GEOLOGIC FRAMEWORK FOR THE PUGET SOUND AQUIFER SYSTEM, WASHINGTON AND BRITISH COLUMBIA

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Geologic Framework for the Puget Sound Aquifer System, Washington and British Columbia

By M.A. Jones

REGIONAL AQUIFER-SYSTEM ANALYSIS—
PUGET–WILLAMETTE LOWLAND

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1424–C

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which, in aggregate, underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and, accordingly, transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number beginning with Professional Paper 1400.

Charles G. Groat
Director

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	*By*	*To obtain*
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
mile (mi)	1.609	kilometer
square mile (mi^2)	2.59	square kilometer
inch per year (in/yr)	2.54	centimeter per year
gallons per minute (gal/min)	0.06308	liter per second
degrees Fahrenheit (°F)	°C=5/9(°F-32)	degrees Celsius (°C)

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

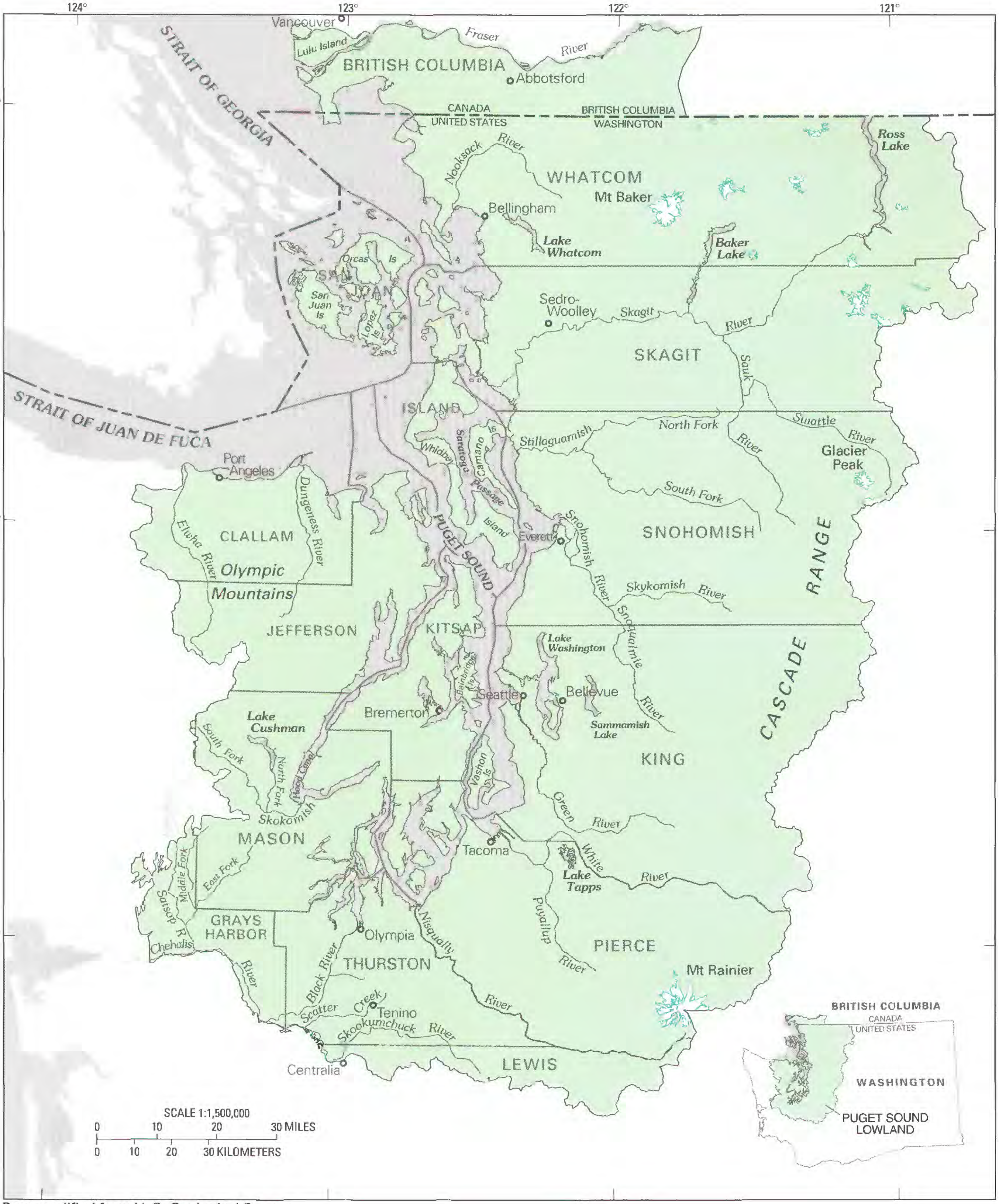

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FIGURE 2.—Major geographic features of the Puget Sound Lowland.

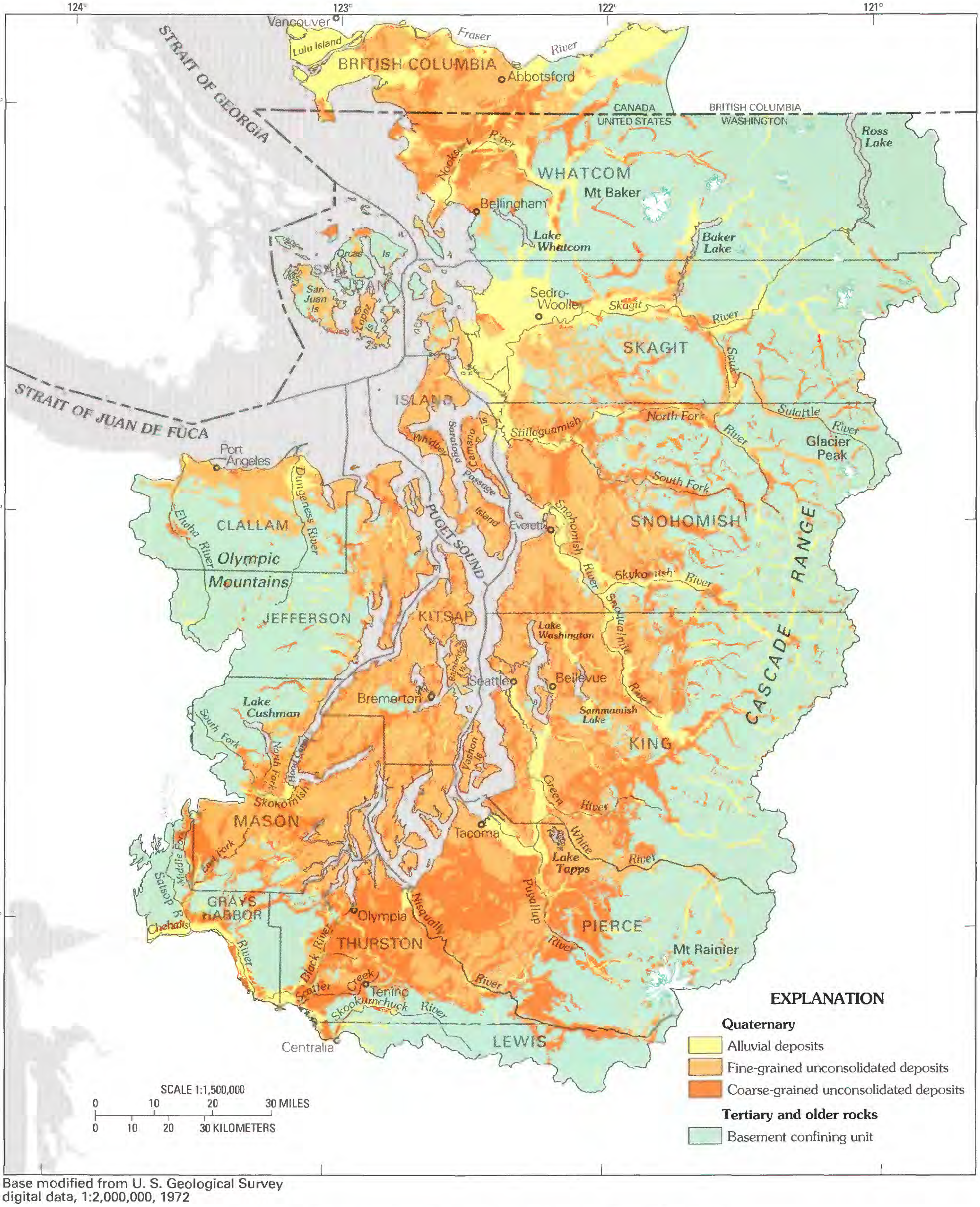


FIGURE 3.—Generalized surficial geology of the Puget Sound Lowland.

GEOLOGIC FRAMEWORK FOR THE PUGET SOUND AQUIFER SYSTEM, WASHINGTON AND BRITISH COLUMBIA

BY M.A. JONES

ABSTRACT

The Puget–Willamette study area is composed of two distinct subareas, the Puget Sound Lowland and the Willamette Lowland. The study area for this report is the Puget Sound Lowland, which is located in western Washington and in a small part of southwestern British Columbia, Canada. The lowland encompasses an area of about 17,610 square miles and contains about 2,615 square miles of saltwater. The unconsolidated Quaternary deposits that compose the Puget Sound aquifer system underlie about 7,183 square miles of the study area.

The extent of the Puget Sound aquifer system is delineated by its lateral and basal boundaries above the Tertiary and older rock units, called the basement confining unit, and the lateral extent of the glacial drift from the last glaciation, the Fraser Glaciation. The unconsolidated Quaternary deposits which compose the aquifer system consist of alluvium, glacial, and interglacial deposits. Of the unconsolidated deposits at the land surface, 1,570 square miles are covered by alluvium, 2,293 square miles are covered by coarse-grained deposits, and about 3,320 square miles are covered by fine-grained deposits. The alluvium and coarse-grained deposits generally compose the aquifer units, and the fine-grained deposits generally compose the semi-confining to confining units.

Four glaciations and three interglaciations are recognized in the Puget Sound Lowland. As a result, the unconsolidated Quaternary deposits consist of one to four regional drift sequences and as many as eight local ones. These sequences are generally separated by unconformities and by interglacial fluvial and lacustrine deposits. These sequences produce an alternating pattern of coarse- and fine-grained deposits from land surface to depths of more than 3,000 feet.

The unconsolidated Quaternary and Recent deposits within the lowland were grouped into local aquifer units and semiconfining and confining units based on their lithologic and hydraulic characteristics. These units were then grouped into regional aquifer units in order to assess the ground-water resources and describe the ground-water flow on a regional basis. The designated regional hydrogeologic units are the alluvial valley aquifers, the surficial semiconfining unit, the Fraser aquifer unit, the confining unit, and the Puget aquifer.

INTRODUCTION

The Puget–Willamette Lowland regional aquifer system study area covers 28,290 square miles in western Washington, western Oregon, and a small part of southwestern British Columbia, Canada (fig. 1). Two major aquifer systems, the Puget Sound aquifer system and the Willamette Lowland aquifer system, are contained in a structural basin that extends from the Fraser River in British Columbia to just south of Cottage Grove, Oregon.

The study area for this report is the Puget Sound Lowland (fig. 2), which encompasses an area of about 17,610 square miles and contains about 2,615 square miles of saltwater. The study area includes all areas that drain to the Puget Sound, including parts of the Cascade Range and the Olympic Mountains. The Puget Sound aquifer system is contained within the Quaternary deposits and covers about 7,183 square miles (fig. 3). Older Tertiary and pre-Tertiary rock units underlying and surrounding the aquifer system are called the basement confining unit.

About 70 percent of the population of Washington resides within the study area, predominantly within the metropolitan areas of Bellingham, Everett, Seattle and vicinity, Bremerton, Tacoma, and Olympia. A growing population is increasing the demand for the available water. The ground water from the aquifer units and the surface water from the major river systems within the study area are the principal sources of water for municipal, industrial, domestic, and irrigation uses. In some areas available water supplies are limited because of contamination from anthropogenic sources and from saltwater intrusion from Puget Sound.

BACKGROUND

The U.S. Geological Survey began a national Regional Aquifer-System Analysis (RASA) program in 1978 in response to congressional concerns about the availability and quality of the Nations' ground water. The RASA program was designed to aid in the effective management of important ground-water resources by providing information on the geohydrology and geochemistry of regional aquifer systems and by providing the analytical

FIGURE 1.—Locations of the Puget Sound Lowland and the Willamette Lowland, which make up the Puget–Willamette Lowland regional aquifer-system study area.

capabilities necessary to assess management alternatives (Sun, 1986). The Puget–Willamette Lowland was chosen as one of the regional study areas in this program. This study is a comprehensive regional assessment of the ground-water resources of the Puget–Willamette Lowland.

In order to meet the overall RASA program goals, the major objectives of this study are (1) to describe the geologic framework, (2) to describe the hydrologic characteristics of the regional aquifer system, (3) to describe the regional ground-water budget on the basis of previous estimates for selected areas, and (4) to provide a synthesis of information on the ground-water flow system.

The results of the Puget–Willamette Lowland study are presented in the U.S. Geological Survey Professional Paper 1424, Chapters A–E. This report, Professional Paper 1424–C, is one of two chapters for the Puget Sound Lowland part of the study. The other chapter, 1424–D (Vaccaro and others, 1998), presents the generalized hydrogeologic framework for the Puget Sound aquifer system and includes a conceptual model for describing regional ground-water flow. Of the chapters remaining, chapter A (Vaccaro and others, 1997) summarizes the results of the Puget–Willamette study, chapter B (Gannett and Caldwell, in press) presents the geologic framework for the Willamette Lowland aquifer system, and chapter E (Woodward and Gannett, U.S. Geological Survey, written commun., 1993) presents the hydrogeologic framework for the Willamette Lowland aquifer system.

PURPOSE AND SCOPE

This report describes the geologic framework of the Puget Sound aquifer system. This framework is essential to the development of a conceptual model describing the regional ground-water flow. Maps provided in this report help portray the hydraulic characteristics and the boundaries of the hydrogeologic units within the Puget Sound aquifer system.

PHYSICAL SETTING

The boundaries of the Puget Sound Lowland study area are defined on the north by the Fraser River in British Columbia, Canada, and the Canada-United States boundary, on the east by the drainage divide of the Cascade Range, on the west by both the drainage divide of the Olympic Mountains and the Canada-United States boundary, and on the south by a series of low hills that lie south of the town of Tenino, Wash. (fig. 2).

The Puget Sound Lowland is an elongated structural basin that extends over 200 mi in a north-south direction and varies from 60 to 120 mi in an east-west direction. The topography of the land within the basin can be classified as lowlands, uplands, and mountains. The lowlands typically consist of alluvial river valleys and glacial outwash and till plains. Altitudes of the lowlands range from sea level to about 500 ft, and the width of the lowlands ranges from 15 to 80 mi and averages about 40 mi. The lowlands are separated from the bordering mountains by rolling hills and terraces of the uplands that generally consist of deposits common to both the lowland and mountains. The altitude of the uplands ranges from about 500 to 1,500 ft. Except near the southern boundary, the transition from the uplands to the mountains is generally abrupt. The altitude of the crest of the Cascade Range averages about 7,500 ft; stratovolcanos within this range rise from 8,000 to 14,000 ft. The altitude of the Olympic Mountains averages about 3,000 ft. Glaciers are present on many of the mountain peaks within the Cascade and Olympic Mountain Ranges and cover a total area of about 116 mi^2 within the study area.

The Puget Sound Lowland has a mid-latitude humid marine climate consisting of a distinct winter precipitation season and summer dry season. Temperatures within the area are moderated by their proximity to the Puget Sound and large bodies of water and by the presence of the adjacent mountains, which provide protection from the southerly moving Canadian cold-air masses and from the Pacific Ocean winter storms. The altitude and location within the study area have a large influence on the distribution of the temperature and precipitation.

The mean annual maximum air temperatures range from about 60°F in the lowlands to about 47°F in the mountains. The mean annual minimum temperatures range from about 40°F in the lowlands to about 31°F in the mountains. Summer daily mean temperatures within the lowlands generally range from 60°F to 80°F, and winter daily mean temperatures generally range from 30°F to 50°F. Because of the high altitudes, summer temperatures in the mountains are cool and winter daily mean temperatures generally are below freezing.

Most of the precipitation falls during the winter season, generally as rain below 1,000 ft, as both rain and snow at altitudes between 1,000 and 1,500 ft, and as snow at higher altitudes. In the lowlands, mean annual precipitation varies from 16 inches near Sequim, Wash., to about 53 inches near Olympia, Wash. In the upland areas, the annual precipitation ranges from 45 to 60 inches and in the mountains from about 60 to more than 100 inches.

GEOLOGIC FRAMEWORK

The present shape and form of the Puget Sound Lowland has been influenced in part by tectonic events throughout geologic time, but has been influenced in a larger part by the tectonic and glacial events during the Tertiary and Quaternary periods.

Plate tectonic processes, including ongoing convergence of the North American continental plate with oceanic plates of the eastern Pacific Ocean, have created the basic structural framework that the Puget Sound occupies. As a result of plate convergence, the thinner and more dense oceanic plates have been at least partially subducted beneath the less dense and buoyant continental plate. The subduction of the oceanic plates has caused repeated episodes of volcanism and plutonism. These events have, in turn, added to the land area of the North American continent. Accretion of remanent crustal material, including material brought from hundreds or even thousands of miles away (exotic terranes), that was scraped off the subducting oceanic plate and attached to the leading edge of the North American plate has also enlarged North America. Throughout Mesozoic and Cenozoic times many terranes were accreted to the North American plate in the Pacific Northwest and have extended the coastline westward.

During the Tertiary period of the Cenozoic era, several Pacific plates converged with the North American plate and began subducting beneath it. One of the last Pacific plates to collide with the North American plate was the Juan de Fuca plate. The subduction of the Juan de Fuca plate formed the tectonically active forearc basin that today is occupied by the Puget–Willamette Lowland. The Puget Sound Lowland is a part of this larger forearc basin (Dickinson, 1976) that lies between the trench and the magmatic arc (fig. 4). The basin has been filled at depth with Tertiary marine sedimentary and volcanic deposits that have been accreted to the North American plate; these deposits bound the Cascade Range, which marks the magmatic arc (Adams, 1984; and Snavely, 1988). The bedrock underlying the Olympic Mountains, the San Juan Islands, and parts of Vancouver Island represents exotic terranes that have been added to the western coastline of western Washington during both Mesozoic and Cenozoic times.

The tectonic activity of the Tertiary period has resulted in the uplift of the Cascade Range and in the formation of the Olympic Mountains, the Puget Sound Lowland, and the major fault zones in the Pacific Northwest. The current tectonic activity is essentially a continuation of the tectonic events and attendant processes that have been operating since the early Tertiary (table 1; McCrumb and others, 1989).

During the Quaternary period, the Puget Sound Lowland continued to be modified, this time by glaciers. Within the geologic record there is evidence of at least four major glacial advances and several partial glacial advances in the Puget Sound Lowland during the Pleistocene epoch (Blunt and others, 1987). Because each succeeding glacial advance and retreat eroded or buried the previous glacial deposits, information for delineating the glacial history prior to the last major glacial advance is sparse. In addition, techniques for dating deposits of the last glaciation, such as radiocarbon dating, are not available for dating the older deposits. It is

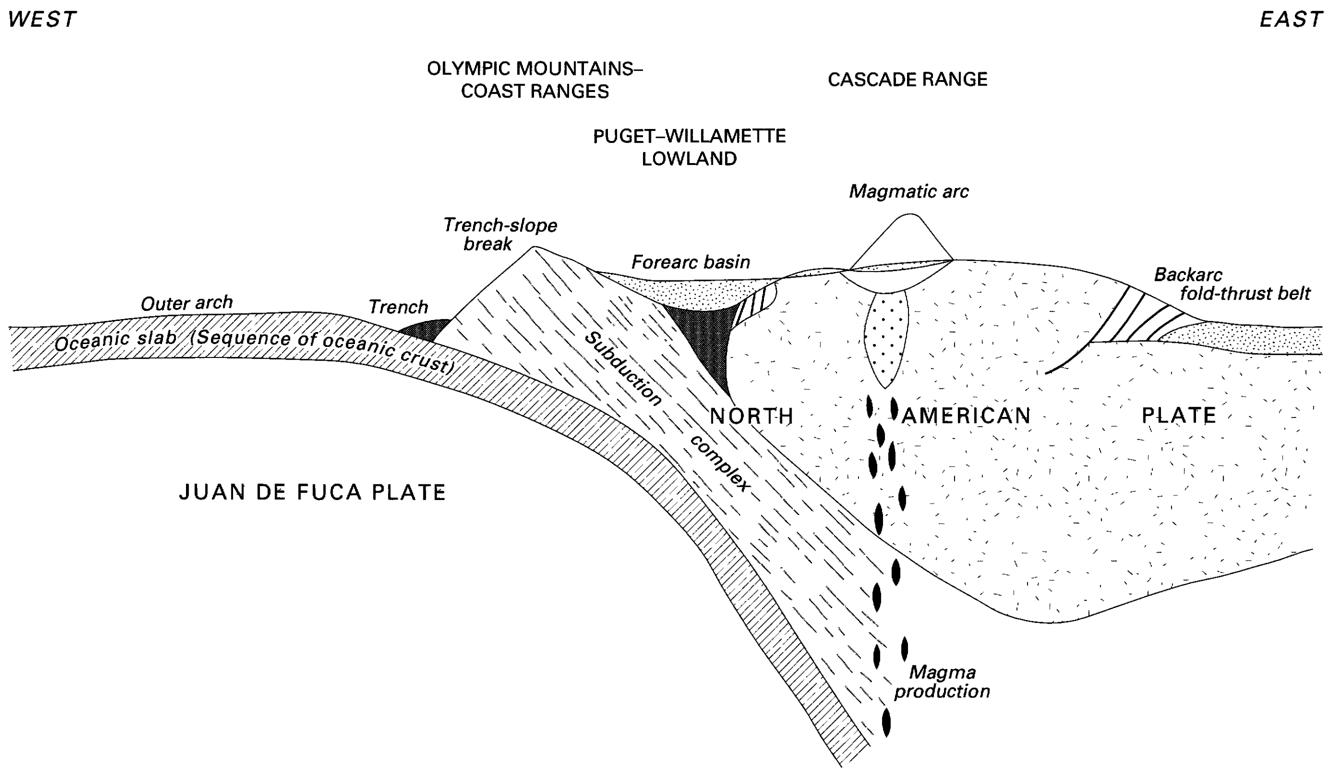


FIGURE 4.—Diagramatic section showing generalized tectonic fractures (modified from Dickinson, 1976).

TABLE 1.—*Summary of Tertiary geologic history*

[Vertical scale is proportional to time (modified from Noble and Wallace, 1966)]

Period	Epoch	Time (millions of years) Duration	Time (millions of years) Years ago	Events
Quaternary	Holocene	.01	0 to 0.1	Erosion and deposition of fluvial sediments.
Tertiary	Pleistocene	1.59	.01 to 1.6	Glaciation and erosion.
	Pliocene	3.7	1.6 to 5.3	Major uplift of present Cascade Range and Olympic Mountains, downwarp of Puget Trough, Piedmont gravel deposition renewed.
				Erosion cycle reformed area to one of low relief. Deep surficial weathering.
	Miocene	18.4	5.3 to 23.7	Uplift of ancestral Cascade Range associated with piedmont deposition. Volcanism prevalent.
	Oligocene	12.9	23.7 to 36.6	Shallow seas prevailed. Volcanic activity nearby. Continued subsidence with accompanying deposition.
	Eocene	21.2	36.6 to 57.8	Shallow warm seas with low swampy coastal area prevailed. Continued subsidence with accompanying deposition. Local deep water sedimentation.
				Large scale basaltic volcanism and associated continental margin sedimentation.
				Continental margin and possible rift sedimentation and volcanism.
				No Record

inferred that the history of the last glacial advance serves as an analog for the preceding glacial advances.

The last glaciation, the Fraser Glaciation, has been divided into the Evans Creek Stade, the Vashon Stade, and the Sumas Stade (Crandell and others, 1958; Armstrong and others, 1965). The Evans Creek and Sumas Stades were periods of partial glacial advances, and the Vashon Stade was the period of the last major glacial advance into the Puget Sound Lowland.

During the early part of the Fraser Glaciation, the Cordilleran ice sheet, originating in the Coast Range of southwestern British Columbia, Canada, advanced into the Fraser River Valley between 18,000 to 21,000 years BP (before present; Blunt and others, 1987). The early glacial advance extended into the Fraser River Valley, but it did not reach the present-day United States–Canadian border. This early advance is thought to be equivalent to the advance of the alpine glaciers of the Cascade Range during the Evans Creek Stade (Crandell and others, 1965). The alpine glaciers grew and extended down the valleys of the Cascade Range, and some of the glaciers in the northern part of the Cascade Range extended into the Puget Sound Lowland. Prior to the glacial advance during the Vashon Stade, the alpine glaciers had receded from the Puget Sound Lowland (Crandell and others, 1958 and 1965; Armstrong and others, 1965).

The ice sheet of the Vashon Stade originated in the Coast Range of British Columbia and moved southward into the Puget Sound Lowland about 18,000 years BP (Blunt and others, 1987). The glacier advanced south until it reached the Strait of Juan de Fuca, where it split into two lobes. The Juan de Fuca lobe flowed west, blocking the Strait of Juan de Fuca. The Puget lobe flowed south into the Puget Sound Lowland, blocking drainage to the north, which formed large freshwater lakes in the central and southern Puget Sound Lowland and diverted drainage southward (Bretz, 1913; Booth, 1986; Thorson, 1980). Runoff from the mountains and glacial meltwater transported sediment into the lakes and deposited it in thin layers of fine sand, silt, or clay in progressively deeper water.

At the maximum extent of the glacier, about 14,000 years BP (Blunt and others, 1987), it spanned from the Cascade Range to the Olympic Mountains and extended south as far as Tenino, Wash., occupying all of the lowland area and the lower mountain valleys. The glacier reached altitudes of about 4,000 ft along the mountain fronts, impounding rivers and creating lakes in many of the alpine valleys (Thorson, 1980). The glacier reached a thickness of about 6,000 ft near the present-day United States-Canada border, about 3,000 ft near Seattle, Wash., and less than 1,000 ft near Olympia, Wash. (Easterbrook, 1979; Blunt and others, 1987). Along the glacier margin, meltwater flowed south to the Chehalis River and then flowed west to the Pacific Ocean, building extensive outwash plains near the glacial terminus and valley trains down the Chehalis River (Noble and Wallace, 1966; Thorson, 1980).

Because of a worldwide warming trend, the Vashon glacier began thinning and retreating northward from its terminus around 14,500 years BP. As it retreated, meltwaters from the glacier again formed large proglacial lakes. The mass-wasting of the glacier deposited recessional outwash and proglacial lacustrine sediments in the southern part of the Puget Sound Lowland until about 14,000 years BP, when the terminus of the glacier reached the latitude of Seattle, Wash. By this time, the Juan de Fuca lobe had retreated from the Strait of Juan de Fuca, and the remaining part of the Puget lobe had thinned sufficiently to allow marine waters to enter the lowland through the Strait of Juan de Fuca. This influx of marine waters caused the remaining ice to be buoyed up and the continued ablation of the floating ice resulted in the deposition of a glaciomarine drift over the central and northern part of the Puget Sound Lowland (Blunt and others, 1987; Easterbrook, 1963, 1969; Armstrong and Brown, 1954).

Following the deposition of the glaciomarine drift, the glacier readvanced into the northern Puget Sound Lowland during the Sumas Stade at about 11,500 years BP. During this last advance, the Sumas drift was deposited predominantly throughout the Fraser River Valley, Canada, and northwestern Whatcom County, Wash. (the Fraser–Whatcom Basin). This last glacier retreated from the area by 10,000 years BP (Armstrong, 1977a, 1981; Blunt and others 1987; Easterbrook, 1963, 1969). Sea level rose as the glaciers retreated from the lowland during the end of the Fraser Glaciation, and the landmass rebounded from the removal of the weight of the glacial ice. Isostatic rebound was nearly complete in most areas of the lowland between 9,000 and 10,000 years BP (Armstrong, 1981).

As a result of the repeated glacial and interglacial episodes within the Puget Sound Lowland, the thickness of the unconsolidated glacial and interglacial deposits ranges from a thin, discontinuous veneer in areas of bedrock outcrop to thicknesses of more than 3,000 ft in the central part of the basin (Hall and Othberg, 1974; Yount and others, 1985). The distribution and thickness of the unconsolidated deposits are related to the configuration of the preglacial bedrock surface, the lithology of the bedrock, and the positions of preglacial, glacial, and post-glacial stream channels.

GEOLOGIC STRUCTURE

The structural geology of the area is very complex, and identification and mapping have been complicated by the large thickness of unconsolidated sediments and dense vegetation cover. Thus, many structures are inferred from seismic reflection, aeromagnetic, and gravity data. Geologic structures are more readily delineated in areas of bedrock outcrop, or where the unconsolidated deposits are thin. Structures are inferred between bedrock highs and outcrops. In some locations, faulting is exhibited within the Quaternary sediments (Wilson and others, 1979), but whether the structure has a tectonic origin or is due to glacial activity generally has not been determined.

The complex geologic structures within the Puget Sound Lowland were initially a result of early to middle Tertiary tectonic activity caused by the subduction of the Juan de Fuca plate beneath the North American plate (McCrumb and others, 1989; Thorson, 1989; and Gower and others, 1985). The area is seismically active with frequent low- and moderate-magnitude earthquakes (Crosson, 1972). Active faults have been recognized along the margin of the unconsolidated deposits, where the deposits are relatively thin (Carson, 1973; Wilson and others, 1979). In the central part of the basin, where unconsolidated deposits are thicker, geophysical data indicate deeply buried fault structures (fig. 5; Rogers, 1970; Gower, 1978; Gower and others, 1985; and Cheney, 1987). The origin of these structures appears to be a result of either faulting or folding that may have begun during the Tertiary but that for many of these structures continued into the Pleistocene (Johnson and others, 1994).

The major structures (fig. 5) are, from north to south, the Vedder Mountain Fault, the Boulder Creek Fault, the Haro Fault, the Mount Vernon Fault, the Devils Mountain Fault, the Northern Whidbey Island Fault, the Southern Whidbey Island Fault, the Mountlake Terrace Anticline, the Seattle Fault, the Seattle Fault Zone, the Hood Canal Fault, the Narrows Structure (fault or monoclinal fold), and the Olympic gravity anomaly (Gower, 1980; Gower and others, 1985; Cheney, 1987; and Gordy, 1988). Previously, letter symbols have been used to identify some of these structures; herein they are given geographic names to provide an improved sense of their location.

These geologic structures appear to subdivide the Puget Sound Lowland into three large subareas: the Fraser–Whatcom Basin, the north–central Puget Sound Lowland, and the southern Puget Sound Lowland. The Fraser–Whatcom Basin lies within the area crossed by the Fraser River and cut by the Mount Vernon, Vedder Mountain, and Boulder Creek Faults. The north-central subarea lies within the central part of the lowland between the Devils Mountain, Mount Vernon, and Boulder Creek Faults on the north and the Seattle Fault on the south. The southern subarea lies between the Seattle Fault and the Olympia gravity anomaly and bedrock highs to the south (fig. 5). The geologic structures have further divided the north-central and southern subareas into five structural basins. These are, from north to south, the Sammish, Everett, Seattle, Belfair, and Tacoma Basins (Rogers, 1970; fig. 5).

The Vedder Mountain and Boulder Creek Faults strike in a southwesterly direction (Gordy, 1988). The Vedder Mountain Fault lies east of Abbotsford, British Columbia, Canada, along the northwest flank of Vedder Mountain and extends in the subsurface to north of Bellingham, Wash., and potentially as far west as the Mount Vernon Fault.

The Haro Fault (fig. 5) is a curved, southeast-dipping thrust fault; it may be a rather young fault and is sufficiently large to have uplifted older San Juan Island terranes to the surface. Cheney (1987) suggested that this fault is part of the Devils Mountain Fault that has been offset by the Mount Vernon Fault (fig. 5). The northwest-striking Mount Vernon Fault extends about 90 mi, and, in general, its strike delineates the boundary between the Puget Sound Lowland and the Cascade Range. The Mount Vernon Fault offsets the Devil's Mountain Fault and the pre-Tertiary terrane of the San Juan Islands and vertically offsets Miocene terrestrial sediment in Whatcom County. The Devil's Mountain Fault bounds the same terrane as the Haro Fault and is truncated by the Mount Vernon Fault south of Mount Vernon, Wash. (fig. 5).

The Northern Whidbey Island Fault was discovered during a search for the westward extension of the Devil's Mountain Fault (Cheney, 1987). The Northern Whidbey Island Fault strikes in a westerly direction and has juxtaposed pre-Tertiary deposits on the north side against as much as 1,500 ft of unconsolidated Quaternary deposits on the south side. This evidence suggests the fault may be late Quaternary in age. The Southern Whidbey Island Fault (fig. 5) is a northwest-striking fault that has been inferred from an aeromagnetic high, bedrock highs, and large differences in thickness (more than 1,200 ft) of Quaternary deposits on either side of the fault. Cheney (1987) suggests that both the Northern and Southern Whidbey Island Faults may be associated with major faults in southern Vancouver Island, British Columbia, that separate the Olympic Mountain terrane from both the older San Juan Island terrane and the Wrangella terrane of British Columbia.

The Mountlake Terrace Anticline is an east-trending gravity high and has been interpreted as an east-plunging anticlinal fold (Gower and others, 1985). The anticline appears to bound a small structural basin within the north–central Puget Sound Lowland, just north of Seattle, Wash., and south of Whidbey Island, Wash.

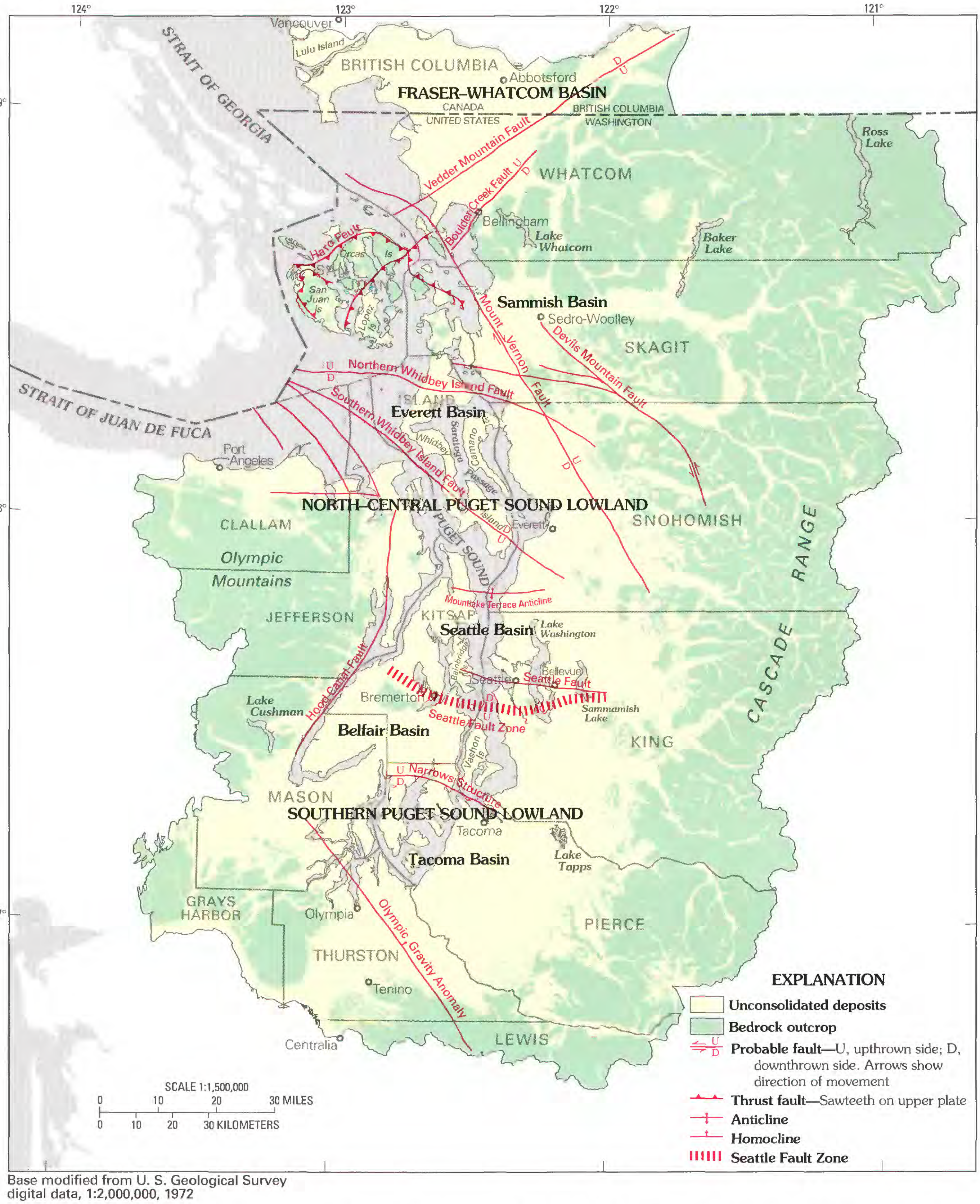


FIGURE 5.—Locations of subareas, structural features, and structural basins in the Puget Sound Lowland, modified from Gower and others (1985), Cheney (1987), and Gordy (1988).

The Seattle Fault and the Seattle Fault Zone define an area of strong seismic activity. The Seattle Fault and Seattle Fault Zone have been downthrown to the north and coincide with (1) a steep gravity anomaly, (2) the northern boundary of a large magnetic high, and (3) steeply dipping Tertiary deposits (Johnson and others, 1994). North of the Seattle Fault Zone lies the Seattle Basin, which contains more than 3,000 ft of unconsolidated Quaternary deposits. Together, the Seattle Fault and the Seattle–Quaternary Fault Zone separate the north-central and southern subareas of the Puget Sound Lowland. Bedrock highs along the traces of these faults suggest that the depositional and geologic history of the Puget Sound Lowland on either side of the faults is different. It has been suggested (Easterbrook, 1968; Blunt and others, 1987) that the topography along the Seattle Fault may have stalled the advance of the glaciers for many years and thus accounts for some of the lithologic and depositional differences.

The Hood Canal Fault abuts the western edge of the Puget Sound aquifer system and is the eastern boundary of a northeast-trending gravity high. It has been suggested that the Seattle Fault terminates against this fault. The Hood Canal fault probably is not important with respect to the movement of ground water because of its close proximity to the aquifer system's western boundary, where the Quaternary deposits are thin. However, the fault may provide a conduit for older water originating at depth in the Olympic Mountains to move upward along the west side of the fault. The Olympia gravity structure is defined as the northeast side of a northwest-trending positive gravity anomaly and is thought to represent a northeast dipping homocline. It does not appear to be structurally important with respect to the Puget Sound Lowland aquifer system because the thickness of the unconsolidated deposits in this area does not indicate a basinal-type structure.

The Narrows Structure is a pronounced east-west gravity and magnetic high that represents a fault or a steep monoclinal fold with the downthrown side to the south (Gower and others, 1985). The fault appears to bound, on the north, one of the thickest sequences of unconsolidated deposits of the Tacoma Basin, and the fault terminates to the west near some of the thinnest sequences of unconsolidated deposits (Hall and Othberg, 1974).

Knowledge of the geologic structure is important for mapping the Quaternary hydrogeologic units and for understanding the movement of ground water in the Puget Sound Lowland. For example, if the faults bounding the Everett Basin enclose a graben, as suggested by Cheney (1987), it implies that the thicknesses of the unconsolidated deposits in the basin are greater than currently mapped and may include water-bearing deposits at depths that are currently unknown. Major faulting not only can partition flow systems, but if extended upward into the Quaternary deposits, it can also disrupt the lateral continuity of aquifer units. For example, a predominantly clay unit could be vertically offset and juxtaposed with a sand unit, thereby truncating lateral ground-water flow along the fault. Although these types of questions may not be answered in this study, the structural history will provide information for the mapping of hydrogeologic units. The structural setting may help to explain depositional sequences, thickness variations, and the segmentation of ground-water flow systems or anomalous head distributions within the Puget Sound aquifer system. Delineation of the structural basins may also indicate areas where coarse-grained glaciofluvial or fine-grained lacustrine deposits might have been deposited.

BASEMENT CONFINING UNIT

The consolidated rocks (bedrock) compose the basement confining unit of the Puget Sound aquifer system. These rocks are of Tertiary age and older. The Tertiary rocks consist largely of marine and non-marine sedimentary rocks, and of volcanic rocks. Outcrops of the Tertiary rocks generally are located in the southern one-half of the study area. The older rocks are composed of an assortment of rocks that include chert, limestone, greenstone, gabbro, diorite, phyllite, and schist. Outcrops of the older rocks generally are located in the northern one-half of the study area.

The altitude of the top of the basement confining unit of the Puget Sound aquifer system is shown on plate 1. The map was constructed by subtracting gridded thickness values of the unconsolidated deposits from gridded land-surface altitudes obtained from digital elevation models (Elassal and Caruso, 1983) and gridded bathymetric data. Contours could not be constructed in Canada and in the area west of Shelton, Wash., in the southern part of the lowland because of insufficient data. Also, contours constructed in the Tacoma Basin may be more representative of the bathymetric topography than the altitude of bedrock because of insufficient marine-seismic data. A comparison of the bedrock surface altitude map (pl. 1) with the unconsolidated thickness map (pl. 2) shows that Pleistocene deposits have essentially filled the basins that were formed prior to or during the Quaternary Period. The map also indicates areas of potentially large quantities of deep ground-water flow and storage. Ground-water flow between the deep basins is probably minimal because of the structural highs and thin, discontinuous unconsolidated deposits separating the basins.

UNCONSOLIDATED DEPOSITS

Repeated episodes of alternating glacial and interglacial intervals have occurred within the Puget Sound Lowland during the Quaternary Period. Willis (1898) first proposed the glacial origin of the Puget Sound Lowland and presented evidence for two continental glaciations. These were named the Vashon and Admiralty Glaciations and were separated by the Puyallup Interglaciation. Bretz (1911, 1913) surveyed the region and added additional evidence for at least two continental glaciations. He further concluded that the arms of the Puget Sound were glacially modified river channels. Studies by Hansen and Mackin (1949) and Crandell and others (1958) established that there was more than one pre-Vashon Glaciation and that there were four glaciations within the southern part of the Puget Sound Lowland. Later studies by Armstrong and others (1965), Easterbrook and others (1967), Thorson (1980), Booth (1984), and Blunt and others (1987) have continued to add to our understanding of the glacial history of the Puget Sound Lowland. In addition to this work, in the 1970's an ambitious mapping program was initiated to produce surficial geology maps at a 1:100,000 scale of 30-minute by 60-minute quadrangles in Washington. To date, much of the Puget Sound Lowland has been mapped as part of this program. However, there is still much debate among glacial geologists and hydrogeologists concerning the extension of contacts of surficial deposits into the subsurface and the correlation of glacial deposits from the Fraser–Whatcom Basin to the north-central and southern subareas of the lowland. A correlation chart of the major stratigraphic units in these subareas indicates some of the potential problems in regional correlation of units (figs. 6A–6C).

The Quaternary deposits within the Puget Sound Lowland consist of materials deposited by (1) advancing and retreating continental glaciations, (2) numerous alpine glaciers and associated streams emanating from the adjacent Cascade Range and Olympic Mountains, and (3) streams and rivers during interglacial episodes when much of the lowland consisted of saltwater embayments and freshwater lakes. Each of these depositional regimes resulted in complex lithostratigraphic patterns and corresponding geologic deposits that are difficult to correlate on a regional scale. The complexity within each depositional sequence was compounded by the erosive action of the glaciers, which repeatedly altered much of the pre-existing topography and geology.

Four glaciations and three interglaciations are recognized in the Puget Sound Lowland. In the Fraser–Whatcom Basin and north-central subarea of the lowland, however, additional localized advances occurred (figs. 6A–6B). As a result, the Quaternary deposits consist of one to four regional drift sequences and as many as eight local ones (Armstrong and others, 1965; Easterbrook and others, 1967; Blunt and others, 1987). These sequences are generally separated by unconformities and by the nonglacial fluvial and lacustrine deposits. Except for the Fraser–Whatcom Basin, which is covered by a younger drift, most of the glacial deposits exposed at the surface were derived from drift deposited during the Vashon Stade of the Fraser Glaciation, which was the last major ice advance into the Puget Sound Lowland. This drift is generally represented by the coarse- and fine-grained undifferentiated Quaternary deposits shown on the generalized geologic map of the Puget Sound Lowland area (fig. 3). The surficial deposits consist predominantly of coarse-grained gravel and sand deposits and fine-grained silt and clay deposits of glacial and interglacial origin, and also include alluvial deposits that began accumulating near the end of the last glaciation and that continue to accumulate at the present time.

The Quaternary and Recent alluvial deposits are not limited to the land only. Many of these deposits that are exposed at land surface extend at depth beneath the waters of the Puget Sound. From the limited high-resolution seismic profiling done in the Puget Sound, some evidence suggests that there are extensive thick recessional outwash deposits and extensive thin post-glacial estuarine deposits (J.C. Yount, U.S. Geological Survey, written commun., 1994). Also, locally thick deltaic deposits are present at the mouths of the modern-day rivers. These Quaternary and Recent deposits are assumed to be of similar composition, hydraulic properties, and depositional regimes to those that crop out on land. In some areas where the coarse-grained recessional and deltaic deposits are thick, they may be a source of freshwater. In other areas these deposits may act as a conduit for the movement of saltwater landward. However, there are only minimal data available, and further study would be needed to define these deposits.

THICKNESS OF UNCONSOLIDATED DEPOSITS

The thickness of unconsolidated deposits, as stated earlier, ranges from a thin discontinuous veneer in areas of bedrock outcrop to thicknesses of more than 3,000 ft in the central part of the lowland. The distribution of thickness for the Puget Sound Lowland is shown on plate 2. The map was compiled from well records and information from several existing reports including unconsolidated thickness maps by Hall and Othberg (1974), Yount and others (1985), Yount (in press, 1994), and Buchanan-Banks and Collins (1994); gravity maps by Stuart (1965), Bonini and others (1974), and Danes and others (1965); aeromagnetic maps by the U.S.

Fraser–Whatcom Basin

Geologic Framework[1]						Hydrologic Framework		
Period	Age Ka	Geologic/climate units[2]		Stratigraphy		Name of Unit		
Quaternary		Interglacial		alluvium marine deposits[3]		Fraser River aquifer Nooksack River aquifer		PUGET SOUND AQUIFER SYSTEM
	10	Fraser Glaciation	Sumas Stade	Sumas Drift		Fraser aquifer		
			Everson Interstade	Everson 'glacio-marine' Drift[4]	Bellingham Drift Deming Sand Kulshan Drift	confining unit		
	12			Fort Langley Formation[5]				
			Vashon Stade	recessional outwash				
				Vashon till				
				advance outwash	Quadra Sand[6]	Puget aquifer	upper Puget zone	
				Esperance Sand Member				
			Evans Creek Stade[7]					
	20	Olympia Interglacial		Quadra Formation	Cowichan Head Formation[8]		lower Puget zone	
	60	Possession Glaciation		Possession Drift—Semiamoo Drift[9]				
	80	Whidbey Interglacial		Whidbey Formation				
	>100	Double Bluff Glaciation		Double Bluff Drift				
pre-Quaternary rock units						basement confining unit		

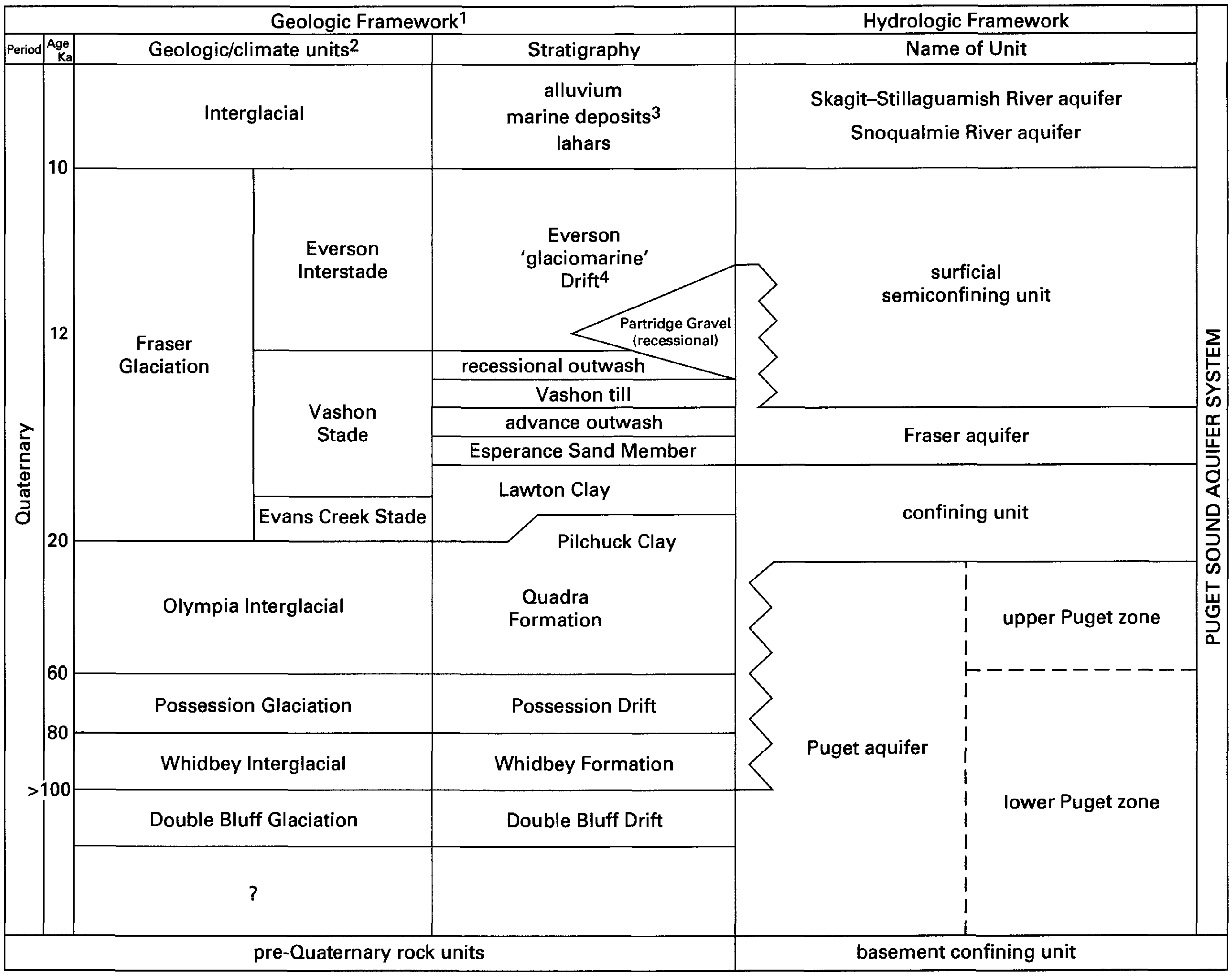
1. Modified from D. Molenaar (written communication, U.S. Geological Survey, 1982) P.C. Haase (written communication, U.S. Geological Survey, 1988), Blunt and others (1987), and Galster and Coombs (1989)
2. Drift sequences are generally separated by unconformities
3. Marine deposits are considered part of aquifer system where saturated with freshwater
4. Also includes glaciofluvial sediments—Everson sand (early Everson) and Everson gravel (late Everson)
5. Canadian name for Everson glaciomarine Drift
6. Canadian name for Vashon deposits older than till, although in many locations the unit does not include the advance outwash
7. Deposits of similar age and older than Evans Creek Stade generally not exposed in the basin, inferred from well-log information and from some exposures in Canada
8. Canadian name for Olympia Interglacial deposits
9. Canadian name for pre-Olympia Interglacial deposits

FIGURE 6A.—Relation between stratigraphic units and regional hydrogeologic units for the Puget Sound aquifer system, Fraser–Whatcom Basin. Location of area is shown on figure 5.

Geological Survey (1977); and tectonic and seismic maps by Rogers (1970), Gower (1978 and 1980), Gower and others (1985), Cheney (1987), and Gordy (1988).

In Washington and Canada combined, more than 6,000 water, oil, coal, and gas well records and marine-seismic shot sites were examined; of these wells and

North-central Puget Sound Lowland

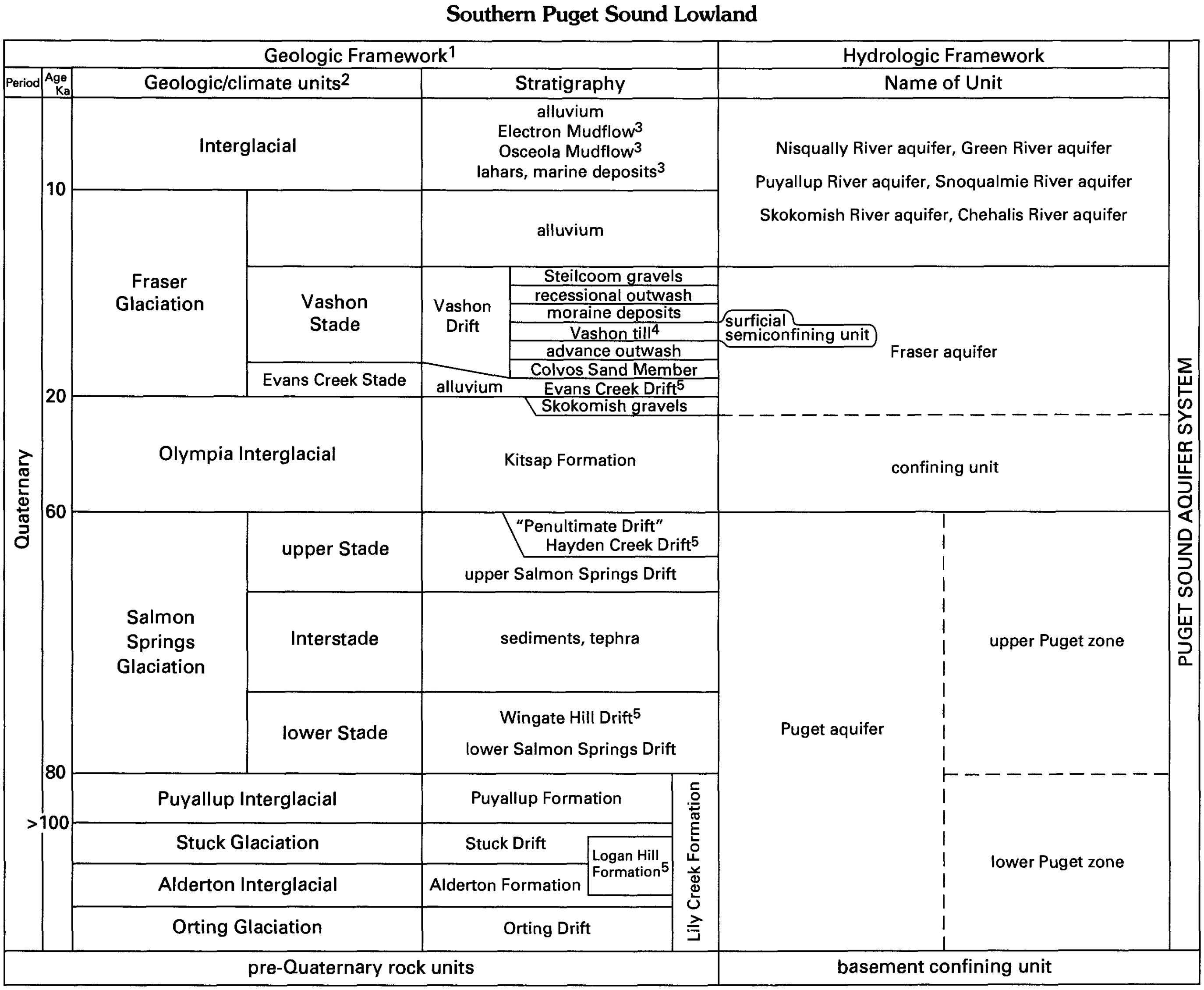


1. Modified from D. Molenaar (written communication, U.S. Geological Survey, 1982), P.C. Haase (written communication, U.S. Geological Survey, 1988), Blunt and others (1987), and Galster and Coombs (1989)
2. Drift sequences are generally separated by unconformities
3. Marine deposits are considered part of aquifer system where saturated with freshwater
4. Also includes glaciofluvial sediments—Everson sand (early Everson) and Everson gravel (late Everson)

FIGURE 6*B*.—Relation between stratigraphic units and regional hydrogeologic units for the Puget Sound aquifer system, north-central Puget Sound Lowland. Location of area is shown on figure 5.

data points, about 4,610 were selected and used for map construction according to the following general criteria. Wells were selected that were completed in bedrock; if there were no wells in the surrounding area completed in bedrock, the deepest well completed in the unconsolidated deposits was generally selected. Well selection was also based on well location and the density of other wells within the surrounding area and on the availability of geophysical logs, geological logs, or drillers' well logs. Marine-seismic shot sites were selected on the basis of data availability and their location within the Puget Sound. All wells and marine seismic data points that penetrated bedrock are shown on plate 2.

The greatest thicknesses of unconsolidated deposits



1. Modified from D. Molenaar (written communication, U.S. Geological Survey, 1982) P.C. Haase (written communication, U.S. Geological Survey, 1988), Blunt and others (1987), and Galster and Coombs (1989)
2. Drift sequences are generally separated by unconformities
3. Mudflows and lahars are part of alluvial valley aquifers where confined in channels and not principal unit in channel, otherwise, considered part of surficial semiconfining unit: marine deposits are considered part of aquifer system where saturated with freshwater
4. Vashon till makes up the surficial semiconfining unit where it outcrops at land surface or is covered by only a thin veneer of younger unsaturated deposits
5. Alpine glacial deposits, generally located in mountainous areas of Cascade Range

FIGURE 6C.—Relation between stratigraphic units and regional hydrogeologic units for the Puget Sound aquifer system, southern Puget Sound Lowland. Location of area is shown on figure 5.

are located in the Fraser–Whatcom, Everett, Seattle, and Tacoma Basins (fig. 5). Unconsolidated thicknesses as much as 1,500 ft were contoured in the Fraser–Whatcom Basin. The largest unconsolidated thickness recorded is about 1,670 ft, based on a coal exploration well located near Abbotsford, British Columbia. Data for contouring the thickness of the Fraser–Whatcom Basin were predominantly from coal exploration records, available geophysical, aeromagnetic, and gravity information, and some drillers' well logs (Gordy, 1988;

Halstead, 1966, 1986). Offshore information on the thickness of the unconsolidated deposits was lacking for Canada and the northern part of the Puget Sound; thus thicknesses in these areas were not contoured.

The Everett Basin lies between the northern and southern Whidbey Island faults (fig. 5). Unconsolidated thickness values as much as 3,600 ft were contoured within this basin. The largest thickness recorded was more than 3,660 ft; this value was obtained from a shot site located in the Saratoga Passage between Whidbey and Camano Islands (Yount, in press, 1994). Most of the data within this basin were from marine-seismic profiles (Yount, in press, 1994), drillers' well logs, and a few oil- and gas-exploration wells.

The Seattle Basin, in general, lies between the Mountlake Terrace Anticline and the Seattle Fault (fig. 5). Unconsolidated thickness values as much as 3,600 ft were contoured in this basin. The largest unconsolidated thickness recorded is about 3,730 ft; this value was obtained from a shot site located near Seattle, Wash. (Yount and others 1985). Most of the available data within this basin are from marine-seismic data (Yount and others, 1985), from driller's well logs, and oil- and gas-exploration wells.

The Tacoma Basin lies to the south of the Seattle Fault (fig. 5). Unconsolidated thickness values as much as 1,800 ft were contoured within this basin. The largest unconsolidated thickness recorded is about 1,980 ft, based on information from a well located near Tacoma, Wash. Most of the available data within this basin are from driller's well logs and some oil-and gas-exploration wells (Buchanan-Banks and Collins, 1994). The mapped thickness of unconsolidated deposits within this basin is probably underestimated because of the scarcity of well logs that penetrate bedrock and the lack of available marine-seismic data.

Very little information is available on the thickness of the unconsolidated deposits within the glacial cut valleys of the Cascade Range and the Olympic Mountains. Some of the unconsolidated deposits within the valleys have been partially contoured, but because of the minimal amount of data available in these areas, the thickness of the unconsolidated deposits is mostly unknown. On the basis of our present knowledge of glacial and geologic process, it has been speculated that the unconsolidated deposits in these valleys could be very thick. However, there are not enough data available to prove or disprove this theory.

HYDROGEOLOGIC UNITS

The unconsolidated Quaternary deposits contain the principal hydrogeologic units of the Puget Sound aquifer system. The lateral extent of the hydrogeologic units is generally delineated by the extent of the Vashon Drift deposits from the last glaciation and the present-day alluvial deposits. The unconsolidated deposits present at the land surface in the Puget Sound Lowland encompass about 7,183 mi^2, excluding the large lakes. Of these deposits, 1,570 mi^2 are alluvium, 3,320 mi^2 are fine-grained deposits, and 2,293 mi^2 are coarse-grained deposits (fig. 3).

The geologic deposits of the Puget Sound have been divided into local and regional hydrogeologic units on the basis of their hydraulic properties. The hydrogeologic units have been divided into aquifer units and semiconfining and confining units. The aquifer units contain coarse-grained sand and gravel deposits from glacial deposits consisting of advance and recessional outwash deposits and from interglacial deposits consisting of proglacial and coarse-grained fluvial deposits (fig. 6). The semiconfining and confining units contain fine-grained silt and clay deposits from glacial deposits consisting of till and glaciomarine deposits and from interglacial deposits consisting of lacustrine, mudflow, and fine-grained fluvial deposits.

An alternating pattern of coarse- and fine-grained deposits occurs within the four major glacial and three interglacial units from the surface to depths of more than 3,000 ft (pl. 2). The pattern can be observed in outcrops along the coastline, cliffs, stream and river valleys, road cuts, and in well logs.

The hydrogeologic units identified in this report do not necessarily correspond to geologic time-stratigraphic units identified in previous reports. In some areas, fine-grained till directly overlies or underlies fine-grained interglacial deposits, and the individual units cannot be differentiated from each other. Thus, the tills and the fine-grained interglacial deposits are grouped as a single confining unit. Conversely, when coarse-grained glacial deposits overlie or underlie coarse-grained interglacial deposits, they are also grouped as a single aquifer unit.

LOCAL HYDROGEOLOGIC UNITS

For the purposes of this report the Quaternary deposits in the Puget Sound Lowland were grouped into hydrogeologic units on the basis of completed and ongoing geologic mapping and on the corresponding lithologic descriptions. In general, the symbols used on the hydrogeologic maps to classify the hydrogeologic units are mostly the same symbols used in the original mapping. Locally restricted geologic deposits have been grouped with the most similar common geologic deposits based on the similarity of their hydraulic properties.

An index map of the 16 hydrogeologic quadrangle maps (plates 3-18) that were compiled and produced at a scale of 1:100,000 is shown on figure 7. The Robinson

Mountain and Mount Baker quadrangles and the Sauk River and Twisp quadrangles have been combined into the Mount Baker and the Sauk River quadrangles, respectively. These hydrogeologic maps were compiled from numerous reports listed in the references on each plate; the lithologic descriptions of the units present on each plate also are listed. Table 2 shows the general relationship among the units described on each plate. These units have been generalized from units described from many studies within the area. The generalized local units are described below. Where information is available, the generalized descriptions include estimates of the thicknesses and hydraulic conductivities of the units.

Recent alluvial deposits (Qal), present at the land surface, occur both as small discontinuous deposits and as extensive deposits in the broad alluvial valleys. The lithology of the alluvial deposits varies from coarse-grained deposits, generally found in the upper valleys, to fine-grained deposits, generally found in the lower valleys. The coarse-grained sand and gravel deposits within the alluvium function as aquifers. On the basis of their lithologic character, the alluvial deposits can be classified as productive aquifer units or as semiconfining units. The thicknesses of the small discontinuous alluvial deposits generally range from 5 to 10 ft. The thicknesses of the deposits in large alluvial valleys range from a few tens of feet in the upper part of the valleys to as much as 600 ft in the lower part of the valleys (Luzier, 1969). The hydraulic conductivity for the fine-grained alluvial deposits ranges from about 1 to 15 ft/d, and the hydraulic conductivity of the coarse-grained alluvial deposits ranges from about 170 to 700 ft/d. The large range in this hydraulic conductivity is partly skewed by the large hydraulic conductivity values for the alluvial deposits along the Dungeness and Elwah Rivers (fig. 2). When the conductivity values for these two areas are not included, the hydraulic conductivity of the coarse-grained alluvial deposits is about 100 ft/d (Vaccaro and others, 1998).

The marsh, bog, and peat deposits (Qb) are scattered throughout the Puget Sound Lowland. Most of the deposits occur near or within the extent of the alluvial deposits and have generally been combined with the alluvial deposits. In some areas, the Qb deposits occur within the limits of the recessional deposits, and they have been mapped together with the recessional deposits.

Mudflow deposits (Qme, Qmo, and Qmu) and lahar and pyroclastic flow deposits (Qlh) have been designated separately on the maps (plates 3 to 18), but are hydraulically similar. The deposits are generally located in the upper reaches of the mountain valleys of the Olympic Mountains and the Cascade Range. However, mudflow deposits from Mount Rainier are present in the southern part of the lowlands (pl. 14). These hydrogeologic units are not mapped on the Mount Baker map because of a lack of geologic information. These hydrogeologic units are generally considered to be semiconfining to confining units, although some small local sand and gravel lenses within the lahar and pyroclastic flow deposits are used as sources of water. Thicknesses of these units range from 0 to 80 ft. The hydraulic conductivities of these units are assumed to be similar to the hydraulic conductivity of the till units, which generally range from 0.005 to 22 ft/d (Vaccaro and others, 1998).

The moraine deposits (Qvm and Qdvm) consist of clay, silt, sand, and gravel, and they also include mixtures of till and outwash deposits that are not separately mappable. The moraine deposits are generally small discontinuous deposits located near the glacial terminus in the southern part of the lowland. The moraine deposits are generally considered to be a semiconfining unit, although small sand and gravel lenses within the deposits locally are used as sources of water. The general thickness of this unit is unknown because of the hummocky nature of the deposit. The hydraulic conductivity is assumed to be similar to the conductivity of the till unit, which generally ranges from 0.005 to 22 ft/d.

The recessional outwash deposits (Qvrg, Qovg, Qs, Qvrf, Qov, Qvr, and Qovs) consist predominantly of coarse-grained, moderately to poorly sorted sand and gravel that was deposited during the retreat of ice during the last glaciation. These deposits are generally discontinuous within the Puget Sound Lowland, but where the deposits are extensive and saturated, they are considered an aquifer unit. The Qvrg and Qovg represent the coarser fraction of the recessional outwash deposits. The most extensive of these is the Steilacoom gravel (Qs), a very coarse cobbly gravel outwash located in the southern Puget Sound Lowland (plates 14 and 17). The Qvrf represents the finer fraction of the recessional outwash deposits. These deposits include the Everson glaciomarine drift, lacustrine, and some ice-contact deposits. Qov, Qvr, and Qovs represent combined coarse- and fine-grained recessional outwash deposits. The locally discontinuous recessional outwash deposits generally average about 10 ft thick. The more extensive recessional outwash deposits generally average about 40 ft thick, and in some areas, these deposits can be as much as 150 ft thick. The hydraulic conductivity of the outwash deposits ranges from about 10 ft/d to about 100 ft/d. The hydraulic conductivity of the deposits that consist predominantly of sand ranges from about 15 to about 50 ft/d. Hydraulic conductivity values for the coarse-grained sand and gravel deposits average about 100 ft/d, and the fine-grained sand and silty sands average about 15 ft/d or less if clay is also present in the

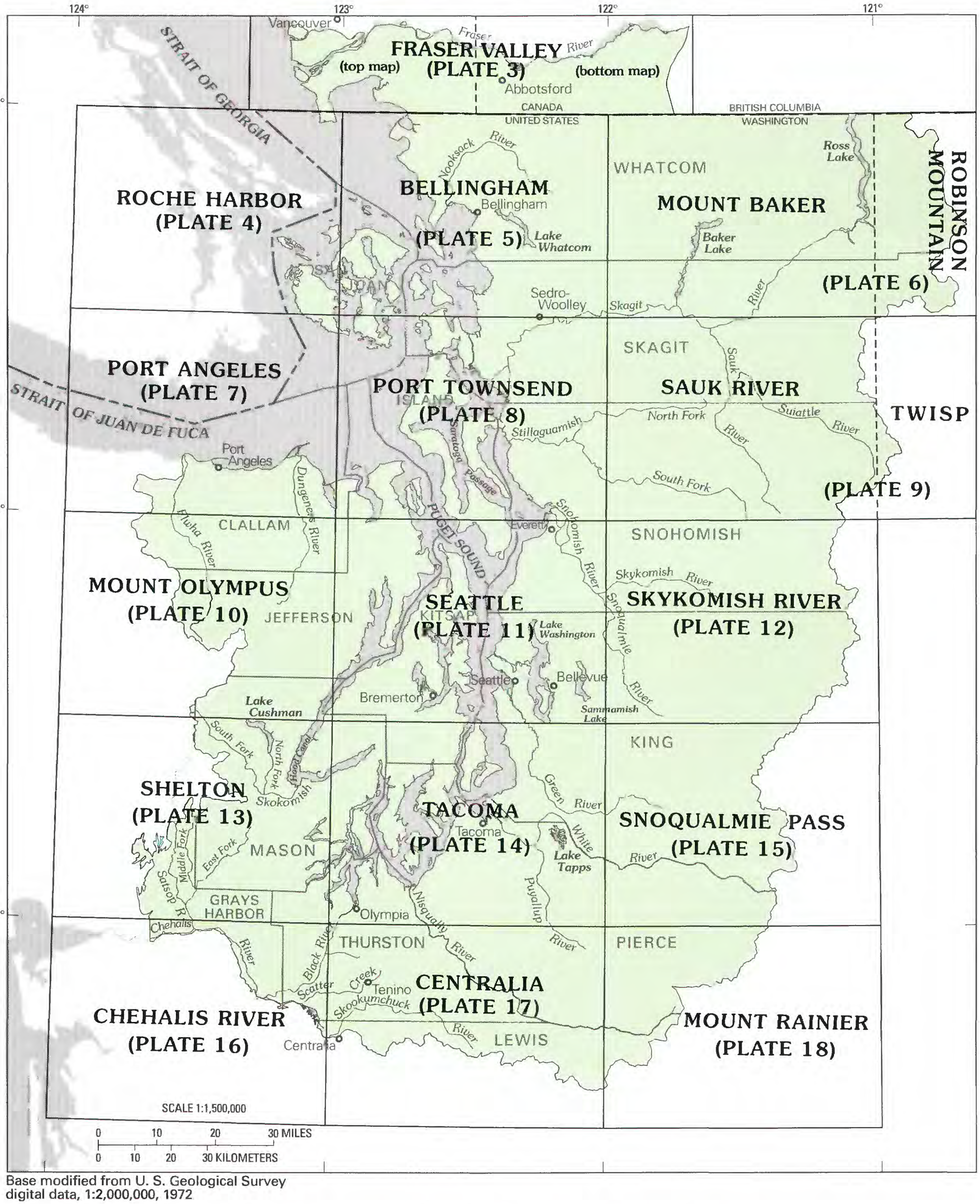


FIGURE 7.—Index map showing locations and names of plates 3 through 18.

TABLE 2.—*Hydrogeologic units present in plates 3 through 18*
[—, not comparable]

Canada (plate 3)	Roche Harbor (plate 4)	Bellingham (plate 5)	Mount Baker (plate 6)	Port Angeles (plate 7)	Port Towsend (plate 8)	Sauk River (plate 9)	Mount Olympus (plate 10)	Seattle (plate 11)	Skykomish River (plate 12)	Shelton (plate 13)	Tacoma (plate 14)	Snoqualmie Pass (plate 15)	Chehalis River (plate 16)	Centralia (plate 17)	Mount Rainier (plate 18)
Qal	Qal	Qal	Qal	Qal	Qal	Qal	Qal	Qal	Qal	Qal	Qal	Qal	Qal	Qal	Qal
Qb	Qb	Qb	—	Qb	Qb	Qb	—	Qb	Qb	Qb	Qb	Qb	—	Qb	—
—	—	—	—	—	—	—	—	—	—	—	Qme/Qmo	—	—	Qme	Qmu
—	—	—	—	—	—	—	Qvm	—	Qvm	Qdvm	Qvm	—	Qdvm	Qvm	—
—	—	—	—	—	—	Qlh	—	—	—	—	—	Qlh	—	—	—
Qvrg/Qvrf	Qvrg/Qvrf	Qvrg/Qvrf	Qvrg/Qvrf	Qvrg/Qvrf	Qvrg/Qvrf	Qvrg/Qvrf	Qvrg/Qvr	Qvrg/Qvrf	Qvrg/Qvrf	Qov	Qvrg/Qvrf	Qvrg/Qvrf	Qovg/Qovs	Qvrg/Qvrf	—
—	—	—	—	—	—	—	—	—	—	—	Qs	—	—	Qs	—
Qvt/Qvtse	Qvt	Qvt/Qvtse	Qvt	Qvt	Qvt	Qvt	Qvt	Qvt	Qvt	Qvt	Qvt	Qvt	Qvt	Qvt	—
Qva	Qva	Qva	Qva	Qva	Qva	Qva	Qva	Qva	Qva	Qova	Qva	Qva	—	Qva	—
—	—	—	—	—	—	—	Qog	Qog	—	Qsk	Qsk	—	—	—	—
—	—	—	Qag	Qag	—	Qag	Qoad	Qoad	Qag	—	—	Qag/Qdg	—	Qde	Qdg
Qns	Qns	Qns	Qns	Qns	Qns	Qns	—	Qns	Qcs	Qk	Qns	—	—	Qpu	—
—	—	—	—	—	—	—	Qdp	—	—	—	—	Qdp	Qdp	—	—
Qpf	—	Qpf	Qpf	Qpf	Qpf	Qpf	—	Qpf	Qpf	Qpf	Qpf	—	—	Qpf	—
—	—	—	—	—	—	—	—	—	—	Qwx/Qwe	—	—	—	—	—
—	—	—	—	—	—	—	—	—	—	—	Qdh/Qdw	Qdh	—	Qdh/Qdw	Qdh
—	—	—	—	—	—	—	—	—	—	—	—	—	—	Qdht/Qdwt	—
—	—	—	—	—	—	—	—	—	—	—	—	—	Qlhf	Qlhf	—
—	—	—	—	—	—	—	—	—	—	—	Qlc	—	—	Qlc	—
—	—	—	Qv	—	—	Qv/Qsf	—	—	QTbc/QTbf	—	—	Qra	—	Qvmr	Qvmr
Bk	Bk	Bk	Bk	Bk	Bk	Bk	Bk	Bk	Bk	Bk	Bk	Bk	Bk	Bk	Bk

EXPLANATION

Qag	Alpine glacial deposits
Qag/Qdg	Alpine glacial deposits
Qal	Alluvial deposits
Qb	Bog, marsh, and peat deposits
Qcs	Pre-Fraser non-glacial lacustrine deposits
Qde	Alpine glacial deposits
Qdh/Qdw	Pre-Fraser alpine drift deposits
Qdht/Qdwt	Pre-Fraser alpine till deposits
Qdp	Pre-Fraser undifferentiated glacial and nongalcial deposits
Qdvm	Vashon morainal deposits
Qk	Pre-Fraser undifferentiated non-glacial deposits
Qlc	Mudflow deposits
Qlh	Lahar deposits
Qlhf	Alpine outwash deposits
Qme	Electron mudflow deposits
Qmo	Osceola mudflow deposits
Qmu	Undifferentiated mudflow deposits
Qns	Pre-Fraser undifferentiated non-glacial deposits
Qoad	Alpine glacial deposits
Qog	Olympia gravel deposits
Qov	Vashon recessional outwash deposits
Qova	Vashon advance outwash deposits
Qovg/Qovs	Vashon recessional outwash deposits
Qpf	Pre-Fraser undifferentiated glacial deposits
Qpu	Pre-Fraser undifferentiated non-glacial deposits
Qra	Andesite units
Qs	Steilacoom gravel deposits
Qsk	Skokomish gravel deposits
QTbc/QTbf	Basalt cinder cone and flow deposits
Qv	Volcanic units
Qv/Qsf	Volcanic and Suiattle Fill deposits
Qva	Vashon advance outwash deposits
Qvm	Vashon morainal deposits
Qvmr	Andesite units
Qvrg/Qvr	Vashon recessional outwash deposits
Qvrg/Qvrf	Vashon recessional outwash deposits
Qvt	Vashon till deposits
Qvt/Qvtse	Till deposits
Qwx/Qwe	Glaciolacustrine and outwash deposits
Bedrock (Bk)	Bedrock deposits

deposits (Vaccaro and others, 1998).

An extensive till sheet (Qvt) overlies about 40 percent of the Puget Sound Lowland aquifer system. This predominantly fine-grained deposit is composed of unsorted and unstratified glacial deposits that range from clay to boulder in size and that vary in degree of compaction and composition throughout the lowland. The till is considered a semiconfining unit. However, numerous shallow domestic wells obtain small quantities of water from this unit. The average thickness of this unit is between 20 and 40 ft, with a maximum thickness of more than 125 ft. In general, the hydraulic conductivity of the till is smaller than the conductivity of the outwash and alluvial deposits and larger than the conductivity of the fine-grained interglacial deposits. Results from field permeameter measurements made during this study showed that the hydraulic conductivity of the tills ranged from 0.002 to 53.0 ft/d, with a median of 0.12 ft/d, and the middle 80 percent of the data ranged from 0.005 to 22 ft/d.

Underlying the till unit is a predominantly coarse-grained deposit (Qva) that is generally associated with the Vashon advance and proglacial periods. The proglacial deposits include the Esperance and Colvos sands (figs. 6A–6C). Often included with these deposits is a coarse-grained nonglacial gravel deposit, the Skokomish gravel (Qsk) and the Olympia gravel (Qog) (plates 10, 11, 13, and 14). Together, the above units compose an aquifer unit that consists predominantly of stratified sand, but also contains irregular lenses of gravel and thin lenses of clay and silt. This unit was nearly continuous throughout the study area at one time, but subsequent erosion has dissected it in many places. Locally the unit is present at the surface and in outcrops along the coastal bluffs and in incised valley walls. The average thickness of this unit varies between 20 and 50 ft. It reaches a maximum thickness of more than 400 ft in some areas, but maximum thicknesses of 150 to 200 ft are more common. Hydraulic conductivities of this aquifer unit are similar to those of the recessional outwash deposits described above which range from 10 ft/d to 100 ft/d.

The Olympia interglacial deposits consist of small discontinuous deposits located in the upland areas and extensive deposits in the lowland areas of the Puget Sound Lowland. These deposits are classified as semiconfining and confining units. The small discontinuous deposits consisting of fine-grained interglacial deposits and undifferentiated alpine drift deposits (Qoad, Qdg, Qde, and Qag) are generally found in the alpine valleys of the Cascade Range and the Olympic Mountains, above the limit of the Vashon ice sheet. The hydraulic characteristics of these upland deposits are unknown. The extensive lowland interglacial deposits consist of fine-grained interglacial and proglacial deposits (Qk, Qns, Qpu, and Qcs), and as mapped, they may include the Lawton Clay, Kitsap Formation, and pre-Fraser undifferentiated nonglacial deposits. Within this unit, lenses of coarse-grained deposits that function as aquifers occur locally and along the margins near the Cascade Range and Olympic Mountains. Outcrops of this unit within the lowland are present along the coastal bluffs and in incised valley walls. The average thickness of this interglacial deposit is between 40 and 65 ft, and in some areas these deposits reach a thickness of more than 150 ft. The hydraulic conductivity of this unit is generally less than 10 ft/d.

The undifferentiated pre-Fraser glacial deposits (Qpf) consist of till, outwash, and moraine deposits and, along the margins of the aquifer system, may include alpine drift deposits. Therefore, this unit contains aquifer zones and semiconfining to confining zones. The thickness and extent of the undifferentiated deposits is unknown. However, on the basis of thickness of the unconsolidated deposits (pl. 2) and on the thickness of the units described previously, this unit can in some areas be more than 1,000 ft thick. The aquifer zones within this unit appear to be composed predominantly of sand and have hydraulic conductivities that range from 34 to 59 ft/d, and average about 41 ft/d (Vaccaro and others, 1998).

The pre-Fraser surficial deposits designated as Qdp are a combination of both the Qns (nonglacial) and Qpf (glacial) deposits that were not mapped separately.

The Weatherwax and Wedekind Creek Formations (Qwx and Qwe) are generally confined to the upper valleys of the Olympic Mountains within the study area and are only identified on the Shelton map (pl. 13). The formations consist predominantly of glaciolacustrine and outwash deposits, but may also contain some nonglacial alluvial deposits and alpine drift deposits. These deposits have been grouped with either the alluvial deposits or the outwash deposits. The thickness and hydraulic conductivity of this unit is unknown.

The Hayden Creek and Wingate Hill deposits (Qdh and Qdw) are located in the southeast part of the Puget Sound Lowland on the Tacoma, Snoqualmie Pass, Centralia, and Mount Rainier maps (plates 14, 15, 17, 18). The deposits consist of pre-Fraser alpine drift deposits that include undifferentiated deposits of till, outwash, and moraines. These deposits are generally considered an aquifer unit. However, information on the thickness and hydraulic conductivity of the unit is lacking. On the Centralia map (pl. 17) certain areas of pre-Fraser till deposits that do not include outwash or moraine deposits are identified: the Hayden Creek and Wingate Hill till deposits (Qdht and Qdwt). These till deposits consist of a compact, weathered, stony till and are considered a semiconfining unit.

The Logan Hill Formation (Qlhf) is a small, local deposit found in the southwest part of the lowland and is identified on the Chehalis River map (pl. 16) and the Centralia map (pl. 17). The unit predominantly consists of alpine outwash sand and gravel and is considered an aquifer unit. The average thickness of the unit is about 100 ft, and it thins to the north to about 50 ft. The hydraulic conductivity of this unit is not known, but yields from wells completed in this unit range from 10 to 15 gal/min (Weigle and Foxworthy, 1962).

The Lily Creek Formation (Qlc) is a local deposit present in the southeastern part of the lowland and is identified on the Tacoma map (pl. 14) and the Centralia map (pl. 17). The formation is composed of weathered mudflow deposits interbedded with pre-Fraser stream deposits. The formation is generally considered a semiconfining unit, but springs issuing from the sand and gravel lenses within this unit indicate that it can locally support domestic water use. The extent and thickness of the formation is unknown, but the maximum exposed thickness is about 270 ft (Walters and Kimmel, 1968).

The Tertiary basalt flow and cinder cone deposits (QTbc and QTbf) and the younger Pleistocene and Holocene andesite and volcanic deposits (Qv, Qsf, Qra, and Qvmr) near Mount Baker, Mount Rainier, and Glacier Peak are mapped separately because of their young age. Hydrologically they have been considered part of the basement confining unit.

The sequence of glacial and interglacial deposits described above-more specifically the alluvial deposits (Qal), recessional outwash deposits (Qvrg and Qvrf), till deposits (Qvt), advance outwash and proglacial deposits (Qva), and the interglacial deposits (Qns)-generally compose the upper 250 ft of the aquifer system. Excluding the alluvium (Qal), deposits more than 250 ft below the land surface are generally undifferentiated, especially on a regional basis. The extent and thickness of the water-bearing zones within the undifferentiated deposits (Qdp and Qpf) are largely unknown because water wells do not commonly penetrate below the upper 250 ft of the Puget Sound aquifer system.

Drillers' well logs from a few deep wells drilled for exploration of petroleum, coal, or water are available, but generally they are too sparse to adequately characterize the deep deposits in the Puget Sound Lowland, except in some small areas where the deeper deposits can be divided into additional hydrogeologic units.

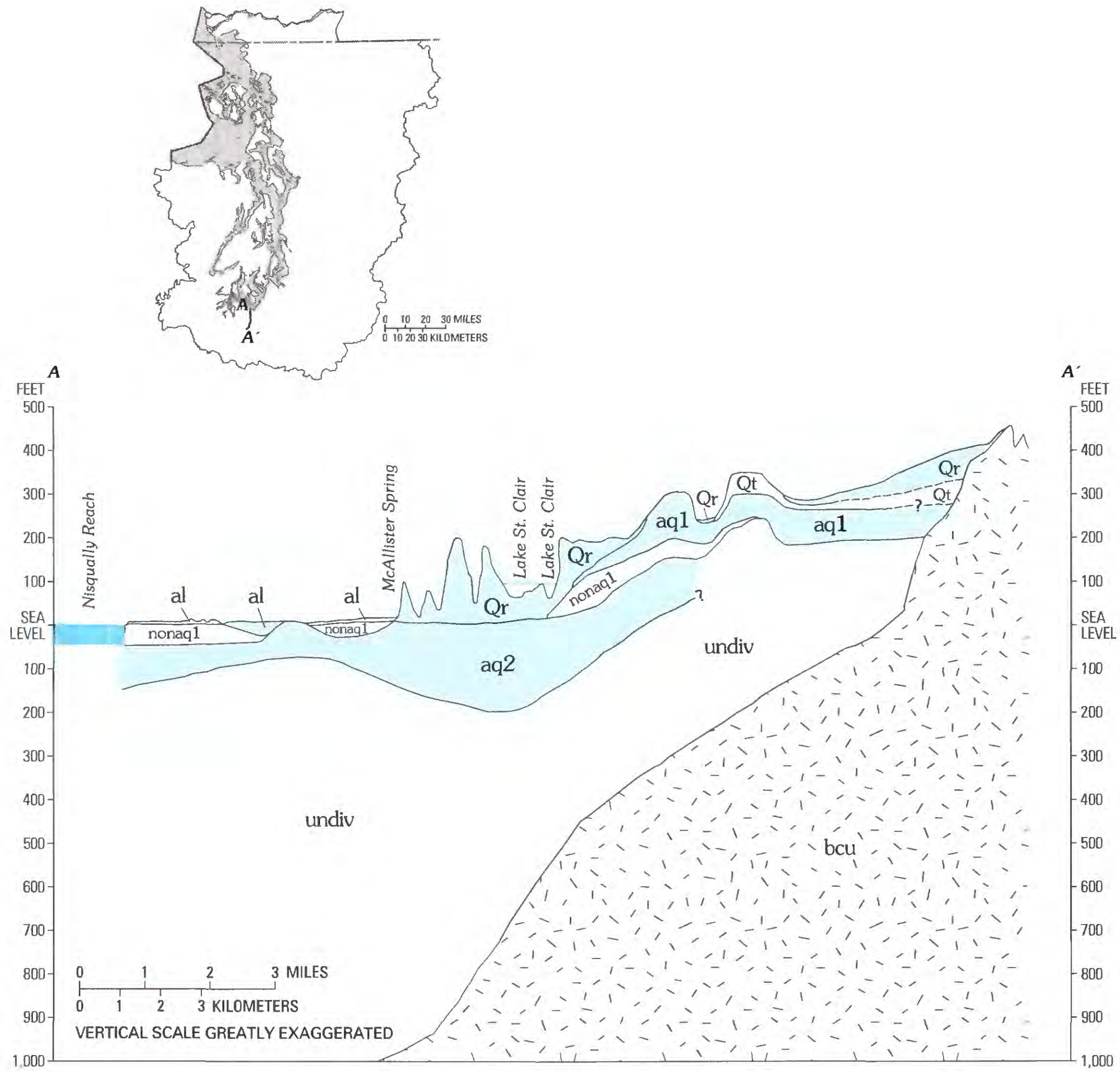
Two hydrogeologic sections showing the typical local sequences and configurations of the hydrogeologic units in the Puget Sound aquifer system (Vaccaro and others, 1998) are shown on figure 8. Because of the large size of the study area and the lack of data to describe the localized hydrogeologic units on a regional basis, the hydrogeologic sections were used to provide information for (1) describing ground-water flow in the Puget Sound Lowland, (2) developing a method for aggregating local units into regionally representative units, (3) testing hydrologic controls on ground-water flow, and (4) developing a conceptual model for describing regional ground-water flow based on the division of the aquifer system into regional hydrogeologic units (Vaccaro and others, 1998).

REGIONAL HYDROGEOLOGIC UNITS

The Puget Sound aquifer system is composed of highly variable sequences of alluvial, glacial, and interglacial deposits. In order to assess the ground-water resources and describe ground-water flow on a regional basis, the local hydrogeologic units were grouped into regional hydrogeologic units. The designated regional hydrogeologic units are the alluvial valley aquifers, the surficial semiconfining unit, the Fraser aquifer, the confining unit, and the Puget aquifer (figs. 6A–6C). The basement confining unit forms the basal and lateral boundary of the aquifer system.

The alluvial valley aquifers are composed of extensive alluvial deposits found in the major river valleys. Nine alluvial valley aquifers have been identified on the basis of the extent of the alluvium in the major river valleys. These are, from north to south, the Fraser River, Nooksack River, Skagit-Stillaguamish River, Snoqualmie River, Green River, Puyallup River, Skokomish River, Nisqually River, and Chehalis River aquifers (figs. 2 and 9). Each of these aquifers closely follows the associated river valley and can be considered a separate aquifer unit. These valley aquifers frequently traverse the glacial and interglacial deposits; thus the valley aquifers may or may not also consist of glacial and interglacial deposits. In the upper reaches of the alluvial valleys, adjacent glacial, interglacial mudflow and lahar deposits, due to their generally small and discontinuous extent, are considered to be a part of the alluvial valley aquifer units. These long valley aquifers tend to be incised into the glacial drift of the lowland and therefore tend to drain, truncate, and control the flow systems in the adjacent unconsolidated deposits (Vaccaro and others, 1998). Minor alluvial deposits that are not located in the major river valleys and display similar characteristics to the adjacent glacial deposits have been grouped with the adjacent glacial deposits.

The surficial semiconfining unit is present in the north-central and southern Puget Sound Lowland (figs. 3 and 9). This unit consists predominantly of the Vashon till, but also includes some mudflow deposits and fine-grained, near-surface Everson glaciomarine deposits



EXPLANATION

Aquifer unit

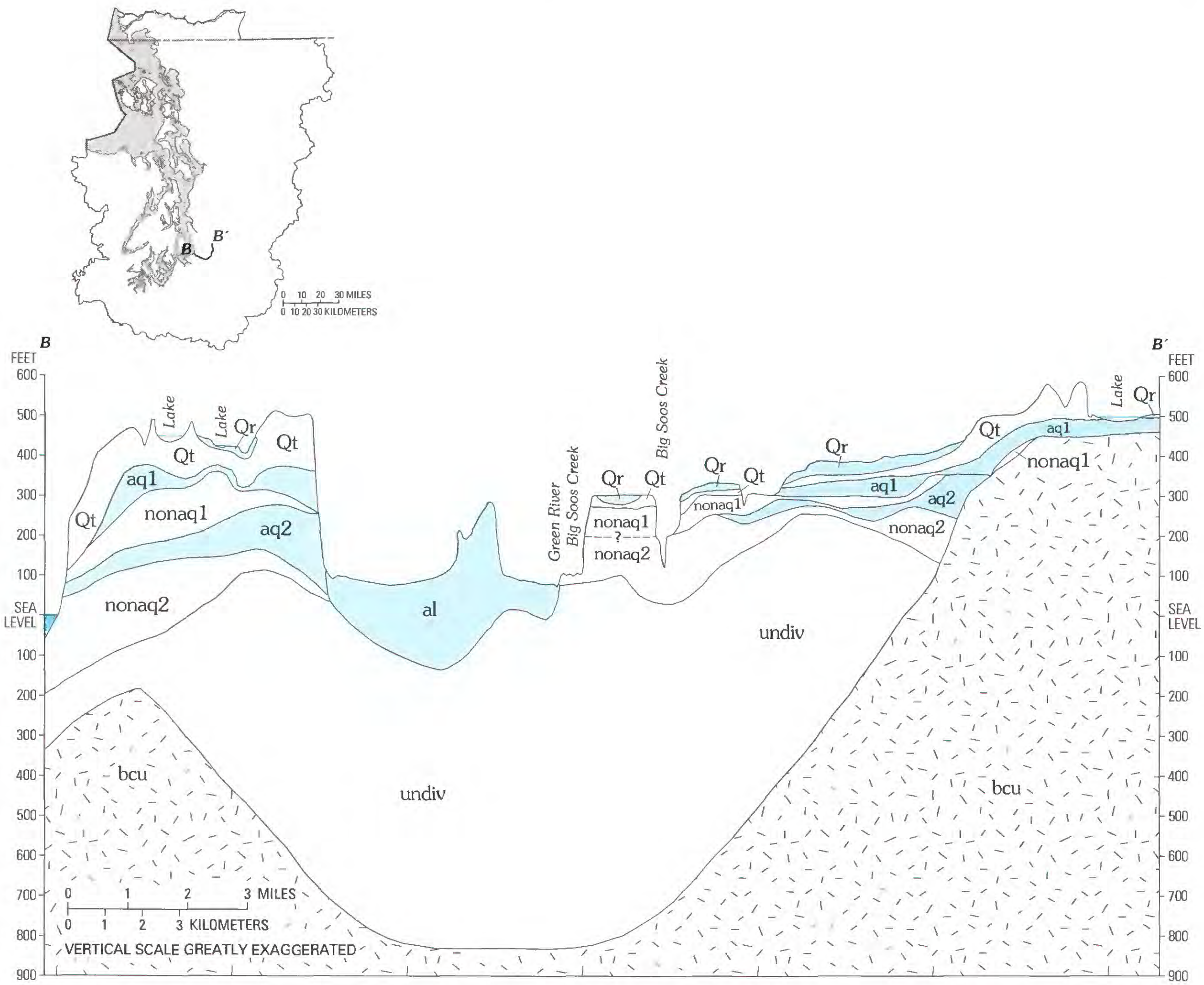
Salt-water body

---?- **Boundary between hydrogeologic units**—Dashed where approximately located; queried where unknown

POTENTIAL RELATIONS BETWEEN HYDROGEOLOGIC AND STRATIGRAPHIC UNITS

SECTION	HYDROGEOLOGIC UNIT	STRATIGRAPHIC UNIT
	al	alluvium, Nisqually River
	Qr	recessional outwash
	Qt	Vashon till
A—A′	aq1	advance outwash–Colvos Sand Member
	nonaq1	Kitsap Formation–(Salmon Springs till?)
	aq2	upper Salmon Springs Drift
	undiv	Salmon Springs Drift and older deposits
	bcu	bedrock, basement confining unit

FIGURE 8.—Typical local sequences and configurations of local hydrogeologic units within the Puget Sound aquifer system.



EXPLANATION

Aquifer unit

Salt-water body

——?– **Boundary between hydrogeologic units**—Dashed where approximately located; queried where unknown

POTENTIAL RELATIONS BETWEEN HYDROGEOLOGIC AND STRATIGRAPHIC UNITS

SECTION	HYDROGEOLOGIC UNIT	STRATIGRAPHIC UNIT
	al	alluvium, Green River
	Qr	recessional outwash
	Qt	Vashon till
	aq1	advance outwash or advance outwash–Colvos Sand Member
B—B′	nonaq1	advance outwash or Kitsap Formation
	aq2	advance outwash–Colvos Sand Member or Salmon Springs Drift
	nonaq2	Kitsap Formation or Puyallup Formation
	undiv	Salmon Springs Drift and older deposits or Stuck Drift and older deposits
	bcu	bedrock, basement confining unit

FIGURE 8.—Continued.

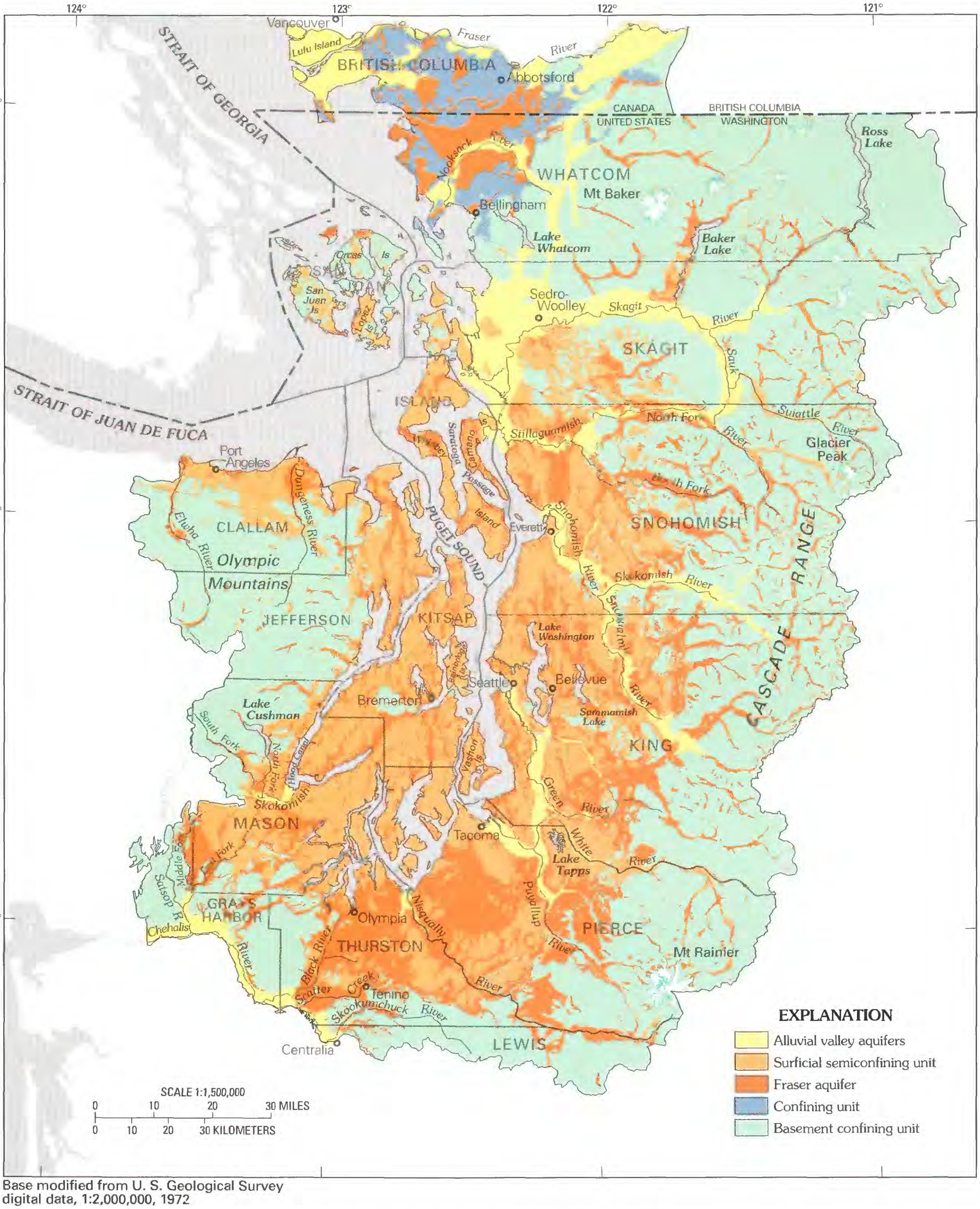


FIGURE 9.—Extent of the surficial regional hydrogeologic units.

(exclusive of the Fraser–Whatcom Basin). On the basis of regional ground-water modeling done for the study area, although this unit does not appear to affect the regional flow system a great deal (Vaccaro and others, 1998), it does limit the ground-water recharge and thus limits ground-water availability and affects contaminant transport and surface-water runoff. Therefore, it was defined as a distinct regional unit (Vaccaro and others, 1998). In the upland and mountain areas, other fine-grained deposits (fig. 9) have been included with the surficial semiconfining unit; these deposits generally include till, mudflow, morainal, lahar, and recessional ice-contact deposits. The average thickness of this unit is between 20 and 40 ft. In areas where this unit directly overlies or underlies the fine-grained interglacial deposits, it is considered a part of the confining unit described in the text below.

The Fraser aquifer (fig. 9) generally consists of the Vashon advance outwash and proglacial deposits and generally represents the uppermost water-table aquifer. This aquifer unit also includes the surficial recessional outwash deposits and other local coarse-grained hydrogeologic units previously described. In areas where the recessional outwash is present, till deposits that underlie this outwash and overlie the advance outwash deposits have been grouped with the Fraser aquifer. This grouping is based on the results of a regional ground-water modeling study of the Puget Sound Lowland (Vaccaro and others, 1998). In the Fraser–Whatcom Basin, the Fraser aquifer consists predominantly of the Sumas Drift (fig. 6). In the upland and mountain areas, the coarse-grained deposits (fig. 9) have been included with the Fraser aquifer; these deposits generally include outwash, alpine drift, and alpine valley alluvial deposits. The average thickness of this unit is between 40 and 50 ft and locally is as much as 150 ft.

The confining unit consists of the shallowest, areally extensive, fine-grained deposits, which are generally of interglacial lacustrine or fine-grained fluvial origin. On a regional basis, this unit has the largest effects on the regional ground-water recharge, movement, and availability. The confining unit present in the southern Puget Sound Lowland generally consists of the fine-grained deposits from the Olympia Interglacial (fig. 6). In the north–central Puget Sound Lowland, the confining unit can consist of the fine-grained deposits from the Olympia Interglacial through the fine-grained deposits from the Whidbey Interglacial. The confining unit in the Fraser–Whatcom Basin generally consists of the Everson glaciomarine deposits but may also include deposits of Vashon recessional outwash and till. The thickness and altitude of the confining unit can vary greatly throughout the Puget Sound Lowland. The average thickness of the confining unit is between 20 and 65 ft, but locally the thickness can exceed 200 ft. Greater thicknesses are generally found in the northern part of the study area in places where the Everson glaciomarine deposits overlie the Vashon till or earlier interglacial deposits. The altitude of the top of the confining unit ranges from below sea-level in the central part of the study area to altitudes of more than 400 ft in areas along the foothills of the Olympic Mountains and Cascade Range.

The Puget aquifer underlies the confining unit. This unit consists of the remaining undifferentiated glacial and interglacial deposits that exist from the base of the confining unit to the top of the basement confining unit. These deposits have been grouped into the Puget aquifer unit because of the lack of data at depth to delineate the aquifer units from semiconfining to confining units on a regional scale. The thickness of the Puget aquifer generally is more than 400 ft. Thicknesses in the Fraser–Whatcom, Everett, Seattle, and Tacoma Basins can exceed 1,000 ft.

The Puget aquifer unit was divided into an upper and lower zone, based on minimal available data that indicate locally the presence of a lower confining clay unit. The presence of this clay unit could potentially divide the water-bearing zones at depth and thus affect the circulation of the ground water at depth. The areal extent and thickness of the clay unit are unknown, and more information and further study would be needed to determine this unit's regional extent and effects on ground-water movement.

SUMMARY AND CONCLUSIONS

The aquifer systems in the Puget–Willamette Lowland were studied by the U.S. Geological Survey as part of a national Regional Aquifer-System Analysis program (RASA). The Puget–Willamette Lowland, located in western Washington, western Oregon, and a small part of southwestern British Columbia, Canada, contains two major aquifer systems, the Puget Sound aquifer system and the Willamette Lowland aquifer system. The study area for this report is the Puget Sound Lowland, which contains the Puget Sound aquifer system. The Puget Sound Lowland encompasses about 17,610 square miles, of which about 2,615 square miles is saltwater. The Puget Sound Lowland is an elongated basin that extends about 200 miles in a north-south direction and varies from 60 to 120 miles in its east-west direction. Areas within the basin can be classified as lowlands, uplands, and mountains.

The topography and geology of the Puget Sound Lowland have been influenced by the tectonic and glacial events during the Tertiary and Quaternary periods. During the Tertiary period, several Pacific plates converged with the North American plate and began subducting beneath it. The subduction of the Pacific plates formed the tectonically active forearc basin that extends from the Fraser River valley in southwestern British Columbia, Canada, to near Cottage Grove, Oregon. The Puget Sound Lowland is a part of this forearc basin.

At least four major glacial advances and several partial glacial advances continued to modify the landscape of the Puget Sound Lowland during the Quaternary Period.

The Quaternary deposits consist of one to four regional drift sequences that are generally separated by unconformities and by non-glacial, fluvial, and lacustrine deposits. In the present-day major alluvial valleys, large thicknesses of alluvial deposits generally overlie the drift deposits of the last major glaciation.

The Puget Sound aquifer system is composed of the unconsolidated Quaternary deposits. The lateral extent of the aquifer system is generally delineated by the extent of the surficial deposits of the Vashon Stade of the Fraser Glaciation, which was the last major glaciation within the lowland. Except for the Fraser–Whatcom Basin on the north, Quaternary coarse- and fine-grained unconsolidated deposits shown on the generalized surficial geologic map generally belong to the Vashon Drift.

The Puget Sound aquifer system predominantly underlies about 7,183 square miles of the Puget Sound Lowland. The surficial unconsolidated deposits consist of about 1,570 square miles of alluvium, 3,320 square miles of fine-grained deposits, and 2,293 square miles of coarse-grained deposits.

The thickness of the unconsolidated deposits mapped in the Puget Sound Lowland, western Washington, and part of British Columbia, Canada, ranges from a thin discontinuous veneer in areas of bedrock outcrop to more than 3,000 feet. Available information shows that the greatest thicknesses of unconsolidated deposits are located in the Fraser–Whatcom, Everett, Seattle, and Tacoma Basins. The greatest thicknesses recorded within each basin were 1,670 feet, 3,660 feet, 3,730 feet, and 1,980 feet, respectively. The actual thickness of the unconsolidated deposits in the Tacoma Basin is probably underestimated because of the scarcity of logs of wells that penetrate bedrock and the lack of available marine-seismic data.

The unconsolidated Quaternary deposits of the Puget Sound aquifer system are grouped into hydrogeologic units based on completed and ongoing geologic mapping and on the corresponding lithologic descriptions. On the basis of this grouping, 16 hydrogeologic maps for quadrangles were compiled and presented at a scale of 1:100,000. The maps show the local surficial hydrogeologic units and provide a description for each. The general relations among the units is described on each plate.

The modified hydrogeologic units do not necessarily correspond to time-stratigraphic units but represent aquifer and semiconfining to confining units contained in the aquifer system. The aquifer units consist mostly of coarse-grained sand and gravel deposits of both glacial advance and recessional outwash deposits and interglacial proglacial and coarse-grained fluvial deposits. The semiconfining to confining units consist mostly of fine-grained silt and clay deposits from both glacial till and glaciomarine deposits and interglacial lacustrine, mudflow, and fine-grained fluvial deposits. An alternating pattern of coarse- and fine-grained deposits occurs from land surface to depths of more than 3,000 feet. Individual units range in thickness from 10 to more than 400 feet. Lateral hydraulic conductivity for the aquifer units generally range from about 10 to 700 feet per day, and median values generally range from 15 to 50 feet per day. Values larger than 50 feet per day generally are associated with coarse-grained outwash or alluvial deposits. Values less than about 10 feet per day are associated with fine-grained deposits.

The local hydrogeologic units are grouped into regional hydrogeologic units. The regional hydrogeologic units consist of the alluvial valley aquifers, the surficial semiconfining unit, the Fraser aquifer, the confining unit, and the Puget aquifer; the basement confining unit forms the lateral and basal boundary of the aquifer system.

The alluvial valley aquifers are composed of extensive alluvial deposits found in the major river valleys. Nine alluvial valley aquifers have been identified and named. Each of these aquifers closely follows the associated river valley and can be considered a separate aquifer unit. In the upper reaches of the alluvial valleys, glacial, interglacial, mudflow, and lahar deposits are considered to be part of the alluvial valley aquifer units.

The surficial semiconfining unit is present in the north-central and southern parts of the Puget Sound Lowland. This unit consists predominantly of the Vashon till, but also includes glaciomarine deposits (except in the Fraser–Whatcom Basin) and some mudflow and ice-contact deposits. The thickness averages between 20 and 40 feet.

The Fraser aquifer in the north-central and southern part of the Puget Sound Lowland generally consists of the Vashon advance outwash and proglacial deposits and may also include some recessional outwash deposits and represents the uppermost aquifer unit. In areas where the recessional outwash deposits are present at the land surface, till that underlies the outwash deposits and overlies the advance outwash deposits is included in the Fraser aquifer. In the Fraser–Whatcom Basin, the Fraser aquifer consists predominantly of the Sumas Drift and generally represents the water-table aquifer. The Fraser aquifer averages between 40 and 50 feet thick and locally is as much as 150 feet thick.

The confining unit, by definition, consists of the shallowest, areally extensive, fine-grained, generally lacustrine deposits that affect the ground-water flow system. The confining unit present in the southern part of the lowland consists of the fine-grained deposits from the Olympia Interglacial. In the north–central Puget Sound Lowland, the confining unit can consist of the fine-grained deposits of the Whidbey Interglacial or the fine-grained deposits from the Olympia interglacial. The confining unit in the Fraser–Whatcom Basin generally consists of the Everson glaciomarine deposits from the Everson interstade.

The average thickness of the confining unit is between 20 and 65 feet. In the northern part of the Puget Sound Lowland where the Everson glaciomarine deposits overlie the Vashon till or earlier interglacial deposits, the thickness of the confining unit is more than 200 feet.

The remaining undifferentiated glacial and interglacial deposits from the base of the confining unit to the top of the basement confining unit have been designated as the Puget aquifer. Thicknesses of the Puget aquifer in the Fraser–Whatcom, Everett, Seattle, and Tacoma Basins are more than 1,000 feet.

SELECTED REFERENCES

Adams, John, 1984, Active deformation of the Pacific Northwest continental margin: Tectonics, v.3, no. 4, p. 449–472.

Anderson, H.W., Jr., 1968, Ground-water resources of Island County, Washington: Washington Department of Water Resources Water-Supply Bulletin 25, part II, 317 p.

Armstrong, J.E., 1956, Surficial geology of Vancouver Area, British Columbia: Geological Survey of Canada, Paper 55–40, 1 sheet.

———1960, Surficial geology of the Sumas Map-Area, British Columbia: Geological Survey of Canada, Paper 59–9, 27 p., 1 sheet.

———1976, Surficial geology map of Mission, British Columbia: Geological Survey of Canada, Map 1485A, 1 sheet, scale 1:50,000.

———1977a, Quaternary Stratigraphy of the Fraser Lowland, *in* Geological excursions in the Pacific Northwest, eds. Brown, E.H., and Ellis, R.C.: Bellingham, Wash., Western Washington University, p. 204–226.

———1977b, Surficial geology map of Chilliwack, British Columbia: Geological Survey of Canada, Map 1487A, 1 sheet, scale 1:50,000.

———1979, Surficial geology of Vancouver, British Columbia: Geological Survey of Canada, Map 1486A, 1 sheet, scale 1:50,000.

———1981, Post-Vashon Wisconsin Glaciation, Fraser Lowland, British Columbia: Geological Survey of Canada Bulletin 322, 34 p.

Armstrong, J.E. and Brown, W.L., 1954, Late Wisconsin marine drift and associated sediments of the lower Fraser Valley, British Columbia, Canada: Geological Society of America Bulletin, v.65, no. 4, p. 349–364.

Armstrong, J.E., Crandell, D.R., Easterbrook, D.J., and Nobel, J.B., 1965, Late Pleistocene stratigraphy and chronology in southwestern British Columbia and northwestern Washington: Geological Society of America Bulletin, v. 76, p. 321–330.

Armstrong, J.E., and Hicock, S.R., compilers, 1976, Surficial geology map of New Westminister, British Columbia: Geological Survey of Canada, Map 1484A, 1 sheet, scale 1:50,000.

Associated Earth Sciences Inc., 1990, Miller Peninsula Project, geology, soils, geologic hazards, and ground water hydrogeology: Associated Earth Sciences Inc., pre-final, Project No. 9008–11, unpaginated.

Blunt, D.J., Easterbrook, D.J., and Rutter, N.W., 1987, Chronology of Pleistocene sediments in the Puget Lowland, Washington: Washington Division of Geology and Earth Resources Bulletin 77, p. 321–353.

Bonini, W.E., Hughes, D.W.,and Danes, Z.F., 1974, Complete bouguer gravity anomaly map of Washington: Division of Geology and Earth Resources, Geologic Map GM–11, 1 sheet, scale 1:500,000.

Booth, D.B., 1984, Glacier dynamics and the development of glacial landforms in eastern Puget Lowland, Washington: Seattle, Wash., University of Washington, Doctor of Philosophy dissertation, 217 p., 1 plate, 1:100,000 scale map.

———1986, The formation of ice-marginal embankments into ice-dammed lakes in the eastern Puget Lowland, Washington, U.S.A., during the late Pleistocene: Boreas, v. 15, no. 3, p. 209–264.

———1990, Surficial geologic map of the Skykomish and Snoqualmie Rivers area, Snohomish and King Counties, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I–1745, 22 p., 1 plate, scale 1:100,000.

Bretz, J Harlan, 1911, Terminal moraine of the Puget Sound glacier: Journal of Geology, v. 19, no. 2, p. 161–174.

Bretz, J Harlan, 1913, Glaciation of the Puget Sound region: Washington Geological Survey Bulletin 8, 244 p, 24 plates.

Brown and Caldwell, 1985, Clover/Chambers Creek geohydrologic study: Seattle, Washington, Brown and Caldwell, unpaginated.

Brown, R.D., Jr., 1970, Geological map of the north-central part of the Olympic Peninsula, Washington: U.S. Geological Survey Open-File Report 70–43, 2 sheets, scale 1:62,500.

Brown, R.D., Jr., Gower, H.D., and Snavely, P.D., Jr., 1960, Geology of the Port Angeles–Lake Crescent area, Clallam County, Washington: U.S. Geological Survey Oil and Gas Investigation Map OM–203, 1 plate, scale 1:62,500.

Buchanan-Banks, J.M., and Collins, D.S., 1994, Map showing depth-to-bedrock in the Tacoma and part of the Centralia 30 x 60' quadrangles, Wash.: U.S. Geological Survey Miscellaneous Field Study Map, MF 2265, 2 sheets, scale 1:100,000.

Cady, W.M., 1975, Tectonic setting of the Tertiary volcanic rocks of the Olympic Peninsula, Washington: U.S. Geological Survey Journal Research, v. 3, p. 573–582.

Cady, W.M., Sorensen, M.L., and MacLeod, N.S., 1972, Geologic Map of the Brothers Quadrangle, Jefferson, Mason, and Kitsap Counties, Washington: U.S. Geological Survey Map GQ–969, 1 sheet, scale 1:62,500.

Cady, W.M., Tabor, R.W., Macleod, N.S., and Sorensen, M.L., 1972, Geologic map of the Tyler Peak Quadrangle, Callam and Jefferson Counties, Washington: U.S. Geological Survey Map GQ–970, 1 sheet, scale 1:62,500.

Carr, J.R., and Associates, 1983, Vashon/Maury Island Water Resources Study: Tacoma, Washington, Carr and Associates, unpaginated.

Carr, J.R., Schmidt, R.G., and Ritzi, R.W., 1983, Water resource management planning criteria for Vashon/Maury Island, Washington—A case study, *in* Nielsen, D.M., and Aller, Linda, eds., Proceedings of the NWWA western regional conference on ground-water management, San Diego, 1983: National Water Well Association, p. 317–325.

Carson, R.J., 1970, Quaternary geology of the south-central Olympic Peninsula, Washington: Seattle, Washington, University of Washington, Doctor of Philosophy dissertation, 67 p.

———1973, First known active fault in Washington: Washington Geologic Newsletter, v. 1, no. 3, p. 1–2.

———1976, Geologic map of north-central Mason County, Washington: Washington Division of Geology and Earth Resources Open-File Report 76–2, 1 sheet, scale 1:62,500.

Carson, R.J., Smith, Mackey, and Foxworthy, B.L., 1975, Geologic conditions related to waste-disposal planning in the southern Hood Canal area, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I–853–D, 1 plate, scale 1:62,500.

Cheney, E.S., 1987, Major Cenozoic faults in the northern Puget Lowland of Washington, *in* Schuster, J.E., ed., Selected papers on the geology of Washington: Washington Division of Geology and Earth Resources Bulletin 77, p. 149–168.

Crandell, D.R., Mullineaux, D.R., and Waldron, H.H., 1958, Pleistocene sequence in the southeastern part of the Puget Sound lowland, Washington: American Journal of Science, v. 256, p. 384–397.

———1965, Age and origin of the Puget Sound trough in western Washington: U.S. Geological Survey Professional Paper 525–B, p. B132 to B136.

Crosson, R.S., 1972, Small earthquakes, structure, and tectonics of the Puget Sound region: Seismological Society of America Bulletin, v. 82, no. 5, p. 1133–1171.

Danes, Z.F., Bonno, M.M., Brau, E., Gilham, W.D., Hoffman, T.F., Johansen, D., Jones, M., Halfait, B., Masten, J., and Teague, G.O., 1965, Geophysical investigation of the southern Puget Sound area, Washington: Journal of Geophysical Research, v. 70, no. 22, p. 5573–5580.

Deeter, J.D., 1979, Geologic map of the north-central part of the Olympic Peninsula, Washington: U.S. Geological Survey Open-File Report 70–43, 2 sheets, scale 1:62,500.

———1979, Quaternary geology and stratigraphy of Kitsap County, Washington: Bellingham, Washington, Western Washington University, Master of Science thesis, 175 p., 7 plates, scale 1:24,000.

Dickinson, W.R., 1976, Sedimentary basins developed during evolution of Mesozoic–Cenozoic arc–trench systems in western North America: Canadian Journal of Earth Sciences, v. 13, p. 1268–1283.

Dion, N.P., Olsen, T.D., and Payne, K.L., 1988, Preliminary evaluation of the ground-water resources of Bainbridge Island, Kitsap County, Washington: U.S. Geological Survey Water-Resources Investigations Report 87–4237, 82 p.

Drost, B.W., 1986, Water resources of Clallam County, Washington, phase 1 report: U.S. Geological Survey Water-Resources Investigations Report 83–4227, 263 p.

Drost, B.W., and Lombard, R.E., 1978, Water in the Skagit River basin, Washington: Washington Department of Ecology Water-Supply Bulletin 47, 247 p.

Easterbrook, D.J., 1963, Late Pleistocene glacial events and relative sea-level changes in the northern Puget lowland, Washington: Geological Society of America Bulletin, v. 74, p. 1465–1484.

———1968, Pleistocene stratigraphy of Island County, Washington: Washington Department of Water Resources Water-Supply Bulletin 25, part 1, 34 p., 1 pl.

———1969, Pleistocene chronology of the Puget lowland and San Juan Islands, Washington: Geological Society of America Bulletin, v. 80, p. 2273–2286.

———1973, Map showing percolation rates of earth materials in western Whatcom County, Washington: U.S. Geological Survey Miscellaneous Geologic Investigations Map I–854–A, 1 plate, scale 1:62,500.

———1976a, Geologic map of western Whatcom County, Washington: U.S. Geological Survey Miscellaneous Investigations Map I–854–B, 1 plate, scale 1:62,000.

———1976b, Map showing engineering characteristics of geologic materials, western Whatcom County, Washington: U.S. Geological Survey Miscellaneous Investigations Map I–854–D, 1 plate, scale 1:62,500.

———1979, The last glaciation of northwest Washington, *in* Armentrout, J.M, Cole, M.R., Ter Best, Harry, Jr., eds, Cenozoic paleogeography of the western U.S. Pacific Coast Paleogeography Symposium No. 3: Society of Economic Paleontologists and Mineralogists Symposium Volume, p. 177–189.

Easterbrook, D.J., Crandell, D.R., and Leopold, E.B., 1967, Pre-Olympia stratigraphy and chronology in the Central Puget Lowland, Washington: Geological Society of America Bulletin, v. 78, p. 13–20.

Elassal, A.A., and Caruso, V.M., 1983, USGS digital cartographic data standards: Digital elevation models, U.S. Geological Survey Circular 895–B, 40 p.

Frizzell, V.A., Jr., Tabor, R.W., Booth, D.B., Ort, K.M., and Waitt, R.B., Jr., 1984, Preliminary geologic map of the Snoqualmie Pass quadrangle, Washington: U.S. Geological Survey Open-File Report 84–693, 43 p., 1 plate, scale 1:100,000.

Gannett, M.G., and Caldwell, R.R., in press, Geological framework of the Willamette Lowland aquifer system, Oregon and Washington: U.S. Geological Survey Professional Paper 1424–B, ____ p.

Garling, M.E., Molenaar, Dee, and others, 1965, Water resources and geology of the Kitsap Peninsula and certain adjacent islands: Washington Division of Water Resources Water-Supply Bulletin 18, 309 p.

Glaster, R.W., and Coombs, H.A., 1989, Cascade ice border dams—Geologic setting, *in* Galster, R.W., compiler, Engineering geology in Washington, volume 1: Washington Division of Geology and Earth Resources Bulletin 78, p. 203–208.

Gordy, P.L., 1988, Evaluation of the hydrocarbon potential of the Georgia Depression: British Columbia Ministry of Energy, Mines, and Petroleum Resources, Petroleum Geology, 88–03, 31 p.

Gower, H.D., 1978, Tectonic map of the Puget Sound region, Washington, showing locations of faults, principal folds, and large-scale Quaternary deformation: U.S. Geological Survey Open-File Report 78–426, 9 p., 1 plate, scale 1:250,000.

Gower, H.D., 1980, Bedrock geologic and Quaternary tectonic map of the Port Townsend area, Washington: U.S. Geological Survey Open-File Report 80–1174, 9 p., 1 plate, scale 1:100,000.

Gower, H.D., Yount, J.C., and Crosson, R.S., 1985, Seismotectonic map of the Puget Sound region, Washington: U.S. Geological Survey Map I–1613, 15 p., 1 plate, scale 1:250,000.

Griffin, W.C., Sceva, J.E., Swenson, H.A., and Mundorff, M.J., 1962, Water resources of the Tacoma area, Washington: U.S. Geological Survey Water-Supply Paper 1499–B, p. B1–B101.

Grimstad, Peder, and Carson, R.J., 1981, Geology and ground-water resources of eastern Jefferson County, Washington: Washington Department of Ecology Water-Supply Bulletin 54, 125 p.

Hall, J.P., and Othberg, K.L., 1974, Thickness of unconsolidated sediment, Puget lowland, Washington: Washington Department of Natural Resources Geologic Map GM–12, 3 p., 1 plate, scale 1:500,000.

Halstead, E.C., 1966, Aldergrove test hole, Fraser Valley, B.C.: Geological Survey of Canada, Department of Mines and Technical Surveys, Paper 64–51, 17 p.

———1986, Ground water supply—Fraser lowland, British Columbia: Environment Canada, National Hydrology Research Institute Paper no. 26, IWD Scientific Series No. 145, 80 p.

Hansen, H.P., and Mackin, J.H., 1949, A pre-Wisconsin forest succession in the Puget lowland, Washington: American Journal of Science, v. 247, p. 833–855.

Heller, P.L., 1979, Map showing surficial geology of parts of the lower Skagit and Baker Valleys, North Cascades, Washington: U.S. Geological Survey Open-File Report 79–964, 16 p., 1 plate, scale 1:62,500.

Johnson, S.Y., Potter, C.J., Armentrout, J.M., 1994, Origin and evolution of the Seattle Fault and Seattle Basin: Washington Geology, v. 22, p. 71–74.

Jones, M.A., 1985, Occurrence of ground water and potential for seawater intrusion, Island County, Washington: U.S. Geological Survey Water-Resources Investigations Report 85–4046, 6 sheets.

Korsec, M.A., compiler, 1987a, Geologic map of the Mount Adams quadrangle, Washington: Washington Division of Geology and Earth Resources Open-File Report 87–5, 39 p., 1 plate, scale 1:100,000.

————1987b, Geologic map of the Hood River quadrangle, Washington: Washington Division of Geology and Earth Resources Open-File Report 87–6, 40 p., 1 plate, scale 1:100,000.

Liesch, B.A., Price, C.E., and Walters, K.L., 1963, Geology and ground-water resources of northwestern King County, Washington: Washington Division of Water Resources Water-Supply Bulletin 20, 241 p.

Logan, R.L., compiler, 1987a, Geologic map of the Chehalis River and Westport quadrangles, Washington: Washington Division of Geology and Earth Resources Open-File Report 87–8, 16 p., 1 plate, scale 1:100,000.

————1987b, Geologic map of the south half of the Shelton and the south half of the Copalis Beach quadrangle, Washington: Washington Division of Geology and Earth Resources Open-File Report 87–9, 15 p., 1 plate, scale 1:100,000.

Lum, W.E., II, Alvord, R.C., and Drost, B.W., 1984, Availability of water from the alluvial aquifer in part of the Green River valley, King County, Washington: U.S. Geological Survey Water-Resources Investigations Report 83–4178, 40 p.

Luzier, J.E., 1969, Geology and ground-water resources of southwestern King County, Washington: Washington Department of Water Resources Water-Supply Bulletin 28, 260 p.

McCrumb, D.R., Galster, R.W., West, D.O., Crosson, R.S., Ludwin, R.S., Hancock, W.E., Mann, L.V., 1989, Tectonics, seismicity, and engineering seismology in Washington: Washington Division of Geology and Earth Resources Bulletin 78, p. 97–120.

Molenaar, Dee, Garling, M.E., and others, 1965, Water resources and geology of the Kitsap Peninsula and certain adjacent islands: U.S. Geological Survey Water Supply Bulletin 18, 309 p.

Molenaar, Dee, and Noble, J.B., 1970, Geology and related ground-water occurrence, southwestern Mason County, Washington: Washington Department of Water Resources Water-Supply Bulletin 29, 145 p.

Mundorff, M.J., Weigle, J.M., and Holmberg, G.D., 1955, Ground water in the Yelm area, Thurston and Pierce Counties, Washington: U.S. Geological Survey Circular 356, 58 p.

Mustard, P.S., 1991, Stratigraphy and sedimentology of the Georgia Basin, British Columbia and Washington State: Washington State Department of Natural Resources, Washington Geology, vol. 19, no. 4, p. 7–9.

Newcomb, R.C., 1952, Ground-water resources of Snohomish County, Washington: U.S. Geological Survey Water-Supply Paper 1135, 133 p.

Newcomb, R.C., Sceva, J.E., and Stromme, Olaf, 1949, Ground-water resources of western Whatcom County, Washington: U.S. Geological Survey Open-File Report 50–7, 134 p.

Noble, J.B., 1960, A preliminary report on geology and ground-water resources of the Sequim–Dungeness area, Clallam County, Washington: Washington Division of Water Resources Water-Supply Bulletin 11, 43 p.

Noble, J.B., and Wallace, E.F., 1966, Geology and ground-water resources of Thurston County, Washington: Washington Division of Water Resources Water-Supply Bulletin 10, v. 2, 141 p.

Othberg, K.L., and Palmer, Pamela, 1979, Preliminary surficial geologic map of the Dungeness quadrangle, Clallam County, Washington: Washington Division of Geology and Earth Resources Open-File Report 79–17, 3 p., 1 plate, scale 1:24,000.

Othberg, K.L., and Palmer, Pamela, 1979, Preliminary surficial geologic map of part of the Gardiner quadrangle, Callam County, Washington: Washington Division of Geology and Earth Resources Open-File Report 79–19, 3 p., 1 plate, scale 1:24,000.

Othberg, K.L. and Palmer, Pamela, 1979, Preliminary surficial geologic map of the Sequim quadrangle, Clallam County, Washington: Washington Division of Geology and Earth Resources Open-File Report 79–18, 4 p., 1 plate, scale 1:24,000.

Pessl, Fred, Jr., Dethier, D.P., Booth D.B., and Minard, J.P., 1989, Surficial geologic map of the Port Townsend 30- by 60-minute quadrangle, Puget Sound region, Washington: U.S. Geologic Survey Miscellaneous Investigations Series Map I–1198–F, 13 p., 1 plate, scale 1:100,000.

Phillips, W.M., compiler, 1987a, Geologic map of the Mount St. Helens quadrangle, Washington: Washington Division of Geology and Earth Resources Open-File Report 87–4, 59 p., 1 plate, scale 1:100,000.

Phillips, W.M., compiler, 1987b, Geologic map of the Vancouver quadrangle, Washington: Washington Division of Geology and Earth Resources Open-File Report 87–10, 41 p., 1 plate, scale 1:100,000.

Piper, A.M., 1930, Water supply of the United States Penitentiary at McNeil Island, Washington: U.S. Geological Survey Open-File Report, 52 p.

Piper, A.M., and Larocque, G.A., Jr., 1938, Ground water in the Tacoma area, Washington, progress report no. 1: U.S. Geological Survey Open-File Report, 105 p.

Richardson, Donald, Bingham, J.W., and Madison, R.J., 1968, Water resources of King County, Washington: U.S. Geological Survey Water-Supply Paper 1852, 74 p.

Ritzi, R.W., Jr., 1983, The hydrogeologic setting and water resources of Vashon and Maury Islands, King County, Washington: Dayton, Ohio, Wright State University, Master of Science thesis, 115 p.

Ritzi, R.W., Schmidt, R.G., and Carr, J.R., 1983, Using computer methods in island water resource management, Vashon and Maury Island, Washington, *in* Nielsen, D.M., and Aller, Linda, eds., Proceedings of the NWWA western regional conference on ground-water management, San Diego, 1983: National Water Well Association, p. 304–312.

Robinson, J.W., 1946, Typical wells and springs of the Tacoma area, Washington: U.S. Geological Survey Open-File Report, 37 p.

Robinson, J.W., and Piper, A.M., 1942, Water levels in observation wells and stages of certain lakes of the Tacoma area, Washington: U.S. Geological Survey Open-File Report, 277 p.

Roddick, J.A., Muller, J.E., and Okulitch, A.V., 1979, Fraser River, British-Columbia–Washington: Geological Survey of Canada Map 1386A, 2 plates, sheet 92, scale 1:100,000.

Rogers, W.P., 1970, A geological and geophysical study of the central Puget Sound lowland: Seattle, Washington, University of Washington, Doctor of Philosophy dissertation, 123 p., 9 plates.

Salisbury and Dietz, Inc., 1980, Geology of the Concrete quadrangle, Washington: U.S. Department of Energy, 1 plate, scale 1:250,000.

Sapik, D.B., Bortleson, G.C., Drost, B.W., Jones, M.A., and Prych, E.A., 1989, Ground-water resources and simulation of flow in aquifers containing freshwater and seawater, Island County, Washington: U.S. Geological Survey Water-Resources Investigations Report 87–4182, 4 sheets.

Sceva, J.E., 1950, Preliminary report on the ground-water resources of southwestern Skagit County, Washington: U.S. Geological Survey Open-File Report, 40 p.

———1957, Geology and ground-water resources of Kitsap County, Washington: U.S. Geological Survey Water-Supply Paper 1413, 178 p.

Sceva, J.E., Wegner, D.E., and others, 1955, Records of wells and springs, water levels, and quality of ground water in central Pierce County, Washington: U.S. Geological Survey Open-File Report, 261 p.

Schasse, H.W., compiler, 1987a, Geologic map of the Centralia Quadrangle, Washington: Washington Division of Geology and Earth Resources Open-File Report 87–11, 28 p., 1 plate, scale 1:100,000.

———1987b, Geologic map of the Mount Rainier quadrangle, Washington: Washington Division of Geology and Earth Resources Open-File Report 87–16, 46 p., 1 plate, scale 1:100,000.

Snavely, P.D., Jr., 1988, Tertiary geologic framework, neotectonics, and petroleum potential of the Oregon–Washington continental margin, *in* Scholl, D.S., Grantz, A., and Vedder, J.G., eds., Geology and resource potential of the continental margin of western North America and adjacent ocean basins—Beaufort Sea to Baja, California: Circum-Pacific Council for Energy and Mineral Resources Earth Science Series 6, p. 305–335.

Stuart, D.J., 1965, Gravity data and bouguer-gravity map for western Washington: U.S. Geological Survey Open-File Report, 52 p., 1 plate, scale 1:500,000.

Sun, R.J., ed., 1986, Regional Aquifer-System Analysis program of the U.S. Geological Survey—summary of projects, 1978–84: U.S. Geological Survey Circular 1002, 254 p.

Tabor, R.W., Booth, D.B., Vance, J.A., Ford, A.B., and Ort, M.H., 1989, Geological map of the Sauk River 30' by 60' quadrangle, Washington: U.S. Geological Survey Open-File Report 88–692, 50 p., 2 sheets, scale 1:100,000.

Tabor, R.W., and Cady, W.M., 1978, Geologic map of the Olympic Peninsula, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I–994, 2 sheets, scale 1:125,000.

Tabor, R.W., Frizzell, V.A., Jr., Booth, D.B., Whetten J.T., Waitt, R.B., Jr., and Zartman, R.E., 1982, Geologic map of the Skykomish River quadrangle, Washington: U.S. Geological Survey Open-File Report 82–747, 31 p., 1 sheet, scale 1:100,000.

Tabor, R.W., Yeats, R.S., and Sorensen, M.L., 1972, Geologic map of the Mount Angeles quadrangle, Callam and Jefferson Counties, Washington: U.S. Geological Survey Quadrangle Map GQ–958, 1 sheet, scale 1:62,500.

Thorson, R.M., 1980, Ice-sheet glaciation of the Puget lowland, Washington, during the Vashon Stade (late Pleistocene): Quaternary Research, v. 13, no. 3, p. 303–321.

———1989, Glacio-isostatic response of the Puget Sound area, Washington: Geological Society of America Bulletin, v. 101, p. 1163–1174.

U.S. Geological Survey, 1977, Aeromagnetic map of northern and eastern parts of the Puget Sound area, Washington: U.S. Geological Survey Open-File Report 77–34, 1 plate, scale 1:100,000.

Vaccaro, J.J., Woodward, D.G., Gannett, M.W., Jones, M.A., Collins C.A., Caldwell R.R., and Hansen A.J., 1997, Summary of the Puget–Willamette Lowland Regional Aquifer-System Analysis, Washington, Oregon, and British Columbia: U.S. Geological Survey Open-File Report 96–A353, 49 p.

Vaccaro, J.J., Hansen, A.J., and Jones, M.A., 1998, Hydrogeologic framework of the Puget Sound aquifer system, Washington and British Columbia: U.S. Geological Survey Professional Paper 1424–D, scale 1:500,000, 77 p., 4 pl.

Vonheeder, E.R., 1975, Coal reserves of Whatcom County, Washington: State of Washington, Department of Natural Resources, Division of Geology and Earth Resources, 86 p., 2 sheets, scale 1:62,500.

Wallace, E.F., and Molenaar, Dee, 1961, Geology and ground-water resources of Thurston County, Washington: Washington Division of Water Resources Water-Supply Bulletin 10, v. 1, 254 p.

Walsh, T.J., compiler, 1987, Geologic map of the south half of the Tacoma quadrangle, Washington: Washington Division of Geology and Earth Resources Open-File Report 87–3, 10 p., 1 plate, scale 1:100,000.

Walsh, T.J., Korsec, M.A., Phillips, W.M., Logan, R.L., and Schasse, H.W., 1987, Geologic map of Washington–southwest quadrant: Washington State Department of Natural Resources Geologic Map GM–34, 28 p., 1 plate, scale 1:100,000.

Walters, K.L., 1971, Reconnaissance of sea-water intrusion along coastal Washington, 1966–68: Washington Department of Ecology Water-Supply Bulletin 32, 208 p.

Walters, K.L., and Kimmel, G.E., 1968, Ground-water occurrence and stratigraphy of unconsolidated deposits, central Pierce County, Washington: Washington Department of Water Resources Water-Supply Bulletin 22, 428 p.

Washburn, R.L., 1954, Preliminary investigation of ground water in East Sound area, Orcas Island, San Juan County, Washington: U.S. Geological Survey Open-File Report, 26 p.

———1957, Ground water in the Lummi Indian Reservation, Whatcom County, Washington: U.S. Geological Survey Open-File Report, 31 p.

Washington Department of Ecology, 1975, Geology and water resources of the San Juan Islands, San Juan County, Washington: Washington Department of Ecology Water-Supply Bulletin 46, 171 p.

———1977, Coastal zone atlas of Washington, v. 1, Whatcom County: Washington Department of Ecology DOE 77–21–1, 8 p.

———1978a, Coastal zone atlas of Washington, v. 3, San Juan County: Washington Department of Ecology DOE 77–21–3, 10 p.

———1978b, Coastal zone atlas of Washington, v. 11, Jefferson County: Washington Department of Ecology DOE 77–21–11, 10 p.

———1978c, Coastal zone atlas of Washington, v. 12, Clallam County: Washington Department of Ecology DOE 77–21–12, 10 p.

———1979a, Coastal zone atlas of Washington, v. 4, Island County: Washington Department of Ecology DOE 77–21–4, 9 p.

———1979b, Coastal zone atlas of Washington, v. 5, Snohomish County: Washington Department of Ecology DOE 77–21–5, 9 p.

———1979c, Coastal zone atlas of Washington, v. 6, King County: Washington Department of Ecology DOE 77–21–6, 9 p.

———1979d, Coastal zone atlas of Washington, v. 7, Pierce County: Washington Department of Ecology DOE 77–21–7, 8 p.

———1979e, Coastal zone atlas of Washington, v. 10, Kitsap County: Washington Department of Ecology DOE 77–21–10, 10 p.

———1980a, Coastal zone atlas of Washington, v. 8, Thurston County: Washington Department of Ecology DOE 77–21–8, 8 p.

———1980b, Coastal zone atlas of Washington, v. 9, Mason County: Washington Department of Ecology, DOE 77–21–9, 8 p.

———1987, Coastal zone atlas of Washington, v. 2, Skagit County: Washington Department of Ecology DOE 77–21–2, 10 p.

Washington Division of Water Resources, 1960, Water resources of the Nooksack River basin and certain adjacent streams: Washington Division of Water Resources Water-Supply Bulletin 12, 187 p.

Weigle, J.M., and Foxworthy, B.L., 1962, Geology and ground-water resources of west-central Lewis County, Washington: Washington Division of Water Resources Water-Supply Bulletin 17, 248 p.

Weigle, J.M., and Washburn, R.L., 1956, Records of wells and springs, water levels, and quality of ground water in Lewis County, Washington: U.S. Geological Survey Open-File Report, 352 p.

Whiteman, K.J., Molenaar, Dee, Bortleson, G.C., and Jacoby, J.M., 1983, Occurrence, quality, and use of ground water in Orcas, San Juan, Lopez, and Shaw Islands, San Juan County, Washington: U.S. Geological Survey Water-Resources Investigations Report 83–4019, 12 sheets, scale 1:62,500.

Willis, Bailey, 1898, Drift phenomena of Puget Sound: Bulletin of the Geological Society of America, v. 9, p. 111–162, plates 6–10.

Wilson, J., Bartholomew, M.J., and Carson, R.J., 1979, Late Quaternary faults and their relationship to tectonism in the Olympic Peninsula, Washington: Geology, v. 7, p. 235–239.

Woodward, D.G., and Gannett, M.G., written communication, Hydrogeologic framework of the Willamette Lowland aquifer system, Oregon and Washington: U.S. Geological Survey Professional Paper 1424–E, ____p.

Yount, J.C., in press, Unpublished preliminary draft copy of the depth to bedrock in the Port Townsend 30' by 60' quadrangle, Washington: U.S. Geological Survey, 1 plate, scale 1:100,000.

Yount, J.C., Dembroff, G.R., and Barats, G.M., 1985, Map showing depth to bedrock in Seattle 30' by 60' quadrangle, Washington: U.S. Geological Survey, Miscellaneous Field Investigations Map MF–1692, 12 p., 1 plate, scale 1:100,000.

Yount, J.C., Minard, J.R., Dembroff, G.R., 1993, Geologic map of surficial deposits in the Seattle 30' by 60' quadrangle, Washington: U.S. Geological Survey Open-File Report 93–233, 2 sheets, scale 1:100,000.

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Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars are reports of programmatic or scientific information of an ephemeral nature; many present important scientific information of wide popular interest. Circulars are distributed at no cost to the public.

Fact Sheets communicate a wide variety of timely information on USGS programs, projects, and research. They commonly address issues of public interest. Fact Sheets generally are two or four pages long and are distributed at no cost to the public.

Reports in the **Digital Data Series (DDS)** distribute large amounts of data through digital media, including compact disc-read-only memory (CD-ROM). They are high-quality, interpretive publications designed as self-contained packages for viewing and interpreting data and typically contain data sets, software to view the data, and explanatory text.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are produced on request (unlike formal USGS publications) and are also available for public inspection at depositories indicated in USGS catalogs.

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Geologic Quadrangle Maps (GQ's) are multicolor geologic maps on topographic bases in 7.5- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

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Metal Industry Indicators (MII's) is a free monthly newsletter that analyzes and forecasts the economic health of five metal industries with composite leading and coincident indexes: primary metals, steel, copper, primary and secondary aluminum, and aluminum mill products.

Mineral Industry Surveys (MIS's) are free periodic statistical and economic reports designed to provide timely statistical data on production, distribution, stocks, and consumption of significant mineral commodities. The surveys are issued monthly, quarterly, annually, or at other regular intervals, depending on the need for current data. The MIS's are published by commodity as well as by State. A series of international MIS's is also available.

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