Hydrogeologic Framework

The Willamette Basin is a topographic and structural trough that lies between the Coast Range and the Cascade Range (fig. 1). The basin lowland is divided into five sedimentary subbasins that are separated by local uplands of the Columbia River Basalt Group lavas. Stream drainages between the basins are restricted by narrow water gaps that cut into the Columbia River Basalt Group or older, low-permeability bedrock. Variations in the depositional histories of each subbasin have created hydrogeologic conditions that are distinct but broadly related by common features of the geologic history of the entire basin (Woodward and others, 1998). A general geologic history of the basin is presented below to provide a setting for understanding the main geologic controls on the ground-water hydrology of the basin. Detailed geologic histories can be found in Gannett and Caldwell (1998), O'Connor and others (2001), Yeats and others (1996), and Orr and others (1992).

The Coast Range is composed of uplifted Tertiary marine sedimentary rocks and related marine volcanic and intrusive rocks. The Cascade Range is an accumulation of volcanic lavas and debris erupted from continental volcanoes. Tertiary marine strata and older Cascade volcanic rocks interfinger at depth beneath the Willamette Valley to form the bedrock foundation of the lowland. During the initial formation of the Cascade Range, around 35–40 million years ago, the ancestral Pacific shoreline was located near the present foothills of the range at the eastern margin of the Willamette lowland (Orr and others, 1992). As the Cascade Range grew by the accumulation of volcanic debris, east-west compressive forces began to uplift the area currently occupied by the Coast Range and depress the area that is now the Willamette lowland. As this process continued, the valley gradually became isolated from the sea and began to accumulate sediments deposited by rivers draining the Cascade Range and the rising Coast Range. Around 16 to 14 million years ago, numerous large-volume lava flows of the Columbia River Basalt Group erupted from vents east of the Cascade Range, entered the northern valley through a gap in the Cascade Range, and flooded low-lying areas as far south as Salem (Beeson and others, 1989a). During and after the emplacement of the Columbia River basalt lavas, the Coast Range continued to rise and the Columbia River basalt lavas and underlying bedrock were distorted by faulting and folding to create five sedimentary subbasins that are separated by local uplands of basalt lava. From north to south, these are the Portland Basin, the Tualatin Basin, the central Willamette Basin, the Stayton Basin, and the southern Willamette Basin (pl. 1). The Stayton Basin is small and, unless mentioned specifically, is included in the southern Willamette Basin in this report. Fluvial and lacustrine sediments have subsequently filled these basins. Sediment thickness exceeds 1,400 ft in the Portland, Tualatin, and central Willamette Basins but is generally less than 500 ft in the Stayton and southern Willamette Basins (Gannett and Caldwell, 1998). After emplacement of the Columbia River Basalt Group, volcanic material continued to be produced from the Cascade Range and covered the lavas east of the lowland.

The bulk of the basin-fill sediments in the Willamette lowland consists of clays and silts that were deposited in low-energy depositional environments that included distal alluvial fans, low-gradient streams, and lakes (Gannett and Caldwell, 1998). Fine-grained deposits predominate in the western portions of the lowland and at depth. Coarse-grained sediments are largely restricted to the eastern side of the basin, where high-gradient streams draining the Cascade Range enter the valley lowland. Most of the coarse-grained, basin-fill deposits south of the Portland Basin were deposited in braided stream environments on alluvial fans and braid-plains that formed during the Pleistocene Epoch (Gannett and Caldwell, 1998; O’Connor and others, 2001). Alluvial fans are thickest on the eastern and southern flanks of the valley where major Cascade Range streams enter the valley lowland. Extensive deposits of coarse-grained sediments are not associated with streams that drain the Coast Range on the west side of the valley. This is particularly evident in the Tualatin Basin, where the bulk of the basin-fill sediments are fine-grained deposits eroded from local highlands within the basin (Wilson, 1997).

Between about 15,000 and 12,000 years ago, repeated glacial outburst floods from Glacial Lake Missoula swept down the Columbia River drainage and inundated the Willamette Basin with water up to elevations of 500 ft (O’Connor and others, 2001). As the flood waters exited the narrow reaches of the Columbia River gorge east of Portland, flood velocities subsided and a large delta of sand and gravel was deposited in the Portland Basin. Elsewhere in the Willamette Basin, lower velocity flood-waters formed temporary lakes that produced the extensive Willamette Silt beds in the area south of the Portland Basin. Following the deposition of the Willamette Silt, the Willamette River and its main Cascade tributaries established new floodplains by eroding steep-walled trenches through the silt. These modern floodplains are occupied by meandering and anastomosing streams that have deposited large tracts of sands and gravels (O’Connor and others, 2001). Smaller streams, such as the Pudding River, have not been able to down cut completely through the Willamette Silt in most areas of the valley lowland. Holocene sediments deposited by the smaller streams are generally restricted to silty sands, silts, or clays.

Hydrogeologic Units

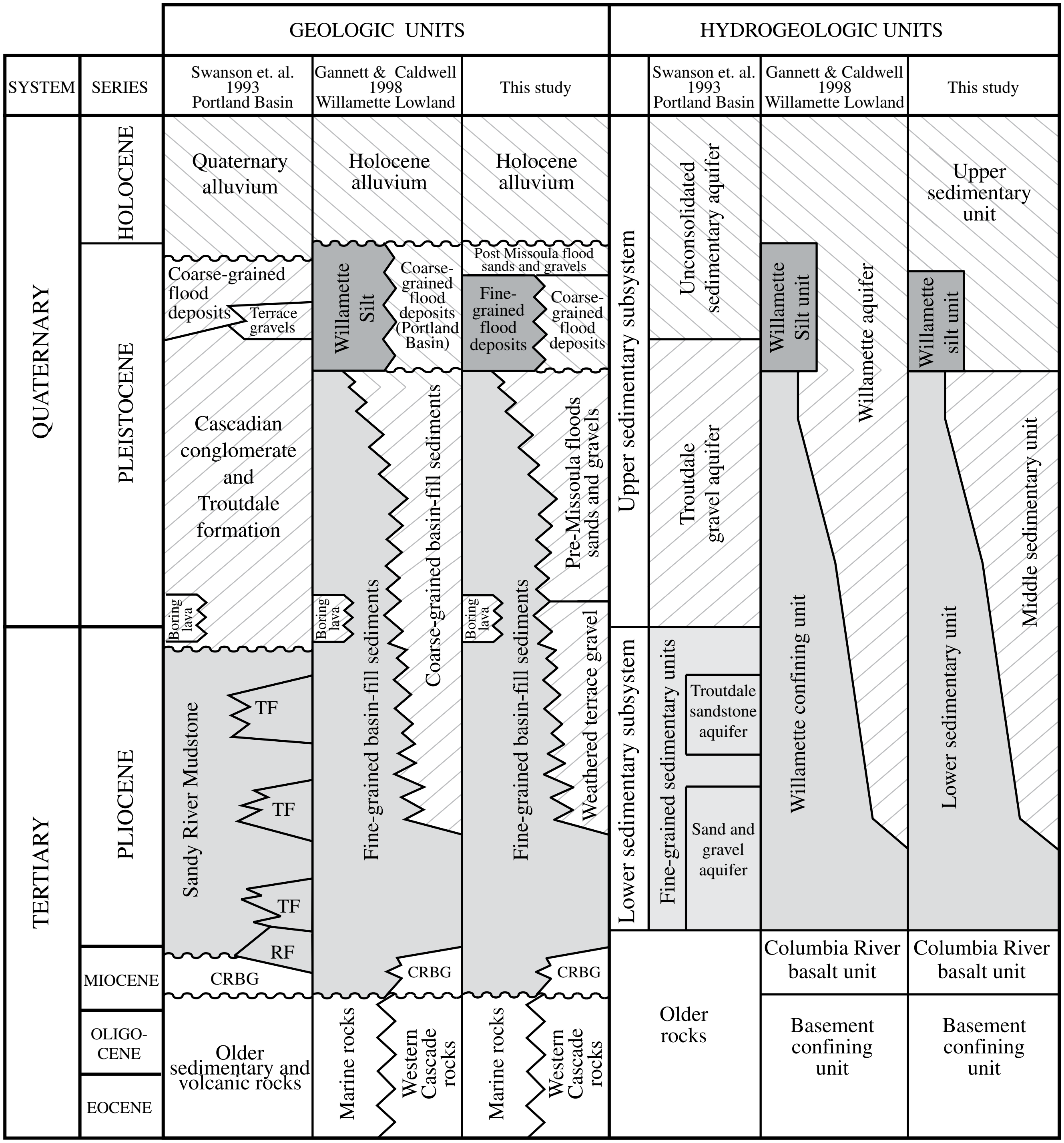
For the purposes of this study, seven regional hydrogeologic units, which consist of one or more geologic units with similar hydrogeologic properties at a regional scale, are defined in the Willamette Basin: (1) the High Cascade unit, (2) the upper sedimentary unit, (3) the Willamette silt unit, (4) the middle sedimentary unit, (5) the lower sedimentary unit, (6) the Columbia River basalt unit, and (7) the basement confining unit. This usage parallels that of Woodward and others (1998) with the addition of the High Cascade unit and the subdivision of their Willamette aquifer into a younger, more permeable upper and older less permeable middle sedimentary unit. Previous investigators (McFarland and Morgan, 1996; Piper, 1942; Price, 1967a; 1967b; Frank, 1973; Woodward and others, 1998) recognized that younger coarse-grained material had higher permeabilities than older coarse-grained material. Information from these studies and mapping by O’Connor and others (2001) allows a broad division of the coarse-grained basin-fill sediments into two regional hydrogeologic units based on permeability contrasts.

The Willamette silt unit and the upper, middle, and lower sedimentary units are unconsolidated, nonmarine, basin-fill sediments that generally post-date the Columbia River Basalt Group. The upper and middle sedimentary units correspond to the Willamette aquifer, and the lower sedimentary unit corresponds to the Willamette confining unit of Woodward and others (1998). Geologic and hydrogeologic units for this investigation and several earlier ground-water studies in the basin are correlated in figure 3. The High Cascade unit, which is only found in the eastern part of the study area, is not included in figure 3.

Descriptions of each hydrogeologic unit are presented in the following sections of this report. General unit descriptions are summarized from Swanson and others (1993), McFarland and Morgan (1996), Gannett and Caldwell (1998), and Woodward and others (1998), which provide the framework for the current study. The reader is referred to these reports for detailed unit descriptions. Additional information is provided where new data and analyses from the current study were used to modify unit characteristics. Most of the modifications were to the productive units: the upper and middle sedimentary units and the Columbia River basalt unit.

A map of the distribution of hydrogeologic units at land surface and cross sections of the distribution of the units in the subsurface are shown in plate 1. Thickness maps for basin-fill sediment units were prepared by modifying maps produced by Gannett and Caldwell (1998) using well data (Orzol and others, 2000) and geologic maps (O’Connor and others, 2001) compiled as part of this investigation.

Hydraulic properties were compiled for each hydrogeologic unit and summarized. Most historic data for aquifer tests are reported as transmissivity, a measure of an aquifer’s ability



TF= Troutdale Formation
RF= Rhododendron Formation
CRBG= Columbia River Basalt Group

Hatches and shading show correlation between hydrogeologic and geologic units for this and previous studies

Figure 3. Correlation chart of hydrogeology, Willamette Basin, Oregon.

to transmit water that is equal to the product of the hydraulic conductivity and the saturated thickness of the aquifer. To facilitate a comparison of hydraulic properties, transmissivity values were converted to hydraulic conductivity by dividing the reported transmissivity by the open interval of the well, which yields a maximum value of hydraulic conductivity in most cases. The other aquifer property estimated from aquifer tests is the storage coefficient, which is defined as the volume of water released from storage per unit surface area of the aquifer per unit change in head.

High Cascade Unit

The High Cascade unit (HCU) consists of young, relatively unaltered volcanic material erupted from Pleistocene to Holocene-age volcanoes (Ingebritsen and others, 1994) along the crest of the Cascade Range. The unit is at land surface on the eastern edge of the study area (pl. 1) and is greater than 1,000 ft (feet) thick. The area underlain by the High Cascade unit is largely forest, barren areas of volcanic material, alpine meadows, and snowfields.

Permeability is high in the upper part of the High Cascade unit and decreases with depth (Ingebritsen and others, 1994; Manga, 1996; Hurwitz and others, 2003; Saar and Manga, 2003, 2004). Saar and Manga (2004) estimate that hydraulic conductivity ranges from 100 to 1,000 ft/d (table 1) in the upper 100 ft and decreases to 0.1 ft/d at depths around 1,000 ft. In a ground-water flow model of the Deschutes Basin, the upper 1,500 ft of material in the High Cascade area was simulated with a hydraulic conductivity of 6 to 20 ft/d (Gannett and Lite, 2004).

These studies suggest that precipitation and snowmelt easily infiltrate into the permeable High Cascade unit. Ground water follows shallow, short flow paths and contributes to the large discharge of cold springs within the High Cascades area. Ground water that follows deeper and longer flowpaths carries heat away from the volcanic arc and discharges as hot springs near the contact of the High Cascade unit and the basement confining unit. Although development of ground water is limited in the High Cascade area, high ground-water recharge and discharge rates of the unit are important in sustaining streamflow through the year in the major streams that drain the Cascade Range.

Upper Sedimentary Unit

The upper sedimentary unit (USU) consists primarily of unconsolidated sands and gravels of late Pleistocene and Holocene age, and is equivalent to the unconsolidated aquifer of McFarland and Morgan (1996) in the Portland Basin and the younger alluvial floodplain deposits (Piper, 1942; Price, 1967a, 1967b; Frank, 1973; Woodward and others, 1998) in the central and southern Willamette Basins. The unit is exposed at land surface throughout its extent. It is absent in the Tualatin Basin.

In the Portland Basin, the unit is largely composed of coarse-grained Missoula Flood deposits. The unit also includes the late Pleistocene and Holocene alluvium, and unconsolidated terrace deposits along major streams. The unit is approximately 50 ft thick in the central part and more than 150 ft thick in the western part of the Portland Basin (fig. 4**).**

In areas south of the Portland Basin, the upper sedimentary unit is generally equivalent to units mapped by O’Connor and others (2001) as post-Missoula Flood gravels and Holocene floodplain deposits. The post-Missoula Flood gravels represent the last pulse of Pleistocene alluvial fan deposition in the Willamette Valley. They occur as sand and gravel at land surface that form the upper surface of Pleistocene alluvial fans or as terraces inset along the upper reaches of major Cascade streams. The upper sedimentary unit includes Holocene floodplain deposits of the Willamette River and its major Cascade tributaries where channel gravels were deposited by meandering and anastomosing river systems. Near the Cascade Range, the floodplain deposits are inset into older alluvial fan surfaces. In the valley lowland, the upper sedimentary unit occurs in floodplains that occupy steep-walled trenches that have been incised through the entire thickness of the Willamette silt unit. The total thickness of these sediments is generally less than 40 ft, and the average thickness is about 20 ft (fig. 4).

The upper sedimentary unit is characterized by high permeability, high porosity, and high well yield. It is the most productive aquifer in the Willamette Basin, especially where it is dominated by thick sections of Missoula Flood gravels or Holocene floodplain gravels. Large diameter wells in the unit are capable of yielding up to 10,000 gal/min (gallons per minute) and commonly yield several thousand gallons per minute. Reported hydraulic conductivities range from 0.03 to 24,500 feet per day (ft/d) (table 1 and fig. 5). McFarland and Morgan (1996) estimate a median hydraulic conductivity in the Portland Basin of 220 ft/d. Data from Woodward and others (1998) indicate a mean conductivity of 600 ft/d in the areas south of the Portland Basin. Ground water in the unit is generally unconfined, and specific yields range from 0.003 to 0.2.

Willamette Silt Unit

The Willamette silt hydrogeologic unit (WSU) includes fine-grained deposits that occur at land surface in the lowland, except in the floodplains of the large streams, where the unit has been removed by erosion. The Willamette silt unit is underlain by the middle sedimentary unit in most places. The bulk of the unit is composed of deposits mapped as fine-grained Missoula Flood sediments by O’Connor and others (2001). These map units largely correspond to the Willamette Silt of Allison (1953) and Glenn (1965). The Willamette silt unit also includes minor amounts of other fine-grained deposits that are laterally or vertically contiguous with the Willamette Silt geologic unit.

The Willamette Silt contains as many as 40 planar beds of micaceous silt and clay that range from several inches to

Table 1. Hydraulic properties of hydrogeologic units in the Willamette Basin, Oregon.

[K_h, horizontal hydraulic conductivity in feet per day; K_v, vertical hydraulic conductivity in feet per day; S, storage coefficient; HCU, High Cascade unit; WSU, Willamette silt unit; USU, upper sedimentary unit; MSU, middle sedimentary unit; LSU, lower sedimentary unit; CRB, Columbia River basalt unit; BCU, basement confining unit; ft, feet]

Unit	K_h	K_v	S	Reference
HCU	10^{-4}–10^{-1}	--	--	Hurwitz and others, 2003, geothermal modeling
	10^{2}–10^{3}	--	--	Saar and Manga, 2004, seismicity and recharge
	10	--	--	Manga, 1996, spring discharge modeling
	10^{-3}–10^{-2}	--	--	Ingebritsen and others, 1994, geothermal modeling
USU	600	2.0	--	Woodward and others, 1998, model calibration, final estimate
	550–24,500	--	--	Woodward and others, 1998, specific capacity tests
	3–450; median = 140	--	--	Morgan and McFarland, 1996, model calibration
	0.03–7,000; median = 200	--	0.003–0.2	McFarland and Morgan, 1996, specific capacity and aquifer tests
	median = 170	--	0.2	Gonthier, 1983, specific capacity tests
WSU	0.03	0.0004	--	Iverson, 2002, model calibration
	0.2	0.008	--	Iverson, 2002, slug and permeameter tests
	1	0.01	--	Woodward and others, 1998, model calibration
	0.3–1.4	--	0.2–0.3	Wilson, 1997, core analysis
		0.04–0.7	--	Conlon and others, 2003, model calibration
	0.01–8		0.2–0.3	Price, 1967a, core analysis
MSU	6–31; mean = 202	--	0.0003–0.0005; 0.0002–0.003	See table 2, aquifer test
	0.002–0.008	--	--	Iverson, 2002, slug test
	6.8	6.8	--	Iverson, 2002, model sensitivity analysis
	200	2.0	--	Woodward and others, 1998, model calibration
	8–2,230	--	--	Woodward and others, 1998, specific capacity
	3–200; median = 16	--	--	Morgan and McFarland, 1996, model calibration
	0.03–1500; median = 7	--	0.0008–0.2	McFarland and Morgan, 1996, specific capacity and aquifer tests
LSU	200–220	--	0.0003	See table 2, aquifer test
	5	0.10	--	Woodward and others, 1998, model calibration
	160	--	0.07	Woodward and others, 1998, aquifer tests

Table 1. Hydraulic properties of hydrogeologic units in the Willamette Basin, Oregon—Continued.

[K_h, horizontal hydraulic conductivity in feet per day; K_v, vertical hydraulic conductivity in feet per day; S, storage coefficient; HCU, High Cascade unit; WSU, Willamette silt unit; USU, upper sedimentary unit; MSU, middle sedimentary unit; LSU, lower sedimentary unit; CRB, Columbia River basalt unit; BCU, basement confining unit; ft, feet]

Unit	K_h	K_v	S	Reference
LSU	0.8–32, median = 4	--	--	Wilson, 1997, core analysis
	1–150	--	--	Morgan and McFarland, 1996, model calibration
	0.02–200	--	0.00005–0.2	McFarland and Morgan, 1996, specific capacity and aquifer tests; higher values reflect Troutdale Sandstone aquifer and sand and gravel aquifer
	median = 19	--	0.001– 0.2	Gonthier, 1983, specific capacity tests
CRB	22–1,100	--	0.0004	See table 2, aquifer tests
	6	--	--	Woodward and others, 1998, aquifer tests
	2.5	0.03	--	Woodward and others, 1998, model calibration
	0.1–3; median = 2.5	--	--	Morgan and McFarland, 1996, model calibration
	<0.001–200; median = 0.3	--	0.0001–0.2	McFarland and Morgan, 1996, specific capacity and aquifer tests
	0.001–0.1	--	--	Woodward and others, 1998, structurally affected basalts
	1–3	--	--	Woodward and others, 1998, undeformed basalts
	0.001–750; median = 1	--	--	Woodward and others, 1998, CRB plateau
	10^{-7}–10^{3}			Reidel and others, 2002, core analysis of interflow zones (Pasco Basin, Washington)
	10^{-10}–10^{-4}; mean = 10^{-8}–10^{-7}	--	--	Reidel and others, 2002, core analysis of flow interiors (Pasco Basin, Washington)
	10^{-5}–10^{3}; 10^{-7}–10^{2}	--	--	Reidel and others, 2002, Wanapum and Grande Ronde basalt flow tops (Pasco Basin, Washington)
BCU	10^{-5}–10^{-2}	--	--	Ingebritsen and others, 1994, geothermal modeling
	0.2–0.3	--	0.00005–0.003	Gonthier, 1983, specific capacity tests

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[1] Hydraulic conductivity calculated by dividing transmissivity by the open interval of well.

[2] Hydraulic conductivity calculated by dividing transmissivity by the thickness of the aquifer (220 ft) in the study area, rather than open interval (40 ft).

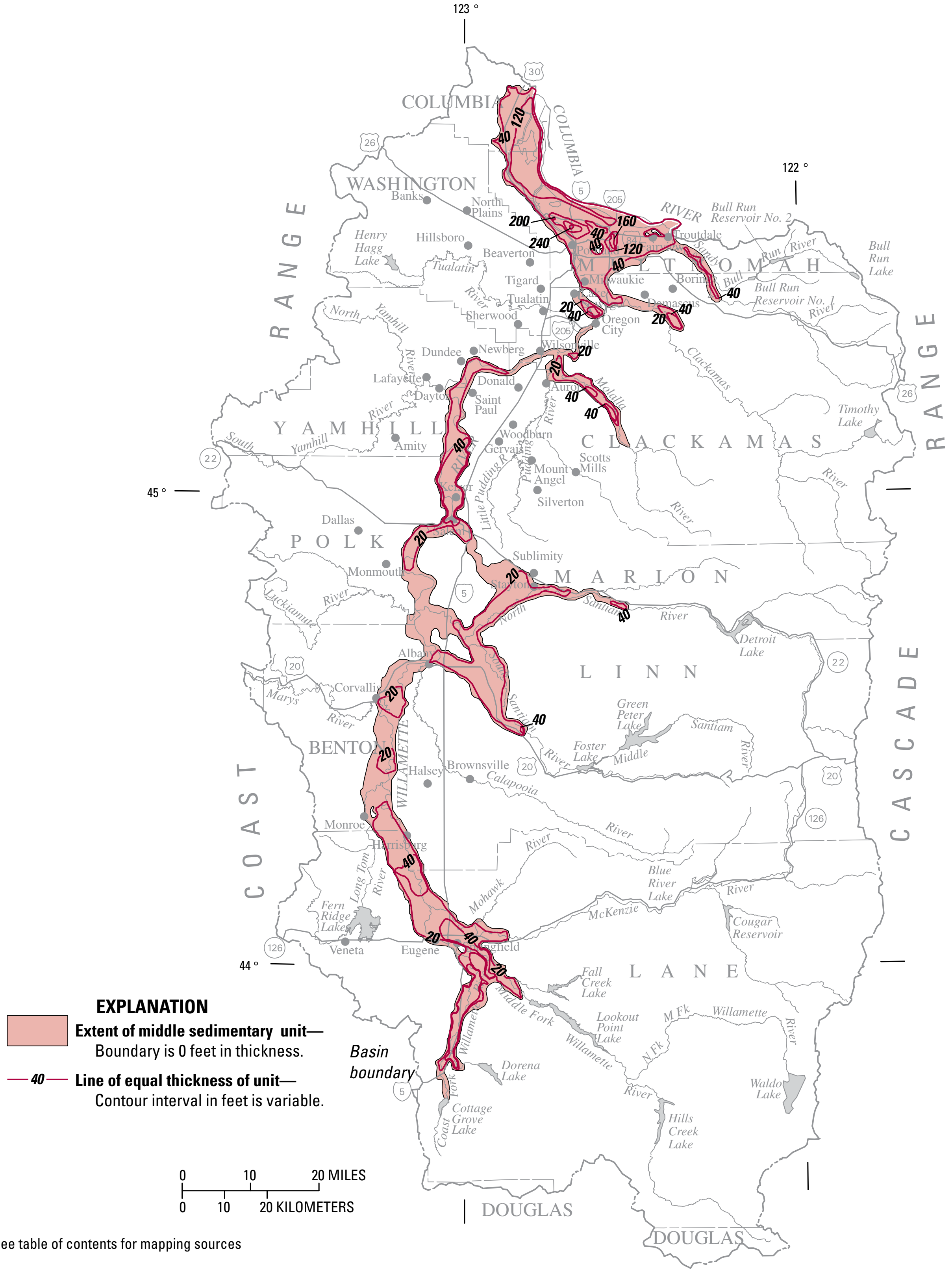

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Figure 4. Extent and thickness of the upper sedimentary unit (modified from O'Connor and others, 2001).

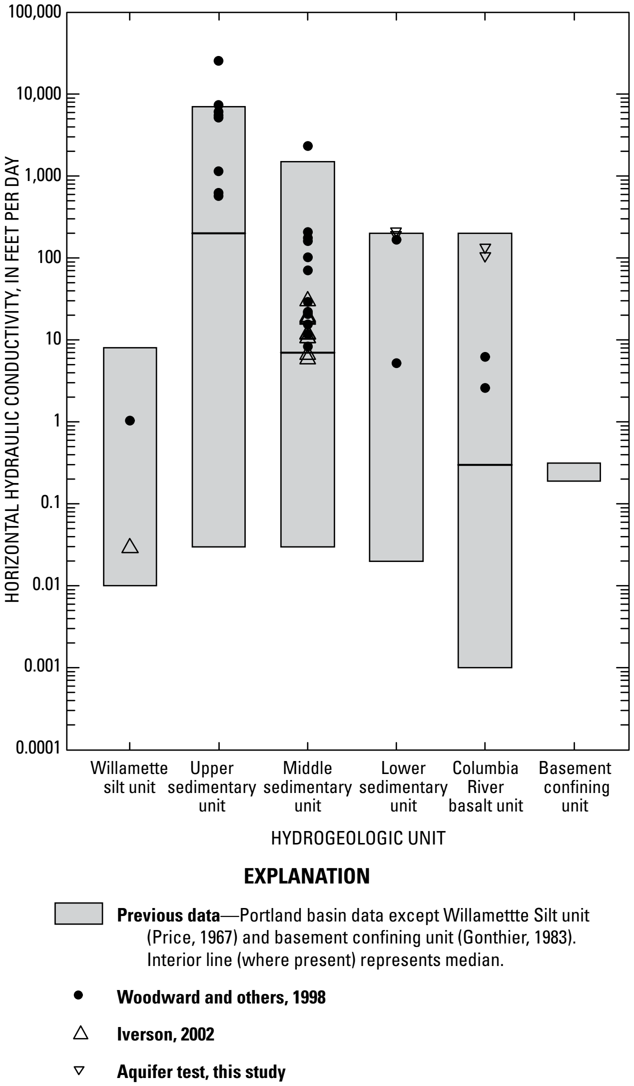

Figure 5. Hydraulic conductivity of hydrogelogic units, Willamette Basin, Oregon.

several feet thick. Many of the beds display a subtle internal grading that produces a rhythmic pattern of alternating bands of relatively coarse and fine-grained sediments. Although the majority of the unit consists of silt, clay can form a sizable fraction of the bulk sediment (Glenn, 1965). In the area southwest of Mount Angel, many of the lower beds are composed of plastic, silty blue clay (Iverson, 2002). These clayey beds are also exposed along the Pudding River near Mount Angel, where they commonly form resistant ledges in cut banks at stream level. Similar silty clay and clayey silt beds are common in the streambeds of many smaller streams, such as Case, Mill, and Champoeg Creeks, which are entrenched into the Willamette Silt in the central Willamette Basin between Salem and Wilsonville.

Although the Willamette Silt forms thick deposits in the Tualatin Basin, it cannot easily be distinguished on water-well logs from the fine-grained basin-fill deposits that underlie it. For this reason, it is not treated as a separate hydrogeologic unit in the Tualatin Basin but is lumped into the lower sedimentary unit.

The Willamette silt unit occurs at land surface throughout most of the Willamette lowland south of the Portland Basin below an elevation of 400 ft, except where it has been removed by erosion in the floodplains of the Willamette River and its main tributaries (pl. 1). In the central basin, the unit is greater than 60 ft thick and locally exceeds 120 ft in thickness (fig. 6). In the southern valley, the unit is generally less than 20 ft thick. The unit thins at the margins of the valley floor where it laps up against the highlands.

The Willamette silt unit generally has high porosity but low permeability. Although the unit is seldom exploited as an aquifer, sandy silts or silty, fine-grained sands that are capable of providing adequate water for domestic needs occur in some areas. Shallow pit wells in the silt were an important water supply for many early settlers in the Willamette Valley (Piper, 1942).

The regional water table generally occurs near land surface in the Willamette silt unit. Although the unit yields little water to wells because of its low permeability, the unit is capable of storing a considerable amount of ground water because of its high porosity. This stored ground water may be an important source of recharge to the underlying middle sedimentary unit.

In the central Willamette Basin, where the silt is thick, the underlying upper sedimentary unit behaves as a confined aquifer. In the southern Willamette Basin, where the silt is thinner, the underlying upper sedimentary unit behaves as an unconfined aquifer.

Because few wells are open to the Willamette silt unit, hydraulic properties based on well tests are lacking. In the central Willamette Basin, Price (1967a) reported hydraulic conductivities that range from 0.01 to 8 ft/d based on four core samples (table 1 and fig. 5). Iverson (2002) reports a horizontal hydraulic conductivity range of 0.2 ft/d based on slug tests and 0.003 ft/d from model calibration in the Mount Angel area. Wilson (1997) reports conductivities of 0.3 and 1.4 ft/d for two core samples of Willamette Silt in the Tualatin Basin. Although the Willamette Silt in the Tualatin Basin is included in the lower sedimentary unit in this report, these samples provide some constraints on the hydraulic properties of the Willamette silt unit in other areas. Core porosity measurements from the above sources indicate porosities ranging from 20 to 45 percent and specific yields of 0.2 to 0.3. All of these values are probably subject to large uncertainties because of the potential effects of sample disturbance during the coring and measurement processes.

Because the Willamette silt unit is widespread at land surface, the vertical hydraulic conductivity of the unit controls infiltration of recharge into the silt, recharge to underlying aquifers, and the exchange of ground water between underlying aquifers and streams underlain by the silt unit. Iverson (2002) reports an average vertical hydraulic conductivity of approximately 0.008 ft/d based on shallow core measurements. Most other reported estimates are derived indirectly from mod-

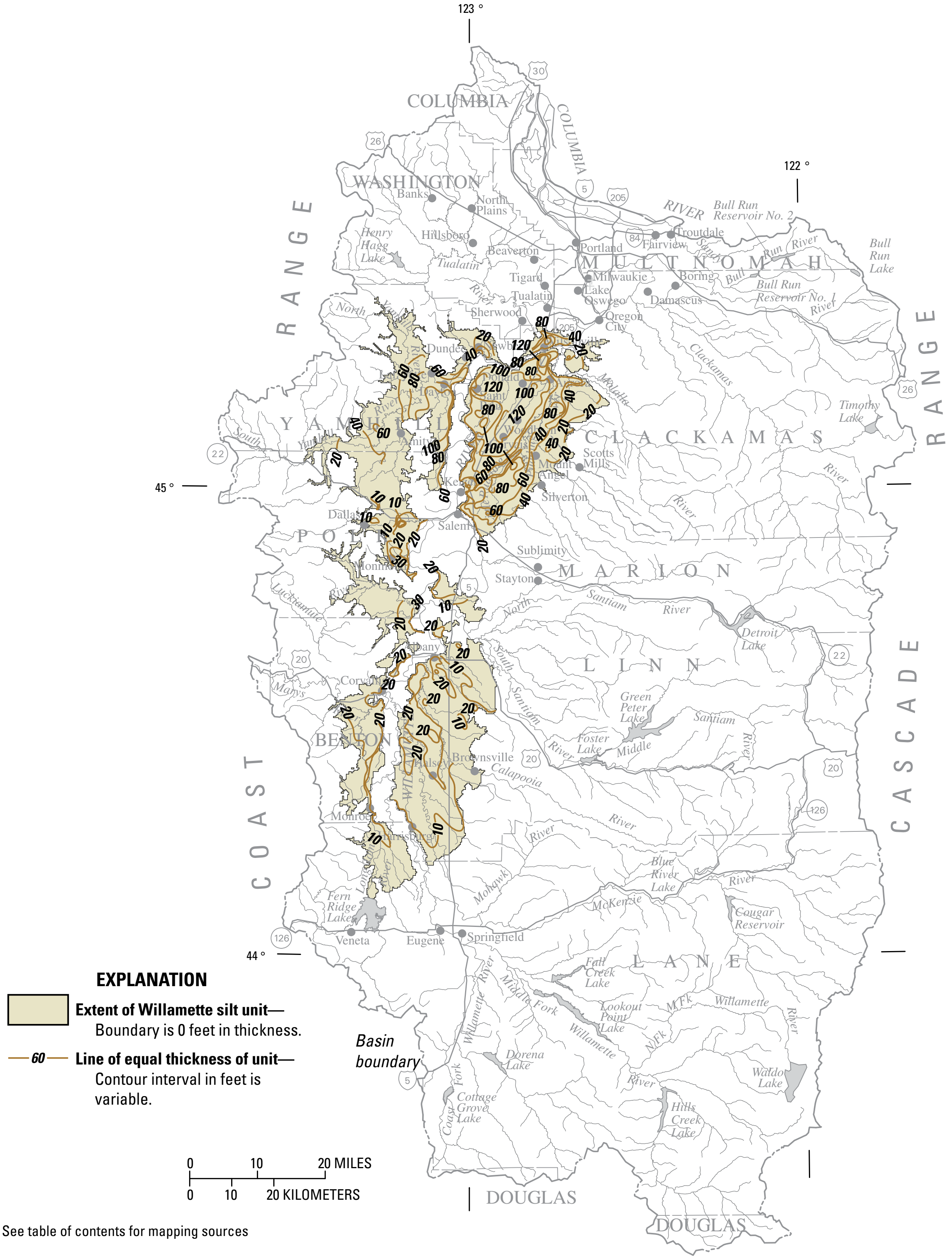

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Figure 6. Extent and thickness of Willamette silt unit, Willamette Basin, Oregon (modified from Gannett and Caldwell, 1998).

els. Conlon and others (2003) obtained values of 0.04 to 0.7 ft/d by simulating heat transport beneath streams in the central Willamette Basin, which probably represent maximum values because the models assume only one-dimensional vertical flow of ground water. Vertical hydraulic conductivity values of 0.01 ft/d (Woodward and others, 1998) and 0.00004 ft/d (Iverson, 2002) were used in numerical ground-water flow models.

Middle Sedimentary Unit

The middle sedimentary unit (MSU) consists mainly of slightly to moderately consolidated Pleistocene sands and gravels that predate the Missoula Floods. The unit overlies the predominantly fine-grained lower sedimentary unit and is generally overlain by the younger sands and gravels of the upper sedimentary unit or the fine-grained Willamette silt unit (pl. 1).

In the Portland Basin, the middle sedimentary unit is equivalent to the Troutdale gravel aquifer of McFarland and Morgan (1996), which largely consists of consolidated gravels of the upper Troutdale Formation and younger volcaniclastic conglomerates derived from the Cascade Range of Pliocene to early Pleistocene age. It also includes basaltic lavas, vent plugs, and volcanic debris of the Boring Lavas, which are the products of Pliocene to Pleistocene volcanoes that erupted within the Portland Basin. The Boring Lavas and interbedded sediments form the highlands east of Oregon City that separate the Portland Basin from the central Willamette Basin. The middle sedimentary unit is generally 300 to 400 ft thick in the Portland Basin but locally exceeds a thickness of 500 ft (fig. 7).

Outside of the Portland Basin, the middle sedimentary unit includes units mapped by O’Connor and others (2001) as the Troutdale Formation, weathered terrace gravels, and pre-Missoula Flood sands and gravels. The Troutdale Formation and the weathered terrace gravels consist of Pliocene to Pleistocene fluvial gravels that generally occur as isolated terraces and alluvial fan remnants at higher elevations on the margins of the valley floor. The pre-Missoula Flood sands and gravels are late Pleistocene alluvial fan and braid-plain deposits that flank the eastern and southern margin of the valley.

The alluvial fan and braid-plain gravels form the bulk of the middle sedimentary unit in the central Willamette Basin and the southern Willamette Basin. The unit thickens where alluvial fans occur along the eastern and southern margins of the valley associated with the Willamette, McKenzie, South Santiam, North Santiam, and Molalla Rivers (fig. 7). Thickness exceeds 150 ft in most of the alluvial fans and is in excess of 200 ft in the larger fans associated with the Willamette, McKenzie, and North Santiam Rivers. On the broad valley floor beyond and between the alluvial fans, the unit is generally less than 60 ft thick. The middle sedimentary unit is commonly unconsolidated near its upper surface but typically becomes more compacted and cemented with depth. On drillers’ logs it is typically described as cemented sand and gravel or conglomerate. In quarry exposures, the middle sedimentary unit commonly shows steep vertical faces, especially in the deeper portions of the unit.

Reported hydraulic conductivities for the middle sedimentary unit (table 1 and fig. 5) in the Portland Basin range from 0.03 to 1,500 ft/d (McFarland and Morgan, 1996). Reported conductivities south of the Portland Basin for buried alluvial fan deposits range from 8 to 2,230 ft/d (Woodward and Gannett, 1998; Iverson, 2002).

Storage coefficients for the unit range from 0.0002 to 0.2 (table 1). In the central Willamette Basin, where the middle sedimentary unit is generally overlain by more than 40 ft of saturated Willamette Silt, the unit is confined and storage coefficients are probably less than 0.001. In the southern Willamette Basin, where the unit is typically overlain by less than 20 ft of saturated Willamette Silt and in the Portland Basin where the unit occurs at land surface, the unit is unconfined to semiconfined, and storage coefficients are probably greater than 0.001.

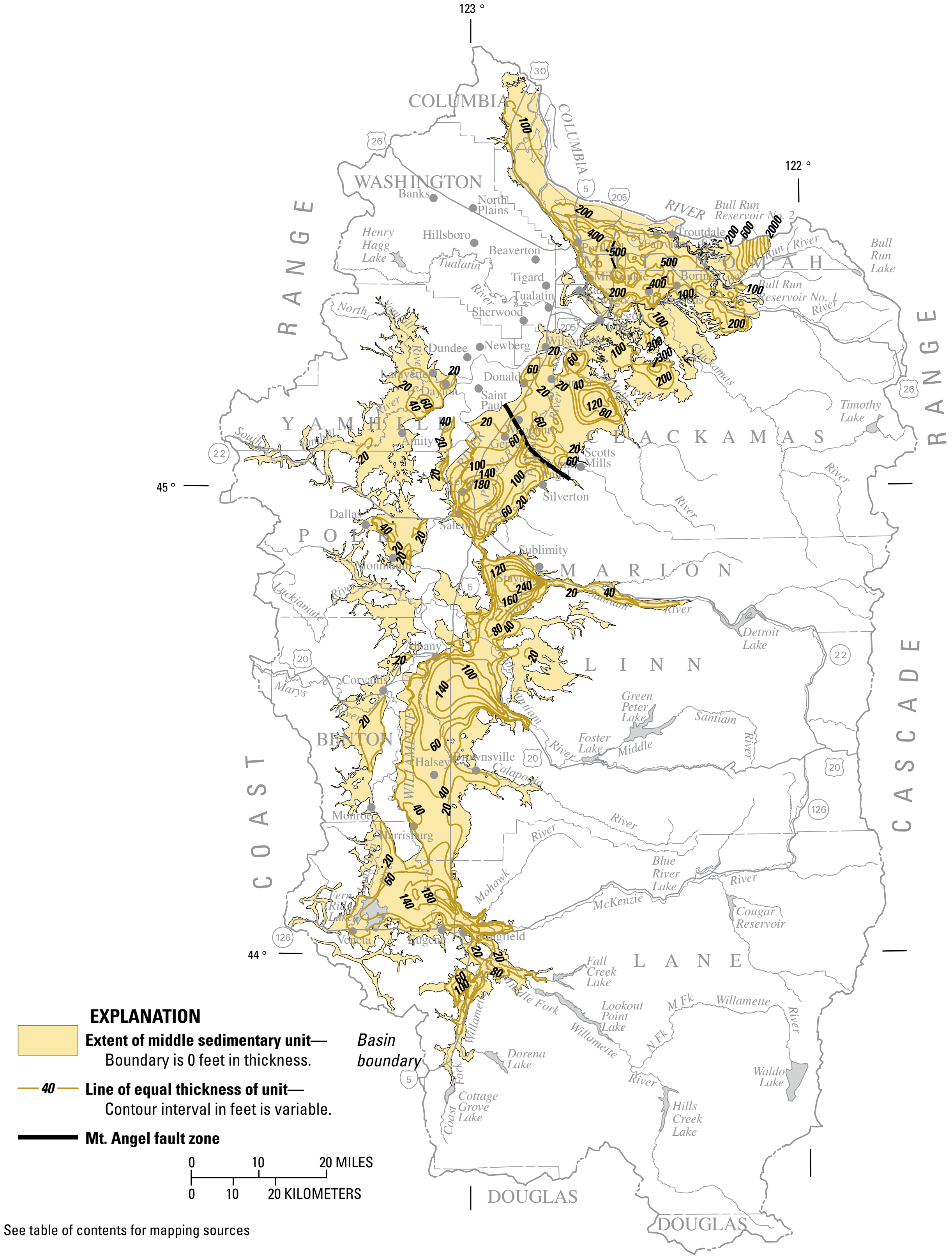
Lower Sedimentary Unit

The lower sedimentary unit (LSU) corresponds to the Willamette confining unit of Gannett and Caldwell (1998) and the lower sedimentary subsystem of Swanson and others (1993) in the Portland Basin (fig. 3). The unit overlies the basement confining unit or the Columbia River basalt unit and is overlain by the middle sedimentary unit or the Willamette silt unit (pl. 1). The lower sedimentary unit constitutes the bulk of the basin-fill sediments in the Willamette Basin.

In the Portland Basin, the lower sedimentary unit includes the Sandy River Mudstone and sands and gravels that are part of the Troutdale Formation (McFarland and Morgan, 1996). The maximum thickness is approximately 1,200 ft in the center of the basin (fig. 8). Fine-grained deposits of the Sandy River Mudstone dominate the unit in the western two-thirds of the basin but are interbedded with coarse-grained Columbia River channel deposits and vitric sandstones of the Troutdale Formation in the east. In these areas, McFarland and Morgan (1996) locally subdivided the unit into the sand and gravel aquifer, the Troutdale sandstone aquifer, and several confining units.

Outside of the Portland Basin, the lower sedimentary unit consists of predominantly fine-grained sediments that include distal alluvial fan deposits, low-energy stream sediments, and lacustrine deposits. On well logs, the unit is commonly described as blue clay with minor interbeds of sand and gravel.

In the Tualatin Basin, the lower sedimentary unit includes the predominantly fine-grained Hillsboro Formation (Wilson, 1997) and the overlying Willamette Silt, which have an aggregate maximum thickness of about 1,400 ft (fig. 8). These geologic units are combined into a single hydrogeologic unit because they are not readily distinguished on the basis of well logs and have similar hydrologic properties at the regional scale. Discontinuous beds of silty sand with minor gravel, deposited by low-gradient meandering streams, are common



EXPLANATION

▨ **Extent of middle sedimentary unit**— Boundary is 0 feet in thickness.

—40— **Line of equal thickness of unit**— Contour interval in feet is variable.

▬ **Mt. Angel fault zone**

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Figure 7. Extent and thickness of the middle sedimentary unit, Willamette Basin, Oregon (modified from Gannett and Caldwell, 1998).

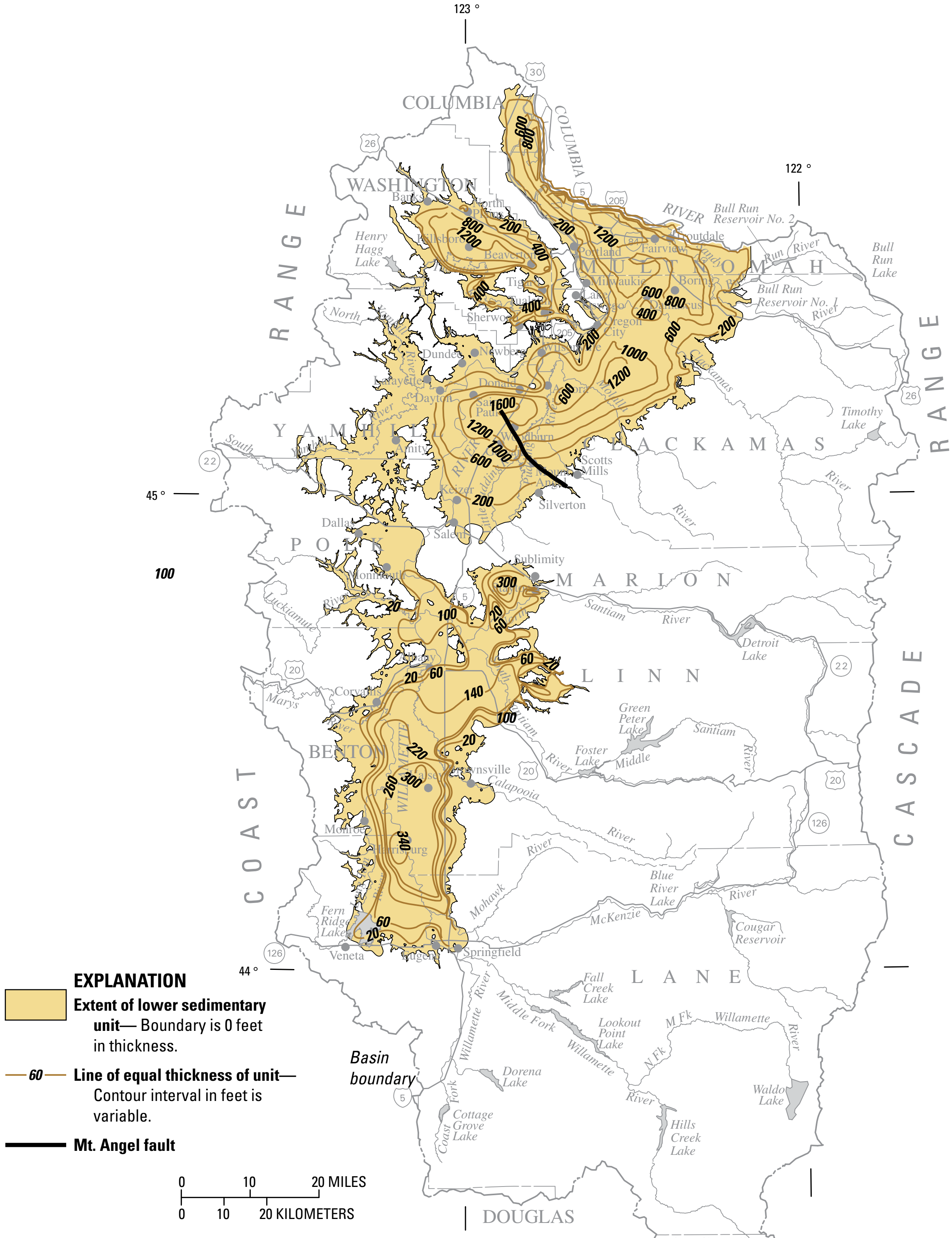

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Figure 8. Extent and thickness of the lower sedimentary unit, Willamette Basin, Oregon (modified from Gannett and Caldwell, 1998).

Table 2. Summary of selected aquifer tests in the Willamette Basin, Oregon.

[OWRD well no., Oregon Water Resources Department well number; gpm, gallons per minute; Analysis method: SC, Theis solution using specific-capacity data (Lohman, 1979); T, Theis non-equilibrium curve matching; SL, straight-line method. Test conducted by: S, study team; C, private consultant. MSU, middle sedimentary unit; LSU, lower sedimentary unit; CRB, Columbia River basalt unit; ft^2/d, square feet per day; mi, miles; ft, feet; ft/d, feet per day; --, value not determined; ft, feet]

Basin	OWRD well no.	Well location and name	Discharge (gpm)	Duration (hours)	Drawdown (ft)	Distance from pumped well (ft)	Analysis method	Test conducted by	Transmissivity (ft^2/d)	Storage coefficient	Radius of influence (mi)	Open interval length (ft)	Hydraulic conductivity[6] (ft/d)	Unit
Portland	CLAC 4396	02S/02E-29DD Clackamas River Water—Well No. 1	300	24	2.9	0	SC	C[1]	22,000	--	0.7 - 0.9	258	85	CRB
Tualatin	WASH 8988	01S/01W-21CDD2 Tualatin Valley Water District—Hanson Rd	880	24	7.2	2,400	SL, T	C[2]	65,500	$4x10^{-4}$		630	100	CRB
Tualatin	WASH 8862	01S/01W-17CDB Tualatin Valley Water District—Schuepbach	770	10	39.9	0	SL, T	C[2]	6,820	--		305	22	CRB
Central	MARI 19624	08S/03W-10DC City of Salem—Woodmansee Park—ASR Well No. 1	1,000	24	5	45–465	SL, T	C[3]	32,000–38,000	$1x10^{-3}$–$1x10^{-4}$	4.8–8.0	36	890–1100	CRB
Central	MARI 50456	06S/01W-09DCA Mount Angel City Well No. 6	950	120	1.4–3.9	ll,000–9,000	SL, T	S[4]	18,000–23,000	$2x10^{-4}$		160	110–140	CRB
Central	MARI 53920	06S/01W-08DAD01 Eder Irrigation Well	180	72	0.7–4.9	435–4,560	SL, T	C[5]	1,380–7,050	$2x10^{-4}$–$3x10^{-4}$		40	6–31	MSU
Central	MARI 18414	05S/02W-08CBC01 Kirsch Irrigation Well	750	120	4.39	2,578	T	S[4]	5,900–6,600	$3x10^{-4}$		30	200–220	LSU

Sources for tests:

[1] Golder Associates, 2000.

[2] CH2M Hill, 1997.

[3] Golder Associates, 1996.

[4] Oregon Water Resources Department, this study.

[5] Justin Iverson, 2002, Master's thesis, Investigation of the hydraulic, physical, and chemical buffering capacity of Missoula Flood deposits for water quality and supply in the Willamette Valley of Oregon.

[6] Iverson values calculated using aquifer thickness equal to 220 ft.

in the upper part of the Hillsboro Formation but become less common with depth (Wilson, 1997).

In the central and southern Willamette Basins, the lower sedimentary unit consists mostly of distal alluvial fan sediments deposited by Cascade Range streams and fine-grained sediments deposited by Coast Range streams. The boundary between the lower sedimentary unit and the sands and gravels of the middle sedimentary unit generally corresponds to a facies boundary between proximal and distal portions of Pleistocene alluvial fans that developed on the eastern and southern margins of valley (Gannett and Caldwell, 1998). Consequently, these unit boundaries are approximate because the change between the predominantly coarse-grained (middle sedimentary unit) and the predominantly fine-grained (lower sedimentary unit) portions of the fans is gradational. In places, near these unit boundaries, the lower sedimentary unit contains considerable proportions of sand and gravel. Also, in some areas, thin sand and gravel beds extend into distal portions of the basin that are included in the lower sedimentary unit.

On a regional scale, the lower sedimentary unit can be characterized as a confining unit. Locally, however, the unit has productive sand and gravel beds or a cumulative thickness of thin sands that are sufficient to allow moderate to high well yields. In the Portland Basin, the production capacity of the coarse-grained deposits in the unit is considerably higher than in most other areas, and large diameter wells can yield up to 3,000 gal/min (McFarland and Morgan, 1996). In the Tualatin Basin, wells that intersect multiple sand beds can yield up to 100 gal/min, but more commonly wells yield less than 10 gal/min (Wilson, 1997). In the central Willamette Basin, wells open to discontinuous sands and gravels in the upper part of the unit are capable of yielding moderate to high quantities of water, especially if they have large open intervals and gravel-pack completions. For example, many irrigation wells between Woodburn and Newberg produce up to 250 gal/min from the lower sedimentary unit and some are capable of producing 1,000 gal/min. Elsewhere in the central Willamette Basin and southern Willamette Basin, sand beds are less common in the lower sedimentary unit and well yields are typically less than 20 gal/min.

Reported hydraulic conductivities for the lower sedimentary unit (table 1 and fig. 5) range from 0.02 to 200 ft/d in the Portland Basin (McFarland and Morgan, 1996). Conductivities of sand beds in the Tualatin Basin range from 0.8 to 32 ft/d (Wilson, 1997). Aquifer tests in the central Willamette Basin indicate conductivities as high as 220 ft/d (table 2). However, since most wells are open to the coarse-grained component of the lower sedimentary unit, the bulk conductivity is probably lower than the reported values in most places. Reported storage coefficients for the unit range from 0.00005 to 0.2 (tables 1 and 2). Since the unit is confined throughout most of its extent, storage coefficients less than 0.001 are assumed to be representative for the unit.

Columbia River Basalt Unit

The Columbia River basalt unit (CRB) consists of a series of flood-basalt lavas of the Miocene Columbia River Basalt Group, which is divided into the Imnaha Basalt, Grande Ronde Basalt, Wanapum Basalt, and Saddle Mountains Basalt formations (Tolan and others, 1989). Only flows of the Grande Ronde and Wanapum Basalt are present in the Willamette Basin. Wanapum flows are present in the Portland Basin and on the margins of the central Willamette Basin but are absent in the Tualatin Basin (Beeson and others, 1989a). More than 50 flows are present in the Portland area, but less than a dozen occur in the Salem area (Beeson and others, 1989a; Tolan and others, 1999, 2000a). Individual basalt flows in the Willamette Basin typically range from 40 to 100 ft thick, but flow thickness is highly variable and may exceed 250 ft in some areas (Beeson and others, 1989a; Tolan and others, 1999, 2000a). Thick flows are common at the base of the Columbia River basalt unit and in paleoriver canyons of the ancestral Columbia River. The unit is underlain by the basement confining unit, generally overlain by the lower sedimentary unit, and locally overlain by the upper and middle sedimentary unit in the lowland. East of the Portland and central Willamette Basins, the unit is both underlain and overlain by volcanic deposits of the basement confining unit.

The extent and altitude of the upper surface of the Columbia River basalt unit (fig. 9) is based on work by Gannett and Caldwell (1998) with modifications from regional scale maps (Tolan and others, 1989; Beeson and others, 1989a), geologic maps (Beeson and others, 1989b, 1991; Broderson, 1994; Madin, 1994; Tolan and others, 1999, 2000a), and well data. The thickness of the unit (fig. 10) is constrained by lithologic descriptions of 600 field located wells (76 of which fully penetrate the unit), measured sections in outcrop areas (Anderson, 1978; Vogt, 1981), published geologic maps, and structural features (Beeson and others, 1989a; Gannett and Caldwell, 1998) that controlled the thickness and distribution of flows. Because of limited well control, the altitude of the upper surface and thickness of the basalt is highly uncertain in many areas.

Contours of the top of the Columbia River basalt unit (fig. 9) show a planar upper surface that dips at low angles (generally less than 10 degrees) toward the centers of structural basins in the northern Willamette lowland. In general, this surface appears to correspond to a dip slope at the top of the uppermost basalt flows with some modification by erosion. Changes in the altitude of the top of the Columbia River basalt unit of more than 400 ft are inferred across the Gales Creek-Mount Angel structural zone (fig. 9) based on well data (Gannett and Caldwell, 1998). The altitude of the upper surface of the basalt is about -1,600 ft in the center of the Portland Basin, -1,200 ft in the center of the Tualatin Basin, -1,600 ft in the center of the central Willamette Basin, and -200 ft in the center of the Stayton Basin.

The total thickness of the Columbia River basalt unit (fig. 10) is greatest east of Portland, where it is more than 2,000 ft thick. Elsewhere in the study area, the unit generally ranges

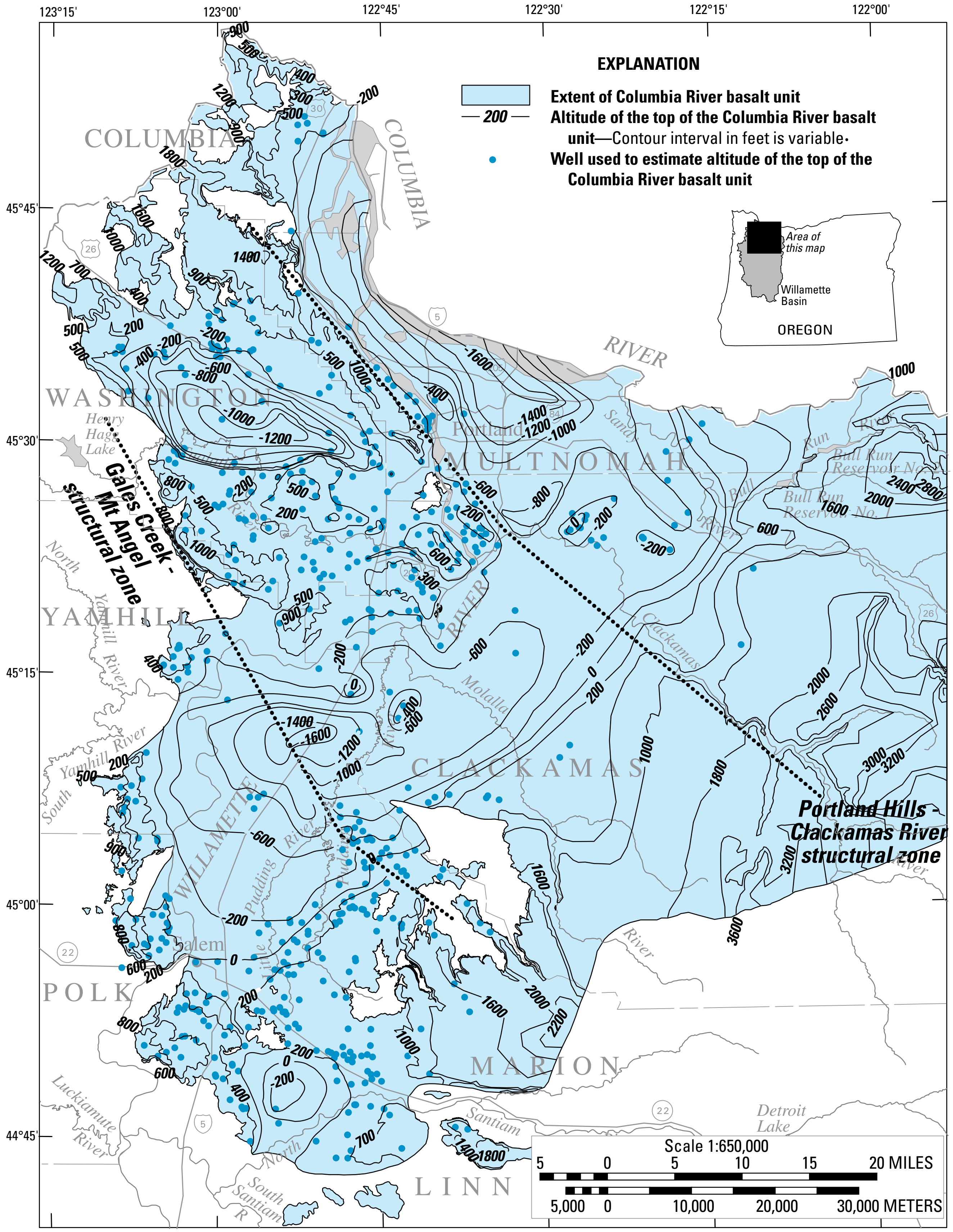

Figure 9. Extent and altitude of the top of the Columbia River basalt unit, Willamette Basin, Oregon (modified from Gannett and Caldwell, 1998).

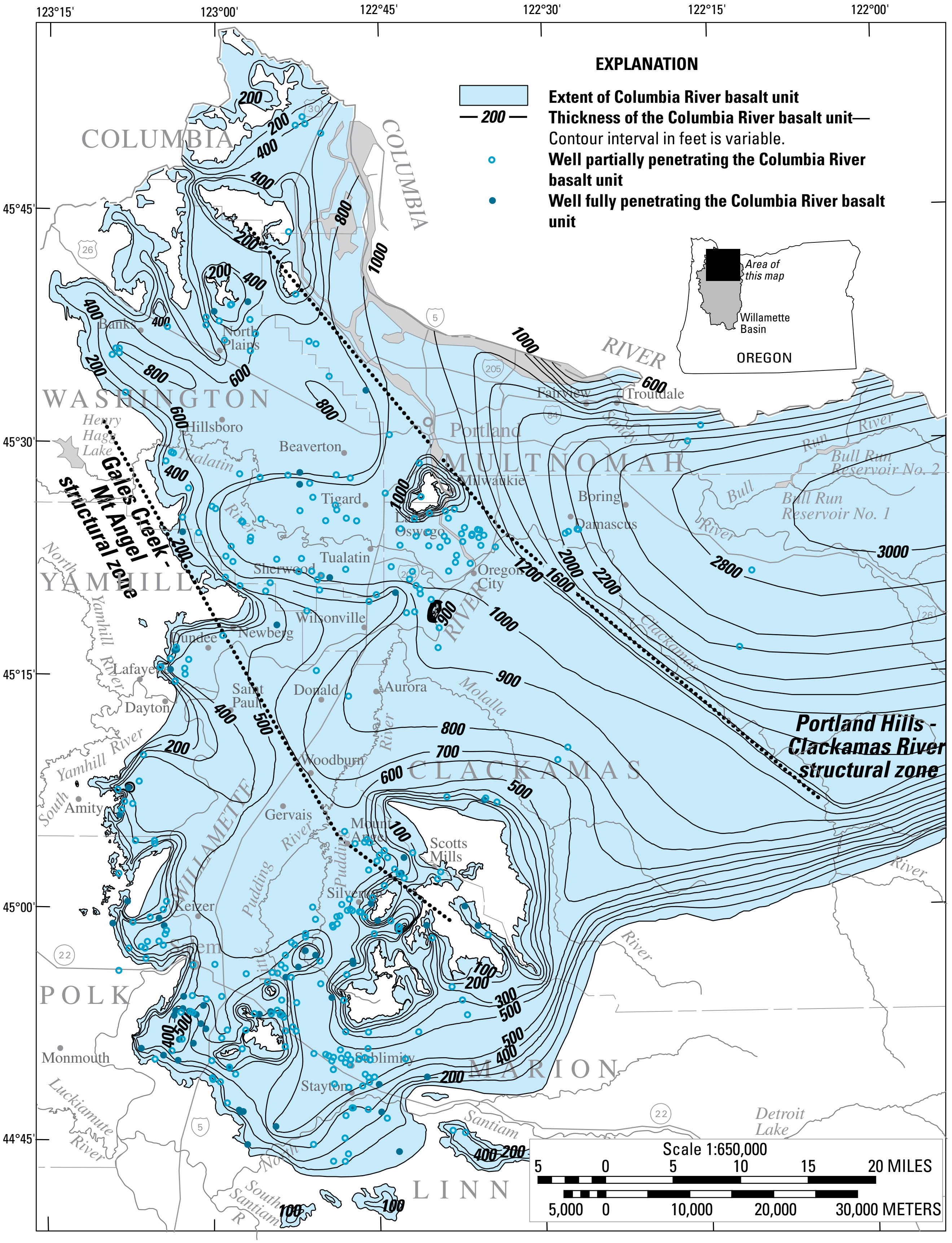

Figure 10. Extent and thickness of the Columbia River basalt unit, Willamette Basin, Oregon.

from 200 to 1,000 ft in thickness. Changes in the thickness of the Columbia River basalt unit are inferred across the Portland Hills-Clackamas River and Gales Creek-Mount Angel structural zones which created topographic barriers to southern movement of many flows (Beeson and others 1989a). Limited well data indicate a thick accumulation of Columbia River basalt lavas in the southern Tualatin Basin along the trend of the Chehelam Mountains (Beeson and others, 1989a). The structure contour and thickness maps show the general geometry of the Columbia River basalt unit on a regional scale. Local variations from faulting and stream incision in outcrop and subsurface areas are not shown on the maps.

The upper surface of the Columbia River basalt unit is commonly weathered to a red, lateritic clay that was produced during prolonged exposure at land surface after the emplacement of the uppermost basalt flow. The thickness of this weathered zone ranges from several ft in the Waldo Hills (Hampton, 1972) to more than 200 ft in the Tualatin Basin (Hart and Newcomb, 1965).

The Columbia River basalt unit is characterized by thin, often permeable, interflow zones separated by thick, low permeability flow interiors. Interflow zones include the top of one flow, the base of an overlying flow, and intervening sediments. Permeability and porosity are enhanced in interflow zones where the basalt surface was vesiculated or brecciated during emplacement. Thicker basal zones of brecciation occur where the basalt flowed over wet soils or standing water. Permeable interflow zones vary considerably in thickness and extent. The uppermost water-bearing zone in a stack of flows is unconfined but lower aquifers are confined.

Because the basalt lavas were generally emplaced as sheet flows, water-bearing zones occur in subhorizontal, tabular interflow zones separated by low-permeability flow interiors that act as confining beds. Permeable interflow zones probably comprise less than 10 percent of the total flow thickness and the porosity of these zones is probably less than 25 percent. Therefore, bulk porosity of the Columbia River basalt unit probably averages less than 3 percent and perhaps as little as 1 percent.

Well yields in the Columbia River basalt unit are moderate to high. Most high-capacity wells are open to multiple interflow zones. Large-diameter irrigation and public-supply wells commonly produce more than 250 gal/min (gallons per minute) and some are capable of 1,000 gal/min; smaller diameter domestic wells are generally capable of producing 20 gal/min. Production rates can be considerably less in areas with few interflow zones or interflow zones that lack permeability from vesiculation and brecciation.

Hydraulic properties in the basalt unit are a function of the permeability, thickness and number of interflow zones. Most reported values for hydraulic properties should be treated with caution because they depend on the assumption that ground-water conditions in the basalt are equivalent to conditions in a porous medium, such as sand and gravel. Reported hydraulic conductivity for the Columbia River basalt unit in the Willamette Basin ranges from 10^{-3} to 10^{3} ft/d (table 1 and fig. 5). Hydraulic conductivity values based on aquifer well tests are 22 and 100 ft/d in the Tualatin Basin, approximately 130 ft/d near Mount Angel, and 1,000 ft/d for brecciated basalt near Salem (table 2 and see aquifer test section). Reported storage coefficients range from 0.0001 to 0.2 (table 1 and 2).

Information about the permeability of interflow zones and flow interiors in the Columbia River basalt unit is available in the Pasco Basin of eastern Washington, where similar sheet flows of Columbia River basalt lava occur. Extensive testing of cores from these basalt lavas (Reidel and others, 2002) indicate horizontal hydraulic conductivities of 10^{-7} to 10^{3} ft/d (table 1) for individual interflow zones and a decrease with depth due to compaction and secondary mineral formation. The geometric mean hydraulic conductivity is 1 ft/d for shallow and 0.01 ft/d for deep interflow zones. Tests on cores from flow interiors indicate hydraulic conductivity ranges from 10^{-10} to 10^{-4} ft/d with a mean value between 10^{-8} and 10^{-7} ft/d (Reidel and others, 2002). Although flow interiors contain a dense network of hackly and columnar cooling joints, the joints are generally filled with secondary minerals, primarily clays (Tolan and others, 2000b; Reidel and others, 2002), which greatly reduce the permeability.

Saline water is common in deeper parts of the Columbia River basalt unit and is probably derived from connate water entrapped in the underlying marine sediments of the basin confining unit (Woodward and others, 1998). Upward flow of saline water may occur naturally along deep fault zones or be induced by pumping in deep basalt wells. Fluid conductivity, which is an indication of fluid salinity, shows the effect of saline water from the marine rocks on water quality in a well (02S/01W-32ADD) open to the Columbia River basalt unit (fig. 11 and pl. 1). The increase in fluid conductivity where the well terminates at the top of the underlying marine rocks of the basement confining unit suggests that the source of salinity is in the marine rocks. The upward flow or diffusion of the saline water affects water quality in the borehole open to the Columbia River basalt unit.

Ground-water pumpage from the unit may have induced the upward flow of deep saline water, causing salinities in the Columbia River basalt unit to increase over time in two irrigation wells in section 26, Township 1S, Range 1W between 1969 and 1996 (OWRD, unpub. data). In the Willamette Basin, the extent of salinity problems in the basalt is not known with certainty because the occurrence of saline water is generally not reported on well reports. Known occurrences are widely scattered throughout the basin and are usually associated with areas underlain by marine rocks.

Basement Confining Unit

The basement confining unit (BCU) includes Tertiary marine sedimentary rocks and Eocene volcanic rocks of the Coast Range, and volcanic and volcaniclastic rocks of the Western Cascade area (Gannett and Caldwell, 1998). The unit is exposed in the Coast Range and Western Cascade area and forms the floor of the Willamette Basin beneath all other

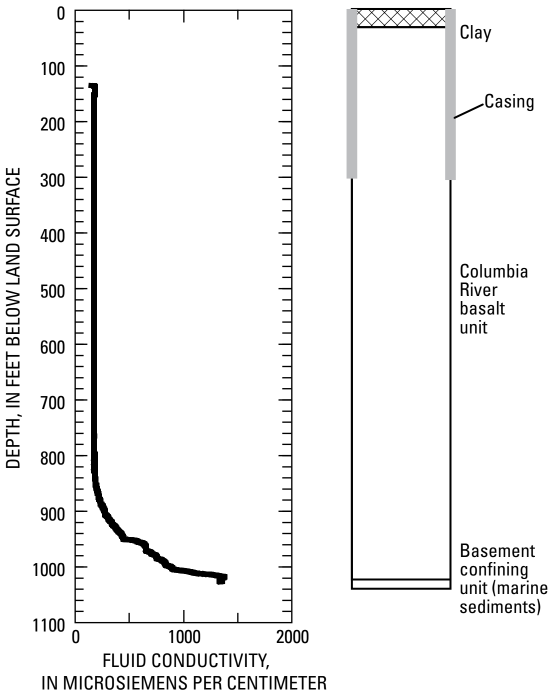

Figure 11. Fluid conductivity of a well (02S/01W-32ADD) open to the Columbia River basalt and basement confining units, Willamette Basin, Oregon.

hydrogeologic units (pl. 1). In areas east of the Portland and central Willamette Basins, volcanic material of the basement confining unit underlies and overlies the Columbia River basalt unit.

The basement confining unit includes a variety of geologic formations and rock types with widely varying properties. Caldwell (1993) provides a detailed description of the hydrogeologic characteristics of the rocks and sediments of the Coast Range near Salem. In general, the unit is composed of rocks in which most of the primary porosity has been destroyed by secondary mineralization.

The basement confining unit is characterized by low permeability, low porosity, and low well yield. Well yields are commonly less than 5 gal/min, and the unit is generally able to provide sufficient water for domestic uses only. Fracture porosity locally produces higher well yields. Individual fractures can have high permeability but the permeability of the matrix material is typically very low. Estimates of hydraulic conductivity (table 1 and fig. 5) of the basement confining unit range from 10^{-5} to 10^{-2} ft/d in the Western Cascade area using geothermal models (Ingebritsen and others, 1994) to 0.2 to 0.3 ft/d near the Coast Range in Polk County using specific capacity tests (Gonthier, 1983). The storage coefficient ranges from 0.00005 to 0.003 (Gonthier, 1983).

High salinity in ground water is common in the Tertiary marine sedimentary rocks of the basement unit (Piper, 1942; Caldwell, 1993; Woodward and others, 1998). Saline water in the unit originated as seawater that was trapped in the pore spaces of buried sediments (Woodward and others, 1998) and is common at depths greater than 100 ft (Piper, 1942). Because of the low porosity and permeability of the unit, fresh water is unable to circulate deep into the rocks to flush out saline waters.

Arsenic is a common natural constituent in ground waters of the basement confining unit, especially in areas underlain by silicic volcanic bedrock in Lane and south-central Linn Counties (fig. 1). Concentrations above the current Environmental Protection Agency (EPA) drinking water standard of 10 micrograms per liter (µg/L; about 10 parts per billion) are common, and concentrations above 500 µg/L have been observed (Hinkle and Polette, 1999).

Aquifer Tests

Aquifer tests were conducted as part of this study and compiled from reports submitted to OWRD from private consulting firms (table 2). The discussion below describes three constant-rate aquifer tests that were conducted in the central Willamette Basin during this study to better define the hydraulic properties of units in the area. A test in the middle sedimentary unit was conducted in cooperation with Oregon State University (Iverson, 2002). Two additional tests were conducted by the OWRD: one in the lower sedimentary unit and a second in the Columbia River basalt unit. For each test, a range in transmissivity is reported in table 2 that corresponds to the analysis of the response in multiple observation wells. In the description of each test, a single rounded value is reported.

An aquifer test of the middle sedimentary unit was conducted by Iverson (2002) using an irrigation well (06S/01W-08DAD01, pl. 1) near Mount Angel. A pumping rate of about 180 gal/min was maintained over a period of 3 days. In the vicinity of the well, about 220 ft of the middle sedimentary unit is overlain by about 60 ft of the Willamette silt unit. The pumped well is screened over a 40-foot interval of sand and gravel at the top of the middle sedimentary unit. Analysis of test results indicates an average transmissivity of 4,500 ft^2/d and a storage coefficient of about 0.0003 (Iverson, 2002). Assuming a unit thickness of 220 ft and neglecting any impacts of partial penetration, average hydraulic conductivity is 20 ft/d (table 2).

An aquifer test of the lower sedimentary unit was conducted using an irrigation well (05S/02W-08CBC01, pl. 1) located several miles south of St. Paul. Pumping was maintained at 750 gal/min over a 2-day period. The well is open over a 30-foot interval of sand beds in the upper part of the lower sedimentary unit. The completion interval is overlain by 70 ft of lower sedimentary unit clay, 30 ft of upper sedimentary unit sands, and 100 ft of the Willamette silt unit. Analysis of test results indicates a transmissivity of approximately 6,000 ft^2/d and a storage coefficient of 0.0003. Hydraulic conductivity is estimated to be 200 ft/d.

A 5-day aquifer test of the Columbia River basalt unit was conducted using a municipal well (06S/01W-09DCA) south of Mount Angel that was pumped at a rate of 950 gal/min. The well is open over an interval of 160 ft in the upper part of the basalt unit. The completion interval is overlain by 450 ft of fine-gained lower sedimentary unit, 190 ft of upper sedimentary unit sands and gravels, and 30 ft of Willamette silt unit. Analysis of the drawdown in observation wells assuming a porous medium indicates a transmissivity of 20,000 ft^2/d and a storage coefficient of 0.0002. A bulk hydraulic conductivity of about 125 ft/d is estimated by dividing the transmissivity by the completion interval of 160 ft. However, the hydraulic conductivity of the permeable interflow zones is likely to be considerably higher since interflow zones probably constitute a small fraction of the completed interval. The effective thickness of these zones in the pumped well could not be determined based on lithologic descriptions on the well log. If only 25 percent of the completion interval consists of permeable interflow zones, the effective permeability of the interflow zones would be 500 ft/d. If only 10 percent is permeable, the effective permeability would be 1,250 ft/d. Test results indicate that the Mount Angel fault zone acts as a barrier to ground-water flow in the vicinity of the city of Mount Angel over the time scale of the test. Observation wells south of the fault zone were affected by pumping from the test well but impacts were not seen north of the fault zone in wells at similar distances from the pumped well.