-ID number	Latitude	Longitude	Well elevation (feet)	Well depth (feet)	Cuttings samples	Rock chemistry	Geo-physical log	Aquifer test
1	09S/14E-14CCC	31000219	44°46'49.28"	121°01'46.48"	1,962	550	—	—	X	—
2	09S/14E-27BBA	31000102	44°45'56.78"	121°02'46.50"	1,885	285	—	—	X	—
3	10S/12E-01CDD2	31000125	44°43'29.42"	121°14'43.44"	1,455	910	—	—	X	—
4	11S/13E-01BCA2	31000427	44°38'48.47"	121°07'27.30"	2,278	451	—	—	—	X
5	11S/13E-07CCD1	31000435	44°37'21.23"	121°13'34.25"	2,680	835	—	—	X	—
6	11S/13E-24BCD1	31000466	44°36'02.05"	121°07'33.30"	2,490	590	—	—	X	—
7	11S/14E-34ABC	31000918	44°34'32.70"	121°02'16.00"	2,990	303	—	—	X	—
8	12S/12E-04BDD1	31000518	44°33'38.72"	121°18'05.74"	2,600	650	—	—	X	—
9	12S/12E-33ACB	31050263	44°29'23.40"	121°17'49.75"	1,985	740	X	X	—	—
10	13S/11E-32DCD	31000853	44°23'40.54"	121°26'19.50"	2,939	620	X	—	—	—
11	13S/12E-21AAC	31000654	44°26'03.12"	121°17'36.77"	2,810	584	—	—	X	—
12	13S/12E-22DAA	31000829	44°25'42.08"	121°16'12.50"	2,801	570	X	—	—	—
13	13S/12E-26CCD	31000830	44°24'30.15"	121°15'56.42"	2,725	200	X	—	—	—
14	13S/12E-36BDB	31000837	44°24'08.50"	121°14'33.72"	2,780	460	X	X	—	—
15	13S/13E-20DAC	31000164	44°25'26.29"	121°11'31.90"	2,865	540	X	—	—	—
16	14S/09E-08ABA	17001804	44°22'41.57"	121°40'54.84"	3,380	403	—	—	X	—
17	14S/10E-23BAA	17008590	44°20'53.00"	121°30'13.55"	3,310	840	X	—	—	—
18	14S/10E-28DDC2	17009175	44°19'16.74"	121°32'16.14"	3,145	149	—	—	X	—
19	14S/10E-28DDC3	17009174	44°19'17.41"	121°32'10.39"	3,146	328	X	—	—	—
20	14S/10E-30DDB2	17001835	44°19'26.20"	121°34'34.07"	3,218	200	—	—	—	X
21	14S/10E-34BCD	17008523	44°18'59.73"	121°31'49.11"	3,180	200	X	—	—	—
22	14S/11E-01DDD1	17001957	44°22'43.08"	121°21'03.83"	2,755	501	—	—	X	—
23	14S/11E-13BCC1	17001973	44°21'29.63"	121°22'13.04"	2,798	442	—	—	X	—
24	14S/11E-18BDB	17009237	44°21'37.98"	121°27'58.50"	3,040	560	X	—	X	—
25	14S/11E-22CDB	17009114	44°20'16.22"	121°24'19.69"	3,100	595	X	—	—	—
26	14S/12E-02CCC	17008626	44°22'45.20"	121°16'04.73"	2,680	160	X	—	—	—
27	14S/12E-15BDC	17008959	44°21'29.62"	121°17'04.92"	2,603	220	X	—	—	—
28	14S/12E-16DDD	17009048	44°20'59.67"	121°17'24.48"	2,660	180	X	—	X	—
29	14S/13E-05BCC	17008568	44°23'11.24"	121°12'21.01"	2,779	220	X	—	—	—
30	14S/13E-06BBD	17009049	44°23'23.11"	121°13'23.92"	2,743	200	X	—	—	—
31	14S/13E-13ACC	17009283	44°21'24.29"	121°06'57.72"	2,902	205	X	—	—	—
32	14S/13E-22CAC	17008542	44°20'18.01"	121°09'42.51"	2,908	260	X	—	—	—
33	14S/13E-27DAA1	17000313	44°19'34.28"	121°08'51.57"	2,953	252	—	—	X	—
34	14S/13E-31ABB	17008574	44°19'09.40"	121°13'02.70"	2,795	200	X	—	—	—
35	14S/13E-35DBD	17008958	44°18'33.93"	121°08'00.19"	3,002	340	X	—	—	—
36	14S/13E-36CAD	17009189	44°18'36.70"	121°07'07.65"	2,969	300	X	—	—	—
37	14S/15E-15DAC1	13000438	44°21'12.57"	120°54'28.10"	2,910	206	—	—	—	—
38	14S/15E-15DAC2	13000909	44°21'12.83"	120°54'28.01"	2,910	50	—	—	—	—
39	15S/10E-01CDD2	17000050	44°17'30.53"	121°29'00.13"	3,115	320	—	—	X	—
40	15S/10E-02DCB	17009187	44°17'41.83"	121°30'00.73"	3,140	200	X	—	—	—
41	15S/10E-05BBB	17002999	44°18'19.23"	121°34'20.56"	3,210	346	—	—	—	X
42	15S/10E-10DBC	17008625	44°16'55.69"	121°31'15.98"	3,161	110	X	—	—	—
43	15S/10E-25CAC	17009190	44°14'15.59"	121°29'10.99"	3,277	360	X	—	—	—
44	15S/10E-25CCA	17008614	44°14'10.16"	121°29'19.33"	3,290	380	X	—	—	—
45	15S/11E-04CDB	17008569	44°17'39.92"	121°25'33.26"	3,075	460	X	—	—	—
46	15S/11E-06ABD	17008601	44°18'14.22"	121°27'27.92"	3,140	520	X	—	—	—
47	15S/11E-16BDB	17003245	44°16'24.18"	121°25'33.36"	2,935	297	—	—	X	—
48	15S/11E-19AAA	17008962	44°15'41.36"	121°27'08.05"	3,152	360	X	—	X	—
49	15S/12E-02DCA	17008599	44°17'37.29"	121°15'17.29"	2,915	340	X	—	—	—
50	15S/12E-14CDD	17003581	44°15'46.63"	121°15'39.87"	2,975	303	—	—	X	—

Table 1. Data for selected wells in the upper Deschutes Basin, Oregon—Continued

Well location: Refer to "Well- and "Spring-Location System" for explanation. Log-ID number: Identification number permanently assigned to the well by the U.S. Geological Survey. Latitude/Longitude of well in °, degrees; ', minutes; ", seconds. Well elevation: Given in feet above sea level. Well depth: Depth of completed well, in feet below land surface. —, no sample or no data collected; X, sample collected.

Well number	Well location	Log-ID number	Latitude	Longitude	Well elevation (feet)	Well depth (feet)	Cuttings samples	Rock chemistry	Geo-physical log	Aquifer test
51	15S/13E-03DBD1	17003703	44°17'46.10"	121°09'10.20"	3,003	320	—	—	X	—
52	15S/13E-04CAB2	17003723	44°17'52.68"	121°10'51.42"	2,954	297	—	—	X	—
53	15S/13E-07CDD	17009192	44°16'36.09"	121°13'15.27"	2,974	300	X	—	—	—
54	15S/13E-20AAD	17051647	44°15'32.34"	121°11'18.12"	2,995	802	X	X	X	—
55	15S/13E-21ADB1	17003949	44°15'25.90"	121°10'17.44"	3,041	390	—	—	X	—
56	15S/13E-22BCD	17003952	44°15'18.53"	121°09'46.25"	3,045	740	—	—	X	—
57	15S/13E-22CBA2	17003951	44°15'14.90"	121°09'46.47"	3,053	801	—	—	—	X
58	15S/13E-29CAD2	17003981	44°14'14.15"	121°11'57.60"	3,090	485	—	—	X	—
59	15S/13E-31DAA	17009103	44°13'31.61"	121°12'35.99"	3,118	475	X	—	—	—
60	15S/14E-03BAA	13002959	44°18'19.43"	121°02'20.65"	2,991	320	X	X	—	—
61	15S/14E-14CDC	13002960	44°15'47.85"	121°01'13.39"	3,060	400	X	X	—	—
62	15S/14E-28DCD	13002967	44°14'01.43"	121°03'13.06"	3,104	450	X	—	—	—
63	15S/15E-01BDA	13000498	44°18'00.64"	120°52'37.73"	3,241	1,000	—	—	X	—
64	15S/15E-23BBB	13003200	44°15'40.68"	120°54'18.92"	3,265	410	X	X	—	—
65	15S/15E-29BAA	13003063	44°14'49.26"	120°57'25.65"	3,210	500	X	—	—	—
66	16S/10E-13BBB2	17009825	44°11'42.77"	121°28'55.57"	3,375	320	X	X	—	—
67	16S/11E-09BAC	17009069	44°12'28.25"	121°24'58.07"	3,221	360	X	—	—	—
68	16S/11E-12ADB	17009059	44°12'21.04"	121°20'47.69"	3,281	650	X	—	—	—
69	16S/11E-12ADB	17008638	44°12'10.46"	121°21'29.43"	3,281	675	X	—	—	—
70	16S/11E-18BAC	17009240	44°11'38.13"	121°27'23.39"	3,319	392	X	X	—	—
71	16S/11E-33DDD	17009104	44°08'19.07"	121°24'13.60"	3,522	750	X	X	—	—
72	16S/11E-35ACA2	17008615	44°08'55.49"	121°22'08.94"	3,410	708	X	—	—	—
73	16S/12E-10DCC	17009081	44°11'49.83"	121°16'20.20"	3,215	528	X	—	—	—
74	16S/12E-13BBB	17008524	44°11'41.35"	121°14'26.64"	3,185	540	X	—	—	—
75	16S/12E-14ACA	17009101	44°11'27.83"	121°14'55.56"	3,185	580	X	—	—	—
76	16S/12E-14BCC	17008612	44°11'23.69"	121°15'36.93"	3,185	430	X	—	—	—
77	16S/12E-17BBD	17008526	44°11'35.15"	121°19'10.35"	3,210	568	X	—	—	—
78	16S/12E-19ABA	17008636	44°10'49.03"	121°19'43.05"	3,265	600	X	—	—	—
79	16S/12E-21BDB	17008637	44°10'41.17"	121°17'50.28"	3,270	600	X	—	—	—
80	16S/12E-30BAA	17009051	44°09'59.43"	121°20'00.13"	3,285	625	X	—	—	—
81	16S/13E-16AAC	17004656	44°11'33.28"	121°10'01.08"	3,164	505	—	—	X	—
82	16S/13E-16CCA	17010139	44°10'59.92"	121°10'04.12"	3,215	580	X	—	—	—
83	16S/14E-17CDD	13050194	44°10'51.81"	121°04'35.20"	3,160	482	X	X	—	—
84	16S/14E-21BBD	13002966	44°10'41.16"	121°03'40.04"	3,241	640	X	X	—	—
85	17S/11E-03BBC1	17004676	44°08'09.07"	121°24'05.59"	3,538	670	—	—	X	—
86	17S/11E-24DCA	17001490	44°05'02.96"	121°20'58.36"	3,665	990	X	X	—	—
87	17S/11E-25CBA1	17004713	44°04'22.60"	121°21'36.31"	3,745	358	—	—	X	—
88	17S/12E-09CCD1	17004896	44°06'35.92"	121°17'57.55"	3,465	454	—	—	X	—
89	17S/12E-11DDB	17009078	44°06'42.09"	121°14'43.43"	3,400	640	X	X	—	—
90	17S/13E-19ABD	17005118	44°05'34.22"	121°12'33.56"	3,462	627	—	—	X	—
91	17S/13E-20DAD	17009161	44°05'08.10"	121°11'03.68"	3,415	625	X	X	—	—
92	17S/14E-02CAA	17009317	44°07'35.39"	121°01'05.95"	3,306	845	X	X	X	—
93	17S/14E-11DCB	17009319	44°06'29.49"	121°00'57.96"	3,350	720	X	X	—	—
94	17S/14E-28ABC	17001610	44°04'34.87"	121°03'14.81"	3,365	680	X	—	—	—
95	18S/09E-20BDA	17005215	44°00'16.82"	121°03'14.81"	6,310	780	—	—	—	X
96	18S/11E-21CDD	17005258	43°59'37.48"	121°24'50.05"	4,060	547	—	—	X	—
97	18S/11E-27ACD	17009163	43°59'14.55"	121°23'22.70"	3,960	205	X	—	—	—
98	18S/11E-27BCB1	17005526	43°59'20.96"	121°24'06.37"	3,942	300	—	—	X	—
99	18S/12E-05BDB	17005576	44°02'47.39"	121°19'01.41"	3,620	701	—	—	X	X
100	18S/12E-05CCC1	17005584	44°02'15.71"	121°19'20.20"	3,633	258	—	—	X	—

Table 1. Data for selected wells in the upper Deschutes Basin, Oregon—Continued

Well location: Refer to "Well- and "Spring-Location System" for explanation. Log-ID number: Identification number permanently assigned to the well by the U.S. Geological Survey. Latitude/Longitude of well in °, degrees; ', minutes; ", seconds. Well elevation: Given in feet above sea level. Well depth: Depth of completed well, in feet below land surface. —, no sample or no data collected; X, sample collected.

Well number	Well location	Log-ID number	Latitude	Longitude	Well elevation (feet)	Well depth (feet)	Cuttings samples	Rock chemistry	Geo-physical log	Aquifer test
101	18S/12E-07DBD1	17001738	44°01'40.99"	121°19'44.07"	3,835	800	X	X	—	—
102	18S/12E-10ADA1	17005597	44°01'55.82"	121°15'52.63"	3,688	750	—	—	X	—
103	18S/12E-14CAD	17009576	44°00'42.73"	121°15'10.16"	3,698	715	X	—	X	—
104	18S/12E-14DBD	17009577	44°00'45.83"	121°14'56.50"	3,703	760	X	—	X	—
105	18S/12E-31DCA	17009399	43°58'01.98"	121°19'41.94"	4,125	670	X	—	—	—
106	18S/13E-01CCD	17005701	44°02'14.49"	121°07'08.54"	3,495	902	—	—	X	—
107	18S/13E-10AAC	17005709	44°02'00.87"	121°08'49.11"	3,570	875	—	—	X	—
108	18S/13E-24DCB	17009222	43°59'43.90"	121°06'58.41"	3,612	710	X	X	—	—
109	19S/11E-16ACC	17005741	43°55'48.04"	121°24'48.39"	4,187	247	—	—	X	—
110	19S/11E-25BAA	17050111	43°54'22.79"	121°21'21.13"	4,515	434	—	—	X	—
111	19S/14E-02DAA2	17009126	43°57'07.94"	121°00'27.71"	3,579	1,135	X	—	—	—
112	20S/10E-12CCC	17008629	43°51'00.33"	121°29'05.35"	4,221	102	X	—	—	—
113	21S/10E-21BDC	17008560	43°44'26.62"	121°32'20.54"	4,257	80	X	—	—	—
114	21S/11E-18CDA3	17007618	43°45'01.88"	121°27'24.05"	4,208	40	—	—	X	—
115	21S/11E-32BBD	17008562	43°42'53.17"	121°26'34.89"	4,265	115	X	—	—	—
116	22S/10E-08DBD	17008561	43°40'44.65"	121°33'04.14"	4,237	40	X	—	—	—
117	22S/10E-14CBB	17008506	43°39'55.73"	121°30'10.49"	4,228	27	X	—	—	—
118	22S/10E-14CCA	17009173	43°39'47.96"	121°30'00.83"	4,227	555	X	—	—	—
119	23S/09E-36BBC	35000136	43°32'31.81"	121°36'03.10"	4,332	470	—	—	X	—
120	23S/10E-36DDC	35000138	43°31'52.61"	121°28'13.86"	4,308	130	—	—	X	—

Fifty samples of lava from cuttings collected from wells within the project area were selected for chemical analysis. The samples were analyzed with an x-ray fluorescence technique at the Washington State University GeoAnalytical Laboratory. The analysis technique used is described in Johnson and others (1999).

GEOLOGIC SETTING

Regional Setting

Most of the upper Deschutes Basin falls within two major geologic provinces (fig. 5), the Cascade Range and the Basin and Range Province (Baldwin, 1981). The Basin and Range Province is considered herein to include the southern part of the High Lava Plains. The geologic processes that have operated in these provinces have overlapped and interacted in much of the upper Deschutes Basin. The Cascade Range is a north-south trending zone of compositionally diverse volcanic eruptive centers with deposits extending from northern California to southern British Columbia. Prominent among the eruptive centers in the Deschutes Basin are large stratovolcanoes such as North, Middle, and South Sister, and Mount Jefferson, all of which exceed 10,000 ft above sea level in elevation. The Cascade Range is primarily a constructional feature, but its growth has been accompanied, at least in places, by subsidence of the range into a north-south trending graben (Allen, 1966). Green Ridge is the eastern escarpment of one of the graben-bounding faults. The Basin and Range Province is a region of crustal extension and is characterized by subparallel fault-bounded down-dropped basins separated by fault-block ranges.

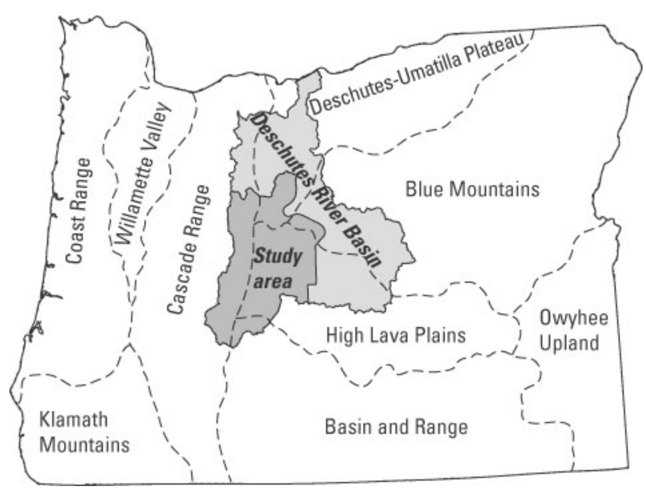


Figure 5. Location of the Deschutes Basin in relation to the physiographic provinces of Oregon. (Provinces from Baldwin, 1981)

Individual basins and intervening ranges are typically 10 to 20 miles across. The Basin and Range Province encompasses much of the interior of the Western United States, extending from central Oregon south through Nevada and western Utah, into the southern parts of California, Arizona, and New Mexico. Although the Basin and Range Province is primarily structural, faulting has been accompanied by widespread volcanism.

Depositional History and Mechanisms

Most of the geologic features in the study area are the result of about 30 million years of volcanic activity related to a north-south trending volcanic arc, the most recent manifestation of which are today's Cascade Range volcanoes. Volcanic and tectonic activity over the past 8 to 10 million years in the Basin and Range and High Lava Plains has also helped shape the present landscape. Most of the rock units in the study area that are important water-bearing units were formed within the past 7 million years.

Various types of volcanic rocks and associated sedimentary deposits have different hydrologic properties, such as permeability. Understanding the volcanic and depositional processes that control the distribution of different rock types, therefore, can provide insight into the geographic distribution of permeability. The hypothetical cross-section in figure 6 illustrates some of those concepts. For example, the proportion of lava decreases, and the proportion of volcanically derived sediment increases, with distance from a volcanic vent. This factor influences distribution of permeability within the Deschutes Basin. In addition, the grain size of volcaniclastic sediment tends to decrease as distance from the volcanic vent increases. This also has a direct bearing on permeability. Some volcanic products, such as gas-charged ash-flows (ignimbrites) and some basalt flows, have enough fluidity to travel miles from their sources, often along preexisting stream drainages. These drainage-filling deposits create variations in permeability, and the paleodrainages may define preferential flow paths within the ground-water flow system. Finally, at some distance away from volcanic vents, fluvial processes dominate volcanic processes and become the major factor controlling grain-size distribution.

The oldest rock unit within the study area, the John Day Formation, is about 20 to 40 million years old. The John Day Formation comprises several thousand feet of diagenetically altered volcanic and volcanically derived sedimentary deposits (Robinson and others, 1984). The unit also contains numerous partially eroded volcanic vents. Powell Buttes, Smith Rock, and Juniper Butte are examples of John Day Formation outcrops within the study area.

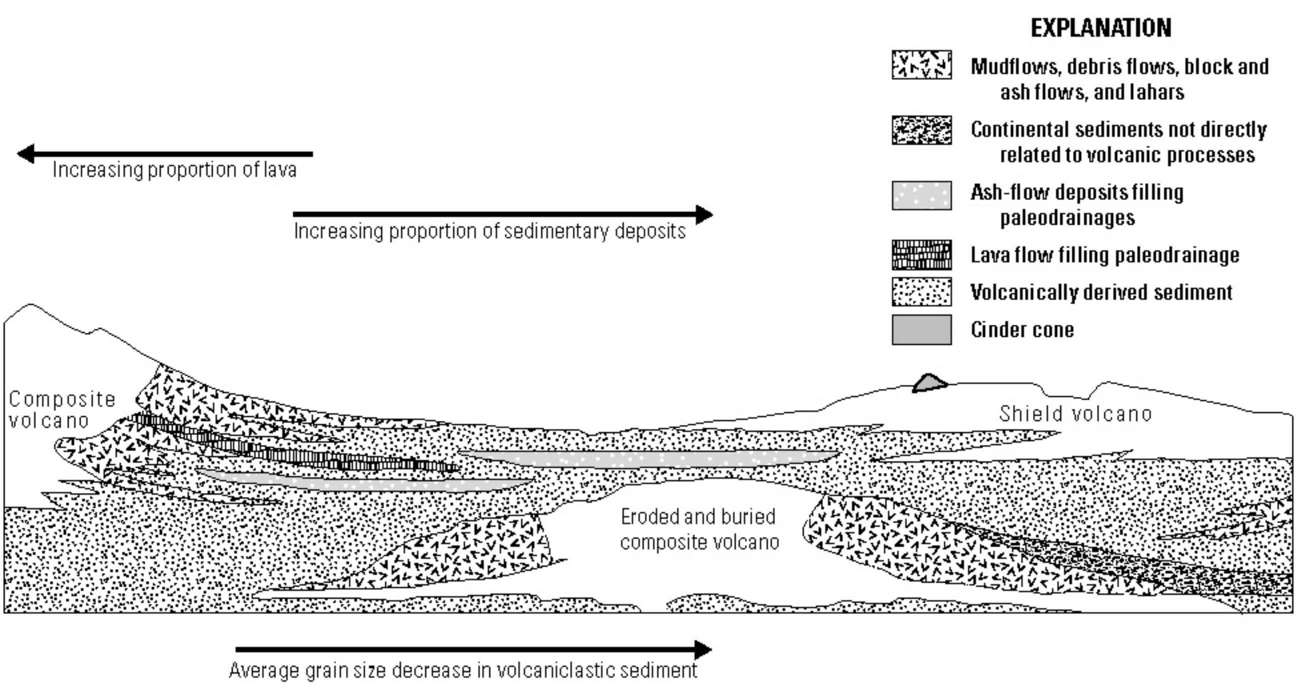


Figure 6. Diagrammatic section through a volcanic arc and adjacent area showing the relation between volcanic and sedimentary facies. (Modified from Sherrod and Smith, 2000)

The next major surge in volcanic activity occurred between 7 and 4 million years ago. That volcanic activity produced the Deschutes Formation, a sequence of lava flows, pyroclastic deposits, volcaniclastic deposits, and sediment more than 2,000 ft thick (Smith, 1986b). The volcanic eruptions that generated the Deschutes Formation culminated with the formation of a down-faulted depression along the axis of the Cascade Range (Allen, 1966; Smith and others, 1987). The western slope of Green Ridge, along the Metolius River, is an escarpment formed by one of the faults bounding the depression. Subsequent volcanic deposits have buried most other bounding faults.

Other volcanic activity was occurring within the High Lava Plains and Basin and Range Provinces coincident with that associated with the Deschutes Formation. Lava flows of today's Horse Ridge and Walker Rim are notable products of that activity.

The last episode of volcanic activity has been ongoing since the late Pliocene, or about the past 3 million years (Sherrod and Smith, 2000). The focus of that activity has been predominately within the Cascade Range and at Newberry Volcano. Volcanic activity in the Cascade Range has produced a few thousand feet of lava flows with lesser pyroclastic material and sediment. Thicker accumulations occur at the sites of the large composite volcanoes such as North, Middle, and South Sister. The youngest volcanic deposit within the study area, an obsidian flow and related pyroclastic deposit at Newberry Volcano, is about 1,300 years old (MacLeod and others, 1995).

Glacial deposits within the study area result from episodic glaciation since the late Pleistocene, a period of about 150,000 years (Scott, 1977; Scott and Gardner, 1992; Sherrod and others, in press). However, most of the glacial material mapped within the study area is from the Suttle Lake advance (of the Cabot Creek glaciation), which culminated about 20,000 years ago (Sherrod and others, in press). Minor Neoglacial deposits, which occur near the summits of the highest peaks, range in age from a few hundred to a few thousand years.

STRATIGRAPHIC UNITS

John Day Formation

The John Day Formation, the oldest unit in the study area, consists of a stratigraphically complex assemblage of early Tertiary lava flows, pyroclastic deposits, sedimentary strata, and volcanic vent deposits (unit Tjd on plate 1) (Robinson and others, 1984; Smith and others, 1998). The unit ranges in age from 39.17 Ma (mega-annum: million years before present) to 22 Ma (Smith and others, 1998). The John Day Formation is exposed in outcrops along the eastern and northern edges of the study area. The unit as a whole has relatively low permeability and is considered to be the hydrologic basement for the ground-water flow system within the study area (Gannett and others, 2001).

Prineville Basalt

Middle Miocene volcanic activity near present-day Bowman Dam produced a few hundred feet of lava flows called the Prineville Basalt (Uppuluri, 1974); its age is about 15.7 Ma (Smith, 1986b). The Prineville Basalt (unit Tpb on plate 1) crops out in the Crooked River canyon near Prineville, the Deschutes River canyon north of Round Butte Dam, and near Gateway. Locally it serves as a source of ground water in the area between the Crooked River and the northern side of Powell Buttes (east of Dry River), and near Madras and Gateway.

Deschutes Formation

Late Tertiary Deschutes Formation and age-equivalent strata constitute the principal aquifer within the study area. The Deschutes Formation ranges in age from 7.5 to 4.0 Ma (Smith, 1986b). The rock units are identified on plate 1. The Deschutes Formation comprises hundreds of volcanic deposits and countless sedimentary beds.

Deschutes Formation material represents a classic example of basin-filling sedimentation resulting from episodic volcanic eruptions. The volcanic and volcaniclastic depositional mechanisms discussed in the previous section apply to the Deschutes Formation.

The Deschutes Formation includes several intrabasin volcanic vents, which range from basalt to rhyolite in composition. Notable mafic vents include Tetherow, Long, and Awbrey Buttes, whereas silicic vents include a rhyolite dome complex at Cline Buttes and a rhyodacite dome complex near Steelhead Falls. The silicic domes exhibit remarkably high permeability.

Smith (1986b) recognized three major depositional environments in the Deschutes Formation: an arc-adjacent alluvial plain, the ancestral Deschutes River, and the inactive-basin margin. These environments are responsible for the compositional variability within the formation (fig. 7). The arc-adjacent alluvial plain comprises Cascade Range derived lava flows, ash-flow tuffs, fallout tephra, volcaniclastic sediment, debris flows, and hyperconcentrated flood deposits. The ancestral Deschutes River deposits include alluvial-channel deposits, hyperconcentrated flood deposits, and intracanyon lava flows and ash-flow deposits. The inactive-basin margin comprises poorly sorted alluvium originating from the Ochoco and Mutton Mountains, reworked fallout tephra from the Cascade Range, and sparse lava flows from vents south and east of the basin.

The permeability of the Deschutes Formation and equivalent rocks ranges from relatively low in fine-grained sedimentary deposits, dense lava flows, and ignimbrites to high in coarse-grained unconsolidated sedimentary deposits and vesicular and brecciated lava flows. Two basalt units within the Deschutes Formation, the Opal Springs basalt and Pelton basalt, are well known for their large springs that discharge to the Crooked and Deschutes Rivers (Stearns, 1931; Sceva, 1968).

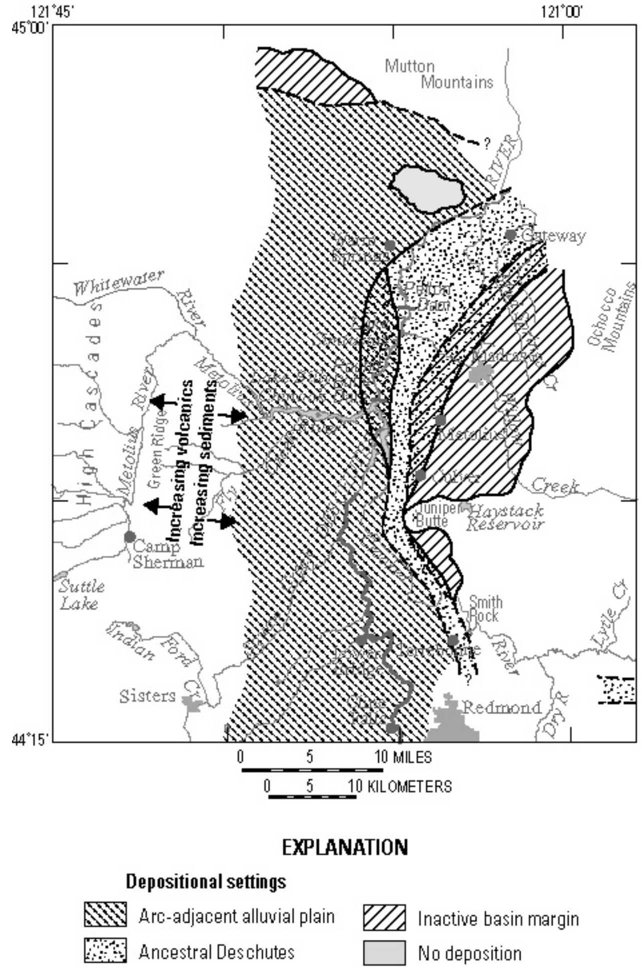


Figure 7. Areal distribution of facies within the Deschutes Formation. (From Smith, 1991)

Deposits of the Cascade Range and Newberry Volcano

The Cascade Range and parts of the High Lava Plains and Basin and Range Provinces consist of late Tertiary to Quaternary lava flows, lava domes, volcanic vents, pyroclastic deposits, and volcaniclastic sediment (Sherrod and Smith, 2000). Newberry Volcano is composed of similar material but is all Quaternary in age. The rock units are identified on plate 1. The relatively young volcanic deposits are thick in the Cascade Range, where 1.8-Ma rocks were found at a depth of 3,044 ft at Santiam Pass (Hill, 1992).

The surfaces of the young volcanic deposits are commonly fractured and brecciated, making them extremely permeable. Much of the precipitation in the Cascade Range percolates through these rocks to recharge the ground-water flow system. The large number of springs and lack of incised surface-water drainages in the Cascade Range, high seepage loss from canals near Bend, and high streamflow loss south of Bend demonstrate the permeable nature of the deposits (Gannett and others, 2001).

Quaternary Sedimentary Deposits

Several Quaternary-age sedimentary deposits occur within the study area (plate 1). Pleistocene to Holocene sedimentary deposits (Qs) resulted from several processes, including mass wasting of upland deposits, alluviation by high-energy streams, and deposition in low-energy streams and lakes. These sedimentary deposits are locally a few hundred feet thick. Glacial deposits (Qg) are predominately Pleistocene-age till. Glacial deposits are generally less than a few tens of feet thick except at lateral moraines, where deposits may be as much as a few hundred feet thick. Alluvial deposits (Qal) are mostly late Pleistocene to Holocene in age and are generally less than a few tens of feet thick. Alluvial deposits have not been distinguished from the generalized sedimentary unit (Qs) on some of the published geologic maps, particularly within the La Pine subbasin.

TECTONIC STRUCTURES

Faults and fault-bounded grabens are the most common geologic structures in the upper Deschutes Basin. Faults can have a profound effect on ground water, serving either as boundaries to flow or as conduits for flow. Faults can act as boundaries to flow where they juxtapose rocks of contrasting permeability. This juxtaposition can be caused by fault movement, or by the fault's influence on subsequent deposition. In the upper Deschutes Basin, it appears that the faults affect ground water primarily by their influence on deposition. The resulting juxtaposition of geologic units has produced permeability contrasts across the faults. Like the stratigraphic units within the study area, the tectonic structures are the result of complex volcano-tectonic interactions over a relatively long (30 million years) time period. However, most of the faults seen at the surface have formed as a result of tectonic activity within the past 7.5 million years. The ages of deformation within the study area generally are not precisely known but are constrained by radiometric ages on many stratigraphic units. The major tectonic structures within the study area include the Cyrus Springs fault zone, Brothers fault zone, faults forming the west side of Green Ridge, the Sisters fault zone (including the Tumalo fault), faults forming the western side of Walker Rim, the Chemult graben, and the La Pine and Shukash grabens (fig. 8). These are all described in the following paragraphs.

Cyrus Springs Fault Zone

The Cyrus Springs fault zone is by far the oldest structural feature identified within the study area. The fault zone cuts the John Day Formation and is believed to have become active between 28 and 30 million years ago (Smith and others, 1998). Faults within the Cyrus Springs fault zone are oriented primarily N 45° to 60°E, and are exposed along a trace only about 3.5 miles long. However, the fault zone exhibits about 3,800 ft of vertical offset and possibly over 4 miles of right-lateral displacement (Smith and others, 1998). Movement on the fault zone appears to be restricted to mid-Oligocene to mid-Miocene time because overlying Deschutes Formation deposits at both ends of the fault trace are undeformed (Sherrod and others, in press). Thus, the Cyrus Springs fault zone is contained entirely within low-permeability strata and does not appear to have any direct influence on the regional ground-water flow system.

Brothers Fault Zone

The Brothers fault zone is a northwest-trending zone of closely spaced en echelon normal faults that extend from the southeastern part of Oregon to the Deschutes Basin, a distance of about 150 miles (Walker and Nolf, 1981). The northern terminus of the fault zone is within the study area and is shown on figure 8. The Brothers fault zone has been recognized as a significant tectonic feature in Oregon (Walker, 1969; Lawrence, 1976; Walker and Nolf, 1981). Walker and Nolf (1981) speculate that the normal faults and many of the volcanic vents along the fault zone are surface manifestations of deformation on a large, deeply buried structure, and that the associated volcanic vents along the fault zone indicate episodic activity over time. Individual faults within the fault zone offset strata between 3 and 300 ft (Walker and Nolf, 1981).

The northernmost segment of the Brothers fault zone is near the boundary between late Miocene and younger rocks to the southwest, and the middle Miocene and older Blue Mountains Province to the northeast. The northwest terminus of the Brothers fault zone offsets 7.5-million-year-old lava on Horse Ridge in the southeast corner of the study area. However, the fault zone does not offset the 0.7-million-year-old lava flows at the Badlands just north of Horse Ridge.

Ground-water flow does not appear to be affected by the Brothers fault zone within the study area. Sparse ground-water-level data within the fault zone suggest that ground-water flow is not interrupted as it crosses several fault strands within the fault zone (fig. 9).

Sisters Fault Zone

The Sisters fault zone trends north-northwest from the vicinity of Newberry Volcano to Black Butte, a distance of about 37 miles (fig. 8). The fault zone comprises about 50 mapped faults and has one fault, the Tumalo fault, that is continuous for about 30 miles (Sherrod and others, in press). The youngest unit offset by the Sisters fault zone is an alluvial deposit near Upper Tumalo Reservoir (Taylor, 1981). The faulted alluvium is overlain by undeformed alluvium, and the youngest probable age of deformation is about 25,000 years (Sherrod and others, in press).

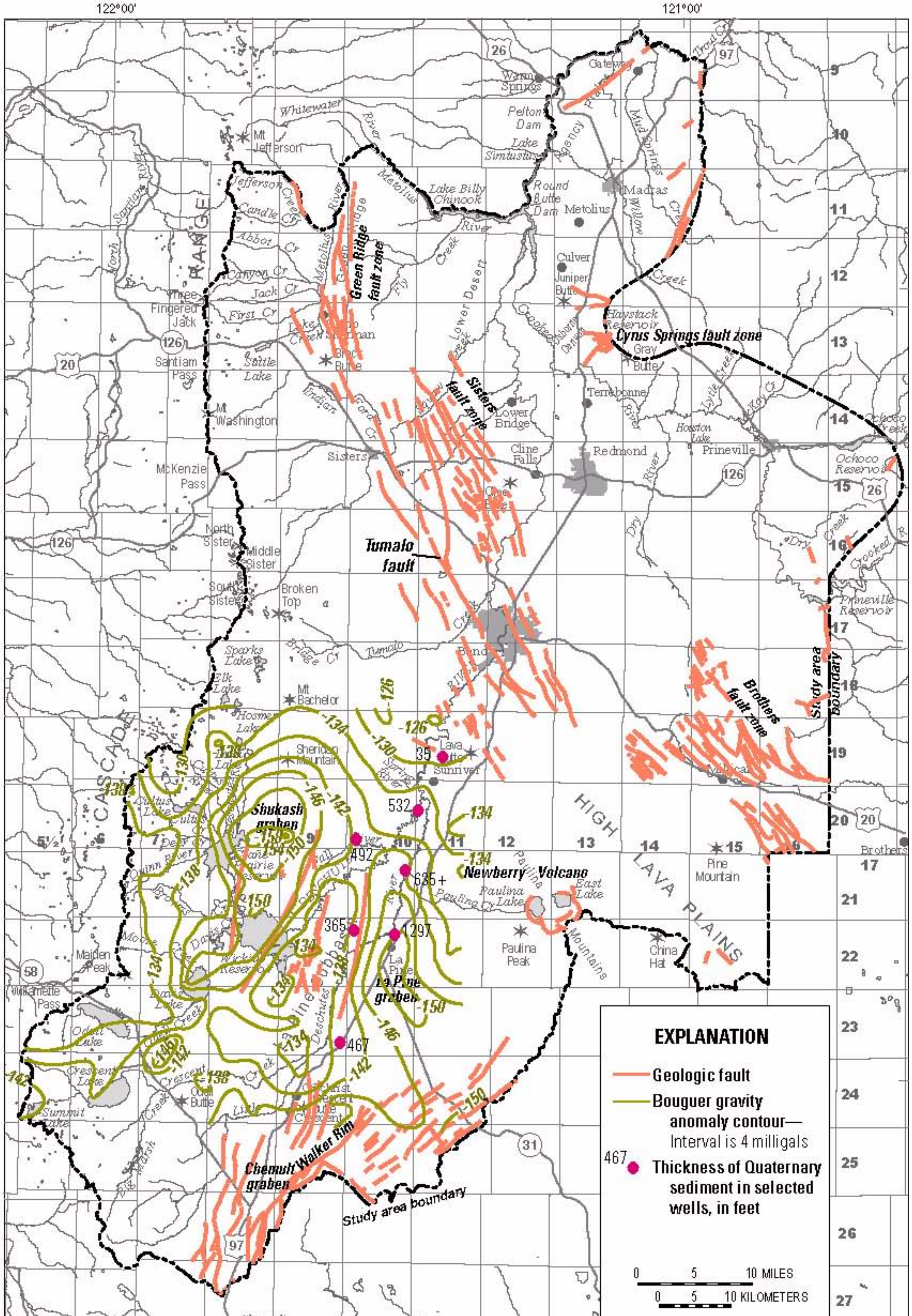


Figure 8. Major tectonic structures in the upper Deschutes Basin, Oregon. (Gravity contours from Pitts and Couch, 1978)

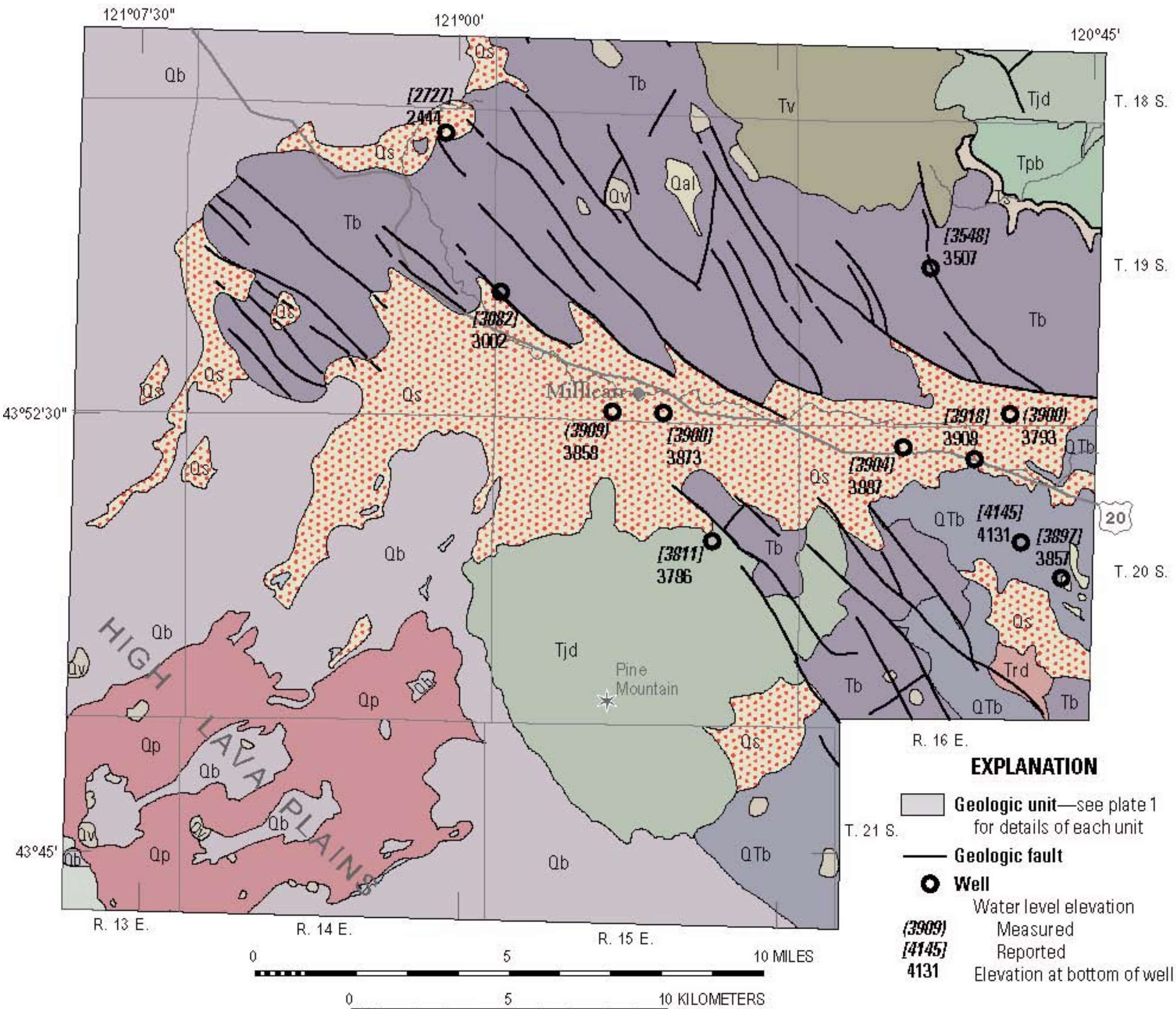


Figure 9. Geologic units, fault traces, and hydraulic head in wells in the vicinity of the Brothers fault zone, upper Deschutes Basin, Oregon.

Movement along the Tumalo fault was chiefly dip slip. As much as 180 to 200 ft of dip separation has occurred near upper Tumalo Reservoir. Quaternary lava flows younger than 0.78 million years, exposed in the same area, exhibit escarpments of 20 to 30 ft (Sherrod and others, in press).

It is difficult to know what, if any, direct influence the Sisters fault zone has on regional groundwater flow. The trace of the fault zone is coincident with the eastern edge of a steep precipitation (and recharge) gradient. The net result is that the water-table gradient also changes slope in the vicinity of the Sisters fault zone, obscuring any direct effects from the fault zone itself (fig. 10).

The westernmost fault strands of the Sisters fault zone that exhibit down-to-the-west displacement (notably the Tumalo fault) were partial barriers to streams flowing eastward from the Cascade Range and, thus, formed depositional centers for Pleistocene volcanic and glacial outwash deposits. The permeability contrast between the Pleistocene deposits and the upper Miocene to Pliocene Deschutes Formation strata has formed several shallow aquifers, the most extensive of which is in the glacial outwash in the vicinity of Sisters (fig. 11).

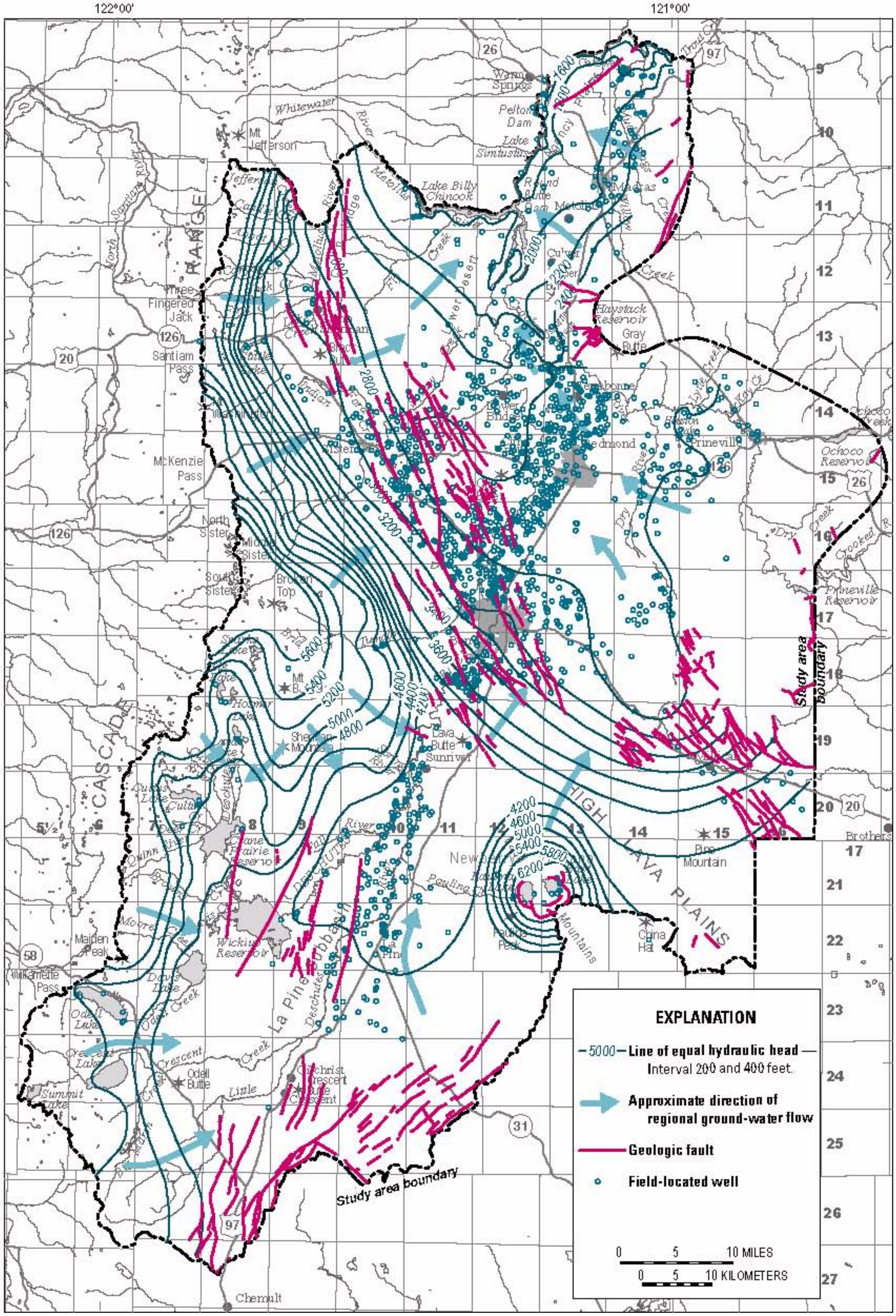


Figure 10. Generalized lines of equal hydraulic head, ground-water flow directions, and major tectonic structures in the upper Deschutes Basin, Oregon. (Head contours from Gannett and others, 2001)

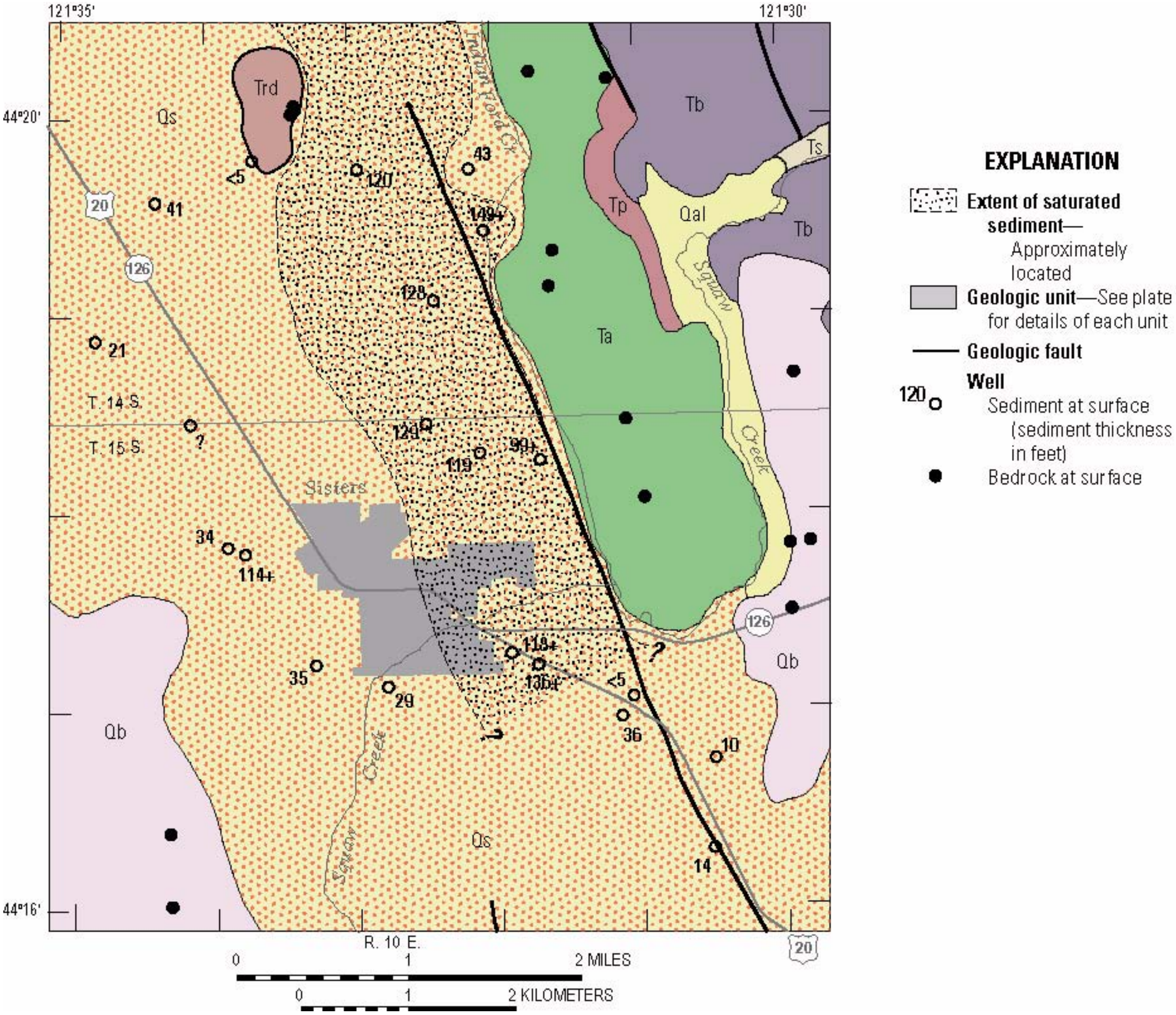


Figure 11. Thickness of Quaternary sediment in field-located wells and the approximate extent of saturated sediment in the Sisters area, upper Deschutes Basin, Oregon.

Green Ridge

Green Ridge is a 20-mile-long, north-trending escarpment in the northwestern part of the study area (fig. 8). The feature represents the east margin of an intra-arc graben within the Cascade Range (Allen, 1966; Taylor, 1981; Smith and others, 1987). Initial subsidence of the High Cascade Range occurred about 5.4 million years ago (Smith and others, 1987). According to Smith and others (1987), Green Ridge and its east-sloping flank are all that remains in this area of a once-stable Pliocene-age eastern Cascade Range foothills. The region to the west of Green Ridge has dropped as much as 3,000 ft (Conrey, 1985).

Virtually all the ground water that is recharged in the Metolius subbasin discharges west of the Green Ridge escarpment (Gannett and others, 2001). Over 1,000 ft^3/s of ground water discharges to the Metolius River and its tributary springs and creeks between the headwaters and the confluence with Jefferson Creek, 10 miles downstream. The precise mechanism that causes the discharge is not clearly known, but it probably is related to the Green Ridge structure. One possible explanation is that a permeability contrast exists between Deschutes Formation rocks forming the escarpment and flooring the eastern margin of the intra-arc graben and the Pliocene and Pleistocene volcanic and volcaniclastic material filling the graben. Another explanation is that the fault zone and possibly related dikes form a boundary to horizontal ground-water flow. The most likely explanation is that a combination of mechanisms is responsible.

Walker Rim Fault Zone and Chemult Graben

The Walker Rim fault zone is a north- to north-east-trending series of basin and range normal faults south of La Pine (fig. 8). The faults form an arcuate pattern with generally down-to-the-west displacement (MacLeod and Sherrod, 1992). The surface traces of the faults terminate on the southern flank of Newberry Volcano. The Walker Rim fault zone forms the east boundary of the Chemult graben. The Chemult graben is about 6 miles wide; its floor is composed of a series of bedrock horst blocks that are thickly mantled by Holocene pyroclastic flow and fall deposits from Mount Mazama (MacLeod and Sherrod, 1992).

Water-level data indicate that a low gradient ground-water divide may be coincident with the Walker Rim fault zone. However, only sparse ground-water elevation data exist in and around the Walker Rim fault zone, so precise characteristics of the ground-water flow system in the vicinity of the Walker Rim fault zone are uncertain.

La Pine and Shukash Grabens

The La Pine and Shukash grabens are two side-by-side, north-northeast trending, elongate structures separated by a north-northeast trending horst block (MacLeod and Sherrod, 1992). The grabens are located in the southwestern part of the study area generally referred to as the La Pine subbasin (fig. 8). Most of what is known about the subsurface in the grabens is based on geophysical data (Couch and Foote, 1985). According to Couch and Foote (1985), the grabens possess 1,800 to 2,400 ft of structural relief that has been filled with sediment. That conclusion is supported in the La Pine area by data from deep (555 to 1,460 ft) water wells. MacLeod and Sherrod (1992) speculate that the La Pine graben marks the structural boundary between the Basin and Range and Cascade Range Provinces.

The La Pine and Shukash grabens formed a depositional center filled by low-permeability, fine-grained sediment. These deposits have resulted in a permeability contrast within the La Pine subbasin that affects ground-water flow. Hundreds of feet of low-permeability, fine-grained sediment in the grabens is juxtaposed and interbedded with permeable lava from Newberry Volcano and the Cascade Range at the graben margins. Many spring complexes occur along the western margin of the Shukash graben. It is likely that these springs occur where water moving eastward from the Cascade Range encounters the low-permeability, basin-filling deposits and is diverted to the surface. The fine-grained basin-filling deposits are overlain by a thin deposit of more permeable, coarser-grained sediment. This stratigraphic sequence results in a shallow, flat water table within the La Pine subbasin. At the northern end of the La Pine subbasin, near Sunriver, the water table slopes steeply towards the north and the depth to water increases (fig. 10) (also see Gannett and others, 2001).

HYDROGEOLOGY

John Day Formation

Ground-water flow in the study area is strongly influenced by a low-permeability boundary at the top of the John Day Formation (Tjd on plate 1). Regional ground water, which flows in a northerly direction across most of the study area, ultimately discharges to the surface when it encounters the low-permeability rocks of the John Day Formation. The same low permeability of the rocks also makes the unit a poor source of water.

The John Day Formation is a sequence of upper Eocene to lower Miocene volcanic, volcaniclastic, and sedimentary rocks that is locally up to 4,000 ft thick (Robinson and others, 1984). The John Day Formation was subdivided into members by Peck (1964) and Smith and others (1998) and into facies by Robinson and others (1984) within and adjacent to the upper Deschutes Basin study area. The upper Deschutes Basin study area borders parts of the western and southern facies of Robinson and others (1984), and contain Peck's (1964) Members A through I (Smith, 1987; Smith and Hayman, 1987; Smith and others, 1998).

Lapilli tuff and tuffaceous claystone make up about 70 to 75 percent of the western facies of the John Day Formation (Robinson and others, 1984). These pyroclastic deposits were once almost entirely glass-rich volcanic ash. Over time, the glass has been weathered or diagenetically altered to clay (Robinson and others, 1984), and the porosity and permeability of the formation has been greatly reduced as a result.

The John Day Formation within the northern part of the study area consists of the western facies deposits and has been correlated to Member I of Peck (1964) (Smith, 1987; Smith and Hayman, 1987). Smith (1987), and Smith and Hayman (1987) describe the unit as tuff, lapillistone, fine-grained volcanic sandstone, and mudstone.

Almost the entire sequence of John Day Formation rocks (units A–H) has been recognized along the northeastern edge of the study area from the vicinity of Smith Rock north to Haystack Reservoir (Smith and others, 1998). Additionally, Powell Buttes has been correlated with the John Day Formation (Robinson and others, 1984; Sherrod and others, in press). Powell Buttes consist of a sequence of rhyolite domes and associated strata (Sherrod and others, in press) about 28 Ma in age, within the age range of John Day Formation unit G.

The John Day Formation in the vicinity of Prineville has been subdivided only on the basis of general compositional characteristics. Swanson (1969) described the John Day rocks near Prineville as principally bedded tuff, lapilli tuff, tuffaceous sediment; welded rhyolitic ash-flow tuff; and rhyolite and dacite flows and domes.

John Day Formation rocks usually are easy to determine from well reports because of the predominance of material described by the drillers as clay or claystone. The wells in the northern part of the study area drilled into John Day Formation clay and claystone are presumably constructed into unit I, based on surface geologic mapping. The predominance of clay, in addition to the generally silicic nature of John Day Formation rocks, also produce a relatively high gamma signature on natural gamma logs. Figure 12 shows the natural gamma trace for two wells (10S/12E-01CDD2, well no. 3, plate 1; and 11S/14E-34ABC, well no.7, plate 1) in the northern part of the study area drilled into the John Day Formation.

Alteration of the rocks within the John Day Formation has affected the unit's permeability and, therefore, well yields. Published hydraulic conductivity estimates for John Day Formation rocks in the upper Deschutes Basin range from 0.01 to 0.1 ft/d (feet per day) (Bolke and Laenen, 1989). Many of the wells open to water-bearing zones within the John Day rocks have yields that are less than 10 gal/min (gallons per minute). The exceptions to this generalization occur where wells intercept water-bearing fractures within some ignimbrite units. A notable example is just outside the study area near Hay Creek, 15 miles northeast of Madras, where wells yield up to a few hundred gallons per minute (Norton, 1988). Those conditions may also exist locally within the study area as well. However, the few good aquifers within the John Day Formation are of limited extent, are poorly connected, and probably have limited long-term water-supply capacity. The overall low permeability of the John Day Formation makes it a boundary to the regional groundwater flow system in the upper Deschutes Basin.

Prineville Basalt

The Prineville Basalt (Tpb on plate 1) is the oldest stratigraphic unit that bears substantial water in the upper Deschutes Basin. The Prineville Basalt is utilized as a source of ground water in three areas: just north of Powell Buttes, between Powell Buttes and the Crooked River, and near Gateway, northeast of Madras.

The Prineville Basalt is a series of middle Miocene lava flows that have a maximum thickness of nearly 700 ft within the upper Deschutes Basin study area (Smith, 1986b). Prineville Basalt flows cover an area of at least 4,200 mi^2, from just south of Bowman Dam to the Portland area (Hooper and others, 1993). The flows are compositionally similar to each other, but chemically distinct from other basalt by their exceptionally high barium and phosphorus contents (Uppuluri, 1974). Smith (1986b) identified variations in silica (SiO_2) content among the flows and characterized flows as either high (~54 percent) or low (~51 percent) in SiO_2. The low-SiO_2 unit near Pelton Dam has an age of 15.7 Ma (Smith, 1986b). The high- and low- SiO_2 flows have also been identified in the northernmost part of the upper Deschutes study area near Gateway (Smith, 1986b; Smith, 1987; and Smith and Hayman, 1987).

The natural gamma log for well 09S/14E-27BBA (well no. 2, plate 1) near Gateway shows the subtle chemical differences between the high-SiO_2 and low-SiO_2 Prineville Basalt flows (fig. 13). The gamma trace for the lava flows reflects the differences in potassium oxide (K_2O) content of the two flows. According to Smith and Hayman (1987), the high-SiO_2 flow contains 3.3 weight percent K_2O and the low-SiO_2 flow contains 2.1 weight percent K_2O. The elevation of the contact at 190 ft depth in well 09S/14E-27BBA is roughly coincident with the elevation of the contact between high-SiO_2 and low-SiO_2 flows mapped nearby by Smith and Hayman (1987). The gamma spike at approximately 230 ft depth represents a 4 ft sedimentary interbed that was described by the well driller as green sand and sandstone. That interbed may be part of the Simtustus Formation of Smith (1986a).

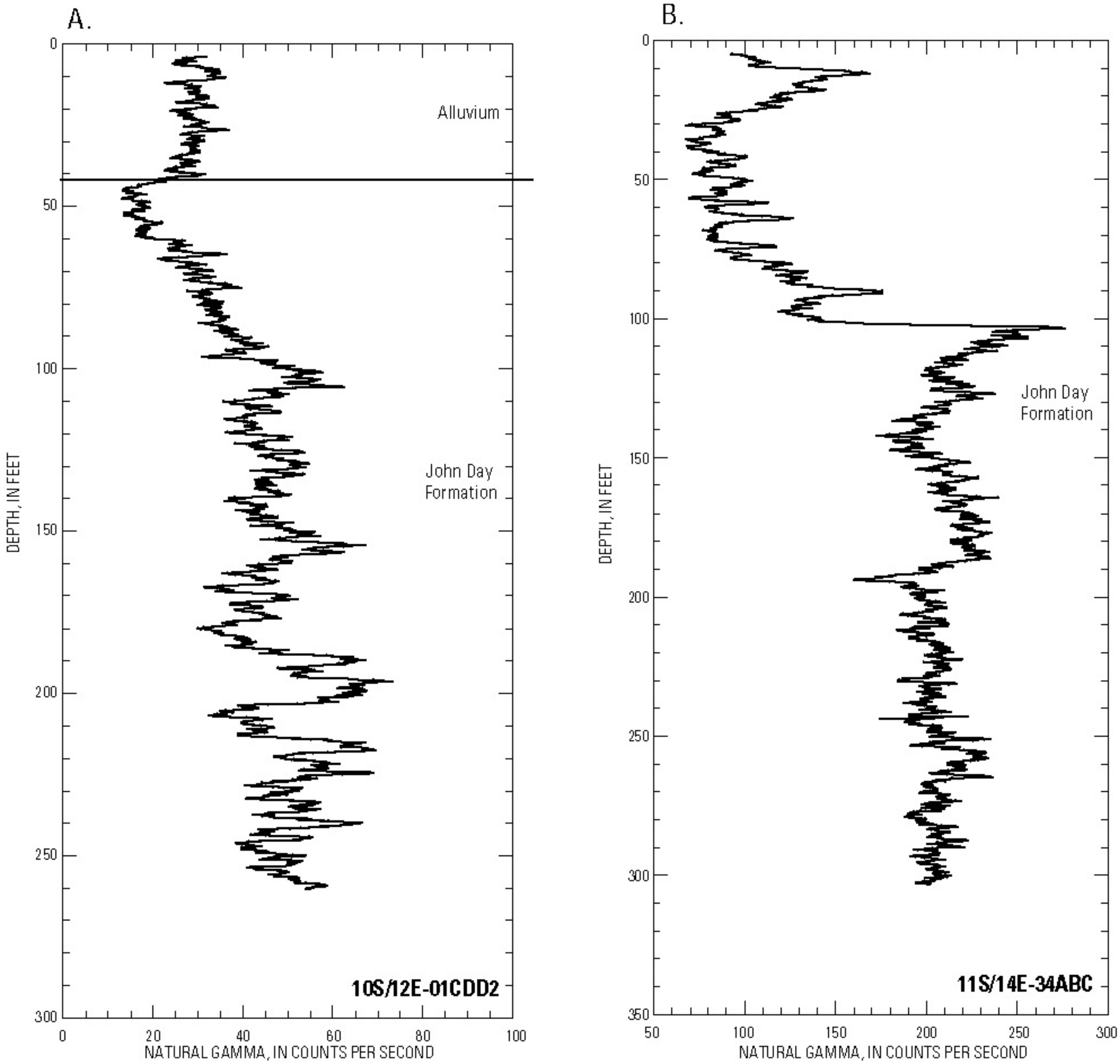


Figure 12. Natural gamma logs for wells constructed into the John Day Formation. A. Well 3 miles south of Warm Springs, Oregon (10S/12E-01CDD2, well no. 3, plate 1); B. Well 5 miles southeast of Madras, Oregon (11S/14E-34ABC, well no. 7, plate 1).

Prineville Basalt was sampled and analyzed from one well (15S/15E-23BBB, samples 14 and 15) for this study (tables 2 and 3). The well is located about 1 mile south of the Prineville airport (well no. 64, plate 1). The rock chemistry for the Prineville samples was typical for the low-SiO_2 Bowman Dam-type lava.

Hydraulic conductivity estimates for middle Miocene basalt flows in the upper Deschutes Basin, assumed to be Prineville Basalt, range from 1 to 50 ft/d (Bolke and Laenen, 1989). Wells constructed into water-bearing zones within the Prineville Basalt typically yield 10 to 30 gal/min. The amount is generally inadequate for irrigation but is satisfactory for domestic and stock uses.

Deschutes Formation

The Deschutes Formation and age-equivalent deposits are by far the most widely used ground-water-bearing units in the study area. The deposits occur at

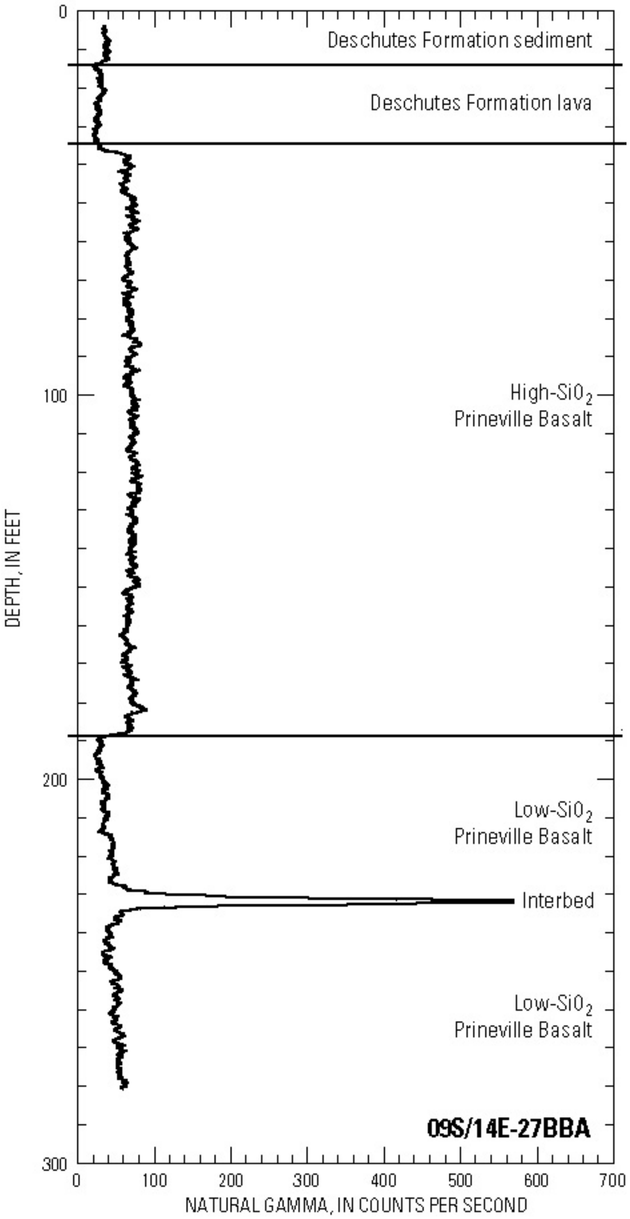


Figure 13. Natural gamma log for a well constructed into the Prineville Basalt near Gateway, Oregon (09S/14E-27BBA, well no. 2, plate 1).

the surface or at relatively shallow depth in the subsurface throughout much of the study area north and east of the Sisters fault zone (fig. 14). The Deschutes Formation consists of a variety of volcanic and sedimentary deposits ranging in age from late Miocene to Pliocene (approximately 7.5 to 4.0 million years before present). However, our map of Deschutes Formation and age-equivalent deposits (plate 1) also include some younger volcanic units. We include the basalt of Redmond and basalt of Dry River, basaltic andesite of Little Squaw Back and Squaw Back Ridge, and andesite of McKinney Butte (Sherrod and others, in press); middle Pliocene and lower Pleistocene basalt flows and basaltic vent rocks of Swanson (1969); and late Pliocene and Pleistocene basalt flows, northwest of Millican (Walker and others, 1967). Our discussion of the Deschutes Formation also includes volcanic units (primarily lava flows) that are found on the High Lava Plains but are age equivalent and compositionally similar to the Deschutes Formation rocks. In fact, some of the lava flows within the Deschutes Formation may have originated from the High Lava Plains Province (Smith, 1986b).

As mentioned in a previous section, Smith (1986b) subdivided the Deschutes Formation into three depositional environments: inactive-basin margin, arc-adjacent plain, and ancestral Deschutes River (see fig. 7). Smith also recognized a fourth subdivision of the Deschutes Formation: the proximal volcanic rocks (predominately lava flows) that form the bulk of Green Ridge. Similar layered lava flows are the predominant Deschutes Formation strata that occur at depth in much of the southeastern part of the study area south of Long Butte. A few of the volcanic eruptive centers are exposed at the surface, such as Long Butte, Awbrey Butte, Horse Ridge, and West Butte, but many more are presumably buried beneath the younger lava flows from Newberry Volcano.

Smith's subdivisions for the Deschutes Formation rocks also effectively characterize the general hydrologic properties of the unit. Generally, the permeability of Deschutes Formation rocks is lowest in the inactive-margin facies (less than 10^2 ft/d), and moderate to very high (10^2 to 10^3 ft/d) in the arc-adjacent plain and proximal volcanic rock facies (Gannett and others, 2001). Lithologic considerations, well-yield data, and the volume of spring discharge indicate that the hydraulic conductivity of the ancestral Deschutes River facies is at least as large as the arc-adjacent plain and proximal volcanic rock facies.

Inactive-Margin Facies

The low permeability of the inactive-margin material is a result of the fine-grained character of the clastic and pyroclastic deposits derived principally from the John Day Formation or as distal fallout from Cascade Range eruptions (Smith, 1986b). Most of the sediment was deposited on low-gradient alluvial fans radiating outward from uplands composed of John Day Formation.

Table 2. Major oxide analyses of cuttings samples from selected wells in the upper Deschutes Basin, Oregon

Well location: Refer to "Well- and "Spring-Location System" for explanation. Sample depth: Given in feet below land surface. Stratigraphic Unit: DF, Deschutes Formation; CR, Cascade Range; NV, Newberry Volcano.

Sample number	Well number	Well location	Sample depth	Sample name	Stratigraphic unit	Major oxides (in weight percent)										Total
						SiO_2	Al_2O_3	TiO_2	FeO	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	
1	9	12S/12E-33ACB	250	RMCOS1250	DF lava	49.09	17.03	1.044	9.19	0.173	11.83	8.97	0.33	2.25	0.142	100.05
2	9	12S/12E-33ACB	280	RMCOS1280	DF lava	49.27	17.00	1.269	9.77	.170	10.64	8.41	.31	2.62	.213	99.67
3	9	12S/12E-33ACB	415	RMCOS1415	DF–Pelton basalt	48.54	16.27	1.812	11.68	.195	9.99	7.19	.52	3.07	.528	99.80
4	9	12S/12E-33ACB	585	LITOPAL585	DF– Pelton basalt	48.18	15.91	1.621	11.46	.195	9.74	7.58	.49	2.95	.404	98.53
5	9	12S/12E-33ACB	725	LITOPAL725	DF–Pelton basalt	48.60	16.07	1.499	10.79	.190	10.21	8.01	.47	2.78	.312	98.93
6	14	13S/12E-36BDB	448–460	LITEA448460	DF–Opal Springs basalt	50.20	17.58	.972	8.30	.171	11.46	8.20	.39	2.59	.129	99.99
7	54	15S/13E-20AAD	520	LITRED520	DF lava	50.04	17.28	1.146	8.75	.167	10.69	7.49	.46	3.09	.226	99.34
8	54	15S/13E-20AAD	670	LITRED670	DF lava	49.98	16.54	1.573	10.36	.181	9.68	6.41	.71	3.29	.394	99.12
9	54	15S/13E-20AAD	775–780	LITRE775780	DF lava	48.12	15.88	1.222	10.09	.182	10.91	9.96	.26	2.51	.175	99.31
10	60	15S/14E-03BAA	294–320	LITIS294320	DF lava	48.55	17.01	.960	9.09	.170	11.22	10.32	.16	2.42	.127	100.03
11	61	15S/14E-14CDC	279	LITSM279	DF lava	48.66	17.33	.989	9.00	.174	11.44	9.07	.22	2.59	.142	99.62
12	61	15S/14E-14CDC	377–400	LITSM377400	DF lava	48.98	17.11	1.240	9.39	.176	10.68	8.15	.39	2.84	.263	99.21
13	64	15S/15E-23BBB	240–250	RCPRTB240250	DF lava	48.17	15.82	1.994	12.11	.209	9.26	8.09	.55	3.17	.469	99.84
14	64	15S/15E-23BBB	270–280	RCPRTB270280	Prineville Basalt	51.05	13.81	2.681	12.13	.229	7.97	4.19	1.79	3.32	1.447	98.62
15	64	15S/15E-23BBB	370–380	RCPRTB370380	Prineville Basalt	51.32	13.84	2.710	11.89	.230	8.04	3.98	1.85	3.36	1.468	98.69
16	66	16S/10E-13BBB2	218–254	RCNMN218254	CR lava	53.36	17.17	1.639	9.11	.156	8.39	4.87	1.04	3.99	.311	100.04
17	70	16S/11E-18BAC	347–360	RCMCT347360	DF lava	54.55	17.02	1.480	9.13	.154	7.99	3.87	1.05	4.29	.375	99.91
18	71	16S/11E-33DDD	195–203	RCPT-195203	DF lava	54.81	16.06	1.965	10.47	.173	7.25	3.25	1.14	4.22	.416	99.75
19	71	16S/11E-33DDD	468	RC-PT-468	DF lava	52.24	15.34	2.310	11.92	.219	8.16	4.06	.73	4.13	.519	99.63
20	83	16S/14E-17CDD	332	PB332	DF lava	48.95	17.39	.714	8.15	.161	12.63	9.95	.15	2.08	.073	100.25
21	83	16S/14E-17CDD	411	PB411	DF lava	49.42	16.89	1.487	10.46	.188	9.99	7.31	.57	3.08	.332	99.72
22	84	16S/14E-21BBD	437–478	LITMR437478	DF lava	48.27	17.49	.982	9.14	.178	11.53	9.14	.24	2.50	.178	99.64
23	86	17S/11E-24DCA	200	RCAWG200	DF lava	54.24	18.17	1.315	8.46	.155	8.68	4.66	.90	3.59	.358	100.53
24	86	17S/11E-24DCA	320	RCAWG320	DF lava	51.95	17.74	1.430	9.98	.166	8.61	5.20	.87	3.40	.397	99.74
25	86	17S/11E-24DCA	400–410	RCAWG400410	DF lava	52.12	18.46	1.425	9.32	.153	8.76	4.32	.90	3.67	.600	99.73
26	86	17S/11E-24DCA	510–520	RCAWG510520	DF lava	52.59	18.17	1.380	9.21	.156	8.67	4.40	1.03	3.70	.606	99.91
27	86	17S/11E-24DCA	820–830	RCAWG820830	DF lava	53.29	18.20	1.295	8.83	.157	9.08	4.53	1.07	3.57	.526	100.55
28	89	17S/12E-11DDB	143–167	RCNLN143167	NV lava	50.35	16.38	1.335	9.09	.163	9.46	8.87	.51	3.27	.259	99.69
29	89	17S/12E-11DDB	233–348	RCNLN233348	DF lava	49.92	17.07	1.641	10.48	.180	10.13	7.23	.34	3.46	.231	100.68
30	89	17S/12E-11DDB	348–412	RCNLN348412	DF lava	49.51	16.59	1.479	9.81	.166	9.67	8.98	.44	3.35	.312	100.31

Table 2. Major oxide analyses of cuttings samples from selected wells in the upper Deschutes Basin, Oregon—Continued

Well location: Refer to "Well- and "Spring-Location System" for explanation. Sample depth: Given in feet below land surface. Stratigraphic Unit: DF, Deschutes Formation; CR, Cascade Range; NV, Newberry Volcano.

Sample number	Well number	Well location	Sample depth	Sample name	Major oxides (in weight percent)											Total
					Stratigraphic unit	SiO_2	Al_2O_3	TiO_2	FeO	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	
31	89	17S/12E-11DDB	465–505	RCNLN465505	DF lava	50.28	16.89	1.439	9.65	.164	9.51	8.22	.55	3.33	.305	100.34
32	89	17S/12E-11DDB	517–520	RCNLN517520	DF lava	53.60	17.66	1.276	8.87	.146	8.72	4.69	.85	4.09	.285	100.19
33	91	17S/13E-20DAD	96–125	RCBART96125	NV lava	51.16	16.37	1.397	9.31	.162	9.35	8.62	.55	3.25	.290	100.46
34	91	17S/13E-20DAD	365–405	RCBAR365405	DF lava	50.33	16.82	1.396	9.71	.166	9.45	7.66	.55	3.29	.307	99.68
35	91	17S/13E-20DAD	430–450	RCBAR430450	DF lava	52.97	15.13	2.307	10.81	.215	8.15	4.46	.75	4.37	.580	99.74
36	91	17S/13E-20DAD	510–555	RCBAR510555	DF lava	50.12	16.67	1.475	9.78	.172	10.13	7.46	.58	3.01	.357	99.75
37	91	17S/13E-20DAD	570–592	RCBAR570592	DF lava	49.57	16.85	1.514	9.52	.175	10.03	7.75	.55	3.08	.354	99.39
38	91	17S/13E-20DAD	592–615	RCBAR592615	DF lava	48.77	16.80	1.559	10.85	.178	10.01	7.54	.36	3.07	.351	99.49
39	92	17S/14E-02CAA	125–192	RCWOG125192	DF lava	48.05	17.32	.698	8.28	.159	12.37	10.19	.14	2.13	.066	99.40
40	92	17S/14E-02CAA	244–327	RCWOG244327	DF lava	48.68	16.31	1.844	11.62	.197	10.17	6.95	.46	3.14	.441	99.81
41	92	17S/14E-02CAA	327–465	LITWO327465	DF lava	50.38	16.64	1.465	10.61	.180	9.00	6.35	.79	3.33	.377	99.12
42	93	17S/14E-11DCB	342–530	LITRD342530	DF lava	48.74	16.7	1.715	10.79	.195	10.13	7.44	.48	3.11	.412	99.71
43	93	17S/14E-11DCB	552–598	LITRD552598	DF lava	48.33	17.41	.910	8.61	.176	11.92	9.52	.17	2.41	.082	99.53
44	93	17S/14E-11DCB	655–675	LITRD655675	DF lava	49.45	17.54	.835	8.31	.161	11.51	9.29	.25	2.36	.157	99.86
45	101	18S/12E-07DBD1	150	RCCTB150	CR lava	53.47	15.81	1.807	10.29	.172	7.57	5.13	1.34	3.74	.411	99.74
46	101	18S/12E-07DBD1	270	RCCTB270	CR lava	54.23	17.17	1.499	9.13	.155	8.33	4.52	.74	4.38	.247	100.40
47	101	18S/12E-07DBD1	310	RCCTB310	CR lava	54.57	17.08	1.519	9.12	.156	8.28	4.4	.74	4.3	.249	100.41
48	101	18S/12E-07DBD1	370	RCCTB370	CR lava	53.89	16.98	1.617	9.03	.155	8.51	4.89	.84	4.06	.302	100.27
49	108	18S/13E-24DCB	170–194	RCDB-170194	NV lava	50.71	16.85	.952	8.64	.167	10.34	9.77	.40	2.77	.155	100.75
50	108	18S/13E-24DCB	194–226	RCDB-194226	NV lava	50.37	16.75	.940	8.98	.169	10.02	10.08	.42	2.70	.154	100.58
51	108	18S/13E-24DCB	226–275	RCDB-226275	NV lava	49.37	16.53	1.000	9.47	.173	10.03	9.91	.41	2.73	.161	99.77
52	108	18S/13E-24DCB	294–352	RCDB294-352	NV lava	49.69	16.78	1.634	11.45	.190	8.97	6.73	.56	3.54	.284	99.83
53	108	18S/13E-24DCB	352–405	RCDB352-405	NV lava	49.41	16.91	1.62	10.14	.192	10.10	7.67	.31	3.28	.267	99.90
54	108	18S/13E-24DCB	424–521	RCDB424-451	NV lava	50.82	17.23	1.367	9.22	.162	9.50	7.59	.57	3.39	.318	100.17
55	108	18S/13E-24DCB	536–632	RCDB536-632	NV lava	51.19	17.85	1.017	8.23	.151	10.08	7.56	.53	3.08	.186	99.87
56	108	18S/13E-24DCB	710–721	RCDB710-721	DF–equivalent lava	54.87	17.27	1.138	7.92	.141	8.78	4.75	1.10	3.39	.272	99.63
57	108	18S/13E-24DCB	721–770	RCDB721-770	DF–equivalent lava	55.04	17.39	1.095	7.92	.139	9.14	5.03	1.08	3.23	.260	100.32
58	108	18S/13E-24DCB	770–785	RCDB770-785	DF–equivalent lava	54.55	17.29	1.055	7.86	.140	9.08	5.44	1.03	3.28	.240	99.97
59	108	18S/13E-24DCB	785–904	RCDB785-904	DF–equivalent lava	55.19	17.28	1.047	7.67	.142	9.16	5.78	1.02	3.31	.243	100.84

Table 3. Trace element analyses of cuttings samples from selected wells in the upper Deschutes Basin, Oregon

Well location: Refer to "Well- and "Spring-Location System" for explanation. Sample depth: Given in feet below land surface. Stratigraphic Unit: DF, Deschutes Formation; CR, Cascade Range; NV, Newberry Volcano.

Sample number	Well number	Well location	Sample depth	Sample Name	Stratigraphic Unit	Trace elements (in parts per million)																
						Ni	Cr	Sc	V	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn	Pb	La	Ce	Th
1	9	12S/12E-33ACB	250	RMCOS1250	DF lava	147	316	40	236	105	4	215	89	27	3.1	17	83	65	1	0	35	4
2	9	12S/12E-33ACB	280	RMCOS1280	DF lava	168	313	40	224	134	5	239	95	29	4.5	16	63	69	0	12	23	1
3	9	12S/12E-33ACB	415	RMCOS1415	DF–Pelton basalt	137	237	36	293	342	7	349	126	34	9.4	20	125	115	0	19	35	4
4	9	12S/12E-33ACB	585	LITOPAL585	DF–Pelton basalt	142	297	32	283	339	4	314	93	28	6.6	19	56	91	2	0	20	2
5	9	12S/12E-33ACB	725	LITOPAL725	DF–Pelton basalt	160	302	37	285	274	5	352	88	26	6.0	22	81	91	1	13	26	2
6	14	13S/12E-36BDB	448–460	LITEA448460	DF–Opal Springs basalt	125	209	35	250	137	6	268	73	24	4.6	17	94	68	5	14	5	1
7	54	15S/13E-20AAD	520	LITRED520	DF lava	106	213	35	226	174	6	255	102	28	7.5	19	69	64	3	9	24	1
8	54	15S/13E-20AAD	670	LITRED670	DF lava	84	168	31	275	322	8	387	136	30	9.6	19	67	92	3	17	16	2
9	54	15S/13E-20AAD	775–780	LITRE775780	DF lava	217	382	38	259	119	3	219	87	25	5.2	16	73	73	2	0	25	2
10	60	15S/14E-03BAA	294–320	LITIS294320	DF lava	225	407	40	221	97	1	204	61	24	3.7	16	69	61	2	4	12	0
11	61	15S/14E-14CDC	279	LITSM279	DF lava	148	287	42	233	111	2	240	65	24	4.3	18	92	66	0	0	9	1
12	61	15S/14E-14CDC	377–400	LITSM377400	DF lava	124	233	36	249	213	4	330	94	26	6.8	17	85	80	0	7	16	2
13	64	15S/15E-23BBB	240–250	RCPRTB240250	DF lava	136	243	39	331	418	7	313	100	30	6.8	19	76	100	0	16	10	1
14	64	15S/15E-23BBB	270–280	RCPRTB270280	Prineville Basalt	3	21	37	349	2,185	41	395	149	49	8.6	20	109	169	5	20	36	7
15	64	15S/15E-23BBB	370–380	RCPRTB370380	Prineville Basalt	9	22	31	354	2,326	41	395	150	49	9.6	22	35	133	5	25	38	4
16	66	16S/10E-13BBB2	218–254	RCNMN218254	CR lava	33	89	21	212	313	22	397	161	31	9.6	22	61	80	5	19	40	3
17	70	16S/11E-18BAC	347–360	RCMCT347360	DF lava	7	51	30	260	473	13	572	146	26	8.6	22	98	87	3	8	43	3
18	71	16S/11E-33DDD	195–203	RCPT-195203	DF lava	0	8	19	284	455	18	483	158	34	10.8	25	40	106	3	12	52	5
19	71	16S/11E-33DDD	468	RC-PT-468	DF lava	0	18	41	302	393	9	417	139	37	8.9	19	24	111	0	10	22	3
20	83	16S/14E-17CDD	332	PB332	DF lava	176	315	44	238	61	2	144	46	22	2.1	14	91	51	0	1	14	0
21	83	16S/14E-17CDD	411	PB411	DF lava	106	168	34	257	277	6	325	109	31	5.9	19	80	90	1	12	23	2
22	84	16S/14E-21BBD	437–478	LITMR437478	DF lava	140	198	42	238	125	1	230	70	25	4.2	16	85	62	0	14	20	1
23	86	17S/11E-24DCA	200	RCAWG200	DF lava	66	76	23	236	433	11	536	135	24	8.4	20	96	89	5	8	38	2
24	86	17S/11E-24DCA	320	RCAWG320	DF lava	80	75	26	237	400	9	549	140	26	8.8	22	76	100	3	20	45	4
25	86	17S/11E-24DCA	400–410	RCAWG400410	DF lava	25	66	27	222	464	10	649	166	30	14.1	19	61	96	4	26	39	3
26	86	17S/11E-24DCA	510–520	RCAWG510520	DF lava	29	66	22	216	473	12	639	160	28	13.9	20	49	93	3	22	63	3
27	86	17S/11E-24DCA	820–830	RCAWG820830	DF lava	38	75	30	205	429	14	592	149	28	11.9	20	64	86	4	16	53	3
28	89	17S/12E-11DDB	143–167	RCNLN143167	NV lava	153	357	22	197	290	7	344	114	24	6.5	14	52	81	1	14	35	0
29	89	17S/12E-11DDB	233–348	RCNLN233348	DF lava	67	134	30	270	150	3	291	112	33	5.3	20	44	80	0	16	24	0
30	89	17S/12E-11DDB	348–412	RCNLN348412	DF lava	166	309	27	215	203	6	327	127	28	7.9	15	61	78	2	0	37	0

Table 3. Trace element analyses of cuttings samples from selected wells in the upper Deschutes Basin, Oregon—Continued

Well location: Refer to "Well- and "Spring-Location System" for explanation. Sample depth: Given in feet below land surface. Stratigraphic Unit: DF, Deschutes Formation; CR, Cascade Range; NV, Newberry Volcano.

Sample number	Well number	Well location	Sample depth	Sample Name	Stratigraphic Unit	Trace elements (in parts per million)																
						Ni	Cr	Sc	V	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn	Pb	La	Ce	Th
31	89	17S/12E-11DDB	465–505	RCNLN465505	DF lava	147	272	25	218	218	8	364	116	25	8.5	18	55	78	3	20	38	1
32	89	17S/12E-11DDB	517–520	RCNLN517520	DF lava	12	65	22	235	364	10	599	116	25	6.4	22	89	82	3	15	34	2
33	91	17S/13E-20DAD	96–125	RCBART96125	NV lava	145	327	27	211	299	6	342	122	26	7.6	18	44	78	0	8	30	0
34	91	17S/13E-20DAD	365–405	RCBAR365405	DF lava	134	250	29	247	229	8	391	109	26	6.8	17	67	77	2	0	30	2
35	91	17S/13E-20DAD	430–450	RCBAR430450	DF lava	8	50	29	264	370	11	407	132	37	8.2	22	44	99	3	3	37	1
36	91	17S/13E-20DAD	510–555	RCBAR510555	DF lava	115	228	32	241	257	7	331	116	29	8.4	15	56	79	4	0	19	0
37	91	17S/13E-20DAD	570–592	RCBAR570592	DF lava	138	239	31	236	257	6	324	113	28	7.4	19	58	88	1	1	16	0
38	91	17S/13E-20DAD	592–615	RCBAR592615	DF lava	135	246	30	256	237	3	321	114	32	8.4	17	87	89	1	0	27	1
39	92	17S/14E-02CAA	125–192	RCWOG125192	DF lava	185	316	38	225	25	1	143	49	22	2.5	12	102	48	1	11	0	0
40	92	17S/14E-02CAA	244–327	RCWOG244327	DF lava	80	173	33	308	356	4	314	119	32	8.6	17	82	100	1	19	15	1
41	92	17S/14E-02CAA	327–465	LITWO327465	DF lava	86	123	31	244	348	10	421	130	27	8.4	21	79	93	7	16	25	2
42	93	17S/14E-11DCB	342–530	LITRD342530	DF lava	103	168	36	273	312	5	327	112	30	8.5	17	77	94	0	12	22	2
43	93	17S/14E-11DCB	552–598	LITRD552598	DF lava	163	276	36	241	85	1	186	50	25	2.6	17	94	59	1	10	11	2
44	93	17S/14E-11DCB	655–675	LITRD655675	DF lava	159	243	32	204	142	4	202	58	23	2.7	14	83	55	1	9	27	2
45	101	18S/12E-07DBD1	150	RCCTB150	CR lava	53	82	25	249	474	31	307	174	36	12.9	18	53	95	7	9	42	4
46	101	18S/12E-07DBD1	270	RCCTB270	CR lava	19	79	21	257	245	10	491	117	24	6.9	21	80	82	1	7	49	1
47	101	18S/12E-07DBD1	310	RCCTB310	CR lava	17	83	20	243	256	10	489	117	25	6.3	20	86	77	1	20	27	2
48	101	18S/12E-07DBD1	370	RCCTB370	CR lava	33	96	19	263	322	11	475	134	29	6.5	22	89	93	2	14	32	4
49	108	18S/13E-24DCB	170–194	RCDB-170194	NV lava	168	379	33	199	144	9	234	77	23	4.1	16	61	64	1	0	22	2
50	108	18S/13E-24DCB	194–226	RCDB-194226	NV lava	185	378	30	191	136	10	218	77	24	5.3	15	62	60	1	16	8	1
51	108	18S/13E-24DCB	226–275	RCDB-226275	NV lava	181	364	30	196	151	10	213	81	25	3.9	14	64	62	2	2	25	2
52	108	18S/13E-24DCB	294–352	RCDB294-352	NV lava	82	99	28	256	284	7	352	122	29	7.9	20	62	98	2	0	25	2
53	108	18S/13E-24DCB	352–405	RCDB352-405	NV lava	90	158	34	256	169	2	261	116	32	5.5	17	71	88	0	9	17	0
54	108	18S/13E-24DCB	424–521	RCDB424-451	NV lava	120	180	30	231	288	8	404	115	25	7.7	17	63	80	4	4	22	2
55	108	18S/13E-24DCB	536–632	RCDB536-632	NV lava	117	158	30	205	232	7	402	78	21	3.8	19	76	73	0	0	22	1
56	108	18S/13E-24DCB	710–721	RCDB710-721	DF–equivalent lava	30	96	31	207	345	21	412	141	28	10.3	20	59	78	4	20	30	2
57	108	18S/13E-24DCB	721–770	RCDB721-770	DF–equivalent lava	33	105	37	192	303	19	409	135	28	10.1	19	53	74	0	19	25	3
58	108	18S/13E-24DCB	770–785	RCDB770-785	DF–equivalent lava	47	122	26	189	285	20	391	127	26	9.6	18	64	70	3	16	33	2
59	108	18S/13E-24DCB	785–904	RCDB785-904	DF–equivalent lava	50	126	28	199	290	19	376	123	25	9.2	16	52	71	5	8	35	3

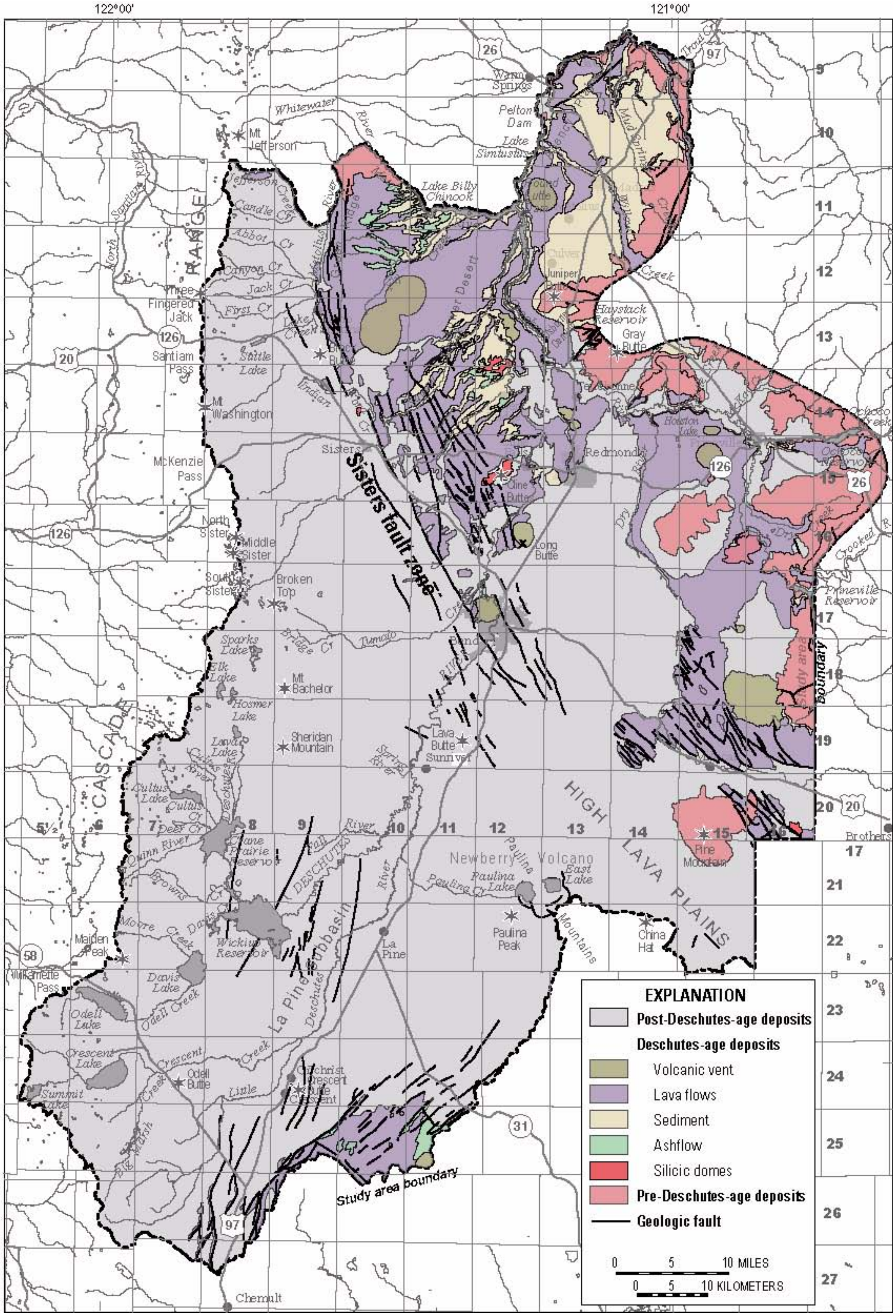


Figure 14. Extent of surface exposures of the Deschutes Formation and age-equivalent deposits.

The deposits reflect the clay-rich and silicic nature of their sources. This is apparent on a natural gamma log (fig. 15) for well 11S/13E-24BCD1 (well no. 6, plate 1) near Madras, where sediment with a high gamma signature is interbedded with contrasting low-gamma basalt flows, all within the Deschutes Formation. Well yields within the inactive-margin deposits are typically less than 30 gal/min but, in a few cases, are as large as 300 gal/min. The larger yields are likely due to interbedded lava flows or locally coarse-grained sedimentary beds.

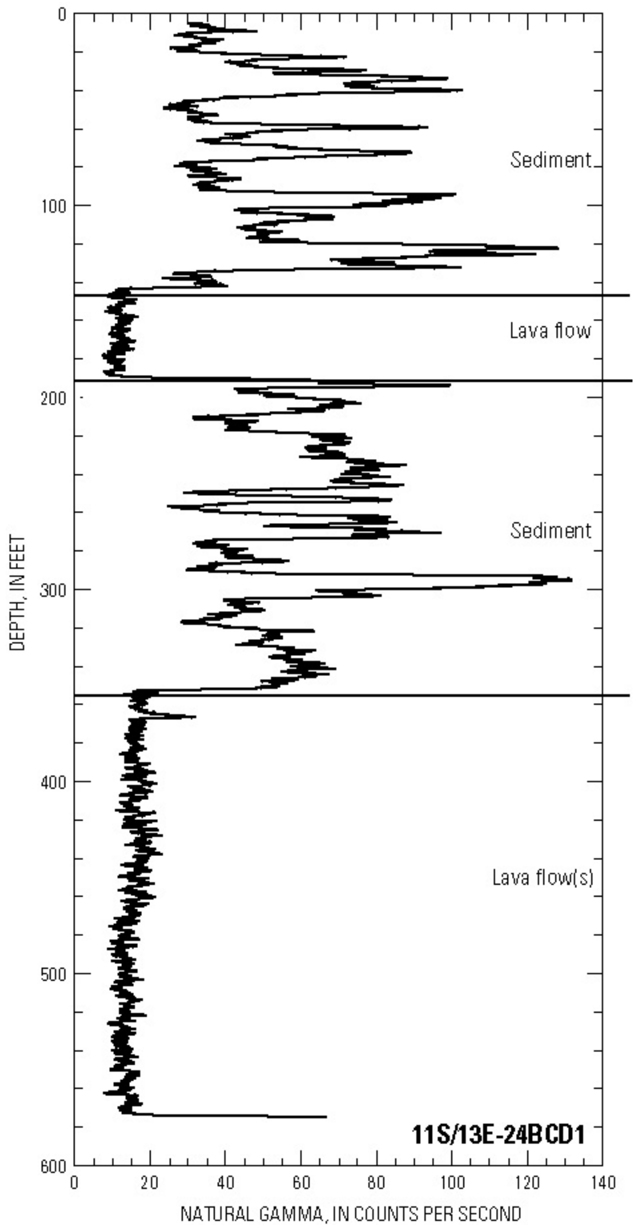


Figure 15. Natural gamma log for a well constructed into the inactive-margin facies of the Deschutes Formation near Madras, Oregon (11S/13E-24BCD1, well no. 6, plate 1).

An aquifer test was conducted at one of the higher-yielding inactive-margin wells during this study. A sand-and-gravel aquifer within the inactive-margin facies was tested at well 11S/13E-01BCA2 (well no. 4, plate 1) in Madras. The aquifer test yielded hydraulic conductivity estimates of 110 to 160 ft/d for the unit (Gannett and others, 2001).

Arc-Adjacent Alluvial-Plain Facies

The arc-adjacent alluvial plain represents a variety of volcanic and volcaniclastic materials that erupted or were otherwise shed from the flanks of active volcanoes approximately 7.5 million years to 4.0 million years ago. The deposits within the arc-adjacent plain include lava flows, volcanic vent material, ash-flows, ash-fallout, and a variety of volcanically derived sediment. The variability of the material encountered within the arc-adjacent alluvial-plain region is illustrated in figure 16A. Figure 16A shows a natural gamma log of well 14S/11E-18BDB (well no. 24, plate 1) near Henkle Butte that has been annotated with material descriptions on the basis of microscopic examination of drill cuttings.

The sedimentary and pyroclastic material within the arc-adjacent alluvial-plain region tends to be relatively coarse-grained because it is near the volcanic source areas. The topographic slope and ongoing drainage development in the source areas resulted in preferential orientation of subsequent lava flows and ash-flows that followed shallow paleodrainages towards the east and northeast (Smith, 1986b). The east to northeast orientation of the units probably results in many local preferential ground-water flow paths in those directions.

Two notable intrabasinal silicic volcanic vents are also found in the arc-adjacent alluvial-plain region. They are the rhyolite and rhyodacite volcanic dome complexes that form Cline Buttes and small hills near Steelhead Falls. The dome complexes have been included in the Deschutes Formation on the basis of radiometric ages (Sherrod and others, in press). Geologic mapping in the Steelhead Falls area has shown that Deschutes Formation ash-flow and sedimentary deposits on-lap the dome rocks (Ferns and others, 1996b). That relation is substantiated by well data and the natural gamma log for well 14S/11E-01DDD1 (well no. 22, plate 1) shown in figure 16B.

The hydrologic character of the arc-adjacent material is as variable as the rock types that form it.

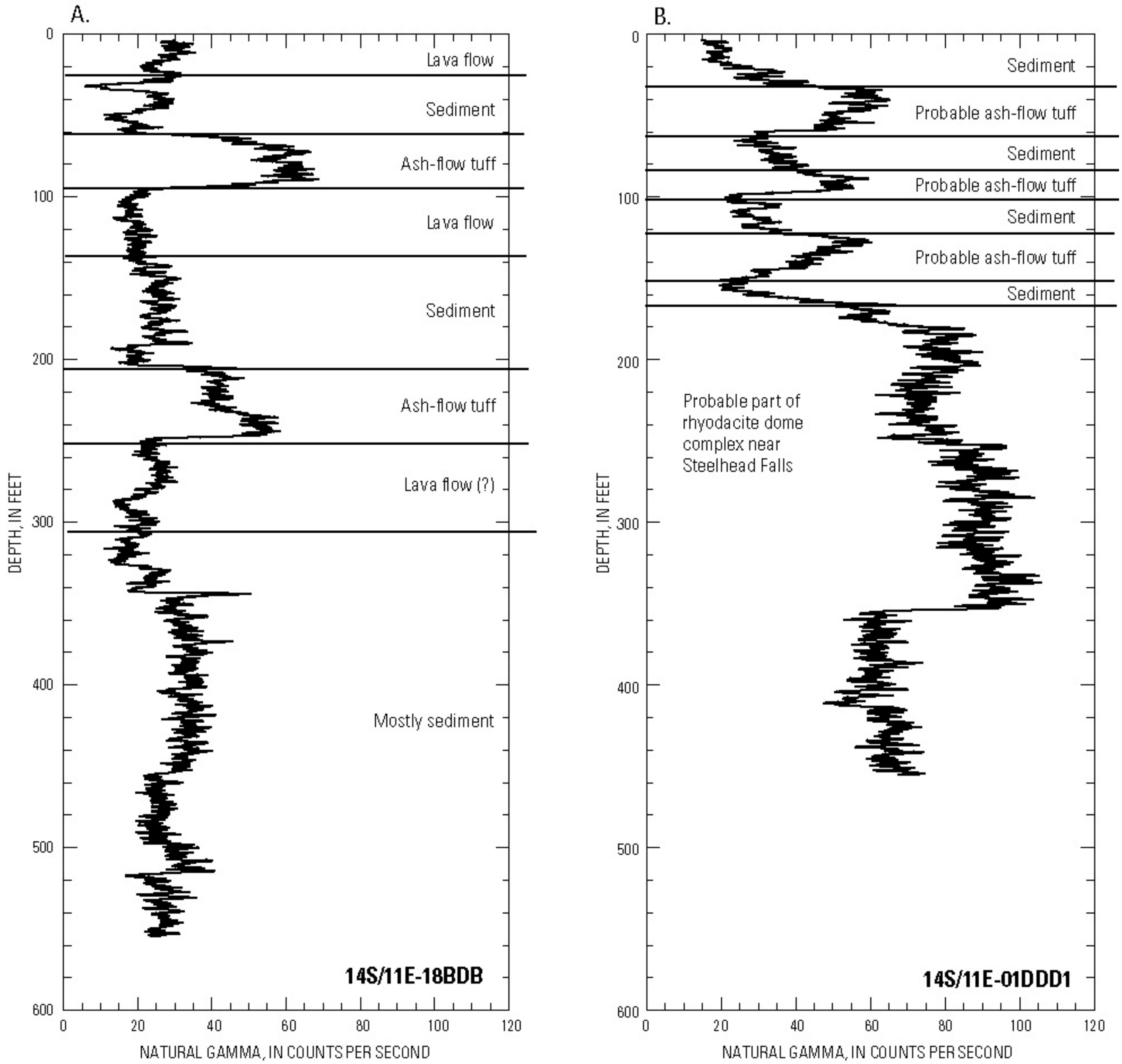


Figure 16. Natural gamma logs for wells constructed into the arc-adjacent alluvial-plain facies of the Deschutes Formation. A. Well near Henkle Butte (14S/11E-18BDB, well no. 24, plate 1); B. Well near Steelhead Falls (14S/11E-01DDD1, well no. 22, plate 1).

The coarse-grained sedimentary strata and the fractured and rubbly character of thin intracanyon lava flows result in well yields of hundreds of gallons per minute. Hydraulic conductivity estimates of 1.5 to 2.3 × 10^3 ft/d were derived from an aquifer test conducted near the Redmond airport (Gannett and others, 2001). The well (15S/13E-22CBA2; well no. 57, plate 1) is open to sand, gravel, and lava deposited in the arc-adjacent plain.

The fractured nature of the breccia associated with rhyolitic domes within the arc-adjacent facies has resulted in some relatively high-yielding wells adjacent to Cline Buttes and near Steelhead Falls. The high permeability of the fractured dome complex near Steelhead Falls also contributes a substantial amount of flow, about 150 ft^3/s, to the Deschutes River (Ferns and others, 1996a).

Proximal Facies

Proximal facies deposits account for most of the geologic material encountered in the Deschutes Formation west of Squaw Back Ridge in the northwestern part of the study area, and south and east of Long Butte in the southeastern part of the study area. The rocks represent deposition that occurred relatively close to their volcanic vents and typically consist of relatively thin (< 50 ft thick) lava flows with interbedded volcanic flow breccia and cinders.

Interbedded pyroclastic material and sedimentary units occur locally within the proximal deposits. On the basis of well data, the interbedded sedimentary and pyroclastic deposits are notably abundant within the proximal deposits near the contact with the John Day Formation. Within the proximal facies rocks in the southeastern part of the study area, interbedded sedimentary and pyroclastic deposits appear more prevalent in an alignment roughly corresponding with the present-day Dry River. Those interbedded deposits probably define paleochannels of an ancestral drainage. The natural gamma log for well 17S/14E-02CAA (well no. 92, plate 1), located adjacent to the southwestern flank of Powell Buttes, shows the interbedded nature of the Deschutes Formation at that locale (fig. 17).

Public supply wells in the Bend area are good examples of the yield potential from layered lava flows within the proximal facies. Yields from large-diameter (greater than 10 inches) wells near Bend range from about 400 gal/min to 2,000 gal/min. An aquifer test conducted for the City of Bend at well 18S/12E-05BDB (well no. 99, plate 1) yielded a hydraulic conductivity estimate of 1.5×10^2 ft/d (Gannett and others, 2001). The well is open to lava and tuff.

Ancestral Deschutes River Facies

The ancestral Deschutes River facies consists predominately of coarse sandstone and conglomerate streambed deposits alternating with fine sandstone and mudstone overbank flood deposits, a variety of volcaniclastic sediment, and distal parts of many ash-flow tuffs and lava flows. Smith (1986b, 1987) described the ancestral Deschutes River deposits as occurring within a relatively narrow area from Redmond to Gateway that corresponds roughly to the present path of the Crooked and Deschutes Rivers (fig. 7).

Some of the geologic materials along the paleochannels are exceptionally permeable, as shown by the enormous quantity (approximately 1,500 ft^3/s) of ground water that discharges to the Crooked and Deschutes Rivers in that region (Stearns, 1931; Sceva, 1968; Gannett and others, 2001). Ground water discharges to the streams mainly through conglomerate

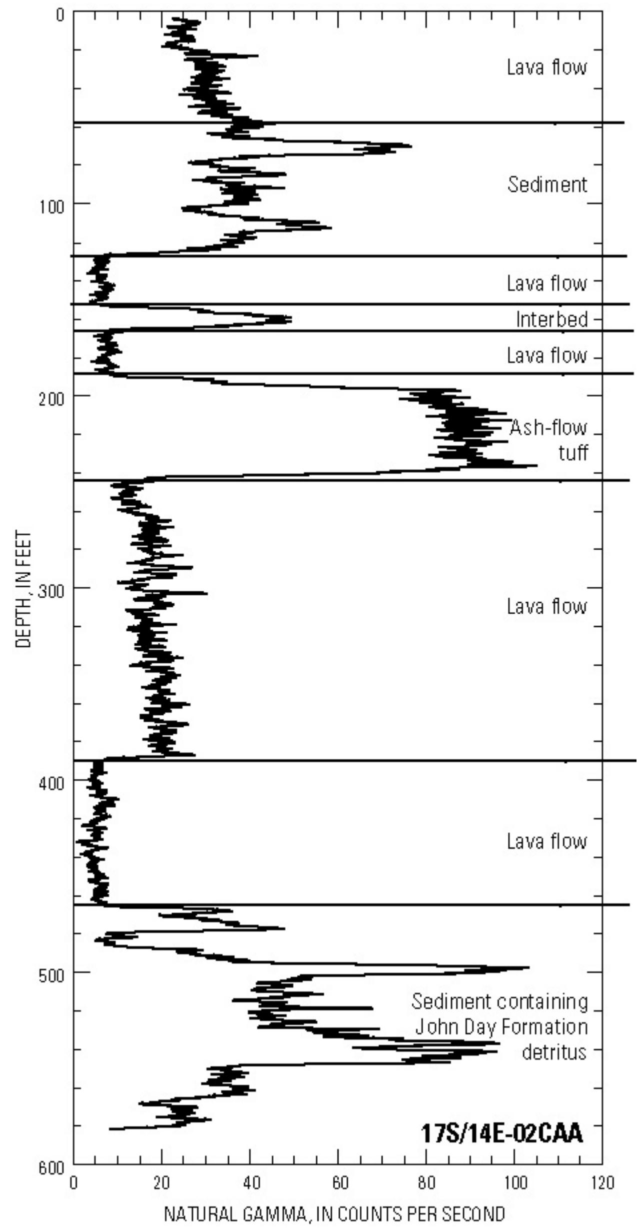


Figure 17. Natural gamma log for a well constructed into layered lava flows within the Deschutes Formation southwest of Powell Buttes, upper Deschutes Basin, Oregon (17S/14E-02CAA, well no. 92, plate 1).

and fractured intracanyon lava flows (Ferns and others, 1996a). As noted by Stearns (1931), most of the ground water that actually discharges to the Crooked River is principally from two intracanyon lava flow sequences within the Deschutes Formation: the Pelton basalt and the Opal Springs basalt.

The Pelton basalt is 7.42 million years old and the oldest exposed volcanic unit within the Deschutes Formation (Smith, 1986b). The unit consists of several lava flows that may have a total thickness of nearly 400 ft.

The Pelton basalt forms part of the abutments for Round Butte Dam and was the subject of intense analysis prior to construction of the dam. The thickness of the Pelton basalt at Round Butte Dam is 260 ft (Bechtel Corporation, 1958). Individual flows within the Pelton basalt have been described and analyzed for major oxides and some trace elements by Jay (1982) and Smith (1986b). Relatively low aluminum oxide (Al_2O_3) (average 15.8 weight percent) from the Pelton lava flows led Smith (1986b) to speculate that the flows may have originated from southeast of the basin, where basalt tends to exhibit lower (less than 16.0 percent) Al_2O_3 values compared to lava flows from Cascade volcanoes. Indeed, lava flows in several wells in the southeastern part of the study area that were sampled and analyzed during this study exhibit rock chemistry similar to the Pelton basalt (fig. 3, tables 2 and 3). This implies that an ancestral Deschutes River and tributary may have existed both northeast and southwest of Powell Buttes, and that a possible source area for the lava flows may be in the West Butte-Bear Creek Buttes area. Unfortunately, many of the lava flows occur above the saturated zone in those areas, so they are not potential sources of ground water.

The thickest sequence of Pelton basalt appears to be a few hundred feet below land surface in the vicinity of Opal Springs. A water well drilled at Opal Springs for the Deschutes Valley Water Company penetrated a 376-ft-thick sequence of Pelton basalt, first encountered at a depth of 364 ft below the canyon floor. The identity of Pelton basalt in the well is based on elevation, thickness, appearance (video tape from a downhole camera), and rock chemistry (tables 2 and 3). The Opal Springs well #1 (12S/12E-33ACB, well no. 9, plate 1) is a flowing well that yields over 4,000 gal/min from an interflow zone near the bottom of the basalt sequence (Steve Bruce, David J. Newton Associates, personal commun., 1998). A thick sequence of lava flows within a now-abandoned well at the Opal City site (Stearns, 1931) reportedly occurs at a similar elevation as the basalt sequence in the Opal Springs well and is probably also Pelton basalt.

The Opal Springs basalt is a sequence of two to four lava flows with interbedded paleosols and tuff that are exposed in the Crooked River canyon from above Osborne Canyon to Opal Springs (Ferns and others, 1996b). Exposures of the Opal Springs basalt, like the Pelton basalt, probably define a paleochannel of the ancestral Deschutes River. The Opal Springs basalt is up to 120 ft thick. A flow low in the sequence has a radiometric age of 5.77 Ma (Smith, 1986b).

The Opal Springs basalt is very permeable. Over 1,000 ft^3/s of ground water discharges from Opal Springs lava exposed in the Crooked River canyon between Osborne Canyon and Opal Springs (Ferns and others, 1996a; Gannett and others, 2001).

Deposits of the Cascade Range and Newberry Volcano

Most of what is known about the hydrogeology of the Cascade Range and Newberry Volcano is based on well data from the eastern margin of the Cascade Range and from wells penetrating lava flows on the flanks of Newberry Volcano. Some information on conditions at higher elevations in the Cascade Range and at Newberry Volcano within the study area has been obtained from a few deep geothermal exploration wells, two deep (800- to 1000-ft) water wells, and several shallow water wells.

The youthful and fractured character of the Cascade Range deposits results in rapid infiltration of precipitation and snowmelt, as shown by the lack of drainage development on the east side of the Cascade Range. The Cascade Range volcanic units provide the primary pathway for most of the ground-water recharge that occurs within the study area. Large rates of canal leakage (Gannett and others, 2001) into the Newberry Volcano lava flows near Bend demonstrate the open-fracture character for those deposits as well.

The Tumalo fault and Green Ridge fault zone generally mark the basinward limit of Quaternary Cascade Range deposits. However, some Cascade Range lava and pyroclastic flows have filled drainages that breached escarpments formed by the Tumalo fault and other strands of the Sisters fault zone between Bend and Sisters (fig. 18).

Lava flows from Newberry Volcano overlie most other geologic units east of the Tumalo fault near Bend. Natural gamma logs of wells penetrating the Newberry flows near Bend reveal a remarkably constant gamma count throughout the entire thickness of the sequence (fig. 19A). That characteristic makes the gamma log a potentially useful tool for distinguishing the Newberry flows from other underlying lava units. The Newberry flows thin to the north away from the volcano (see cross-section B in MacLeod and others, 1995).

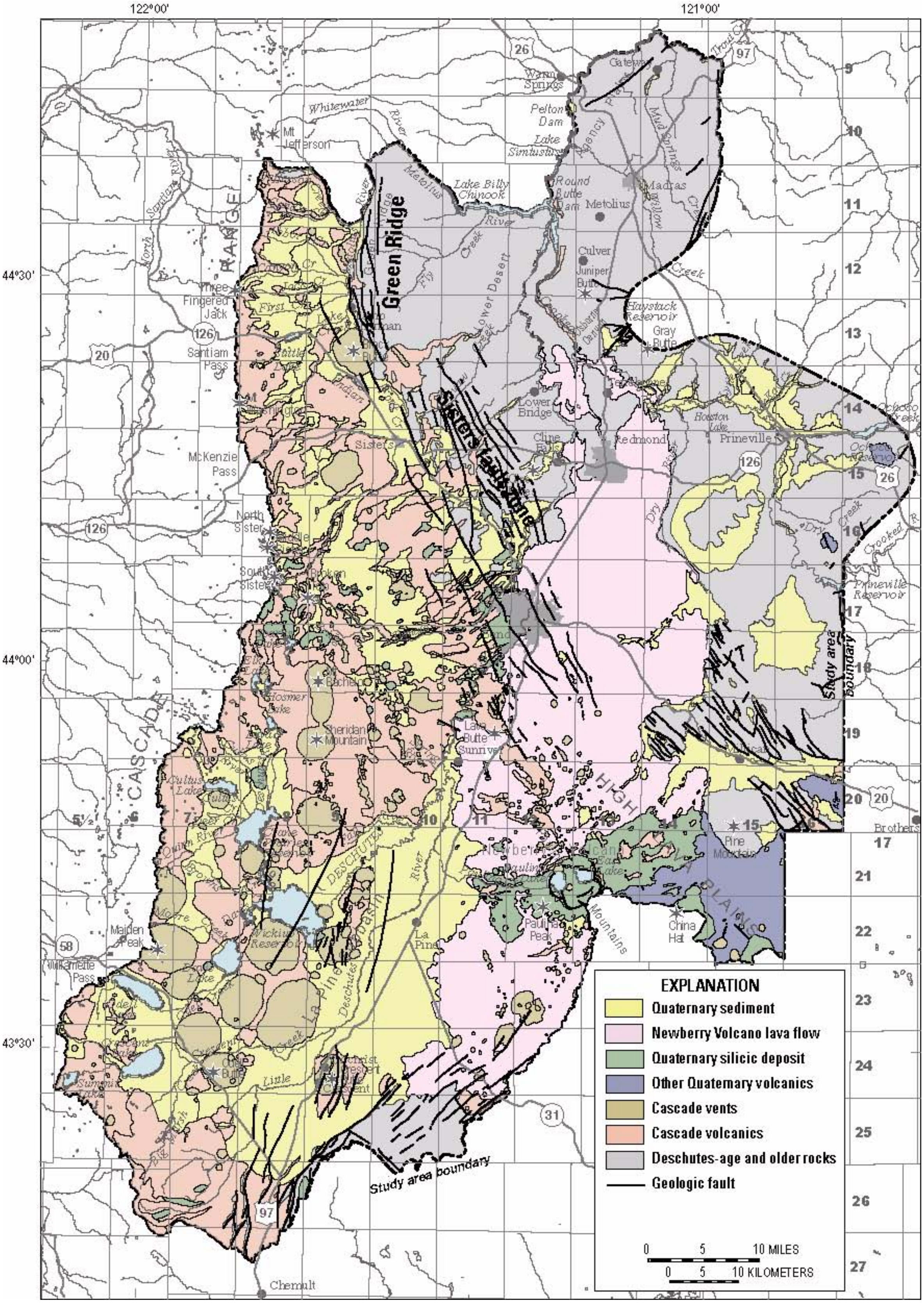


Figure 18. Extent of deposits of the Cascade Range and Newberry Volcano.

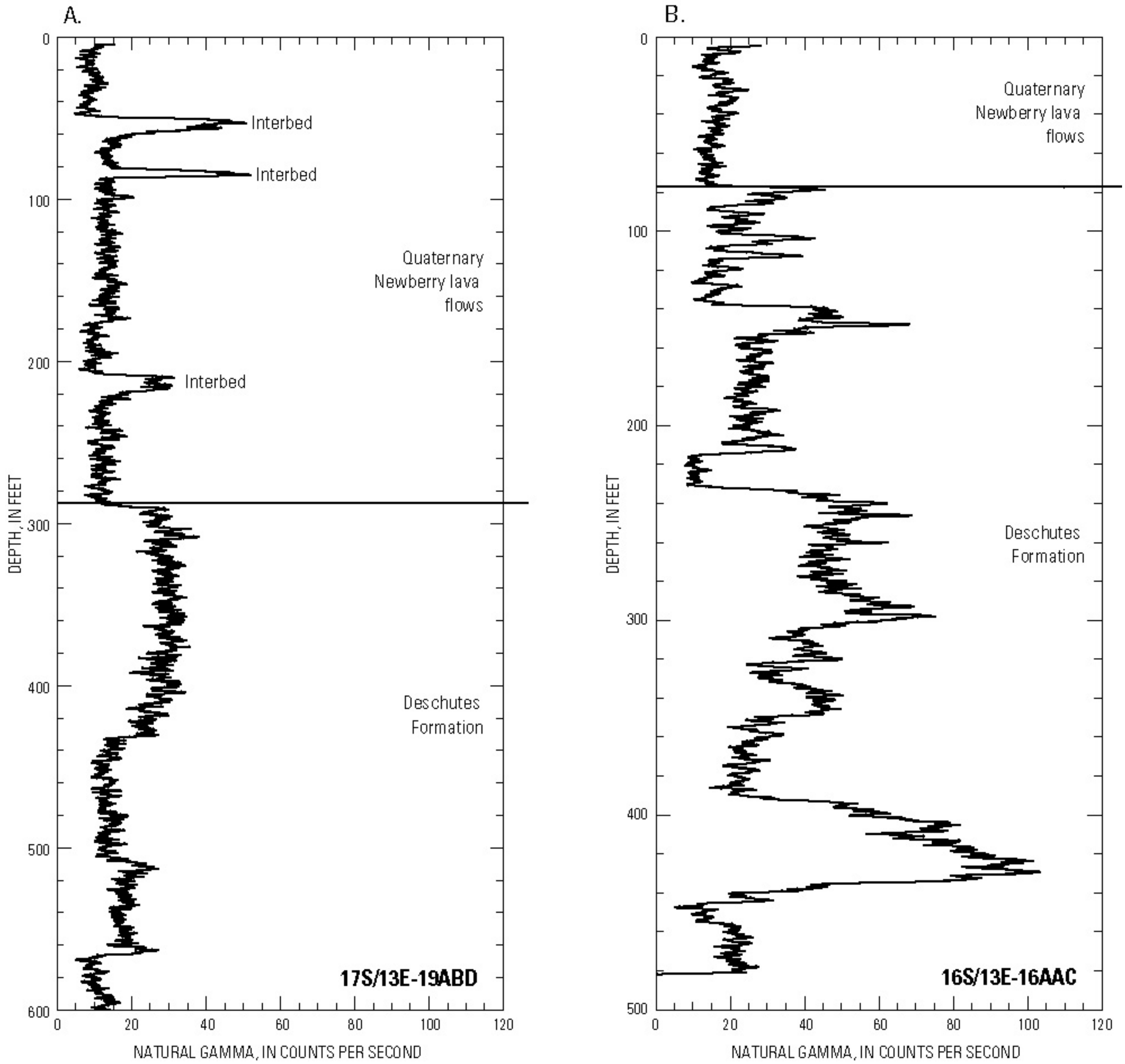


Figure 19. Natural gamma logs for wells penetrating Quaternary lava flows from Newberry Volcano and underlying Deschutes Formation strata. A. Well near Bend airport (17S/13E-19ABD, well no. 90, plate 1); B. Well 5 miles east-northeast of Long Butte (16S/13E-16AAC, well no. 81, plate 1).

On the basis of natural gamma logs and geologic material descriptions, it appears that the flows thin from about 285 ft thick near the Bend Airport in well 17S/13E-19ABD (well no. 90, plate 1) (fig. 19A) to approximately 75 ft thick in well 16S/13E-16AAC (well no. 81, plate 1) (fig. 19B) located 5 miles east-northeast from Long Butte, a distance of about 7 miles.The Newberry flows serve as conduits for canal leakage and other incidental recharge but are only locally saturated north and east of Bend.

West of the Sisters fault zone and south of Bend, the Cascade Range and Newberry deposits are saturated and are an important source of ground water. Numerous wells have been drilled into those deposits. In addition, Cascade Range deposits provide water to many spring-fed streams. In fact, approximately 2,600 ft^3/s (or about one-half the total basin discharge) of stream flow is derived from springs discharging from Cascade Range deposits (Gannett and others, 2001). Many of the springs within the Cascade Range units are associated with lava flows. Paulina Springs near the head of Indian Ford Creek and springs at the head of Fall River are good examples. Paulina Springs (which discharges about 10 ft^3/s) is one of several springs that discharge from the toe of a Cascade Range lava flow. The head of Fall River (nearly 100 ft^3/s) appears to issue near the boundary of a young drainage filled by lava flows.

Well yields from the few deep water wells developed in the Cascade Range deposits are relatively large. The yields range from a couple of hundred gallons per minute to nearly 2,000 gal/min. For example, one of the wells at Mount Bachelor yields 1,850 gal/min.

Permeability measurements in rocks of the Cascade Range and Newberry Volcano are sparse and limited to relatively shallow depth. Two aquifer tests conducted in Cascade Range deposits have yielded estimates of hydraulic conductivity ranging from 9 to 600 ft/d (Gannett and others, 2001). The 9 ft/d value is from well 18S/09E-20BDA (well no. 95, plate 1) at Mount Bachelor, and is open to cinders. The 600 ft/d value is from well 14S/10E-30DDB2 (well no. 20, plate 1) located near Sisters, and open to lava.

There are no permeability measurements below several hundred feet in the Cascade Range or on Newberry Volcano. Knowledge about permeability distribution at depth is inferred from geothermal gradient measurements and heat-flow studies. In simulating ground-water flow and heat transport in the Cascade Range, Ingebritsen and others (1992) estimated the permeability of rocks younger than 2.3 Ma to be about 10^{-14} m^2 (square meters), which is equivalent to a hydraulic conductivity of about 0.018 ft/d assuming a water temperature of 5°C. The permeability of rocks with ages between 4 and 8 Ma was estimated to be 5.0×10^{-16} m^2 which is equivalent to a hydraulic conductivity of about 9.1×10^{-4} ft/d. Ingebritsen and others (1992) found that higher near-surface permeability, on the order of 10^{-14} to 10^{-12} m^2 (.018 to 1.8 ft/d), was required in their simulation to match ground-water recharge estimates.

Blackwell and Priest (1996) suggest that the heat transfer pattern in the Cascade Range is predominantly conductive, indicating that the permeability in all but the youngest rocks below a depth of 300 to 900 ft is orders of magnitude lower than the estimates of Ingebritsen and others (1992). They also suggest that ground-water flow at velocities sufficient to affect heat flow in the high Cascade Range is restricted to local regions, such as high-permeability fault zones, except in the 0 to 1,500 ft depth range. The volume of water moving through the low-permeability strata at depths greater than 1,500 ft in the Cascade Range is sufficiently small to be considered negligible compared to the overall ground-water budget, and these low-permeability strata are for all practical considerations the base of the regional ground-water flow system. Temperature gradient data (Swanberg and others, 1988) and hydrothermal mineralization data (Keith and others, 1986) suggest that a similar loss of permeability occurs at depth beneath Newberry Volcano.

Mathematical modeling of ground-water discharge to spring-fed streams in the Cascade Range by Manga (1996, 1997) yielded permeability values for near-surface rocks less than about 2.0 Ma of about 10^{-11} m^2, which equates to a hydraulic conductivity of about 18 ft/d assuming a water temperature of 5°C. This estimate is an order of magnitude larger than the upper value of Ingebritsen and others (1992) for near-surface rocks, where most of the ground-water flow occurs. The permeability estimates of Manga (1996, 1997) and Ingebritsen and others (1992) are considered to be a reasonable range of values for the younger, near-surface strata in the Cascade Range.

The depth beneath the Cascade Range and Newberry Volcano at which permeability is greatly reduced due to hydrothermal alteration and secondary mineralization varies from place to place and is poorly constrained. The overall geometry of this boundary surface is not well known. Data from geothermal test wells indicate that the transition occurs at depths ranging from 300 to 1,200 ft and that primary permeability can be assumed to be virtually absent below 1,500 ft (Blackwell and others, 1990; Ingebritsen and others, 1992; Blackwell and Priest, 1996).

Quaternary Sedimentary Deposits

Numerous relatively small, shallow, water-bearing zones exist within Quaternary sediment located throughout the study area (fig. 20). Those localized aquifers provide an important source of water to communities such as Sisters, Prineville, La Pine, and Camp Sherman.

Relatively coarse-grained glacial outwash deposits (included in unit Qs on fig. 11 and plate 1) are the principal water-bearing units in the vicinity of Sisters and Camp Sherman. Wells constructed into those deposits and interbedded Pleistocene lava flows have yields ranging from 30 to 2,000 gal/min.

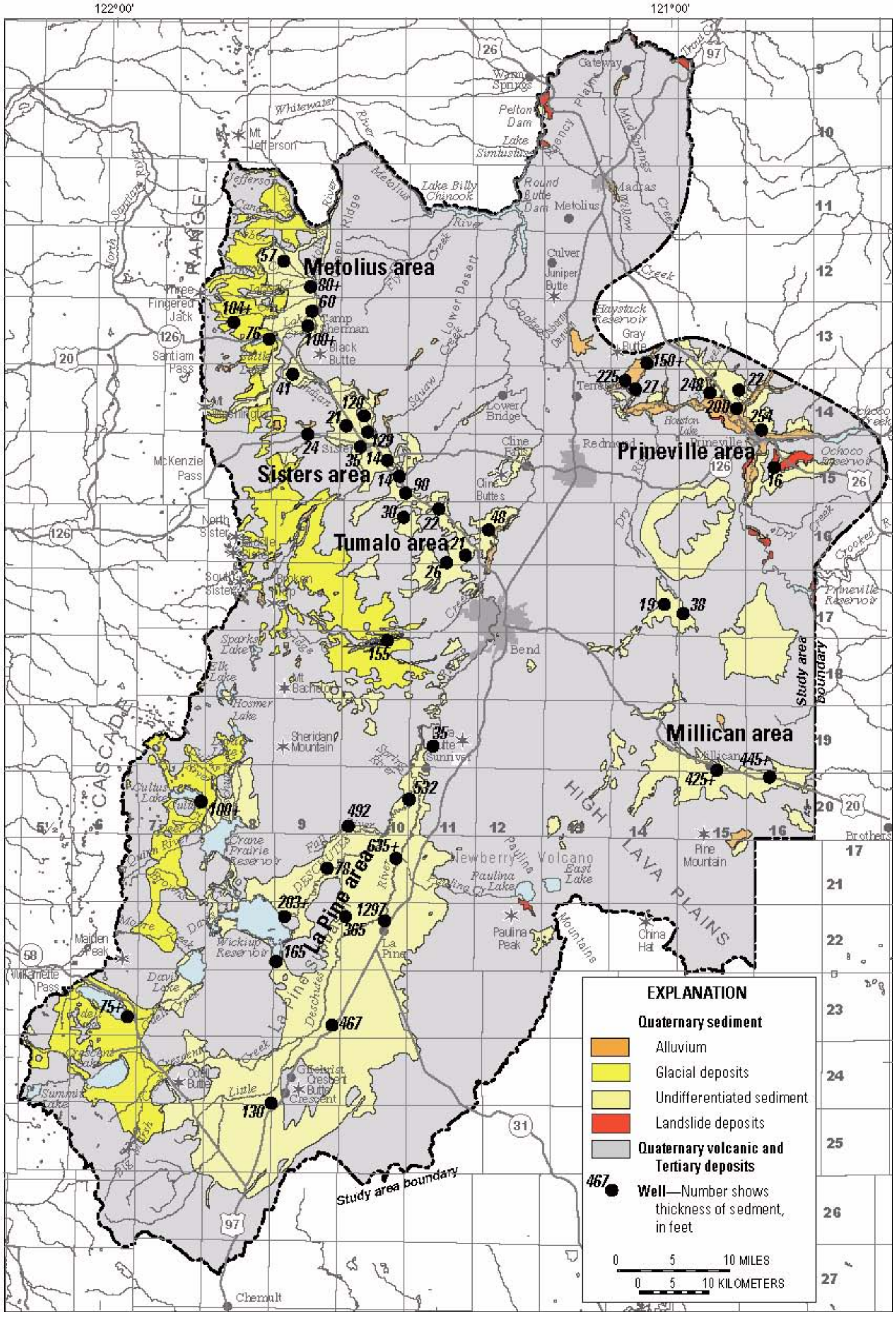


Figure 20. Distribution and thickness of Quaternary sediment.

An aquifer test conducted on well 15S/10E-05BBB (well no. 41, plate 1) near Sisters yielded a hydraulic conductivity estimate of 100 ft/d (Gannett and others, 2001). The well is open to glacial outwash and interbedded lava.

The Tumalo fault escarpment near Sisters appears to have provided an elongate depositional center for the thickest accumulation of the sediment in that area (fig. 11). The outwash sediment is locally over 100 ft thick in the Sisters area. A natural gamma log for a well near Black Butte (14S/09E-08ABA) (well no. 16, plate 1) that penetrates outwash deposits and underlying Cascade Range lava flows shows an unremarkable gamma trace (fig. 21A). The similarity of the gamma signature in the outwash deposit and the underlying lava flows results from the similarity of the sedimentary material (mostly mafic volcanic debris) and that of the underlying lava. A natural gamma log for a well near Sisters (14S/10E-28DDC2) (well no. 18, plate 1) that is completed only into outwash deposits shows a similar gamma trace (fig. 21B).

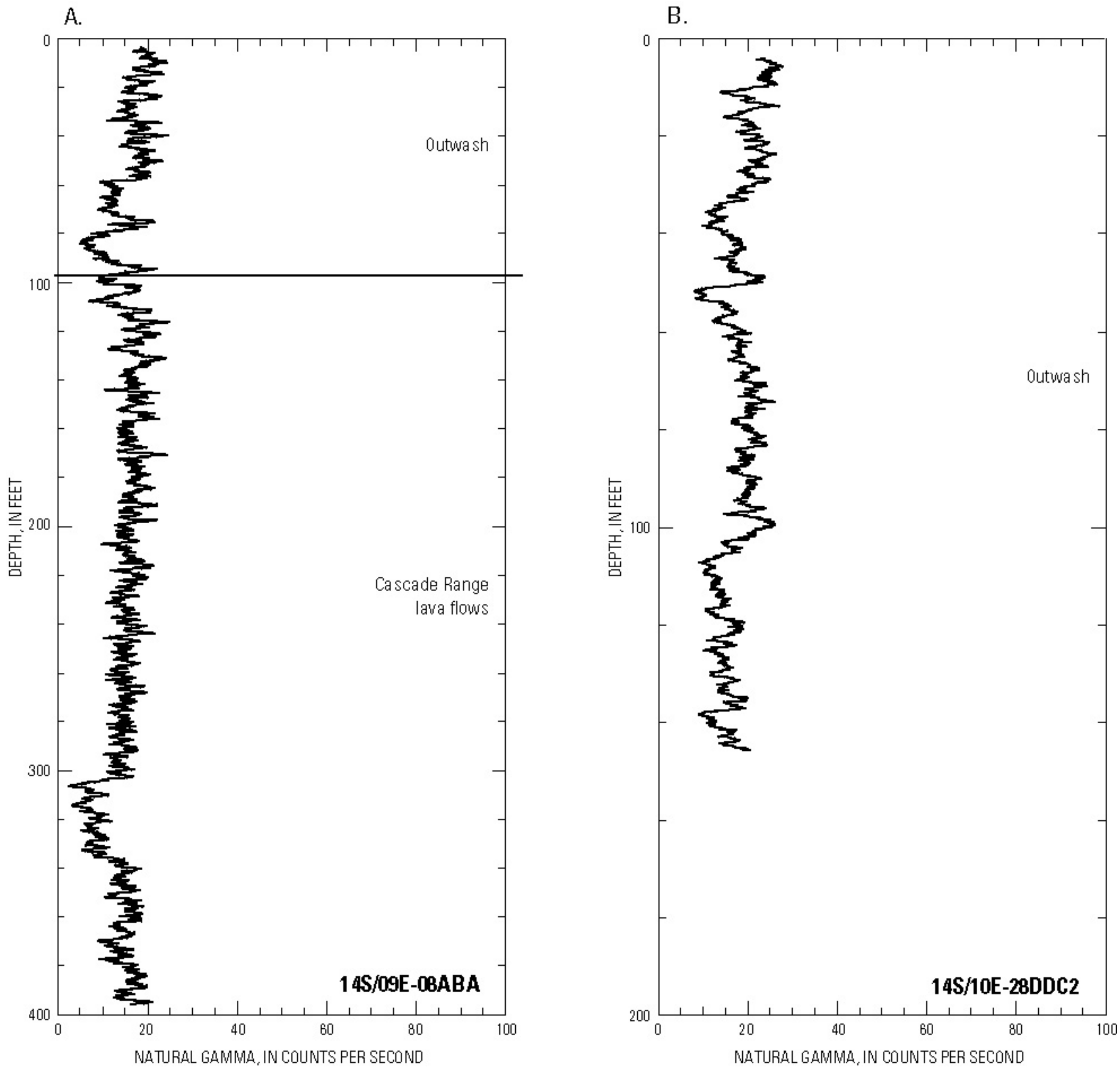


Figure 21. Natural gamma logs for wells penetrating Quaternary outwash deposits and lava flows.
A. Well near Black Butte (14S/09E-08ABA, well no.16, plate 1); B. Well near Sisters (14S/10E-28DDC2, well no. 18, plate 1).

Outwash deposits near Camp Sherman are also locally more than 100 ft thick. Subsurface data are too sparse in the upper Metolius River area to construct a meaningful thickness map of the outwash deposits and thus determine the geometry of the unit. However, the Green Ridge escarpment and its associated down-dropped blocks formed a boundary to east-draining streams that probably resulted in a north-trending depositional center for the sediment. Well yields in the upper Metolius River area outwash deposits generally range from 20 to 30 gal/min, to approximately 200 gal/min.

Reworked glaciofluvial material provides a locally important aquifer for domestic users in the vicinity of Tumalo (fig. 20). The source of that water is probably canal leakage. The unit thickness is generally less than 50 ft; however, thicknesses up to 200 ft occur locally. Well yields from the reworked glacial deposits are generally less than 30 gal/min.

A few wells have been drilled into glacial till (Qg on plate 1), which occurs exclusively within the Cascade Range. Those wells mostly serve youth camps and campgrounds. The deposits consist primarily of poorly sorted silt, sand, and gravel. The fine-grained matrix material and poor sorting of the deposits result in modest well yields of less than 30 gal/min.

Quaternary sediment near the eastern and southern boundaries of the study area also serves as an important water-bearing unit. Robinson and Price (1963) described the Quaternary deposits near Prineville as fluviolacustrine sediment locally overlain by alluvium along the Crooked River and Ochoco Creek. The greatest total thickness of the fluviolacustrine unit is in excess of 250 ft (fig. 20). The fluviolacustrine sediment sequence consists of an upper unit (up to 100 ft thick) consisting primarily of sand with some gravel that overlies a fine-grained (mostly silt and fine sand) section (approximately 150 ft thick) that in turn overlies a thin (approximately 10 ft thick), relatively coarse sand and gravel unit. Remarkably, that general sequence is consistent over several square miles. The lower sand and gravel unit is artesian and is capable of yields of a few hundred gallons per minute. Wells producing from the upper coarse-grained unit have yields in the range of 10 to 20 gal/min and are mostly suitable for domestic supplies.

Robinson and Price (1963) documented higher head in the lower aquifer than in the shallow water-bearing unit. That phenomenon persists, at least locally, as exhibited in a pair of adjacent wells identified in this study. Well 14S/15E-15DAC1 (well no. 37, plate 1), completed to 206 ft, has a hydraulic head that is about 35 ft higher than that in the adjacent shallow well 14S/15E-15DAC2 (well no. 38, plate 1) completed to 50 ft.

Recent alluvium (Qal) occurs adjacent to the Crooked River and Ochoco Creek. The alluvium may be as thick as 100 to 200 ft in the vicinity of Prineville. However, it is nearly impossible to distinguish the younger sediment from the older Quaternary sedimentary strata using only well-log information.

The Millican valley is a small, east-trending subbasin containing a sequence of presumably Quaternary sediment (fig. 20). The subbasin is underlain by over 445 ft of sand, clay, and gravel, and, near the basin margin, interbedded lava flows. The unit appears to be saturated only near the bottom of the sedimentary sequence, and wells typically yield less than 20 gal/min.

The largest occurrence of Quaternary sediment within the upper Deschutes study area is in the vicinity of La Pine (fig. 20). This sedimentary sequence commonly consists of a lower unit of mostly silt and fine sand as much as several hundred feet thick, and an upper unit of silt, sand, and gravel as thick as 100 ft. Well drillers sometimes describe organic (woody) material within the lower unit. The organic component has been identified as a potential source of methane and hydrogen sulfide gases observed in some wells within the La Pine subbasin (Stephen R. Hinkle, U.S. Geological Survey, oral commun., 1999). A gamma log for well 23S/09E-36BBC (well no. 119, plate 1) located in the southernmost part of the La Pine subbasin (fig. 22A) reveals an irregular and mostly low gamma signature for the lower, fine-grained unit. The few spikes that occur on the log probably represent thin fallout tephra layers interbedded within the sedimentary sequence.

Few wells develop water from the lower, predominately fine-grained sedimentary unit. Low to moderate yields (5 to 30 gal/min) are derived from interbedded sand and gravel layers in the unit, and moderate (50 to 90 gal/min) yields come from interbedded lava flows and cinders.

Most wells in the La Pine subbasin are constructed in the upper sediment unit. The upper unit differs from the lower unit in that the sediment is slightly coarser grained and lacks the organic debris characteristic of the lower unit. The uppermost part of the upper sediment also commonly contains pumice, probably reworked Mount Mazama tephra, although some may be derived from Newberry Volcano. A gamma log for a well (21S/11E-18CDA3) (well no. 114, plate 1) in the northeastern part of the La Pine subbasin (fig. 22B) clearly shows a thin layer at a depth of about 10 ft with a high gamma count characteristic of silicic tephra.

Well yields in the upper sedimentary unit are typically 10 to 30 gal/min. The upper alluvium generally becomes coarser grained, however, in the northern part of the La Pine subbasin, resulting in well yields as great as 300 gal/min. An estimate of hydraulic conductivity of the upper sedimentary unit is 88 ft/d based on aquifer tests conducted near La Pine (Century West Engineering Corporation, 1982). The tested wells produced from fine to coarse-grained sand with occasional fine gravel.

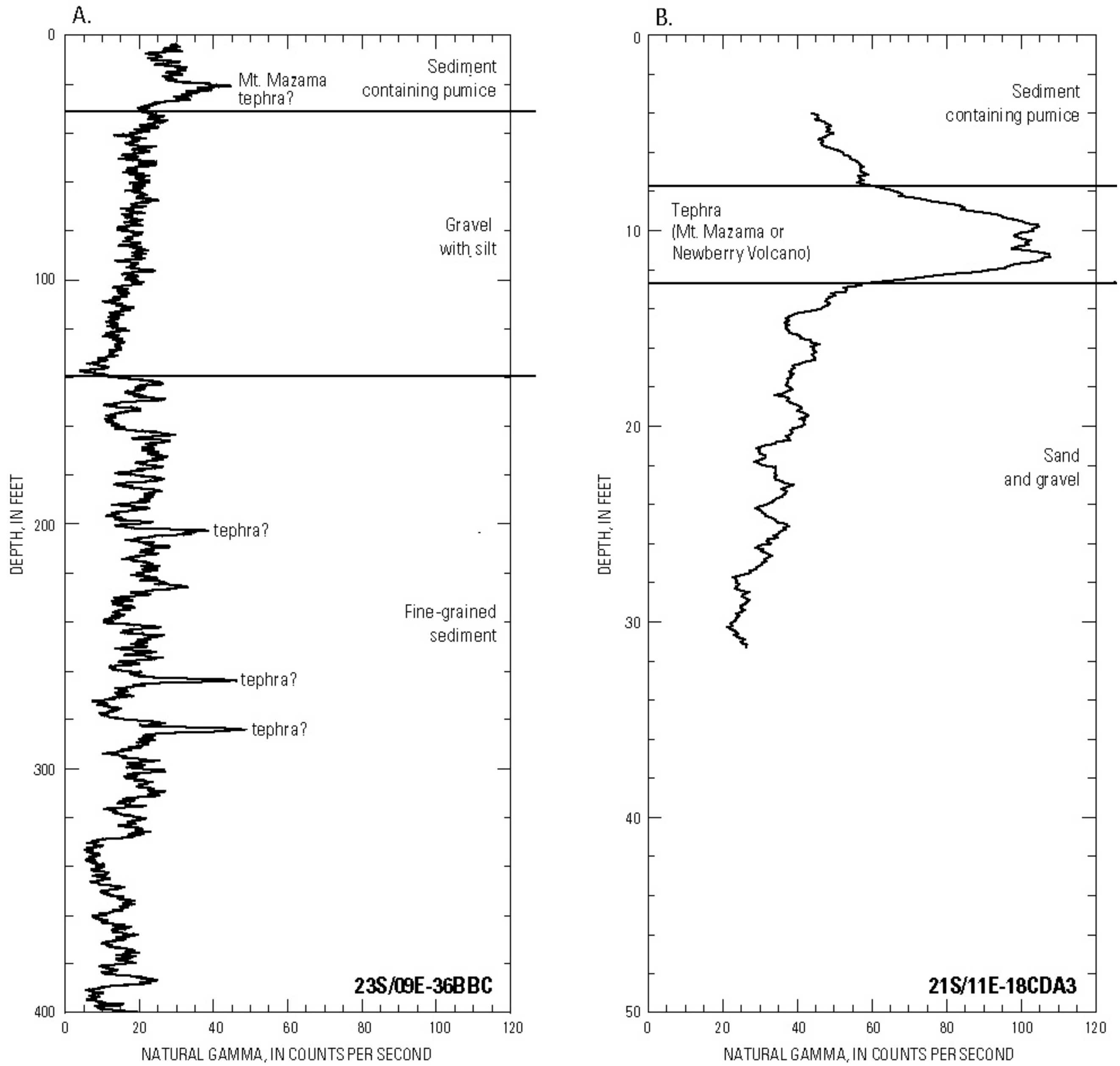


Figure 22. Natural gamma logs for wells penetrating Quaternary basin-fill deposits in the La Pine subbasin. A. Well in southernmost part of La Pine subbasin (23S/09E-36BBC, well no. 119, plate 1); B. Well in northern part of La Pine subbasin (21S/11E-18CDA3, well no. 114, plate 1).

HYDROGEOLOGIC UNITS

For purposes of hydrologic analysis, geologic units are commonly combined or subdivided into groupings or subsurface regions, referred to as hydrogeologic units, characterized by distinct hydrogeologic properties. Hydrogeologic units are typically defined as having hydrologic or geologic properties that are distinct from surrounding units. Hydrogeologic units may consist of a single geologic unit, groups of geologic units, or discrete zones within a single geologic unit. All three cases occur in the upper Deschutes Basin.

Delineating hydrogeologic units in the upper Deschutes Basin is complicated by geologic heterogeneity and the lack of subsurface information over large areas. The large range of hydrologic conditions within single geologic units is difficult to specify in many instances.

Seven hydrogeologic units have been delineated in the upper Deschutes Basin (fig. 23): (1) Quaternary sediment, (2) permeable deposits of the Cascade Range and Newberry Volcano, (3) proximal lava flows of the Deschutes Formation, (4) the arc-adjacent alluvial-plain facies of the Deschutes Formation, (5) the ancestral Deschutes River-channel facies of the Deschutes Formation, (6) the inactive-margin facies of the Deschutes Formation, and (7) pre-Deschutes Formation rocks and hydrothermally altered rocks at depth beneath the Cascade Range and Newberry Volcano. The characteristics of the units are based on surficial geology and knowledge of subsurface conditions derived from well data. Boundaries between some of the hydrogeologic units are approximate because geologic contacts are gradational and subsurface data are sparse. Boundaries of other units are more precise because the geologic contacts are sharp and well defined by surface exposures. The hydrogeologic units are discussed in the following paragraphs of this section.

Coarse-grained surficial Quaternary sedimentary deposits constitute one hydrogeologic unit. This unit includes alluvial- and glacial-outwash deposits. These materials are generally permeable and productive where saturated. The fine-grained basin-filling deposits with low permeability that occur at depth in the La Pine graben are not considered part of this unit. Well yields are typically 10 to 300 gal/min.

Permeable volcanic deposits of the Cascade Range and Newberry Volcano constitute another hydrogeologic unit. This unit consists primarily of permeable lava flows and minor pyroclastic and volcaniclastic interbeds, and comprises a large part of the upper Deschutes Basin. Hydrothermally altered rocks with low permeability that occur at depth beneath the Cascade Range and Newberry Volcano are not considered part of this unit. There may be areas within this unit that are hydrologically distinct, but no data were available on which to further subdivide this unit.

The Deschutes Formation can be divided into four hydrogeologic units. These units generally correspond to the depositional facies of the Deschutes Formation defined by Smith (1986b) and previously discussed.

- The most voluminous and areally extensive unit consists largely of proximal lava flows. It also includes undifferentiated volcanic deposits, primarily lava flows, not generally mapped as Deschutes Formation but of a similar age. This unit is generally permeable and locally is highly permeable. Many large-capacity public-supply wells in the Bend area produce from this unit. Well yields range up to 2,000 gal/min.
- The second hydrogeologic unit in the Deschutes Formation corresponds to the arc-adjacent alluvial-plain facies. This unit consists of sediment interbedded with lava flows and ash-flow tuff. This unit is more geologically heterogeneous than surrounding units, and hydrologic conditions are variable as a result. The unit is generally permeable and locally highly permeable. Many large-capacity irrigation wells in the Lower Bridge area produce from this unit. Well yields range up to 4,000 gal/min.
- The third hydrogeologic unit within the Deschutes Formation corresponds to the ancestral Deschutes River channel facies. This unit consists predominately of coarse sand and gravel, distal parts of ash-flow tuffs, and intracanyon lava flows. It is generally highly permeable due to the large proportion of coarse-grained material and fractured basalt flows; for example, the very productive Pelton and Opal Springs basalt members. Many large-capacity wells in the Redmond area produce from both sediment and lava flows of this unit. Well yields range up to 2,300 gal/min near Redmond and up to 5,000 gal/min at Opal Springs.

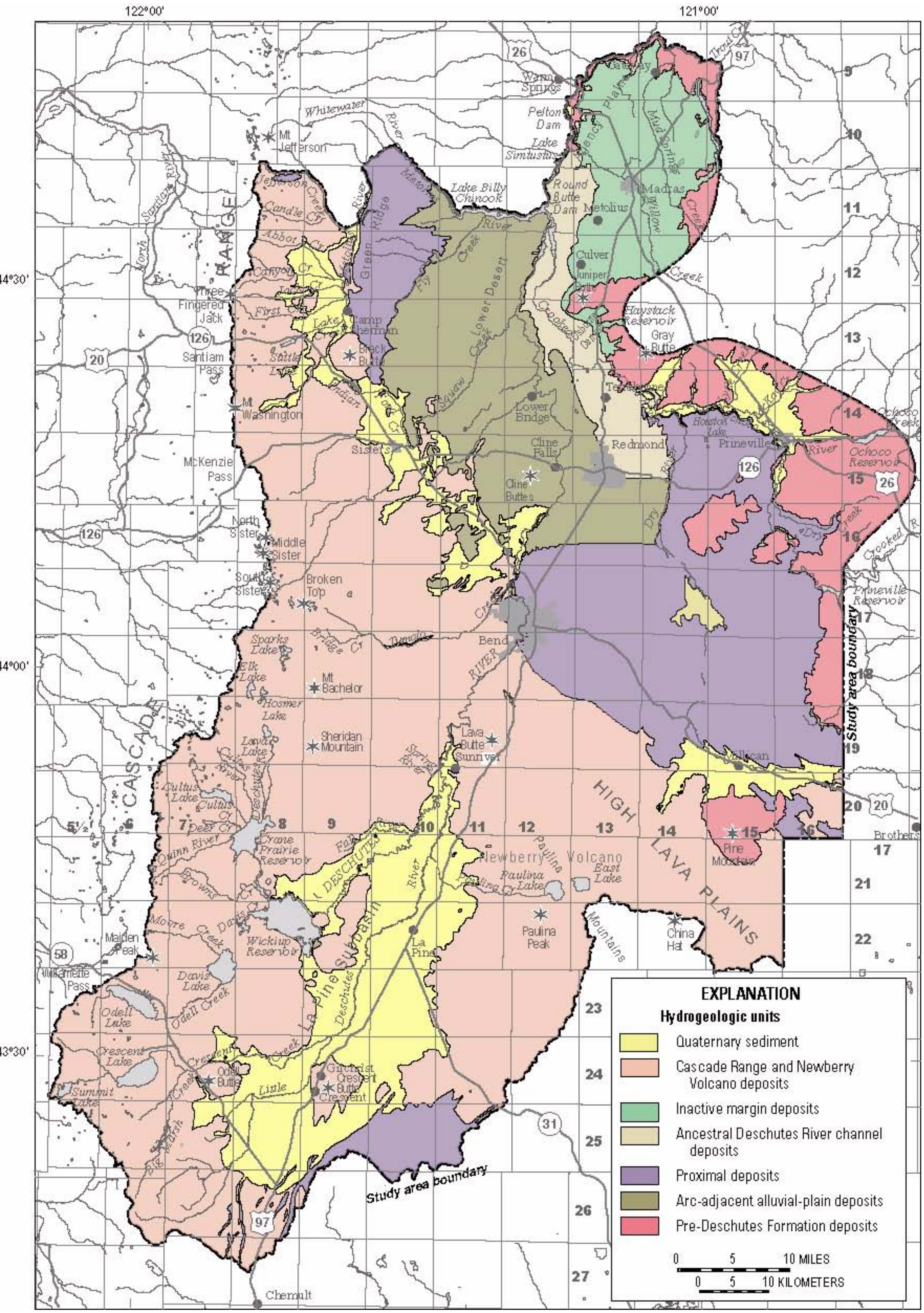


Figure 23. Hydrogeologic units in the upper Deschutes Basin, Oregon.

- The fourth hydrogeologic unit within the Deschutes Formation corresponds to the inactive-margin facies. This unit consists of relatively fine-grained clastic and pyroclastic material, much of which was derived from the John Day Formation. Because this unit consists largely of fine-grained, poorly sorted material, it has low permeability. Well yields from this unit are lower than yields from other units, ranging from 30 to 300 gal/min.

The lowest hydrogeologic unit recognized in the upper Deschutes Basin consists of pre-Deschutes Formation rocks including the Prineville Basalt, John Day Formation, and hydrothermally altered rock with extremely low permeability at depth beneath the Cascade Range and Newberry Volcano. The Prineville Basalt has moderate to low permeability (with hydraulic conductivity ranging from 1 to 50 ft/d), and the John Day Formation has extremely low permeability (with hydraulic conductivity ranging from 0.01 to 0.1 ft/d). The John Day Formation and hydrothermally altered rocks are generally considered the boundary to regional ground-water flow system in the upper Deschutes Basin.

SUMMARY

The stratigraphic and structural framework of the upper Deschutes Basin influences many aspects of recharge, flow, and discharge of the ground-water flow system. Episodic volcanic activity in the region over the past several million years has resulted in a variety of volcanic, volcaniclastic, and volcanically derived sedimentary deposits. The volcanic activity and subsequent deposition and alteration of some deposits have produced strata that range widely in permeability.

Alteration and weathering of the John Day Formation rocks has resulted in very low permeability. The low-permeability rocks of the John Day Formation form a boundary to regional ground-water flow.

The Deschutes Formation is the most extensively used water-bearing unit in the study area. Depositional environments for the formation that were described by Smith (1986b) have proven to be useful hydrogeologic subdivisions. The ancestral Deschutes River deposits and some units within the arc-adjacent alluvial-plain region are among the highest yielding units within the Deschutes Formation. Yields of up to a few thousand gallons per minute have been observed from wells constructed into some of the ancestral Deschutes River deposits and parts of the arc-adjacent alluvial-plain region. Opal Springs basalt, Pelton basalt, and the rhyodacite dome complex near Steelhead Falls are particularly productive units and provide tens to hundreds of cubic feet per second of ground-water discharge to the Deschutes and Crooked Rivers, upstream of Round Butte Dam.

Ground-water recharge in the upper Deschutes Basin occurs chiefly in deposits of the Cascade Range and Newberry Volcano. The youthful and fractured character of the Cascade Range volcanic deposits facilitates rapid infiltration of precipitation and snowmelt in the Cascade Mountains. Additional recharge from canal leakage occurs along sections of unlined canals constructed near Bend into lava flows from Newberry Volcano.

Although surficial rocks and deposits of the Cascade Range and Newberry Volcano are very permeable in the upper Deschutes Basin, hydrothermal alteration and secondary mineralization have drastically reduced the permeability of the material at depth in those regions. The depth at which permeability is reduced is variable, ranging from 300 to 1,500 ft. Most ground-water flow in the Cascade Range and Newberry Volcano occurs above those depths.

Several small water-bearing regions occur throughout the study area within Quaternary sedimentary deposits. Glaciofluvial, fluvial, and fluviolacustrine deposits provide important water sources to communities such as Sisters, Prineville, La Pine, and Camp Sherman.

Tectonic structural features influence ground-water flow within the upper Deschutes Basin primarily by their influence on deposition. Several small depositional centers have formed along the base of fault-line scarps within the study area, resulting in accumulations of sand and gravel; Quaternary deposits in the vicinity of Camp Sherman and Sisters are good examples. The La Pine subbasin occupies a complex graben structure where up to 1,000 ft of sediment was subsequently deposited by streams.

The variety of volcanic and tectonic processes within the upper Deschutes Basin has resulted in a highly heterogeneous accumulation of deposits. Few distinct, well-defined hydrogeologic units have resulted from the geologic evolution of the area. However, knowledge about the general character of the deposits, their depositional environments, and areal distribution has allowed us to define the general distribution and range of hydraulic properties for the units. That distribution leads to a delineation of seven hydrogeologic zones within the upper Deschutes Basin.

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