TECTONICS OF THE WILLAMETTE VALLEY, OREGON

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ABSTRACT

The Willamette Valley is a lowland separating the Oregon Coast Range from the Cascade Range. Three separate basins within this lowland were studied: the southern Willamette Valley south of and including the Salem and Waldo Hills, the northern Willamette Valley between the Salem and Waldo Hills and the Chehalem Mountains, and the Tualatin basin northeast of the Chehalem Mountains and southwest of the Tualatin Mountains.

The rocks of the Willamette Valley are similar to those of the Coast Range, beginning with oceanic basalt of the Siletz River Volcanics of early and middle Eocene age and deep-water turbidite strata of the Tyee Formation of middle Eocene age. Overlying strata of late Eocene and early Oligocene age grade westward from volcanogenic rocks to deep-water sedimentary rocks, showing that arc volcanism east of the Willamette Valley may have begun as early as 47 Ma but not as early as 50 Ma, the age of the Tyee Formation. Nonmarine and marine strata as young as early Miocene were tilted westward prior to 16–14.5 Ma, when flows of the Columbia River Basalt Group moved through a lowland in the Cascade Range, across the northern Willamette Valley, and thence to the coast as intracanyon flows. The Columbia River Basalt Group is overlain, locally with angular unconformity, by fluvial deposits of the proto-Willamette River and its tributaries, the first strata to be limited to the modern Willamette Valley. These deposits are poorly dated but may range in age from late Miocene to Pleistocene. In the northern Willamette Valley, these strata are overlain by vents and intruded by small stocks of the Boring Lavas. After a period of erosion, the fluvial deposits were succeeded by glacial-outwash deposits of the Rowland Formation and by catastrophic flood deposits of the Willamette Formation, both of late Pleistocene age.

Faults and folds began to develop in Eocene time, accompanying clockwise rotation of crustal blocks. Most prominent of these early structures is the Corvallis fault, a low-angle thrust fault with horizontal separation estimated to be 11–13 km. Faults and folds affecting the Columbia River Basalt Group and younger fluvial deposits include a high-angle reactivation of the Corvallis fault, the Owl Creek fault, the Harrisburg anticline, the Mill Creek fault, the Waldo Hills range-front fault, the Gales Creek-Mount Angel structural zone, the Yamhill-Sherwood structural zone, the Northern Willamette downwarp, the Beaverton and Helvetia faults in the Tualatin valley, and faults at the northern margin of the Willamette Valley probably related to emplacement of Boring Lavas.

Faults postdating the Columbia River Basalt Group trend predominantly northwest and northeast, and folds trend predominantly east-west, compatible with the modern stress field in which maximum horizontal compressive stress is oriented north-south. Limited evidence suggests relatively low slip rates, probably less than 0.5 mm/year. Individual faults are relatively short, but brittle crust may extend to depths as great as 30 km, indicating a capability of generating moderate-size earthquakes with long recurrence intervals.

INTRODUCTION

The Willamette Valley is part of a broad lowland separating the Oregon Coast Range from the Cascade Range (fig. 76). The lowland is 120 km long and extends north from Eugene, Oreg., to about 30 km north of Vancouver, Wash. The lowland is more than 60 km wide at the latitude of Portland, where it includes the Portland and Tualatin basins, and only 30 km wide in the southern Willamette Valley south of Albany (fig. 77). The lowland contains four metropolitan areas, Portland-Vancouver, Salem, Corvallis-Albany, and Eugene-Springfield, and many smaller towns. The lowland is divided into separate basins by narrow ridges underlain by the Miocene Columbia River Basalt Group (fig. 77). The Tualatin Mountains (Portland Hills) separate the Portland

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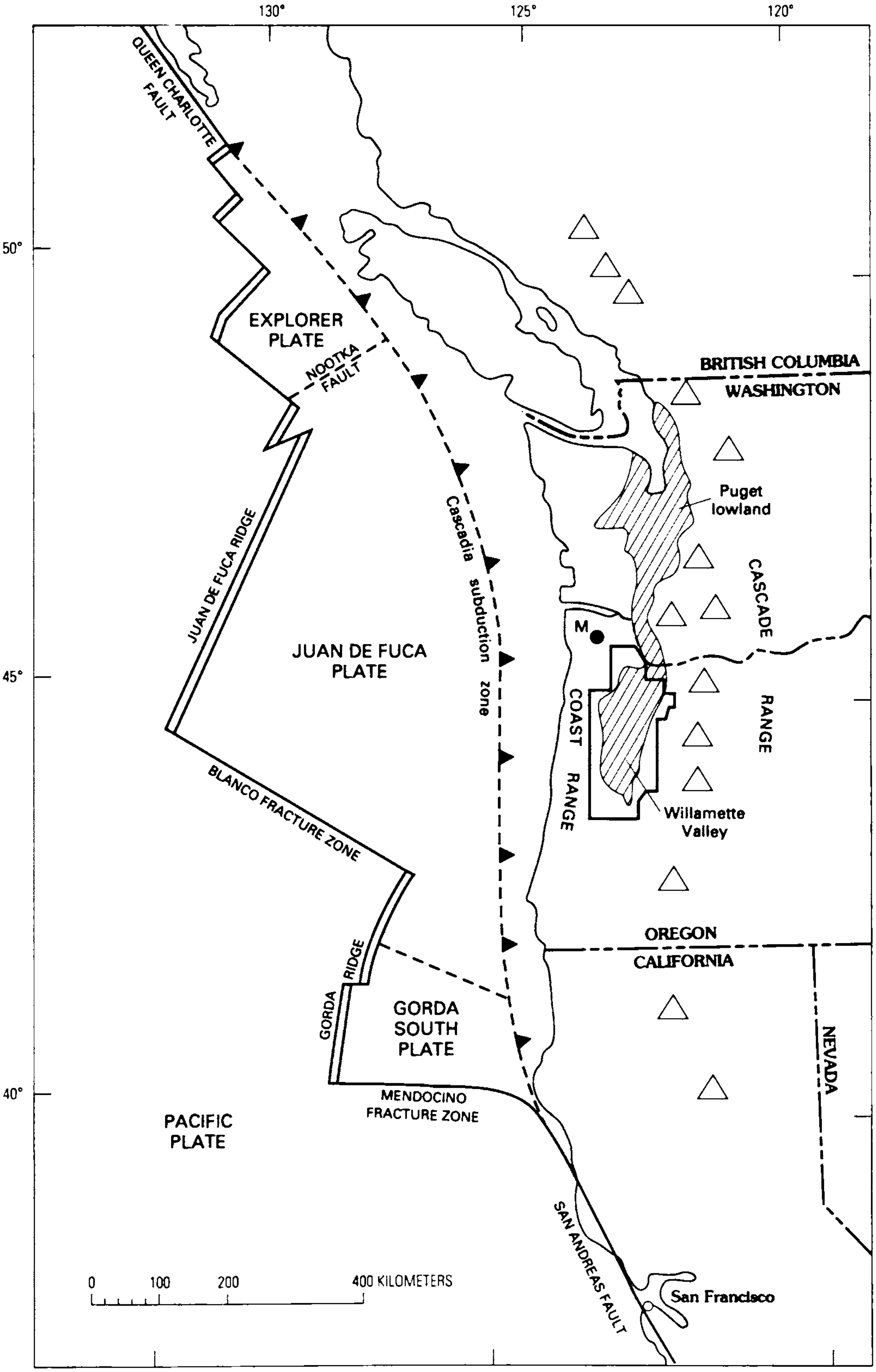
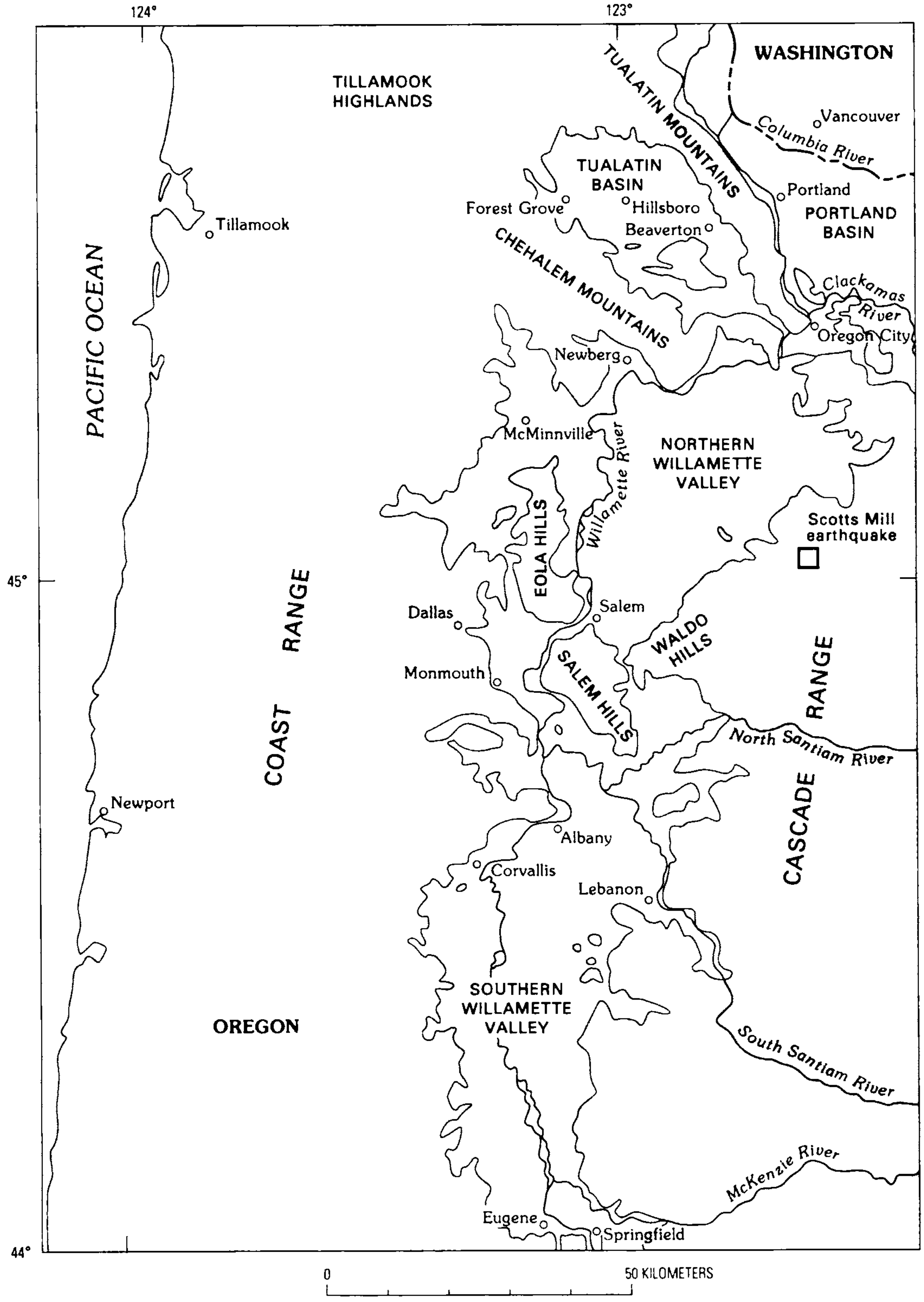


Figure 76. Plate boundaries of the Pacific Northwest showing locations of tectonic features and the Willamette Valley study area. Heavy line, study-area boundary; hatched area, Willamette Valley and Puget lowland; sawteeth denote upper plate of thrust fault. Major stratovolcanoes are shown by open triangles. Dot labeled "M" in northwestern Oregon is the Mist gas field.



EXPLANATION

☐ Lowlands of Willamette Valley

☐ Uplands

Figure 77. Geographic and physiographic features of the Willamette Valley and Portland and Tualatin basins, northwestern Oregon. The square indicates the epicenter of the March 25, 1993, Scotts Mills earthquake.

and Tualatin basins, the Chehalem Mountains separate the Tualatin basin and the northern Willamette Valley, and the Salem and Waldo Hills separate the northern Willamette Valley and southern Willamette Valley.

With respect to the Cascadia subduction zone and Cascade volcanic arc, the Willamette Valley has the same structural position as the Puget lowland (fig. 76), but the two lowlands are not connected (fig. 77). North of Vancouver and south of Eugene, east-dipping rocks of the Coast Range abut directly against and are overlain by rocks of the Cascade Range. The pre-middle Miocene stratigraphic sequence underlying the Willamette Valley is similar to that of the Coast Range, the upper part of the section containing a higher percentage of volcanic and volcaniclastic rocks than the lower part, reflecting the proximity of the valley to Cascade arc volcanoes.

The structure of northwestern Oregon is dominated by a broad, north-plunging anticlinorium centered over the Coast Range. The western flank of this anticlinorium, including the Oregon coast, contains strata of the same age as those of the eastern flank dipping into the Willamette Valley. The strata dip east across the Willamette Valley and into the western Cascade Range, so that most of the strata that predate the Columbia River Basalt Group of the Willamette Valley are older than rocks of the western Cascade Range. The north plunge of the anticlinorium permits correlation of strata as young as Miocene across the Coast Range near the Columbia River (Niem and Niem, 1985). Smaller scale structures include faults and open folds in both the Coast Range and Willamette Valley. Some of these structures involve the Miocene Columbia River Basalt Group and younger strata, but other structures formed mainly in Eocene time.

The oldest exposed rocks in the region are the Siletz River Volcanics, which are basalt flows and breccias of early and middle Eocene age. The lavas are similar in composition to ocean-ridge or oceanic-plateau basalt and are interpreted to be a result of rifting and extension of an elongate basin prior to the deposition of the Tyee Formation of middle Eocene age (Wells and others, 1984). The Tyee Formation, derived from pre-Tertiary plutonic rocks and a volcanic-arc terrane to the south, prograded northward along a basin axis centered on the Coast Range. The Tyee consists of distal turbidites in the latitude of the southern Willamette Valley (Chan and Dott, 1983).

The lower part of the upper Eocene Yamhill Formation, largely fine grained, overlaps the Tyee Formation to rest directly on the Siletz River Volcanics. It is the oldest formation in the Willamette Valley that grades eastward into volcanic rocks possibly related to the early western Cascade Range (Baker, 1988). In the northern Coast Range, the Yamhill is overlain by and possibly interbedded with the Tillamook Volcanics (Wells and others, 1983). In the Willamette Valley, the Yamhill is overlain by the sand-rich upper Eocene Spencer Formation, which grades northward into the Cowlitz Formation and southeastward into the volcanic-rich Fisher Formation. The overlying marine Eocene and Oligocene Eugene Formation and the marine and nonmarine Oligocene and early Miocene Scotts Mills Formation grade southeastward into volcanic rocks of the western Cascade Range and rest unconformably on western Cascade volcanic rocks. The equivalents of the Eugene and Scotts Mills formations on the coast are the Alsea and Yaquina Formations.

About 16–14.5 Ma, basalt flows of the Columbia River Basalt Group moved through a lowland in the Cascade Range between the Columbia River and the Clackamas River into the northern Willamette Valley (Beeson, Tolan, and Anderson, 1989). The N_2 flows of the Grande Ronde Basalt and Ginkgo flows of the Frenchman Springs Member of the Wanapum Basalt have identical counterparts on the Oregon coast, indicating that these flows also crossed the Coast Range, probably as intracanyon flows (Beeson, Tolan, and Anderson, 1989).

Alluvial deposits that postdate the Columbia River Basalt Group are the oldest strata to be confined principally to the present lowland areas. These deposits include the lacustrine (informal) Monroe clay of late Miocene to early Pliocene age (Roberts, 1984; Roberts and Whitehead, 1984) in the southern Willamette Valley and the Helvetia Formation (Schlicker and Deacon, 1967), Sandy River Mudstone (Trimble, 1963), and Troutdale Formation (Lowry and Baldwin, 1952) in the northern Willamette Valley; the Troutdale Formation was derived in large part from the ancestral Columbia River. In late Pliocene to Pleistocene time, the Boring Lavas were erupted from vents in the Portland basin, Tualatin basin, and northernmost Willamette Valley (fig. 77) (Allen, 1975). Some volcanic centers in the western Cascade Range are also of this age.

The Quaternary history of the area is characterized by alluvial deposits and land surfaces influenced by glaciation in the Cascade Range and changes in sea level or in the longitudinal profile of the Columbia River (McDowell, 1991). Near the end of Pleistocene time, catastrophic glacial-outburst floods from the Columbia River repeatedly inundated the Willamette Valley as far south as Eugene and deposited the Willamette Formation (Balster and Parsons, 1969; Allison, 1978).

We have compiled and field checked existing bedrock mapping (pl. 2) in and around the Willamette Valley lowland except for the Portland basin, which is being described separately by the Oregon Department of Geology and Mineral Industries. We mapped the subsurface geology of the lowland itself using data from oil-exploration wells (plotted on pl. 2A and 2B) and multichannel seismic profiles that were part of an exploration campaign in the 1970's and 1980's together with a network of gravity stations, the data from which were already in the public domain. The subsurface interpretation of sediments younger than the Columbia River Basalt Group is based largely on data from water wells and boreholes drilled for engineering purposes by the Oregon Department of Transportation.

Responsibilities for individual parts of the geologic map (pl. 2) are: southern Willamette Valley, E.P. Graven; Corvallis fault, Chris Goldfinger; northern Willamette Valley, K.S. Werner; and Tualatin valley, T.A. Popowski. A more detailed description of the geology is in Goldfinger (1990), Graven (1990), Werner (1990), and Popowski (1995).

ACKNOWLEDGMENTS

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We benefited much from discussions of Coast Range stratigraphy with Jack Meyer, Alan Niem, Wendy Niem, Ulrich Franz, and Ray Wells; of Columbia River Basalt Group distribution with Marvin Beeson; of western Cascade Range geology with George Priest, David Sherrod, and Edward Taylor; of Portland basin and eastern Tualatin basin geology with Ian Madin; of Willamette Valley alluvial stratigraphy with Marshall Gannett, Bernard Kleutsch, and Patricia McDowell; and of Willamette Valley gravity data with Richard Couch, Robert O'Malley, and Gerald Connard. Marvin Beeson, Ian Madin, and George Priest reviewed the manuscript.

STRATIGRAPHY

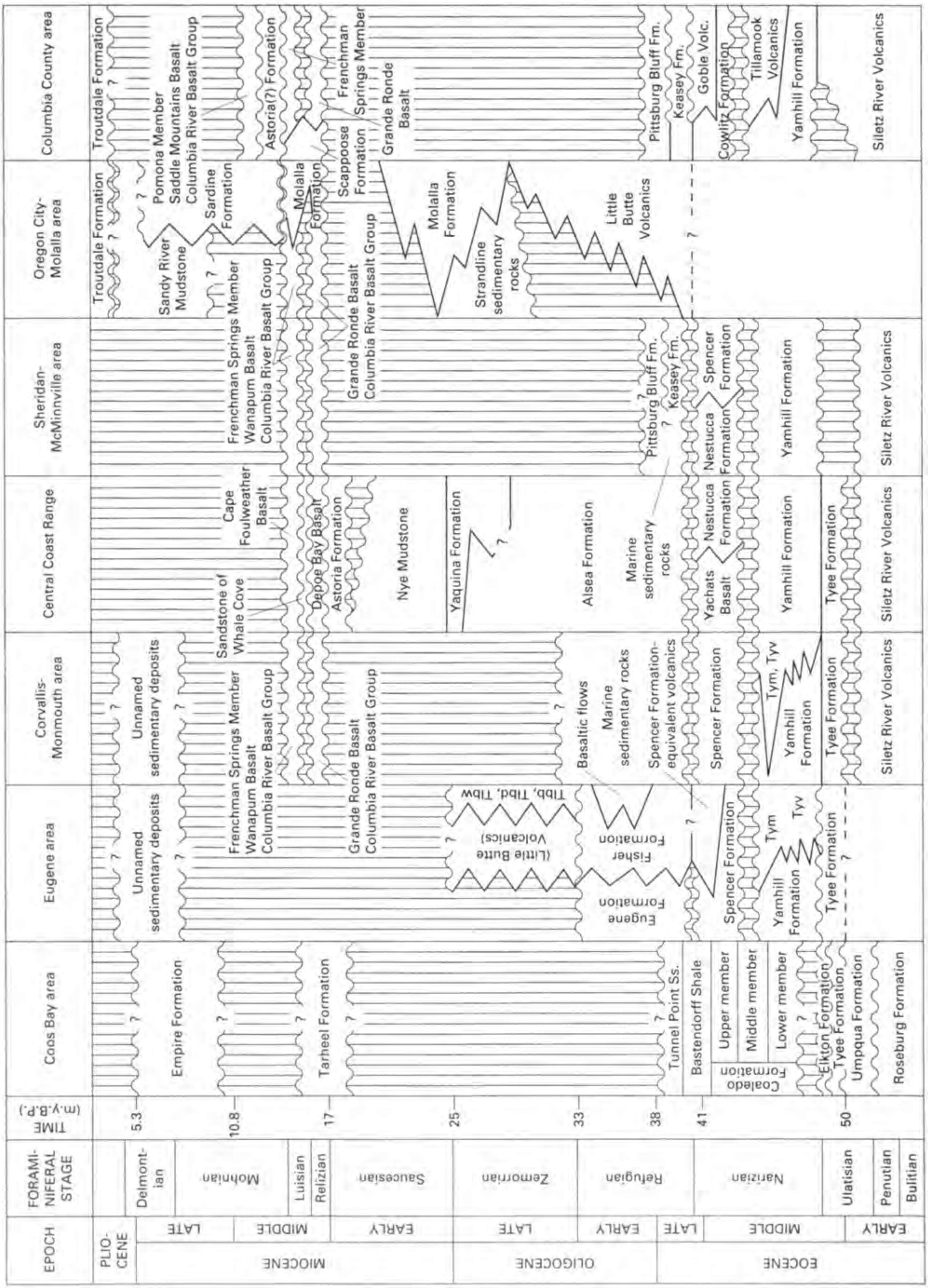
Correlation of stratigraphic units (fig. 78) is based on radiometric ages, benthic foraminifers, and calcareous nannoplankton. Nannoplankton are correlated to zones that are widely distributed in the northern Pacific Ocean and are believed to be close to contemporaneous throughout this region. A preliminary zonation for Paleogene strata based on coccoliths (Bukry and Snavely, 1988) shows some discordance with zonation based on benthic foraminifers. Benthic foraminiferal zones shown here are those of Kleinpell (1938) and Mallory (1959) and are based on stratigraphic sections in California. These zones are strongly influenced by bathymetry and sedimentary environments. Comparisons with open-ocean planktic zones show that the benthic zones are time transgressive within California basins (Crouch and Bukry, 1979; Poore, 1976, 1980); extension of these zones to Oregon adds additional uncertainty in time correlation. Nonetheless, most of the fossils found in northwest Oregon are benthic foraminifers, hence the Kleinpell and Mallory benthic zones are the only ones available for biostratigraphic correlations of most surface and subsurface sections.

SILETZ RIVER VOLCANICS

Oceanic basalts and interbedded basaltic sedimentary rocks assigned to the Siletz River Volcanics and dated as 58.1±1.5 to 50.7±3.1 Ma (Duncan, 1982) form the basement that underlies the Tertiary rocks of the Coast Range and Willamette Valley. The formation was originally named the Siletz River Volcanic Series by Snavely and Baldwin (1948) for exposures on the Siletz River and its tributaries in the central Oregon Coast Range. Snavely and others (1968) renamed the formation the Siletz River Volcanics and divided it into a lower unit consisting of submarine tholeiitic, fine-grained, amygdaloidal pillow basalt and breccia and an upper unit of submarine and subaerial alkali basalt, with the upper unit of much smaller volume than the lower unit. Sedimentary interbeds yielded marine microfossils that Snavely and others (1968) and McWilliams (1980) referred to the Penutian and Ulatisian benthic stages of Mallory (1959), in general agreement with the radiometric ages. Coccoliths from this formation in the Coast Range west of the Willamette River are referred to Subzone CP 10, estimated as about 55.3–53.7 Ma (Bukry and Snavely, 1988).

The Siletz River Volcanics exposed northwest of Corvallis belong mainly to the lower unit of the formation as described by Snavely and others (1968). The volcanic rocks are overlain by, and partly interbedded with, as much as 1,000 m of thin-bedded brown to gray tuffaceous marine siltstone and shale called the Kings Valley Siltstone Member (of the Siletz River Volcanics) by Vokes and others (1954). The Kings Valley Siltstone Member contains thin lenses of basaltic sandstone, a few thin layers of white tuff, and rare foraminifers and carbonaceous debris. The sandstone lenses contain clasts of basalt together with a terrigenous component derived from the east. Coccoliths from the Kings Valley Siltstone Member, as well as similar strata farther west, are referred to Subzone CP 11, estimated as about 53.7–52.5 Ma (Bukry and Snavely, 1988).

Northwest of McMinnville, the Siletz River Volcanics consist of vesicular basalt flows, pillow basalt, flow breccia, and tuff breccia with interbeds of red to green calcareous sandy tuff (Baldwin and others, 1955). The top of the unit contains medium- to dark-gray, calcareous, tuffaceous shale, siltstone, and sandstone (Brownfield and Schlicker, 1981a; Brownfield, 1982b).


EPOCH
FORAMINIFERAL STAGE
TIME (m.y.B.P.)
Coos Bay area
Eugene area
Corvallis-Monmouth area
Central Coast Range
Sheridan-McMinnville area
Oregon City-Molalla area
Columbia County area
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
LATE
MIDDLE
EARLY
LATE
EARLY
LATE
MIDDLE
EARLY
Delmontian
Mohnian
Luisian
Relizian
Saucesian
Zemorrian
Refugian
Narizian
Ulatisian
Penutian
Bulitian
5.3
10.8
17
25
33
38
41
50
Empire Formation
Tarheel Formation
Tunnel Point Ss.
Bastendorff Shale
Coaledo Formation
Upper member
Middle member
Lower member
Elkton Formation
Tyee Formation
Umpqua Formation
Roseburg Formation
?
Unnamed sedimentary deposits
Frenchman Springs Member
Wanapum Basalt
Columbia River Basalt Group
Grande Ronde Basalt
Columbia River Basalt Group
(Little Butte Volcanics)
Tibb, Tibd, Tibw
Eugene Formation
Fisher Formation
Spencer Formation
Yamhill Formation
Tym
Tyv
Tyee Formation
Unnamed sedimentary deposits
Frenchman Springs Member
Wanapum Basalt
Columbia River Basalt Group
Grande Ronde Basalt
Columbia River Basalt Group
Basaltic flows
Marine sedimentary rocks
Spencer Formation-equivalent volcanics
Spencer Formation
Tym, Tyv
Yamhill Formation
Tyee Formation
Siletz River Volcanics
Sandstone of Whale Cove
Cape Foulweather Basalt
Depoe Bay Basalt
Astoria Formation
Nye Mudstone
Yaquina Formation
Alsea Formation
Marine sedimentary rocks
Yachats Basalt
Nestucca Formation
Yamhill Formation
Tyee Formation
Siletz River Volcanics
Frenchman Springs Member
Wanapum Basalt
Columbia River Basalt Group
Grande Ronde Basalt
Columbia River Basalt Group
Pittsburg Bluff Fm.
Keasey Fm.
Nestucca Formation
Spencer Formation
Yamhill Formation
Siletz River Volcanics
Troutdale Formation
Sandy River Mudstone
Sardine Formation
Frenchman Springs Member
Wanapum Basalt
Columbia River Basalt Group
Molalla Formation
Grande Ronde Basalt
Columbia River Basalt Group
Molalla Formation
Strandline sedimentary rocks
Little Butte Volcanics
Troutdale Formation
Pomona Member
Saddle Mountains Basalt
Columbia River Basalt Group
Astoria(?) Formation
Scappoose Formation
Frenchman Springs Member
Grande Ronde Basalt
Pittsburg Bluff Fm.
Keasey Fm.
Goble Volc.
Cowlitz Formation
Tillamook Volcanics
Yamhill Formation
Siletz River Volcanics

The Siletz River Volcanics were found in the Gulf Porter 1 and Humble Miller 1 exploratory wells (pl. 2B) in the southern Willamette Valley, where they contain interbeds of marine strata 3–30 m thick. In the northern Willamette Valley, the Reichold Finn 1 well (pl. 2A) contains 1,110 m of the Siletz River Volcanics, predominantly gray tuff, tuffaceous shale, siltstone, and sandstone with Ulatisian (including late Ulatisian) microfossils indicating lower middle bathyal to tropical inner neritic bathymetry (McKeel, 1984). The Siletz River Volcanics in the Reserve Bruer 1 well (pl. 2A) consist of volcanic breccia and red and green tuff. Synthetic seismograms of the Reserve Bruer 1 and Reichold Finn 1 wells show an abrupt increase in sonic velocity at the top of the Siletz River Volcanics and a gradual increase below, except for a sharp increase at the top of the volcanic breccia (Werner, 1990). The seismic expression of the top of the Siletz River Volcanics is irregular or discontinuous, possibly due to preservation of original flow tops or to erosion, as suggested for field exposures by Brownfield (1982b).

The base of the Siletz River Volcanics is neither exposed nor found in wells, so the thickness of the unit is unknown, although Snavely and others (1968) proposed that its thickness exceeds 6 km. An east-west seismic profile in the southern Willamette Valley near Bellfountain shows a zone of horizontal to gently west-dipping reflectors beneath the Siletz River Volcanics, suggesting a maximum thickness of 8 km, thinning eastward beneath the Willamette Valley (Keach and others, 1989). The Siletz River Volcanics have resistivities of around 100 ohm-meters; this resistive unit is underlain by a near-horizontal unit of low resistivity (Wannamaker and others, 1989). If this low-resistivity unit is not part of the Siletz River Volcanics, the thickness of the Siletz River could be as little as 2 km.

The Siletz River Volcanics are correlative with basalts of the Roseburg Formation (Baldwin, 1974) in southern Oregon, the Crescent Formation of Washington, and the Metchosin Volcanics of southern Vancouver Island (Snavely and others, 1968; Tabor and Cady, 1978); volcanic rocks at the northern and southern ends of the outcrop areas of these units are older than those closer to the Columbia River (Duncan, 1982). Taken together, these volcanic formations are considered to be part of a seamount chain (Siletzia) accreted to North America prior to deposition of the Tyee Formation of middle Eocene age (Duncan, 1982) or, alternatively, they are basalts erupted during oblique rifting of allochthonous terranes now found in southern Alaska (Wells and others, 1984). The location of the eastern boundary of this seamount terrane is unknown; it may lie beneath the western Cascade Range. A linear zone of high-frequency magnetic anomalies beneath the western Cascade Range foothills (Committee for the Magnetic Anomaly Map of North America, 1987) is similar to the magnetic signature of ophiolite and thus may be caused by mafic and ultramafic rocks marking the suture zone between Siletzia and North America (Johnson and others, 1990).

Figure 78 (facing page). Stratigraphic correlation chart for Tertiary rocks of western Oregon. Foraminiferal stages from Kleinpell (1938) and Mallory (1959). Tym, Miller sand of the Yamhill Formation; Tyv, volcanic rocks of the Yamhill Formation; MOd, dacite and rhyodacite of the Little Butte Volcanics; MOb, basalt and basaltic andesite of the Little Butte Volcanics; MOt, welded to nonwelded ash-flow tuff of the Little Butte Volcanics; m.y.B.P., million years before present. Modified from Armentrout and others (1983).

TYEE FORMATION

Sandstone that forms the Tyee Formation, first described by Diller (1896) in the southern Oregon Coast Range, extends for more than 260 km along the Coast Range from the Rogue River north to the latitude of Salem (Molenaar, 1985). The Tyee Formation consists of a deltaic facies to the south and a deep-sea fan facies to the north (Lovell, 1969; Chan and Dott, 1983; Heller and Dickinson, 1985). Its thickness is 1,200 m near Eugene and decreases northward to 500 m west of Dallas, where mudstone and thin-graded sandstone and siltstone of the Tyee Formation abut a highland underlain by the Siletz River Volcanics. Farther north, the Tyee is overlapped by the Yamhill Formation. The thickness of the Tyee Formation also decreases eastward in the southern Willamette Valley to 315 m in the Gulf Porter 1 well and 51 m in the Humble Miller 1 well (pl. 2B). In the Gulf Porter 1 well, strata assigned to the Yamhill Formation may be fine-grained equivalents of the Tyee Formation in the Coast Range. The Mobil Ira Baker 1 well was terminated after penetrating 92 m of fossiliferous siltstone and arkosic sandstone correlated with the Tyee Formation. The age of the Tyee is Ulatisian or middle Eocene (Molenaar, 1985), and microfossils in its most distal northern exposures indicate deposition in at least middle bathyal water depths (McKeel, 1985; Heller and Dickinson, 1985). Coccoliths from the Tyee Formation in the Coast Range west of the Willamette Valley are referred to Subzones CP 12a and 12b, resulting in an age estimate of 52.5–50 Ma for the Tyee (Bukry and Snavely, 1988).

The Tyee Formation is derived from the south, and it shows no evidence of Cascade volcanism to the east. The source was largely plutonic but included a volcanic arc, also south of the Coast Range (Chan and Dott, 1983). Snavely and others (1964) suggested that the source of Tyee sandstones was the Klamath Mountains of southern Oregon and northern California. Heller and others (1985) subsequently found evidence of a Precambrian crustal component in Tyee sedimentary materials, and they concluded that the major source of the Tyee was the Idaho batholith, now far away to the east but presumably closer to the Oregon Coast Range prior to clockwise rotation of the Coast Range (Wells and Heller, 1988).

YAMHILL FORMATION

The Yamhill Formation was named by Baldwin and others (1955) for exposures in Mill Creek, a tributary of the South Yamhill River southwest of Sheridan. In the type locality, the formation consists of 150 m of tuffaceous siltstone and shale overlain by 150 m of basaltic sandstone and siltstone and 1,050 m of micaceous mudstone and siltstone. In the subsurface of the northern Willamette Valley, the Yamhill Formation consists largely of shale and siltstone with minor tuffaceous strata and fine-grained graded sandstone showing partial Bouma sequences (Richard E. Thoms, Portland State University, oral commun., 1991). The Yamhill thickens eastward across coeval normal faults to at least 932 m thick in the Reichold Bagdanoff 23–28 well (pl. 2A), where it includes basalt and tuff.

The Yamhill Formation includes the informally named Miller sand of Bruer and others (1984), known only from the subsurface in the Willamette Valley south of Salem. This is a sandy to conglomeratic volcaniclastic unit overlain by and interfingering northwestward with faintly bedded micaceous siltstone and mudstone (Baker, 1988). The Miller sand pinches out to the northwest, suggesting coeval displacement on the nearby Corvallis fault. The Miller sand increases in thickness southeastward as an underlying mudstone unit decreases in thickness, although the overall thickness of the Yamhill Formation increases as well. Farther southeast, both the Miller sand and the underlying mudstone grade into a volcanic facies. The Gulf Porter 1 well (pl. 2B) penetrated 1,055 m of volcaniclastic sandstone and siltstone and basaltic conglomerate, and the Mobil Ira Baker 1 well (pl. 2B) contains 1,961 m of basalt, andesite, dacite, tuff, and minor tuffaceous mudstone, siltstone, volcaniclastic sandstone, and breccia, all probably equivalent to the Yamhill.

The Miller sand contains microfossils indicating shallow-marine deposition, whereas the overlying and underlying mudstone members of the Yamhill Formation were deposited in upper to middle bathyal water depths (McKeel, 1984, 1985). Foraminiferal assemblages in the type section of the Yamhill are assigned to the early Narizian stage (McWilliams, 1980; Brownfield, 1982b; D.R. McKeel, written comm., 1987). Foraminifers in the Reserve Bruer 1 and Reichold Finn 1 wells in the northern Willamette Valley are early Narizian in age at the base of the Yamhill and Narizian in age for the remainder of the formation. The Yamhill in the Reichold Bagdanoff 23–28 well yielded early Narizian to late Ulatisian foraminiferal assemblages (McKeel, 1984). In the Coast Range south of Eugene, the Elkton Formation and Lorane Siltstone (Bird, 1967; Heller and Dickinson, 1985) have Ulatisian and early Narizian foraminifers. Coccoliths from the Yamhill Formation in the Coast Range west of the northern Willamette Valley are referred to Subzone CP 13c and CP 14a, the ages of which are estimated as 47 Ma to about 42.5 Ma (Bukry and Snavely, 1988). However, coccoliths from the Elkton Formation and Lorane Siltstone are referred to Subzone CP 12b, close to the age of the Tyee Formation (Bukry and Snavely, 1988), suggesting that these formations are older than the Yamhill Formation despite the presence of Ulatisian and early Narizian foraminifers in all three formations. The Yamhill changes facies eastward in the subsurface of the Willamette Valley to arclike volcanic rocks (Baker, 1988), suggesting either that the Cascade arc began to develop earlier than the 43–41 Ma (Lux, 1982; Priest and Vogt, 1983; Verplanck and Duncan, 1987; Taylor, 1990) or 35 Ma (Priest, 1990) ages that are generally accepted based on surface geology or that the volcanism that produced the Clarno Formation, widespread in eastern Oregon, extended this far to the west.

In the Coast Range west of the Tualatin valley, the Yamhill Formation interfingers with and is overlain by the Tillamook Volcanics (Wells and others, 1983). The Yamhill is intruded by a sill of zeolitized gabbro with a potassium-argon age on plagioclase of 43.2±1.8 Ma (L.G. Pickthorn, *in* Bukry and Snavely, 1988). Strata with Narizian microfossils underlying the Cowlitz Formation in the Mist gas field (fig. 76) are also referred to the Yamhill Formation by Bruer and others (1984), but these beds contain late Narizian microfossils and overlie the Tillamook Volcanics; they were described by Niem and Niem (1985) as their informal Hamlet formation. The Yamhill Formation in the northern Willamette Valley, where volcanics are not present, may include in its upper part strata equivalent to the informal Hamlet formation of the northern Oregon Coast Range, although no late Narizian microfossils have been found in the Yamhill Formation.

TILLAMOOK VOLCANICS

The Gales Peak area (pl. 2A) west of the Tualatin basin is underlain by basalt correlated by Wells and others (1983) with the Tillamook Volcanics of the northern Coast Range. Contact relations with adjacent sedimentary rocks are unclear due to faulting and poor exposure. In the Nahama and Weagant Klohs 1 well (pl. 2A) in the Tualatin basin, Refugian strata overlie zeolitized basalt that is interbedded with unfossiliferous marine siltstone, claystone, and minor sandstone; this basalt may either be the Tillamook Volcanics, Goble Volcanics, or basalt of Waverly Heights. The Yamhill Formation and Tillamook Volcanics may be interbedded in the Texaco Cooper Mountain 1 well (pl. 2A) between 945 and 2,823 m well depth. The volcanic rocks below 2,124 m in the Richfield Barber 1 well (pl. 2A) may be the Tillamook Volcanics.

In the Tillamook Highlands (fig. 77), the Tillamook Volcanics consist of a lower unit of submarine basalt with sedimentary interbeds containing early Narizian microfossils (W.W. Rau, *in* Wells and others, 1983) overlain by mostly subaerial basalt. Potassium-argon ages from the middle and lower parts of the sequence are 46.0±0.9 to 42.7±0.5 Ma (Magill and others, 1981); an age of 33.4±0.5 Ma is reported in Wells and others (1983).

BASALT OF WAVERLY HEIGHTS

At Waverly Heights in Milwaukie, along the Willamette River south of Portland, the Columbia River Basalt Group is underlain with angular unconformity by a sequence of subaerial basalt flows and associated sedimentary rocks, probably marine (Beeson, Tolan, and Madin, 1989). The top of the unit is marked by a thick soil zone. Potassium-argon ages from two flows are dated about 40 Ma (R.A. Duncan, *in* Beeson, Tolan, and Madin, 1989), younger than the Siletz River Volcanics, and the unit is probably correlative with the Tillamook Volcanics. This unit may be present in wells in the Tualatin basin, but its presence has not been confirmed.

SPENCER FORMATION AND CORRELATIVE UNITS (COWLITZ AND NESTUCCA FORMATIONS)

The Spencer Formation, named by Turner (1938) for exposures near Eugene, crops out along the western edge of the Willamette Valley from south of Eugene north to the Chehalem Mountains adjacent to the Tualatin basin. Microfossils are referred to the late Narizian. The Spencer is divided into two members.(Al Azzaby, 1980; Baker, 1988; Richard E. Thoms, Portland State University, oral commun., 1991). The lower member consists of micaceous, arkosic sandstone, siltstone, and minor coal deposited in a strandline to middle-shelf environment. West of the Tualatin basin, the lower member ranges in thickness from 60 m near Henry Hagg Lake to about 300 m of predominately clean arkosic sand south of Patton Valley (Richard E. Thoms, Portland State University, oral commun., 1991). In the Quintana Gath 1, Linn County Oil Barr 1, American Quasar Hickey 9–12, and Mobil Ira Baker 1 wells (pl. 2B) in the southern Willamette Valley, this member changes to tuffaceous strata eastward and interfingers and grades upward into volcanic rocks of Cascade Range origin. In the American Quasar Wolverton 13–31 and Humble Miller 1 wells (pl. 2B) north of Albany, the lower member includes basalt, andesite, and tuff. Microfossils studied by McKeel (1984, 1985) indicate middle to inner neritic water depths along the western side of the valley and inner neritic water depths to possibly nonmarine along the eastern edge of the valley (Hickey 1 well). Thicknesses in the southern Willamette Valley vary from 230 m in the Reichold Northwest Natural Gas Merrill 1 and Oregon Natural Gas Independence 12–25 wells (pl. 2B) to 310 m in the American Quasar Wolverton 13–31 well.

The upper member consists of mudstone, siltstone, and subordinate sandstone, grading eastward to tuffaceous strata and volcanic rocks (American Quasar Wolverton 13–31 and Gulf Porter 1 wells, pl. 2B). Along the eastern edge of the valley (Quintana Gath 1, American Quasar Hickey 9–12, Linn County Oil Barr 1, and Mobil Ira Baker 1 wells, pl. 2B), the upper member consists of volcanic and volcaniclastic strata correlative in part with the lower part of the Fisher Formation in the Eugene area. The mudstone and siltstone of the upper member of the Spencer Formation in the southern Willamette Valley were deposited in upper bathyal water depths deepening upsection to middle bathyal depths (McKeel, 1984, 1985). The thickness of the upper member in the southern Willamette Valley ranges from 100 m in the American Quasar M & P Farms 33–24 and American Quasar Wolverton 13–31 wells to 178 m in the Gulf Porter 1 well (pl. 2B).

Near the Corvallis fault, the Spencer Formation overlies the Tyee Formation directly with an angular unconformity of as much as 90° difference in dip. The Spencer Formation, where it is in fault contact with the Siletz River Volcanics along the Corvallis fault between Corvallis and Philomath, consists of fossiliferous tuffaceous, basaltic sandstone and conglomerate with clasts as much as 2 m in diameter derived from the Siletz River Volcanics.

The Spencer Formation also consists of a lower (predominantly sandstone) member and an upper (siltstone and mudstone) member in the northern Willamette Valley. The formation thins northward from 760 m near Dallas to 490 m in Yamhill and Washington Counties, and it thins eastward from 325 m in the Reserve Bruer 1 well to 45 m in the Oregon Natural Gas DeShazer 13–22 well (pl. 2A). In the Tualatin basin, the Spencer Formation is 400 m thick near Henry Hagg Lake. North of Forest Grove, strata correlative with the Spencer Formation are referred to the Cowlitz Formation, which rests unconformably on the Tillamook Volcanics. The Cowlitz comprises a lower unit consisting of a basal conglomerate overlain by siltstone (the informal Hamlet formation of Niem and Niem, 1985), the C&W sandstone of local usage that produces gas in the Mist gas field, and an upper siltstone member. The upper two members may be present in the Texaco Cooper Mountain 1 well (pl. 2A).

The Nestucca Formation, originally described by Snavely and Vokes (1949), overlies the Yamhill Formation with angular unconformity in the Coast Range west of McMinnville. It appears to be a deeper water facies equivalent of the Spencer Formation and correlates with the informal Hamlet formation of the northern Coast Range of Oregon. The Nestucca Formation consists of tuffaceous shale and siltstone and thin-bedded sandstone with interbeds of pillow basalt, breccia, and tuff (Baldwin and others, 1955) grading into the Yachats Basalt and the basalt of Cascade Head. Foraminifers are assigned to the late Narizian (W.W. Rau, *in* Wells and others, 1983), and coccoliths are assigned to Subzones CP 15a and CP 15b, giving an age estimate by Bukry and Snavely (1988) of about 38.5–36.7 Ma.

FISHER FORMATION

Nonmarine volcaniclastic strata and interfingering flows in the Eugene area as far north as Cox Butte, west of Junction City, are mapped as the Fisher Formation (Vokes and others, 1951). This formation is 1,680 m thick and consists of andesitic lapilli tuff and breccia, tuffaceous sandstone and siltstone, and pebble to boulder conglomerate interbedded with flows of predominantly andesite and subordinate basalt and dacite (Hoover, 1963). These rocks extend south of Eugene and may be stratigraphically equivalent to the Calapooya Formation and Colestin Formation of the southern Oregon Cascade Range (Wells and Waters, 1934; Peck and others, 1964). They make up unit T_5 of Sherrod and Smith (1989), with an age estimated as 45–35 Ma.

Fossil leaves in the lower part of the Fisher Formation south of Cottage Grove (25 km south of Eugene) suggest a late Eocene age (R.W. Brown, *in* Hoover, 1963). Radiometric ages from basalt and basaltic andesite near the top of the formation are 40–35 Ma (Lux, 1982), close to the youngest age inferred for the Narizian stage of Mallory (1959). The Fisher appears to interfinger northward with the marine Eugene Formation of latest Eocene (Narizian) and Oligocene (Refugian) age (Vokes and others, 1951). The basalt flows dated by Lux (1982) were considered by Vokes and others (1951) to overlie the Fisher and Eugene Formations unconformably, but Walker and Duncan (1989) suggest that these flows are age equivalents of (and thus part of) the Fisher Formation.

In the subsurface of the southern Willamette Valley, the Mobil Ira Baker 1 well (pl. 2B) penetrated 143 m of volcanic and volcaniclastic rocks overlying Narizian marine strata. Between the Salem Hills and Tualatin basin, the marine equivalents of the Fisher Formation are notably free of volcanic rocks. In the Quintana Gath 1 well (pl. 2B), a 440-m-thick volcanic unit bracketed by strata with late Narizian and Refugian microfossils may be equivalent to the Fisher Formation. Still farther north, the Goble Volcanics are interbedded with the Cowlitz Formation; the Goble Volcanics, like the Fisher Formation, are arc-related rocks (Phillips and others, 1989).

EOCENE AND OLIGOCENE MARINE STRATA

North and west of the Tualatin basin, marine strata of Eocene and Oligocene age are mapped as the Keasey Formation and the overlying Pittsburg Bluff Formation (Wells and others, 1983). The Keasey Formation is predominantly thick, light-gray tuffaceous claystone and siltstone with minor mudstone and sandstone; foraminifers are late Narizian and early Refugian in age (McWilliams, 1968, 1973; Brownfield and Schlicker, 1981a). North of Henry Hagg Lake, the Pittsburg Bluff Formation consists of as much as 1,400 m of greenish-gray to gray, tuffaceous, glauconitic and basaltic litharenite sandstone, siltstone, and minor conglomerate with foraminifers of the Refugian Stage (Richard E. Thoms, Portland State University, oral commun., 1991).

West of the Eola Hills, the Keasey Formation consists of sandy tuffaceous siltstone, and the Pittsburg Bluff Formation consists of tuffaceous sandstone, tuff, and tuffaceous shale and siltstone deposited in shallower water than the Keasey Formation. The Reichold Werner 14–21 and Oregon Natural Gas Werner 34–21 and DeShazer 13–22 wells (pl. 2A) in the northern Willamette Valley document an angular unconformity between the Keasey Formation and the Pittsburg Bluff Formation. The two units together are about 715 m thick in the Eola Hills near Amity (Brownfield, 1982b).

In the southern Willamette Valley, feldspathic, tuffaceous sandstone and siltstone containing Refugian foraminifers of Eocene and Oligocene age constitute the Eugene Formation. The formation is 550 m thick in the hills east of Coburg, which includes 343 m of strata penetrated in the Mobil Ira Baker 1 well, more than 800 m thick in the Lebanon area, including strata in the American Quasar Hickey 9–12 well, and 780 m thick beneath the Salem Hills, based on data from the Oregon Natural Gas Independence 12–25 and Reichold Northwest Natural Gas Merrill 1 wells (pl. 2B). The formation is best exposed in the hills east of Coburg, at Peterson Butte, and at the base of the Salem Hills. To the south, the Eugene Formation interfingers with the nonmarine Fisher Formation.

LITTLE BUTTE VOLCANICS

The Little Butte Volcanic Series of Wells (1956) and Peck and others (1964), which is here renamed the Little Butte Volcanics in accordance with Article 38 of the (1983) North American Stratigraphic Code, makes up the base of the exposed western Cascade Range sequence on the eastern margin of the southern Willamette Valley, where it overlies the Eugene Formation, and the northern Willamette Valley, where it is overlain unconformably by the Oligocene and Miocene Scotts Mills Formation and the Miocene Columbia River Basalt Group (Miller and Orr, 1988).

We subdivide the Little Butte Volcanics into basalt and basaltic andesite flows of Walker and Duncan (1989), porphyritic andesite flows of Hampton (1972), dacite to rhyodacite vent complexes of Walker and Duncan (1989) and Bristow (1959), and welded ash-flow tuff in the foothills of the Cascade Range northeast of Eugene (Walker and Duncan, 1989). The age range of the Little Butte Volcanics is 35–17 Ma (Sutter, 1978; Lux, 1982; Walker and Duncan, 1989), corresponding to the T_4 and T_3 time units of Sherrod and Smith (1989). However, many of the rocks in the Eugene area described as Little Butte Volcanics by Lux (1982) yield radiometric ages older than 35 Ma. Lux (1982) reported radiometric ages of 41.5±0.9 Ma and 39.2±0.5 Ma east of Lebanon. However, Verplanck (1985) redated a sample from one of these localities as 31.7±0.4 Ma.

In the Eugene area, Little Butte Volcanics unconformably overlie the Eocene and Oligocene Fisher and Eugene Formations (W.N. Orr, *in* Armentrout and others, 1983). However, Peck and others (1964) found tongues of Eugene Formation interfingering with Little Butte Volcanics south of Brownsville, Beaulieu (1974) noted similar relations to the north in Linn County, and the Quintana Gath 1 well in southwestern Marion County near Salem contains volcanic rocks interbedded with the Eugene Formation. These volcanic rocks are more likely correlated to the Fisher Formation discussed above rather than to the Little Butte Volcanics. The volcanic rocks are not found in the Reichold Northwest Natural Gas Merrill 1, Oregon Natural Gas Independence 12–25, and Erntson Schermacher 1 wells (pl. 2B) to the west. Following eruption, the Little Butte Volcanics were tilted gently to the east and eroded prior to deposition of the Scotts Mills Formation in the northern Willamette Valley (discussed below). Peck and others (1964) considered the volcanic sequence to be between 1,300 and 2,600 m in thickness throughout most of the western Cascade Range. The volcanic rocks appear to thin to the west. Near Washburn Butte, about 750 m of volcanic rocks lie between the Eugene Formation and Miocene-Pliocene andesite that probably overlies the Little Butte Volcanics with angular unconformity. The Humble Wicks 1 well, 10 km southeast of Silverton, penetrated 1,830 m of volcanic rocks, which may include units other than the Little Butte Volcanics.

Sedimentary formations correlative with the Little Butte Volcanics include the Alsea Formation and Yaquina Formation near Newport and the informally named Oswald West formation of Niem and others (1985) of the northern Oregon coast. These formations are older than 25 Ma and thus fall within the time range of the Little Butte Volcanics. The Alsea Formation is referred to Coccolith Zone CP 16 of 36.5–35 Ma age (Bukry and Snavely, 1988). The Scotts Mills Formation and Molalla Formation (Lowry and Baldwin, 1952) are late Oligocene and early Miocene in age (Miller and Orr, 1988), also within the time range of the Little Butte Volcanics. However, these formations overlie the Little Butte Volcanics unconformably in the Molalla and Silverton areas (Miller and Orr, 1988).

INTRUSIVE ROCKS OF THE COAST RANGE

Gabbroic sills, dikes, and laccoliths are common in the central and northern Oregon Coast Range. The best known is the Marys Peak sill, 390 m thick, which intrudes the Tyee Formation near its basal contact with the Kings Valley Siltstone Member of the Siletz River Volcanics. The sill is a highly differentiated, titanium-rich body of granophyric gabbro and granophyric diorite with abundant aplite dikes near its upper chilled contact (Roberts, 1953). The Marys Peak sill was dated as 29.7±1.2 Ma (middle Oligocene) (P.D. Snavely, Jr., *in* Clark, 1969). Other large intrusive bodies of similar lithology are found south of Philomath and at Bald Hills, Dimple Hill, Vineyard Hill, Coffin Butte, Logsden Ridge, and Witham Hill (Snavely and Wagner, 1961; Snavely and others, 1980). The remanent magnetization of the Marys Peak sill is normally polarized (Clark, 1969), as it is for all the other intrusions field checked in the Corvallis and Albany area, supporting the suggestion of Snavely and Wagner (1961) that the middle Oligocene intrusive episode was of short duration. Elongate dikes striking west to west-northwest are found near the Corvallis fault. Northeast-striking dikes intrude the fault, and northeast-striking sills occupy fold hinges parallel to the fault in the Tyee and Spencer Formations, indicating that strong folding predated intrusion. A dike intrudes the west-northwest-striking Philomath fault that offsets the Corvallis fault, but no other intrusions were found associated with other northwest-striking faults offsetting the Corvallis fault.

Sills, presumably of Eocene age, intrude Eocene marine strata of the Willamette Valley as young as the Eugene Formation. In the southern Willamette Valley, a sill intruding at the Spencer-Yamhill Formation contact was found in the Gulf Porter 1 well (pl. 2B) and is marked by a high-amplitude reflector on a seismic profile. There are dikes in several of the buttes on the eastern edge of the valley. An intrusion at Skinner Butte in Eugene was dated at 30.3±0.9 and 29.4±0.9 Ma (J.G. Smith, *in* Walker and Duncan, 1989), the same age as the Marys Peak sill. Intrusions along the eastern edge of the valley are mapped as Oligocene to Miocene in age (Beaulieu, 1974; Walker and Duncan, 1989) and presumably fed volcanic rocks of the western Cascade Range.

SCOTTS MILLS FORMATION

Marine and nonmarine strata of the Scotts Mills Formation (Miller and Orr, 1988) of late Oligocene and early Miocene age are exposed in the Cascade Range foothills east of Silverton adjacent to the northern Willamette Valley. Miller and Orr (1988) divide the Scotts Mills Formation into the Marquam Member, 300–500 m thick, overlain by and interfingering with the Abiqua Member, 300 m thick, which grades laterally into the Crooked Finger Member, 200 m thick. The Marquam Member unconformably overlies the Little Butte Volcanics on a surface with regional relief of as much as 100 m. The marine Marquam Member includes cross-stratified barnacle limestone, fossiliferous conglomerate, burrowed claystone, tuffaceous sandstone, and graded mudstone, indicating deposition along a rocky coast (Miller and Orr, 1988). The Abiqua Member is composed of marine and nonmarine volcanic arkose, and the Crooked Finger Member consists of nonmarine volcanic conglomerate and mudstone. The three members constitute a prograding delta complex that developed southwest of a volcanic headland underlain by the Little Butte Volcanics. The Scotts Mills

Formation is found in two wells drilled in the Waldo Hills, the Humble Wicks 1 well (pl. 2B) that penetrated 239 m of volcanic rocks, claystone, siltstone, sandstone, and rare volcanic conglomerate and the RH Exploration Anderson 1 well (pl. 2A), which penetrated 140 m of an upward-coarsening sequence of sandstone, siltstone, and claystone with volcanic fragments. These strata overlie the Little Butte Volcanics in both wells. The absence of the Scotts Mills in other wells to the west is probably due to eastward tilting and erosion prior to deposition of the Columbia River Basalt Group.

It is unclear how the Scotts Mills Formation is related to other formations of the same age in western Oregon.

MOLALLA FORMATION

The Molalla Formation (Harper, 1946; Lowry and Baldwin, 1952) consists of about 300 m of nonmarine tuffaceous conglomerate, sandstone, siltstone, and water-laid tuff with paleosols in the foothills of the northern Willamette Valley east of Silverton. The Molalla Formation is exposed in stream valleys in the Waldo Hills; it is not found in any exploratory wells. The lower part of the Molalla Formation rests unconformably on the Little Butte Volcanics, is interbedded with the upper members of the Scotts Mills Formation, and is overlain unconformably by the Columbia River Basalt Group (Miller and Orr, 1988), volcanic rocks of the Sardine Formation, and the upper part of the Molalla Formation. Strata included in the upper part of the Molalla Formation appear to be interbedded with the Columbia River Basalt Group (Miller and Orr, 1988). Fossil leaves in the Molalla Formation were dated as early Miocene (J.A. Wolfe, *in* Peck and others, 1964). Radiometric ages of tuff beds in the Molalla are 15.9±1.0 Ma and 15.0±0.7 Ma (Fiebelkorn and others, 1983). Thus, the age of the Molalla Formation ranges from perhaps as old as late Oligocene to middle Miocene. Conglomerate mapped as part of the Troutdale Formation by Peck and others (1964) in this area is considered to be part of the Molalla Formation.

SCAPPOOSE FORMATION

Fine-grained shallow marine sedimentary deposits interfingered with fluvial sandstone, coal-bearing mudstone, and conglomerate make up the middle Miocene Scappoose Formation (Van Atta and Kelty, 1985). The weakly consolidated strata are commonly exposed in steep slopes capped by the resistant Columbia River Basalt Group. More than 275 m of Scappoose strata disconformably overlie the Keasey and Pittsburg Bluff Formations north of the Tualatin basin, and at least 335 m overlie Pittsburg Bluff strata on the western flank of the Chehalem Mountains.

The Scappoose Formation was deposited in an estuarine or deltaic to shallow-marine environment over a dissected paleotopography with relief of as much as 245 m. Basaltic conglomerate derived from low-magnesium flows of the Grande Ronde Basalt commonly occurs near the base of the formation. The upper contact is conformable with the Columbia River Basalt Group; Scappoose strata frequently are intercalated with Grande Ronde flows and overlain by flows of either the Grande Ronde Basalt or Wanapum Basalt (Frenchman Springs Member) (Van Atta and Kelty, 1985).

The Scappoose Formation is probably entirely middle Miocene in age, based on the occurrence of clasts of the Grande Ronde Basalt within the basal conglomerate and flows of the Columbia River Basalt Group overlying the unit. Partly correlative strata in the northern Coast Range and northern Willamette Valley are the Astoria and Scotts Mills Formations, respectively.

COLUMBIA RIVER BASALT GROUP

Flood-basalt flows of the Columbia River Basalt Group were erupted from fissures in eastern Oregon and Washington and western Idaho from 16.5–6 Ma. Some of these flows traversed the Cascade Range via the Columbia trans-arc lowland, which extended from the Columbia River 60 km south to the Clackamas River (Beeson, Tolan, and Anderson, 1989; Beeson and Tolan, 1990) and reached as far as the present-day Pacific coast, where they are interbedded with marine strata. As noted by Beeson and others (1975) and Beeson, Tolan, and Anderson (1989), some of the broad folds and faults of the Oregon Cascade Range and Willamette Valley were active during the emplacement of the Columbia River Basalt Group. These folds and faults include the Portland Hills-Clackamas River structural zone that limited some of the flows of the Grande Ronde Basalt and Wanapum Basalt into the Portland basin and the lower reaches of the Columbia River, and the Gales Creek-Mount Angel structural zone, which formed a barrier to some flows of the Wanapum Basalt. Only the R_2 and N_2 flows of the Grande Ronde Basalt (about 16–15.6 Ma) and the basalts of Ginkgo, Silver Falls, Sand Hollow, and Sentinel Gap of the Wanapum Basalt (about 15.3 Ma; Beeson and others, 1985) crossed the Portland Hills-Clackamas River structural zone and entered the northern Willamette Valley.

The Columbia River Basalt Group underlies nearly all of the Portland, Tualatin, and northern Willamette Valleys. Water wells penetrate more than 200 m of basalt beneath parts of the Tualatin basin (Popowski, 1995). Erosionally resistant basalt comprises most of the exposures in the Waldo, Salem, and Eola Hills, the Red Hills of Dundee, the Tualatin Mountains (Portland Hills), Petes Mountain, Parrett Mountain, Cooper and Bull Mountains, and the Chehalem Mountains. The Grande Ronde Basalt makes up most of the volume of the Columbia River Basalt Group west of the

Cascade Range, as it does in the Columbia Plateau to the east, extending into the Willamette Valley as far south as Franklin Butte, 3 km southeast of Scio. There were no active Cascade Range volcanic centers in the lowland through which the flows of the Grande Ronde Basalt crossed the Cascades (Beeson, Tolan, and Anderson, 1989). Whereas the flows of the Grande Ronde Basalt blanketed most of the northern Willamette Valley, some of the flow units of the Wanapum Basalt tended to follow channels. One channel of the Ginkgo flows crossed the Cascade Range beneath the future site of Mt. Hood and followed the southward-convex arc of the Waldo, Salem, and Eola Hills (Beeson, Tolan, and Anderson, 1989). Basalt on the Oregon coast near Newport is geochemically identical to the Ginkgo flows, suggesting that the Ginkgo flows continued across to the coast prior to most of the uplift of the Coast Range. Another Ginkgo flow passed north of the Willamette Valley in such a way that the intervening northern Willamette Valley contains no flows of the Wanapum Basalt, only those of the Grande Ronde Basalt (Beeson, Tolan, and Anderson, 1989; Tolan and others, 1989; Wells and others, 1989). Similarly, the Wanapum Basalt is absent in the Tualatin basin. The Silver Falls and Sand Hollow basalt flows moved southwest along the axis of the Waldo Hills, and the basalt of Sand Hollow at Hungry Hills is the southernmost exposure of the Columbia River Basalt Group in the Willamette Valley (Beeson and others, 1985; Beeson, Tolan, and Anderson, 1989). The Waldo, Salem, and Eola Hills show a reversal in topography because they were a low area during the time of Ginkgo eruptive activity. The Columbia River Basalt Group is 100–180 m thick in the Salem Hills.

The Columbia River Basalt Group rests with angular unconformity on older units: the Molalla Formation and Scotts Mills Formation east of the Willamette Valley and the Eocene and Oligocene marine sequence in the Salem and Eola Hills. Thus, the homocline composing the western Cascade Range dipped east prior to the eruption of the Columbia River Basalt Group (Priest, 1990).

SARDINE FORMATION

Volcanic and volcaniclastic rocks of the western Cascade Range, erupted after emplacement of the Columbia River Basalt Group, were called the Sardine Formation by Peck and others (1964). The volcanic rocks postdate a period of relative quiescence in the Cascade Range between 17 and 13.5 Ma (Sherrod and Smith, 1989), between Episodes 1 and 2 of Priest (1990). The Sardine Formation is regarded as Miocene and Pliocene in age. The formation is equivalent to the Sardine Series of Thayer (1939) and includes rocks described as the Fern Ridge Tuffs by Thayer (1939), the Rhododendron Formation by Hodge (1933), and the Outerson Basalt by Hammond (1979) and Hammond and others (1980). In the study area, the Sardine Formation includes basalt at Marks Ridge northeast of Sweet Home, basaltic andesite at Washburn Butte, nonmarine tuffaceous strata overlying the Columbia River Basalt Group in the Waldo Hills, and volcanic and volcaniclastic rocks resting on east-dipping rocks of the Little Butte Volcanics southeast of the Waldo Hills. Adjacent to the northern Willamette Valley, breccia and tuff of the Rhododendron Formation are overlain unconformably by pyroxene andesite flows, with the unconformity marked by a laterite (Hampton, 1972). This volcanism was more calc-alkaline than that prior to eruption of the Columbia River Basalt Group, and it consists of lava flows and debris flows of intermediate composition with locally abundant basalt and basaltic andesite (Priest and Vogt, 1983). The basalt at Marks Ridge was dated at 4.5±0.28 Ma (Episode 3 of Priest, 1990), and the basaltic andesite at Washburn Butte was dated at 11.9±0.3 Ma (Verplanck, 1985; Episode 2 of Priest, 1990).

NONMARINE FINE-GRAINED SEDIMENTARY DEPOSITS

In the Portland, Tualatin, and Willamette basins, the Columbia River Basalt Group and older rocks were deeply eroded, developing a topographic surface with as much as 250 m relief. These rocks are overlain unconformably by moderately to poorly lithified siltstone, sandstone, mudstone, and claystone with common wood fragments and local volcanic ash and pumice sand. The sequence exposed along the Clackamas and Sandy Rivers was named the Sandy River Mudstone by Trimble (1963), who considered the mode of deposition to be lacustrine. However, sedimentary structures along the Clackamas River suggest a fluvial origin (C.D. Peterson, Portland State University, and A.R. Niem, Oregon State University, oral commun., 1989). Deeply weathered fluvial and loessal silts interbedded with gravels dominated by clasts of the Columbia River Basalt Group in the Tualatin basin were mapped as the Helvetia Formation by Schlicker and Deacon (1967). These sedimentary deposits are at least 240–275 m thick in the Portland basin, 350 m thick west of Beaverton, and 410 m thick beneath Hillsboro in the center of the Tualatin basin. The presence of clasts of granite and quartzite together with abundant quartz and mica and more locally derived clasts suggests that the greater part of these sedimentary materials was deposited by the ancestral Columbia River with some contribution by side streams draining the Cascade Range and the rising Tualatin Mountains.

South of the Portland basin, correlative sedimentary deposits are identified mainly in the subsurface, where they are known to water-well drillers as the so-called blue clay. In the northern Willamette Valley (pl. 2B), the contact between these deposits and the Columbia River Basalt Group is marked in some wells by a laterite. The sedimentary deposits increase in thickness northeastward, from 160 m in the Reichold Bagdanoff 23–28 well and Reichold

Werner 14–21 well to 265 m in the Oregon Natural Gas DeShazer 13–22 well and 300 m in the Damon Stauffer Farms 35–1 well. In the northern Willamette Valley and Tualatin basin, the sedimentary deposits are characterized on seismic profiles as a lower sequence with low-amplitude reflectors and an upper sequence with medium- to high-amplitude reflectors. Paleontologic analysis of borehole cuttings from the Tualatin basin indicates that this upper sequence probably is latest Pliocene or early Pleistocene in age (Unruh and others, 1994).

In the southern Willamette Valley south of the Salem Hills, a sequence of clay with intercalated sand and gravel was found to overlie marine Eocene strata along a surface of moderate relief (Niem and others, 1987) and is as much as 100 m thick near the center of the valley. Corehole DH 13–88 obtained by the Oregon State Highway Division at Corvallis penetrated 42 m of greenish-blue to blue-gray micaceous clay with minor interlayered sand, dark-brown organic clay, and poorly developed paleosols with rootlets in growth position, suggesting a fluvial origin (fig. 79). In another corehole at Corvallis, a multicolored paleosol is at the base of the clay unit. In corehole DH 14–90 between Sublimity and Stayton, the Columbia River Basalt Group is overlain by blue to dark-gray clay with intercalations of volcaniclastic sand and with paleosols with rootlets in growth position (fig. 80). Near Monroe, several coreholes penetrated a clay unit informally named the Monroe clay and dated as late Miocene to early Pliocene on the basis of palynology (Roberts and Whitehead, 1984). Roberts and Whitehead (1984) interpreted the Monroe clay as lacustrine in origin, in contrast to the fluvial interpretation for clays from the Oregon State Highway Division coreholes. Toward the center of the southern Willamette Valley, the clay is interbedded with sand and gravel that Graven (1990) interpreted as part of the main channel of the proto-Willamette River (figs. 81 and 82). However, more detailed study of water wells by Marshall Gannett (U.S. Geological Survey, oral commun., 1993) and Paul Crenna (Oregon State University, oral commun., 1993) shows that the coarser grained deposits are part of glaciofluvial fans from the Cascade Range. Drainage from a fan emerging from the drainage basin of the North Santiam River at Stayton (pl. 2B) appears to have flowed through a narrow water gap at the eastern margin of the Salem Hills now occupied by Mill Creek, an underfit stream. A channel beneath the present-day Willamette River west of the Salem Hills is filled by fine-grained sedimentary deposits rather than the sand-and-gravel fan facies found in the channel beneath Mill Creek. The main entry point is in the Eugene-Springfield area, where a 90-m-thick sequence of sand and gravel was called the Springfield delta by Frank (1973). A similar gravel fan is found near Salem at the north end of the Mill Creek watergap. Seismic profiles in the northern Willamette Valley and Tualatin basin show a prominent series of reflectors midway in the sedimentary sequence that are coarse clastic units in the Tualatin basin, based on water-well logs. Other side channels underlie the present North Santiam River and South Santiam River on the east side of the valley and Long Tom Creek at the southwestern corner of the valley.

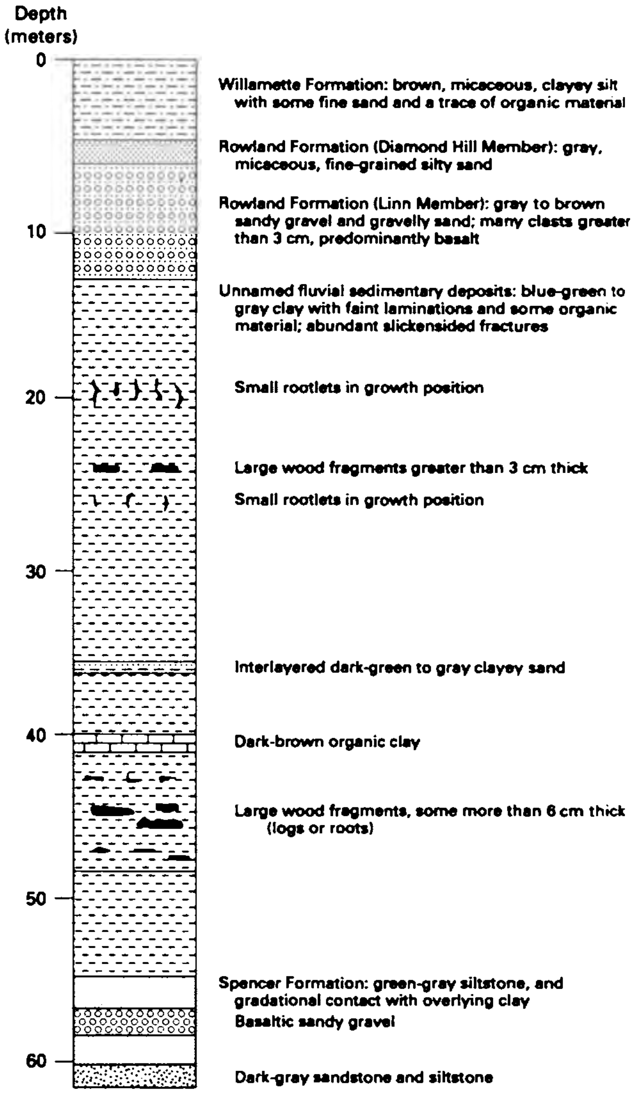


Figure 79. Graphic log of corehole DH 13–88, drilled on the southeast side of Corvallis, Oreg., just east of the intersection of State Highways 34 and 99W (see pl. 3 and fig. 82 for location of corehole). Total depth represented is 47.9 m.

TROUTDALE FORMATION

The moderately to well-indurated pebble to cobble conglomerate with a silt and sand matrix in the Portland basin is referred to the Troutdale Formation (Hodge, 1933; Trimble, 1963). The conglomerate clasts are predominantly derived from the Columbia River Basalt Group with significant percentages of exotic clasts such as quartzite and granite, indicating deposition by the ancestral Columbia River (ancestral Columbia River facies of the Troutdale Formation of Tolan and Beeson, 1984). The upper part of the ancestral Columbia River facies includes sandstone containing basaltic glass together with interbeds of conglomerate with clasts of high-alumina basalt derived from the Boring Lavas and the informally named High Cascade lavas, and the subordinate foreign clasts (Tolan and Beeson, 1984; Swanson, 1986).

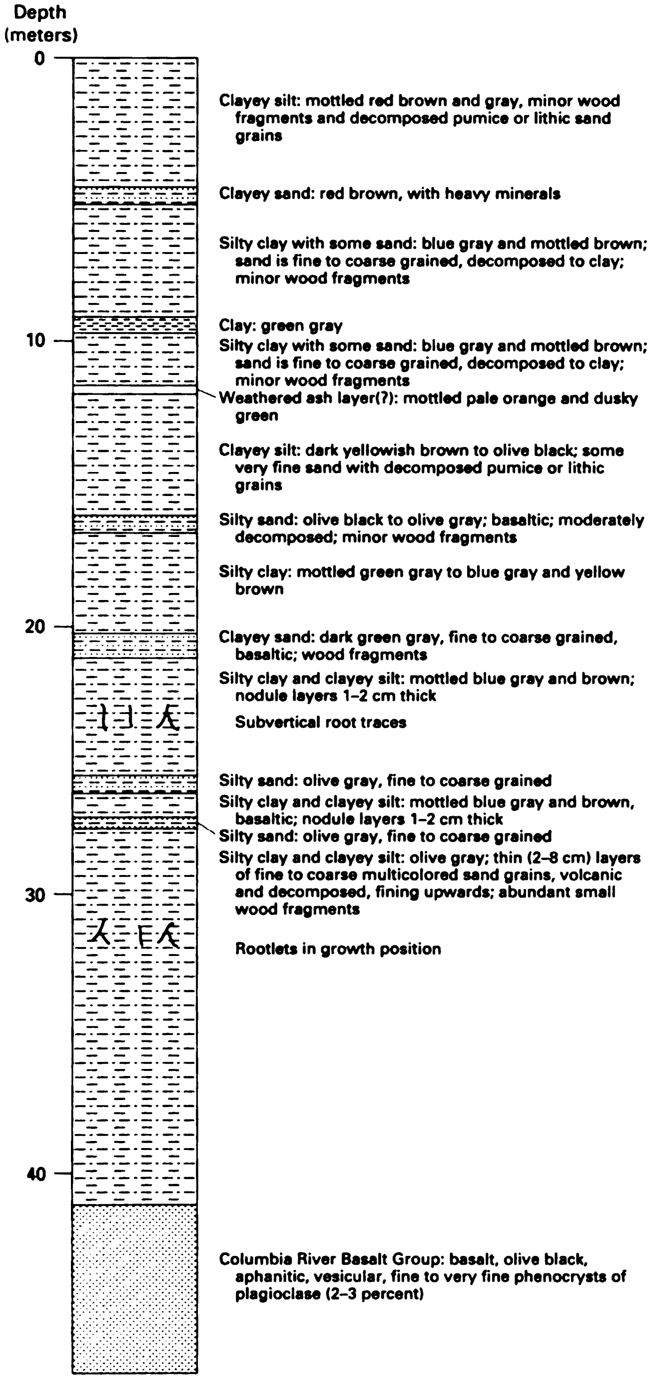


Figure 80. Graphic log of corehole DH 14–90, drilled 1.4 km west of Sublimity at State Highway 22 north of Mill Creek on the southern edge of the Waldo Hills, Oregon, showing unnamed nonmarine sedimentary deposits overlying the Columbia River Basalt Group.

Correlative conglomerate in the southeast part of the Portland basin contains a predominance of clasts derived from the Cascade Range (Tolan and Beeson, 1984; Hartford and McFarland, 1989). The Troutdale overlies the Sandy River Mudstone and locally may be interbedded with it. Plant fossils in the Troutdale are of early Pliocene age (Trimble, 1963), but the upper part of the formation could be younger.

BORING LAVA AND SNOW PEAK VOLCANO

Vents and flows of high-alumina, diktytaxitic, porphyritic olivine basalt and basaltic andesite with subordinate pyroclastic rocks, breccia, and ash in the Portland basin were named the Boring Lavas by Treasher (1942) and renamed the Boring Lavas by Allen (1975). These lavas intrude the Sandy River Mudstone and Troutdale Formation and form cones of interlayered cinders and lava (such as Mt. Sylvania and Mt. Scott in the middle of urban Portland) on an eroded surface of the Troutdale Formation (Trimble, 1963) as well as forming stocks from which the surrounding country rock has been eroded (Rocky Butte). East of Portland, high-alumina basalt flows overlie and are interbedded with the Troutdale Formation (Lowry and Baldwin, 1952; Tolan and Beeson, 1984; Tolan and others, 1989). The Boring Lavas are older than latest Pleistocene flood deposits (Allen, 1975). In the eastern Tualatin basin and the northern Willamette Valley, subsurface bodies visible on seismic lines as bowing up the Columbia River Basalt Group are interpreted as basalt intrusions correlated with the Boring Lavas. An intracanyon flow at Carver in the Clackamas River valley southeast of Portland has a potassium-argon age of 612±23 ka (R.A. Duncan, Oregon State University, oral commun. to I.P. Madin, 1989); other potassium-argon ages are as old as 5 Ma (Luedke and Smith, 1982; Swanson, 1986). The Boring Lavas of the Oregon City plateau are dated as 2.6 Ma (Swanson, 1986).

Snow Peak, just east of the study area, consists of nearly 1,000 m of basaltic andesite flows and breccia with minor basalt (Beaulieu, 1974). These rocks were dated by Verplanck (1985) as 3.3±0.6 Ma and 2.8±0.3 Ma, equivalent in age to the Boring Lavas. The shield volcano is deeply dissected by U-shaped valleys carved by glaciers.

PLEISTOCENE TERRACE GRAVELS

Sedimentary materials younger than the Boring Lavas, Troutdale Formation, and nonmarine fine-grained sedimentary deposits are described by McDowell (1991). Gravels in the eastern parts of the Willamette Valley and Portland basin are glaciofluvial, derived from the Cascade Range, whereas gravels on the west side of these basins are fluvial and derived from the Coast Range. Allison (1953) described three terrace-gravel units on the eastern margin of the southern Willamette Valley; from oldest to youngest, these are the Lacomb, Leffler, and Linn Gravels. The Lacomb and Leffler Gravels are preserved as high terraces at altitudes of 70–200 m along the edge of the valley (Allison, 1953; Allison and Felts, 1956). We do not separate the Lacomb and Leffler Gravels but instead refer to these units and other deeply weathered gravels as high-terrace gravels (fig. 83). Roberts (1984) suggested that the high-terrace gravels are the constructional top of his informally named Monroe clay. Subsequent erosion was accompanied by development of deep

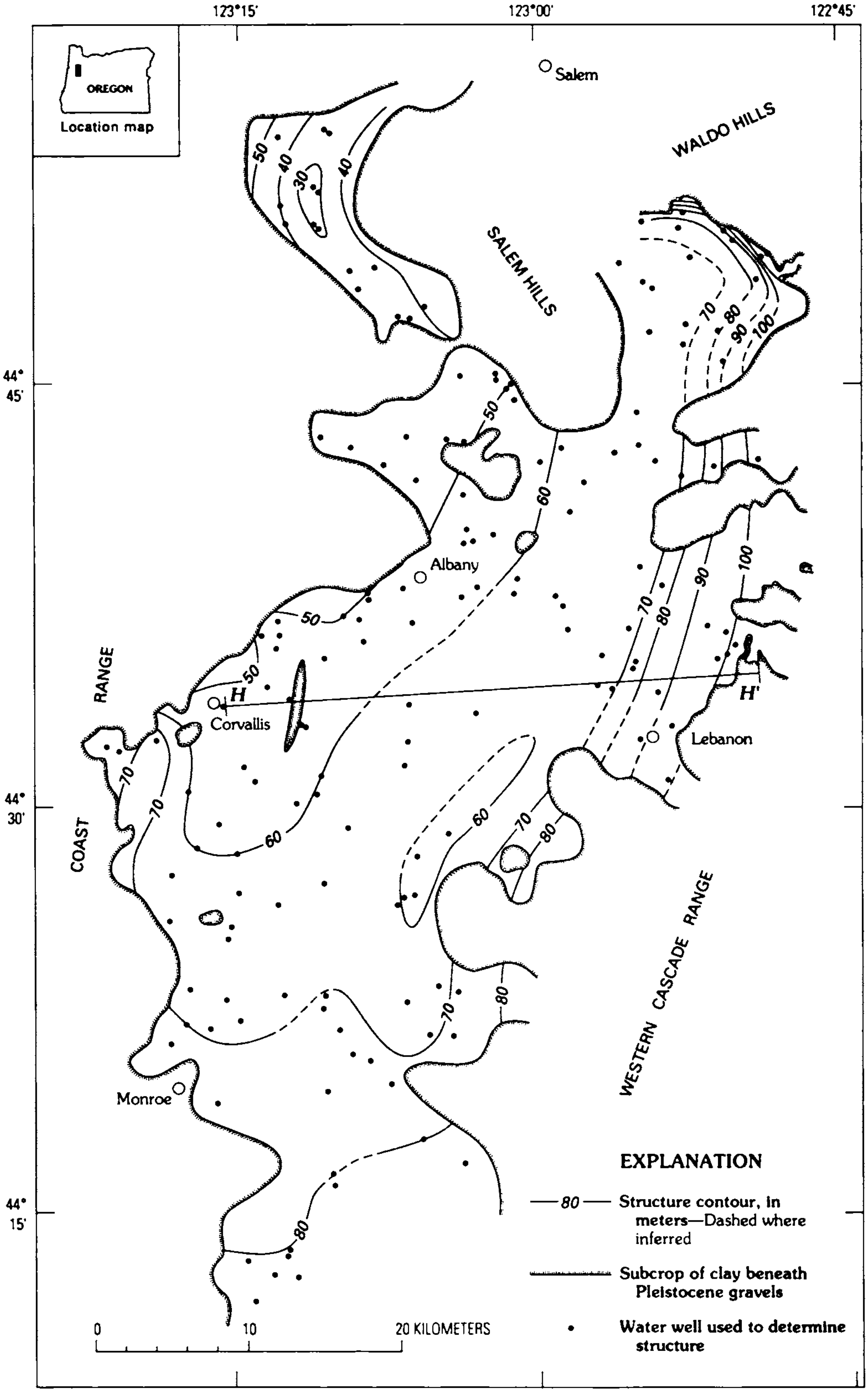


Figure 81. Structure contour map of the top of the nonmarine sedimentary deposits overlying the Columbia River Basalt Group, which is the contact with the base of the Pleistocene Rowland Formation (Balster and Parsons, 1969), in the southern Willamette Valley, Oregon. *H–H'* is the line of section for the cross section shown in figure 82.

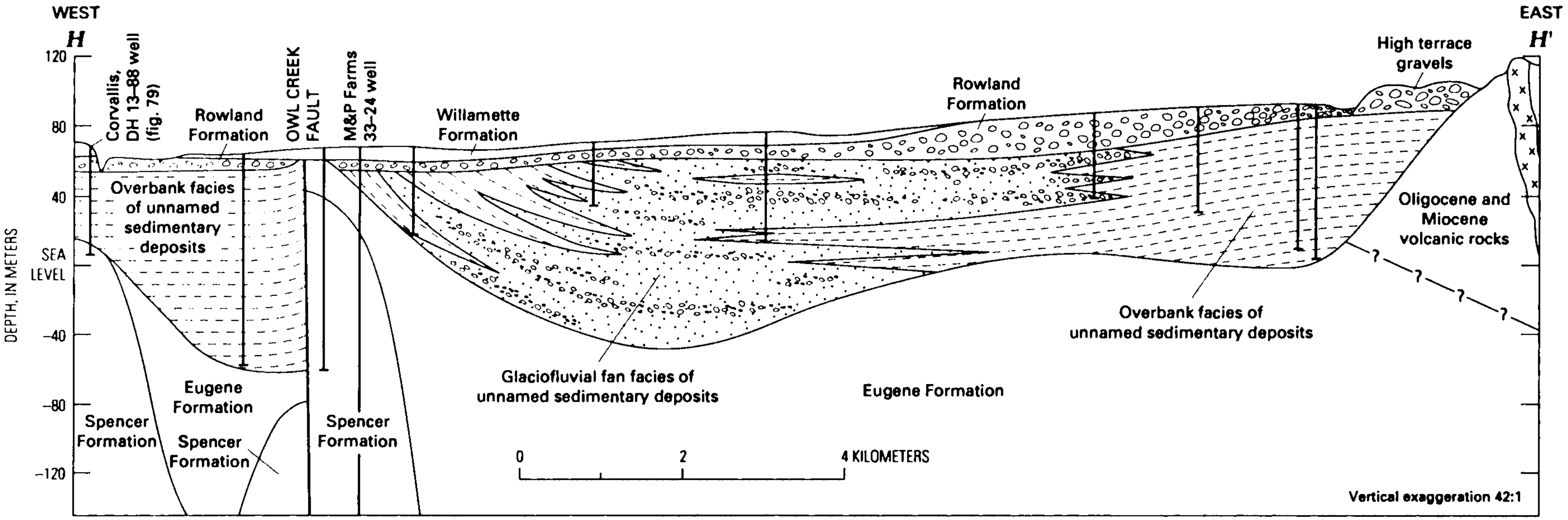


Figure 82. Structural cross section between Corvallis and Lebanon, Oreg., showing channel and overbank facies of unnamed fluvial sedimentary deposits, high-terrace gravels, late Pleistocene outwash deposits of the Rowland Formation, and catastrophic flood deposits of the Willamette Formation. Data are from water wells, engineering bore holes, and petroleum-exploration wells.

soils atop the Eola surface of Balster and Parsons (1968), evidence that the soils of the Eola surface are not correlative with the paleosol on top of the Spencer Formation near Corvallis or on top of the Columbia River Basalt Group in the northern Willamette Valley.

The materials forming the Linn Gravels, at or below the present Willamette Valley floor, were called the Rowland Formation by Balster and Parsons (1969) and divided into two members in the southern Willamette Valley: the Linn Member, predominantly silt, sand, and gravel, and the overlying Diamond Hill Member, predominantly sand and silt capped by a paleosol. The Linn Member is 6 m thick at Corvallis and thickens to about 20 m along the eastern edge of the valley. Allison (1953) suggested that the Linn Gravels are glacial outwash sediments derived from the Cascade Range, a view supported by a surface morphology of coalescing alluvial fans recognized by Piper (1942). The North Santiam, South Santiam, Willamette, McKenzie, and Calapooia Rivers all appear to have contributed to these deposits. Radiocarbon dates show that deposition of the Diamond Hill Member began before 36,000 years B.P. and continued past 28,500 years B.P. (McDowell and Roberts, 1987).

In the Portland basin, Trimble (1963) mapped the Springwater, Gresham, and Estacada Formations, consisting largely of glaciofluvial boulder and cobble gravels interbedded with mudflows and forming terraces along the Clackamas and Sandy Rivers. Madin (1990) found that the Estacada Formation includes several terraces, and he has recommended that Trimble's (1963) nomenclature be discontinued.

The relation between the Willamette Valley terraces and Pleistocene glacial sequences of the Cascade Range is poorly understood.

PORTLAND HILLS SILT

Poorly indurated quartz- and mica-bearing silt mantling hills around the Portland and Tualatin basins was named the Portland Hills Silt [Member] of the Troutdale Formation by Lowry and Baldwin (1952); this unit was subsequently raised to formational rank as the Portland Hills Silt by Baldwin (1964). The silt is more than 30 m thick in the Portland Hills but thinner elsewhere, and it is absent in the Red Hills of Dundee and farther south. Lentz (1981) demonstrated that the Portland Hills Silt is predominantly loess derived from the Columbia basin east of the Cascade Range. Lentz (1981) delineated as many as four silt units separated by paleosols, indicating that the loess accumulated over a considerable time span in the Quaternary. At one locality, the silt is apparently interbedded with what Lentz (1981) calls the Boring Lavas.

CATASTROPHIC FLOOD DEPOSITS

The Willamette Valley floor as far south as Eugene is mantled with horizontally bedded silt and gravel derived from the Columbia basin by glacial-outburst floods caused by the catastrophic drainage of Glacial Lake Missoula, an origin first recognized by Allison (1932, 1936, 1978). Treasher (1942) used the term "Willamette Valley terraces" for light brown, homogeneous silt interbedded with coarser grained deposits. Allison (1953) subsequently referred to these deposits as the Willamette Silts, and Baldwin and others (1955) called them the Willamette Silt. The unit contains boulders of exotic lithology found around the margins of the Willamette Valley, and a type section at Irish Bend was described by Allison (1953). Balster and Parsons (1969) used the name "Willamette Formation" for the unit and subdivided it into four members. The basal Wyatt Member consists of sand and silt that overlie the Rowland Formation unconformably as localized channel fills. The overlying Irish Bend Member resulted from multiple catastrophic floods that deposited silt in low-lying areas across much of the Willamette Valley (fig. 83). The coarse-grained equivalents of these silts in the northern Willamette Valley were called the River Bend Member (of the Willamette Formation) by Roberts (1984), and they consist of at least 40 rhythmically deposited beds of silt and fine sand, each apparently deposited by an individual catastrophic flood (Glenn, 1965). A paleosol separates the Irish Bend Member from the overlying Malpass Member, an extensive but discontinuous clay unit (Parsons and others, 1968; Balster and Parsons, 1969). The uppermost Greenback Member consists of silt accompanied by erratic boulders draped over the landscape at altitudes as high as 122 m by one catastrophic flood (fig. 8) (Allison, 1953). In the Portland basin, the flood deposits include boulder gravel, sandy gravel, and sand with a Columbia Basin provenance (Allen and others, 1986). The floods occurred later than 15,000 years B.P. (Baker and Bunker, 1985; Waitt, 1985), and a bog overlying flood deposits near Portland is dated as 13,000 years B.P. (Mullineaux and others, 1978; McDowell, 1991).

HOLOCENE DEPOSITS

During the Holocene, the Willamette River has incised the main Calapooyia-Senecal surface (fig. 83) and cut and deposited three additional surfaces, the Winkle, Ingram, and Horseshoe (Balster and Parsons, 1968). The surfaces reflect a change from a more braided channel pattern to the present meandering channel pattern (McDowell, 1991). Holocene sand, gravel, silt, and clay are largely confined to channels and flood plains of major rivers and their tributaries.

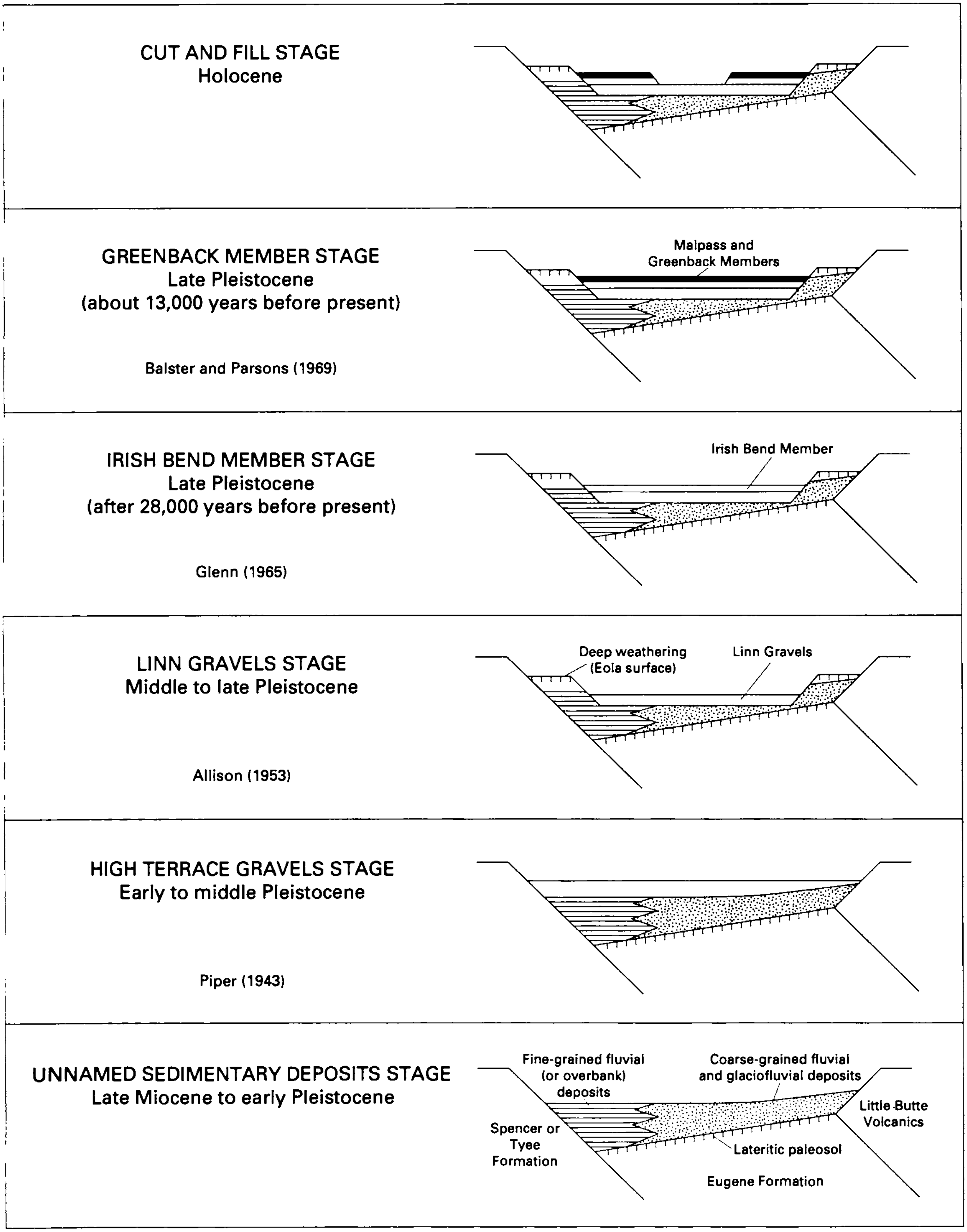


Figure 83. Depositional history of the southern Willamette Valley, Oregon, after Miocene time. Modified from Roberts (1984).

STRUCTURE

Faulting and folding have taken place in the Willamette Valley and Coast Range since the emplacement of the Siletz River Volcanics. Angular unconformities are common. The region has been near a subduction zone for the entire Cenozoic era, with plate convergence rates decreasing and the strike-slip component of subduction increasing from the Paleocene to the present (Wells and others, 1984; Riddihough, 1984). This history has resulted in clockwise rotation of structural blocks, with the amount of rotation decreasing from Eocene time to the present and from west to east.

In this chapter, we focus on deformation affecting the Columbia River Basalt Group and younger deposits. Older structures are examined briefly; they are important to our discussion only because in some places they are zones of weakness reactivated by younger faulting and thus they may have seismogenic potential. Faults cutting Oligocene and older strata but having unknown age relations to the Columbia River Basalt Group and younger deposits are discussed by Graven (1990) and Werner (1990). Most faults are shown on plate 2A and 2B and in figures 84 and 85.

DEFORMATION PREDATING THE COLUMBIA RIVER BASALT GROUP

COAST RANGE ANTICLINORIUM

Present-day exposures of the Siletz River Volcanics commonly correspond to basement highlands that existed during the time Eocene strata were deposited. The Tyee Formation onlapped a highland composed of the Siletz River Volcanics in the Valsetz area west of Dallas. The Siletz River Volcanics in the hanging wall of the Corvallis fault occupied a positive area that caused the informally named Miller sand of the Yamhill Formation to lens out toward the fault (Baker, 1988; Graven, 1990). This positive area provided detritus to the upper Eocene Spencer Formation (Goldfinger, 1990). In the northern Willamette Valley, strata as young as the Scotts Mills Formation (Oligocene and Miocene) were tilted to the east prior to the formation of the Columbia River Basalt Group, presumably reflecting uplift of the Coast Range, yet the Coast Range was low enough that intracanyon flows of the Columbia River Basalt Group were able to cross the range to the present-day coastline.

CORVALLIS FAULT

The northeast-trending Corvallis fault (fig. 84; pl. 2B) is at least 50 km long, and for part of its length, it is the western boundary of the southern Willamette Valley. The fault cannot be traced across the Willamette River to the Salem Hills, although the small-displacement Turner fault in the Salem Hills has the same trend and sense of displacement. Two recent gravity profiles show that the primary fault is a thrust that dips about 10° northwest (Goldfinger, 1990). Dips of strata in the hanging wall average 20° northwest, and beds in both the hanging wall and the footwall are overturned close to the fault, suggesting a fault-propagation fold geometry. Vertical separation on the Corvallis fault at seismogenic depths is about 6.7 km, a figure obtained by adding the separation on the fault at the surface and the separation implied by considering surface folding as caused by fault propagation (Yeats, 1988). Using a fault dip of 20°, the horizontal shortening is calculated as 11–13 km. The fault was active in late Eocene time, an interpretation based on isopachs on a map of the Miller sand that show thinning of the sand in the direction of the Corvallis fault (Baker, 1988) and on sedimentary breccia with clasts of the Siletz River Volcanics present within the Spencer Formation, adjacent to the fault west of Corvallis (Goldfinger, 1990). A younger high-angle fault parallel to the Corvallis thrust is exposed in a quarry 2 km northeast of Philomath and has left-lateral horizontal slickensides and mullion structure. The main fault trace is offset by several northwest-trending faults. Because this high-angle fault may displace Pleistocene sedimentary deposits, it is discussed further below.

EOLA HILLS-AMITY HILLS NORMAL FAULTS

A proprietary seismic profile shows that the Siletz River Volcanics and the lower part of the Yamhill Formation in the Eola Hills and Amity Hills are cut by two normal faults showing movement down to the east (fig. 85). This profile and a residual gravity map (Werner, 1990) suggest that the faults strike north-northeast. The Yamhill Formation increases in thickness eastward across the faults from 950 to 1,450 m. The Spencer Formation and the upper part of the Yamhill Formation are only slightly warped across the westernmost of the two faults.

DEFORMATION YOUNGER THAN THE COLUMBIA RIVER BASALT GROUP

COAST RANGE ANTICLINORIUM AND WILLAMETTE VALLEY SYNCLINORIUM

Flows of the Columbia River Basalt Group can be traced to the western margin of the northern Willamette Valley where they are exposed in an east-dipping homocline. Subaerial flows and invasive flows identical to those mapped in the Willamette Valley are found on the Oregon coast from Seal Rock north to the Columbia River. The absence of the Columbia River Basalt Group in the intervening Coast Range is due to younger warping of the Coast Range (Niem and Niem, 1985). As the Coast Range arched upward, the

Willamette Valley subsided and accumulated sediments of the proto-Willamette and proto-Columbia rivers and major tributary side streams. At Monroe, these sedimentary deposits are dated by palynology as late Miocene to early Pliocene (Roberts and Whitehead, 1984), but contact relations as young as 0.6 Ma with the Boring Lavas suggest that these sedimentary materials may be as young as Pleistocene. We suggest that the aggradation in the Willamette Valley and adjacent Columbia River valley was caused by a relative change in base level as the Coast Range was uplifted.

Farther east, the western Cascade Range underwent tilting (Priest, 1989). Beeson, Tolan, and Anderson (1989) recognized more than 1,200 m of uplift of the Cascade Range near the Columbia River, based on the structure of the Columbia River Basalt Group and overlying Troutdale Formation.

CORVALLIS FAULT

In the main Corvallis fault zone, horizontal slickensides are found in rocks as young as Oligocene intrusions, suggesting reactivation in a stress field compatible with north-south compression. In Corvallis and along the lower reaches of the Marys River, the contact between gravel possibly correlated with the Rowland Formation and the Willamette Formation dips 6°–12° east and southeast. The gravel is capped by the Quad surface of Balster and Parsons (1969), a probable continuation of their Calapooyia surface. Adjacent to the Corvallis fault, this surface is 30–40 m higher than it is farther east, suggesting to Balster and Parsons (1969) that the surface was uplifted by faulting. At the Mid Valley quarry between Philomath and Corvallis, the contact between the Willamette Formation and the underlying gravels is at an altitude of 107 m, near the highest elevation at which the Willamette Formation has been found (McDowell and Roberts, 1987). This contact is at an altitude of 68 m in the Willamette River channel east of the Mid Valley quarry. In addition, pre-Rowland Formation overbank facies deposits of the proto-Willamette River similar to those present at and east of the Willamette River (figs. 79, 81, and 82) are absent beneath the gravels at the Mid Valley quarry. These relations suggest eastward tilting or east-side-down faulting. Alternatively, the gravels at the Mid Valley quarry may be older than the Rowland Formation at the Willamette River.

In north Corvallis between Walnut Boulevard and a saddle at the entrance to Chip Ross Park, south of Jackson Creek, a scarp ranging from a few centimeters to 1 m in height marks the trace of the Corvallis fault. It has the same sense of displacement as the main fault, steeply dipping with the southeast side down, as based on relations exposed in a hand-dug pit. This scarp could be a slump rather than a fault. Low-sun-angle aerial photographs show northwest-trending scarps that may be related to left steps on the Corvallis fault. These scarps occur in areas of outcrops of the Siletz River Volcanics and high-terrace gravels. The neotectonic origin of these features is not confirmed (Goldfinger, 1990).

Goldfinger (1990) identified three earthquakes that have been felt along the general trend of the Corvallis fault, one of intensity III in 1957, one of intensity III–IV in 1961, and one of intensity V probably in 1946 or 1947 (incorrectly reported as May 12, 1942, by Berg and Baker, 1963).

OWL CREEK FAULT

The Owl Creek fault (figs. 82 and 84) strikes N. 10° E., has reverse separation with the east side up, and is associated with an anticline in the hanging wall. The Spencer Formation is 220 m thick on the crest of this fold but 550 m thick east of the fold, suggesting growth during Eocene time (Graven, 1990). Water-well data show that the bedrock surface is 115 m higher on the crest of the anticline than it is to the east and west (fig. 82). By comparison, the base of the Spencer Formation is 725 m higher on the crest of the anticline than it is to the east and west. In the upthrown block, proto-Willamette River overbank deposits dip east with respect to gravels of the Rowland Formation, and the Rowland Formation is eroded away near the fault so that the Willamette Formation rests directly on the Eugene Formation (fig. 82). Gravel in the Rowland Formation of Cascade Range provenance is exposed in the banks of the Willamette River at Corvallis, west of the fault, suggesting that the Rowland Formation was deposited over the Owl Creek structure, then uplifted and eroded from the hanging-wall block prior to the deposition of the Willamette Formation, which appears to postdate all faulting.

HARRISBURG ANTICLINE

A broad east-northeast-trending anticline between Corvallis and Eugene plunges east (fig. 84) and has about 100 m relief on the Eugene-Spencer Formation contact. The axis of the channel of the proto-Willamette River is warped upward about 50 m where it crosses the anticline at Harrisburg (fig. 86). There is no evidence of faulting associated with this anticline.

JEFFERSON ANTICLINE

A broad anticline (fig. 84, pl. 2B) north of Albany creates the concave-to-the-west map trace of the base of the Eugene Formation, as expressed by structure contours. There is no evidence of stratigraphic thinning of Eocene strata across the structure, indicating that the fold developed later. Topography resulting from anticlinal growth may have diverted flows of the Columbia River Basalt Group, particularly the Ginkgo flows of the Frenchman Springs Member of the Wanapum Basalt, northwestward around the anticline.

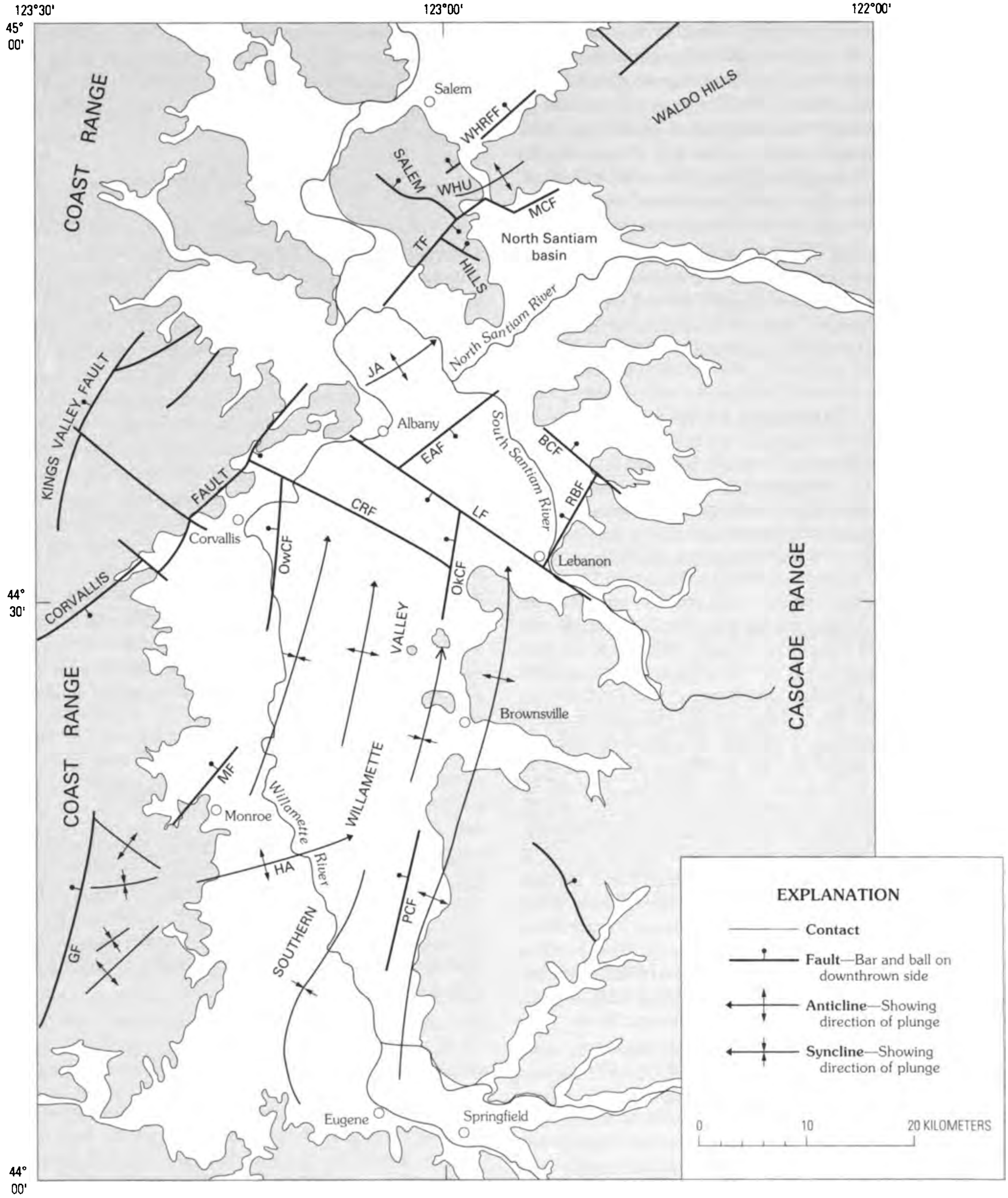


Figure 84. Tectonic map of the southern Willamette Valley, Oregon. Areas underlain by alluvial and fluvial deposits that postdate the Columbia River Basalt Group are unshaded; areas underlain directly by bedrock are shaded. BCF, Beaver Creek fault; CRF, Calapooia River fault; EAF, East Albany fault; GF, Glenbrook fault; HA, Harrisburg anticline; JA, Jefferson anticline; LF, Lebanon fault; MCF, Mill Creek fault; MF, Monroe fault; OwCF, Owl Creek fault; OkCF, Oak Creek fault; PCF, Pierce Creek fault; RBF, Ridgeway Butte fault; TF, Turner fault; WHRFF, Waldo Hills range-front fault; WHU, Waldo Hills uplift.

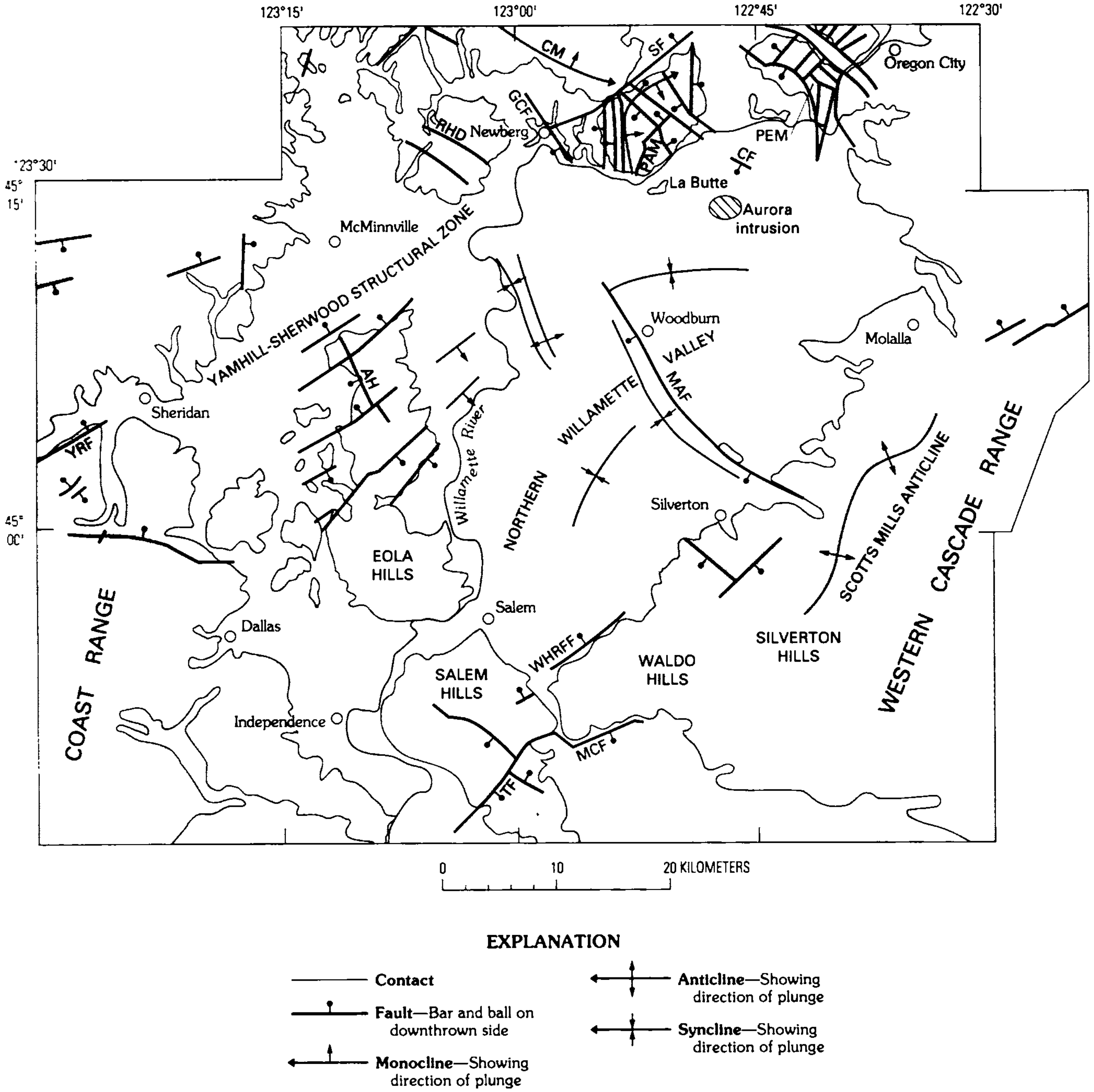


Figure 85. Tectonic map of the northern Willamette Valley, Oreg. Unshaded areas are underlain by alluvial and fluvial deposits that post-date the Columbia River Basalt Group. AH, Amity Hills; CM, Chehalem Mountains; PAM, Parrett Mountain; PEM, Petes Mountain; RHD, Red Hills of Dundee; CF, Curtis fault; GCF, Gales Creek fault; MAF, Mt. Angel fault; MCF, Mill Creek fault; SF, Sherwood fault; TF, Turner fault; WHRFF, Waldo Hills range-front fault; YRF, Yamhill River fault.

The axis of a channel of the proto-Willamette River west of the Salem Hills crosses a bedrock highland north and east of Albany including Spring Hill, Scravel Hill, and Hale Butte (fig. 81; pl. 3), and it is likely that this channel was warped upward across the Jefferson anticline. However, the base of the Rowland Formation does not appear to be warped (fig. 81). The Jefferson anticline may be a northeast continuation of the hanging-wall block of the Corvallis fault in which the Siletz River Volcanics are at the surface. The northwest-striking contact of the Siletz River Volcanics with younger rocks is expressed as a positive gravity anomaly in residual-gravity contours (Werner, 1990).

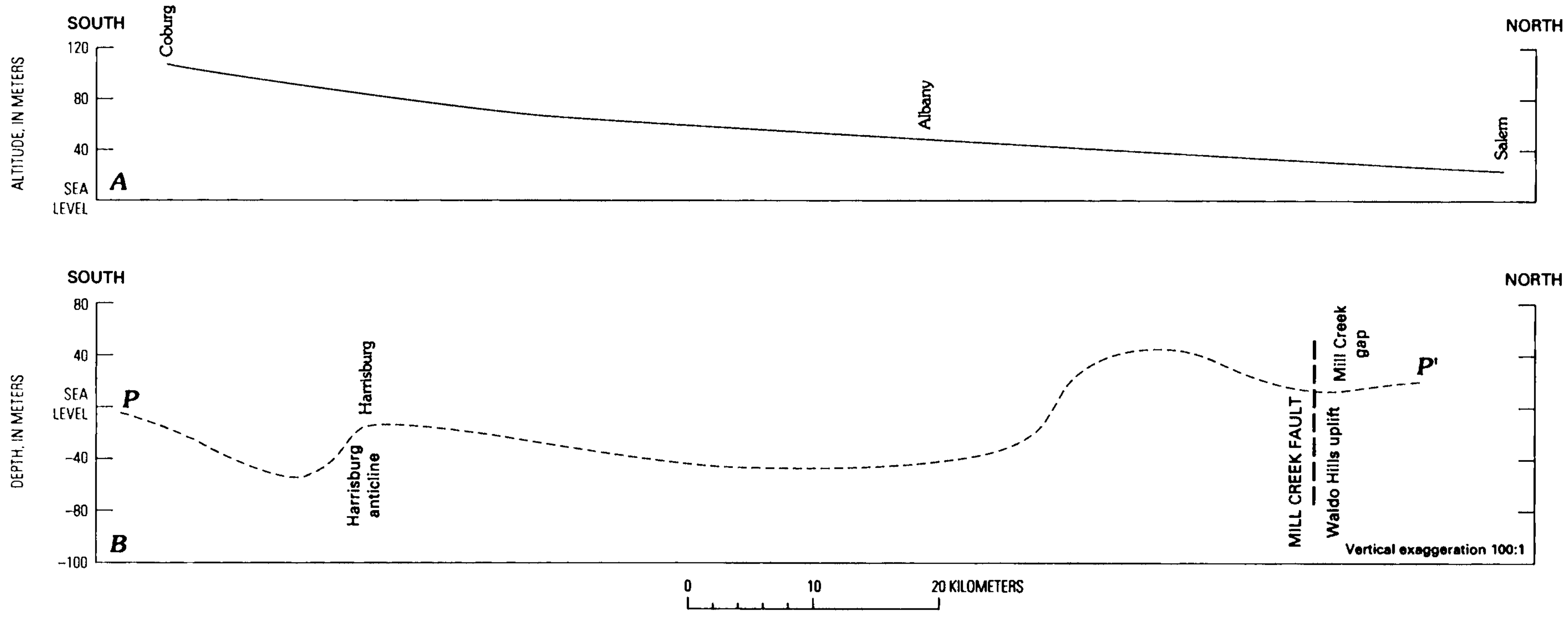


Figure 86. Longitudinal profiles of the modern and proto-Willamette Rivers, Oreg. *A*, profile of the modern river. *B*, profile of the proto-Willamette River showing deformation of the axis of the main stream channel. See plate 3 for location of line of section *P–P'*.

NORTH SANTIAM BASIN

The North Santiam River crosses a basin bounded by the Waldo Hills on the north, the Salem Hills on the west, and the western Cascade Range on the east. The minimum structural relief at the top of the Columbia River Basalt Group in the North Santiam basin is 260 m, based on the maximum depth to basalt in water wells in the basin and also the top of the Columbia River Basalt Group in the adjacent Waldo Hills. Except for the Mill Creek fault discussed below, no faults have been recognized in this basin, perhaps because of the difficulty of correlating horizons in the sedimentary deposits postdating the Columbia River Basalt Group across the basin.

MILL CREEK FAULT

The southern edge of the Waldo Hills is marked by a fault that displaces the Columbia River Basalt Group about 100 m (pl. 2B). The base of the Columbia River Basalt Group is exposed along the western end of the Waldo Hills near Turner, whereas the top of the group is near sea level in the North Santiam basin south of the range front. The Mill Creek fault may be the eastern extension of the Turner fault in the Salem Hills.

WALDO HILLS RANGE-FRONT FAULT

The northern range front of the Waldo Hills is marked by a pronounced northeast-trending aerial-photograph lineation that is on a trend with the Corvallis fault to the southwest. The contact between the Columbia River Basalt Group and underlying marine strata is exposed near the range front southeast of Salem; several wells also penetrate this contact (fig. 87). Northwest of the range front, water wells reach the top of the Columbia River Basalt Group, indicating vertical separation of at least 50 m. The fault may extend farther northeast than shown; vertical separation decreases toward the northeast. No clear evidence shows that the fault cuts strata younger than the Columbia River Basalt Group.

GALES CREEK-MOUNT ANGEL STRUCTURAL ZONE

The Gales Creek-Mount Angel structural zone is the southernmost of several northwest-trending, seismically active linear features in northwestern Oregon and southwestern Washington (Werner, 1990). Both the Gales Creek-Mount Angel structural zone and the Portland Hills-Clackamas River structural zone were active during formation of the Columbia River Basalt Group. The Mount Angel fault, part of the Gales Creek-Mount Angel structural zone, formed a barrier to three Silver Falls flows of the Frenchman Springs Member of the Wanapum Basalt (Beeson, Tolan, and Anderson, 1989).

Geological evidence exists for three segments of the Gales Creek-Mount Angel structural zone: the Gales Creek fault, the Newberg fault, and the Mount Angel fault, which have the same strike but are offset (fig. 85). The Gales Creek fault segment follows the Gales Creek valley between Gales Peak and David Hill, juxtaposing rocks equivalent to the Tillamook volcanics to the southwest with the Columbia River Basalt Group on the northeast. The fault has been extended south toward Gaston, where seismic profiles reveal a complex zone of deformation extending from Gaston to the base of the Chehalem Mountains. Modeling of a gravity profile across this zone suggests three fault segments having a total vertical separation, largely earlier than the Columbia River Basalt Group, of almost 3 km, down to the northeast (H.J. Meyer, Oregon Natural Gas Corp., oral commun., 1991). It is unclear whether this zone connects with the Newberg fault segment.

Werner (1990) mapped the Newberg fault on the basis of water-well data (fig. 88). North of the fault, the base of the Columbia River Basalt Group is exposed on the south side of the Chehalem Mountains and dips northeast. South of the fault, the top of the Columbia River Basalt Group is exposed in the Red Hills of Dundee and also dips northeast. The group is juxtaposed against Oligocene and Miocene marine strata along the fault, though the apparent sense of vertical offset is opposite that expressed in the Gaston area (Popowski, 1995). Gradient analyses of aeromagnetic and gravity data support the fault location. A seismic profile across the projection of the fault zone between Newberg and Woodburn shows no displacement of the top of the Columbia River Basalt Group (Werner, 1990).

The Mount Angel fault (fig. 85) was first mapped near Mount Angel by Hampton (1972) using water-well data. Based on additional data from seismic profiles and water wells, we extend the Mount Angel fault from the Waldo Hills northwest past Woodburn (figs. 89 and 90). Vertical offset of the top of the Columbia River Basalt Group increases to the southeast from 100 m in seismic section *A–A'* (fig. 91) to 200 m in seismic section *B–B'* (fig. 92), and at least 250 m in cross section *C–C'* (fig. 93). The presence of the Frenchman Springs Member of the Wanapum Basalt at the top of Mount Angel (M.H. Beeson, Portland State University, oral commun., 1990) indicates that the top of the Columbia River Basalt Group would have been close to the present summit prior to erosion, constraining offset to about 250 m. A seismic reflector within the overlying fluvial sequence is offset about 40 m and the dip of the fault is 60°–70° NE., based on seismic section *B–B'* (fig. 92). On the southwest side of the fault, the top of the Columbia River Basalt Group is warped into a shallow syncline that increases in prominence northward as offset on the Mount Angel fault decreases (fig. 88).

Evidence for the Mount Angel fault is limited in the Waldo Hills, although a Ginkgo intracanyon flow of the

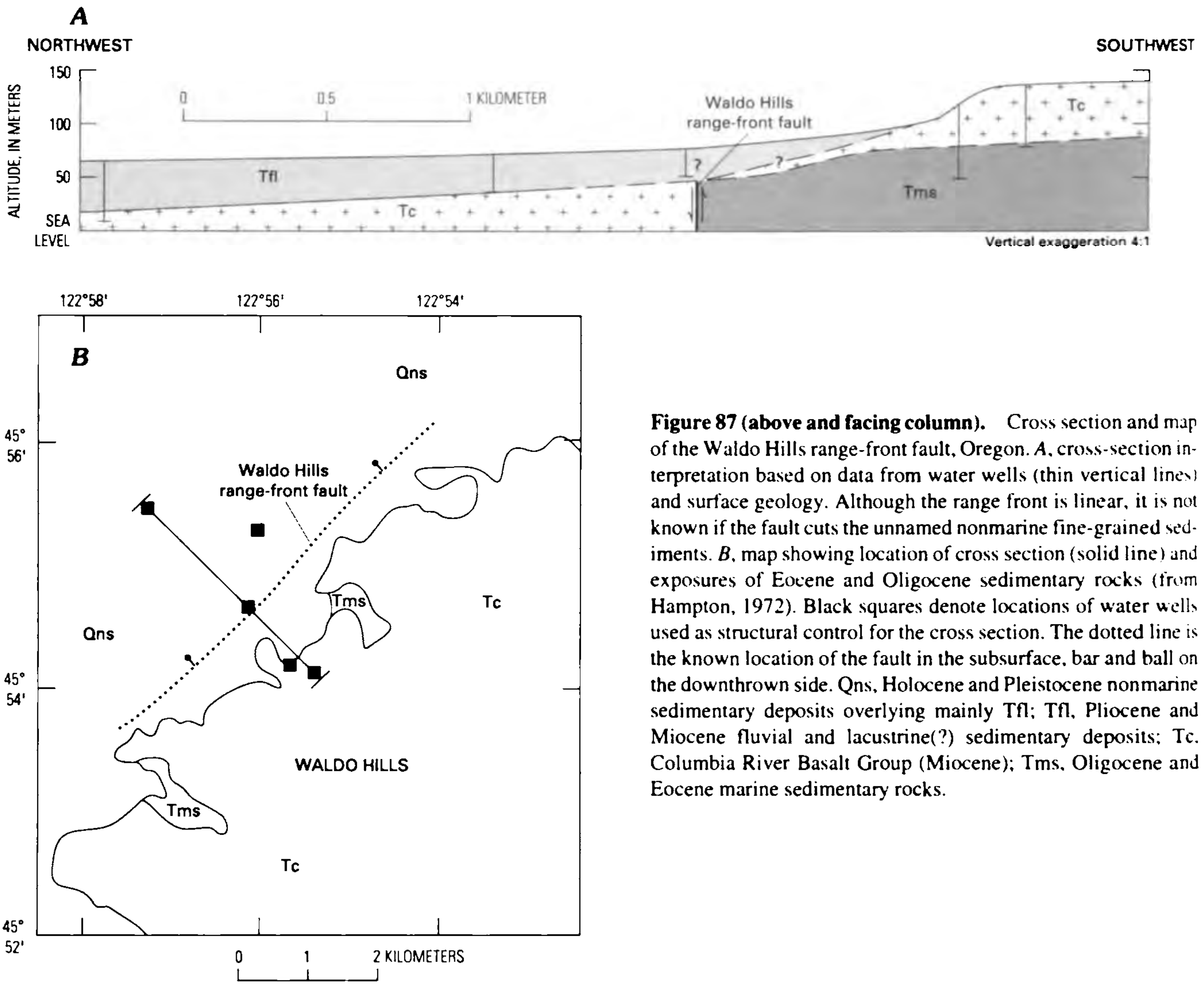
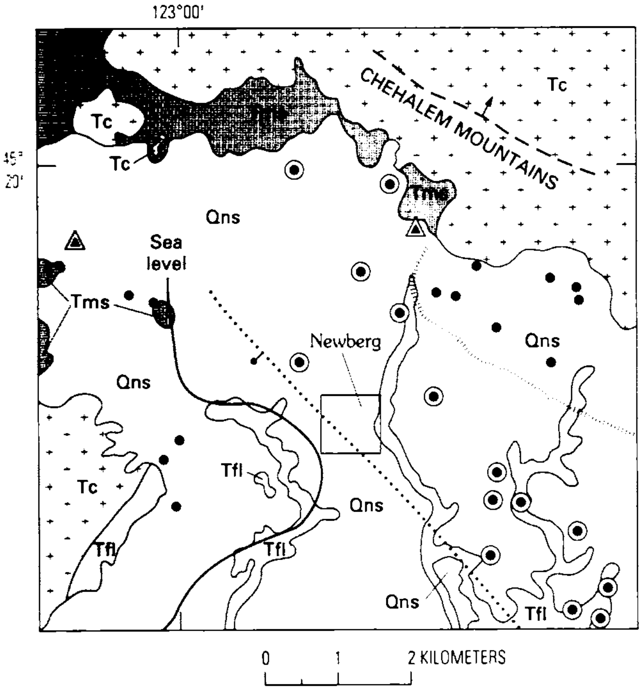


Figure 87 (above and facing column). Cross section and map of the Waldo Hills range-front fault, Oregon. *A*, cross-section interpretation based on data from water wells (thin vertical lines) and surface geology. Although the range front is linear, it is not known if the fault cuts the unnamed nonmarine fine-grained sediments. *B*, map showing location of cross section (solid line) and exposures of Eocene and Oligocene sedimentary rocks (from Hampton, 1972). Black squares denote locations of water wells used as structural control for the cross section. The dotted line is the known location of the fault in the subsurface, bar and ball on the downthrown side. Qns, Holocene and Pleistocene nonmarine sedimentary deposits overlying mainly Tfl; Tfl, Pliocene and Miocene fluvial and lacustrine(?) sedimentary deposits; Tc, Columbia River Basalt Group (Miocene); Tms, Oligocene and Eocene marine sedimentary rocks.

Columbia River Basalt Group in the Waldo Hills is offset about 1 km right laterally across the fault (M.H. Beeson, Portland State University, oral commun., 1990).

Six small earthquakes with m_c (m_c is coda-length magnitude) of 2.0, 2.5, 2.4, 2.2, 2.4, and 1.4 occurred on August 14, 22, and 23, 1990, near Woodburn (Werner and others, 1992). Epicenter locations (fig. 90) were determined using the broadband seismic station in Corvallis (epicentral distance, 68 km) and the Washington Regional Seismograph Network. Three earthquakes in 1980 and 1983 having m_c less than 1.7 occurred at the same locality. The waveforms for the six earthquakes are so similar that the locations of all events are considered to be much closer together than shown in figure 90. The preferred focal mechanism (fig. 94) is a right-lateral strike-slip fault (with a small normal component) striking north-south and dipping steeply to the west.

On March 25, 1993, an earthquake with m_c of 5.6 struck the Waldo Hills near the town of Scotts Mills (fig. 77) (Thomas and others, 1993), causing about $28 million in damage. The focal depth was 15 km. A preliminary determination of the focal mechanism has one nodal plane with a strike of N. 56° W. and a dip of 58° NE. A subset of aftershocks defines a plane with a west-northwest strike dipping 55°–60° NE. Rupture was by right-lateral strike slip and reverse slip, consistent with motion on the Mount Angel fault, although the earthquake occurred east of the southeast projection of the Mount Angel fault in the Waldo Hills.



EXPLANATION

———— **Contact**

……⫯…… **Concealed Fault**—Bar and ball on downthrown side

— ⊥ — — **Homocline**—Showing direction of dip

———— **Structure contour of the top of Columbia River Basalt Group**—Altitude west of contour is above sea level

· · · · · **Subcrop of contact between Columbia River Basalt Group and Eocene and Oligocene sedimentary rocks**

● **Water well**—Reaches Columbia River Basalt Goup, located to the quarter-quarter section

◉ **Water well**—Constrains altitude of top of Columbia River Basalt Group, located to the quarter-quarter section

▲ **Water well**—Constrains altitude of top of Columbia River Basalt Group, field located

Figure 88. Buried trace of the Newberg fault, Newberg, Oreg., juxtaposing marine strata on the northeast against the Columbia River Basalt Group on the southwest. Sediments postdating the Columbia River Basalt Group do not appear to be faulted. Map-unit symbols are same as in figure 87.

YAMHILL-SHERWOOD STRUCTURAL ZONE

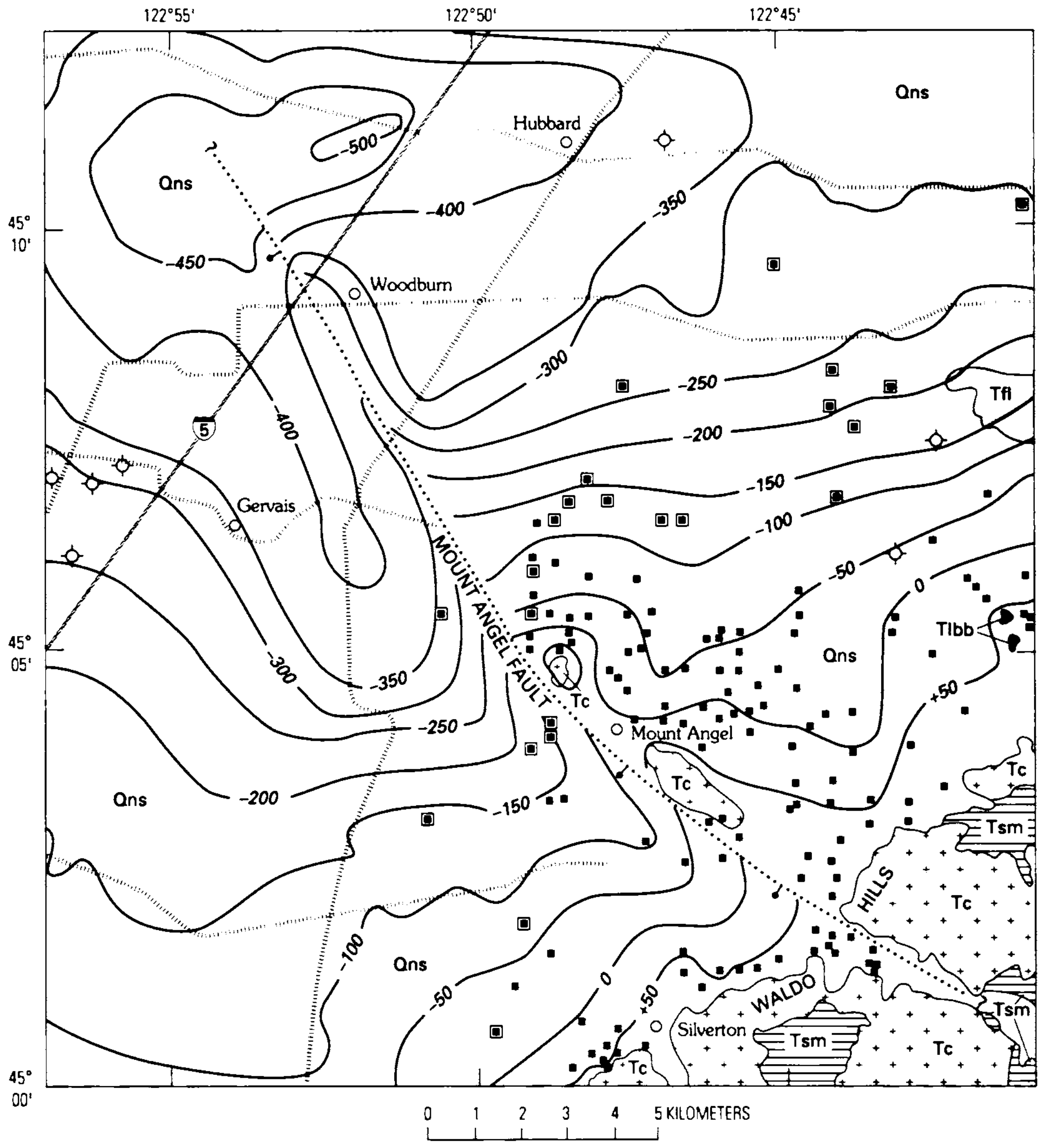
This northeast-trending zone (fig. 85) includes the Yamhill River fault of Baldwin and others (1955) and Brownfield (1982a, b), which juxtaposes the Nestucca Formation on the north against the Yamhill Formation on the south (pl. 2A) with maximum vertical separation greater than 300 m (Baldwin and others, 1955). The fault may continue along the northern end of the Amity Hills, based on a proprietary seismic profile. Farther northeast, the Sherwood fault between Parrett Mountain and the Chehalem Mountains has created 100–150 m of vertical separation in the Columbia River Basalt Group (Hart and Newcomb, 1965; Beeson, Tolan, and Anderson, 1989), though it is poorly expressed in aeromagnetic and gravity data. The Sherwood fault appears to be the southwest continuation of the northern margin of the Columbia trans-arc lowland through which the Columbia River Basalt Group traversed the Cascade Range (Beeson, Tolan, and Anderson, 1989). The structure may be part of the Yamhill-Bonneville lineament, which may have influenced the distribution of vents of the Boring Lavas in the Portland area (Allen, 1975).

NORTHERN WILLAMETTE DOWNWARP

The northern Willamette Valley generally trends northeast, but the northern end of the valley is underlain by an east-trending downwarp in which the top of the Columbia River Basalt Group is as deep as 500 m below sea level. The downwarp cuts across the northern extension of the Mount Angel fault but is most prominent east of the fault. The northern flank is steeper than the southern flank; this may indicate upwarping influenced by the emplacement of intrusions related to the Boring Lavas, such as the Aurora stock (pl. 2A). Sedimentary deposits postdating the Columbia River Basalt Group are warped to a lesser degree than the top of the group, as shown by proprietary seismic data. This downwarp may be part of a western extension of the Yakima fold belt, like other structures to the northeast, as suggested by Beeson, Tolan, and Anderson (1989).

FAULTS AT PARRETT MOUNTAIN, PETES MOUNTAIN, AND IN THE ADJACENT NORTHERN WILLAMETTE VALLEY

Faults at Parrett Mountain and Petes Mountain were mapped by Marvin H. Beeson and Terry L. Tolan of Portland State University (oral commun. to Ian P. Madin, Oregon Department of Geology and Mineral Industries, 1990) based on juxtaposition of flows of the Columbia River Basalt Group identified using geochemical data. Displacements are commonly tens of meters. To the south, seismic profiles show that the top of the Columbia River Basalt Group is



EXPLANATION

———	**Contact**
……┬……	**Concealed Fault**—Bar and ball on downthrown side; queries mark limits of where the fault can be traced in the subsurface
—-50—	**Structure contour on top of basalt**—Datum is sea level
······ ··· ··	**Seismic-reflection profile line**
⌖	**Petroleum-exploration well**
■	**Water well that reaches basalt**
▣	**Deep water well that does not reach basalt**

Figure 89. Structure contour map of the top of basalt units near Mount Angel, Oreg. The basalt is primarily the top of the Columbia River Basalt Group except near exposures of the Miocene basalt and basaltic andesite around the Mount Angel fault. Qns, Holocene and Pleistocene nonmarine sedimentary deposits; Tfl, Pliocene and Miocene fluvial and lacustrine(?) sedimentary deposits; Tc, Columbia River Basalt Group (Miocene); Tsm, Miocene and Oligocene Scotts Mills Formation of Miller and Orr (1988); Tlbb, Miocene basalt and basaltic andesite.

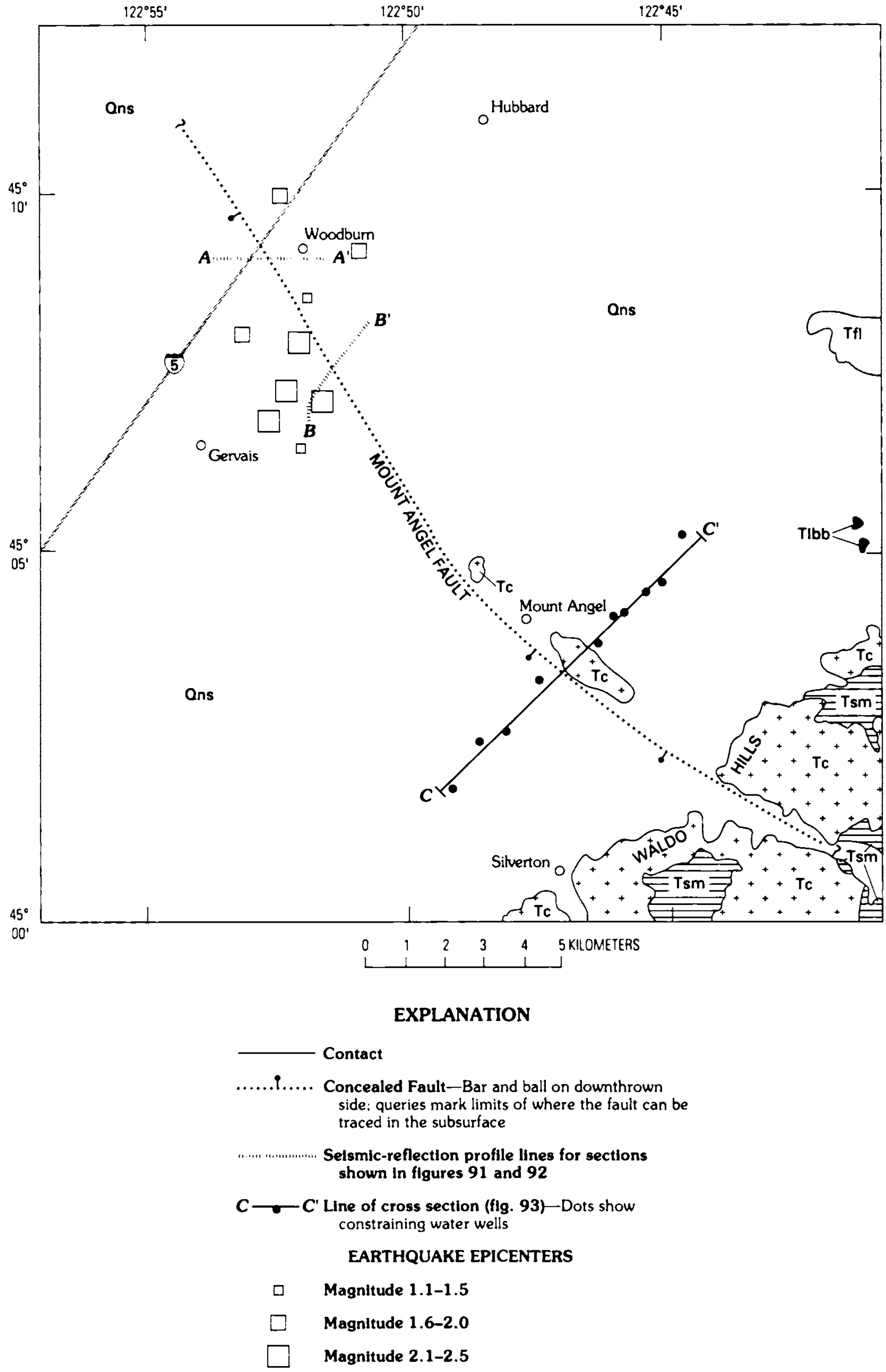


Figure 90. Locations of seismic and water-well cross sections, and epicenters of earthquakes that occurred between 1980 and 1990 near Woodburn, Oreg. Map-unit symbols are same as in figure 89.

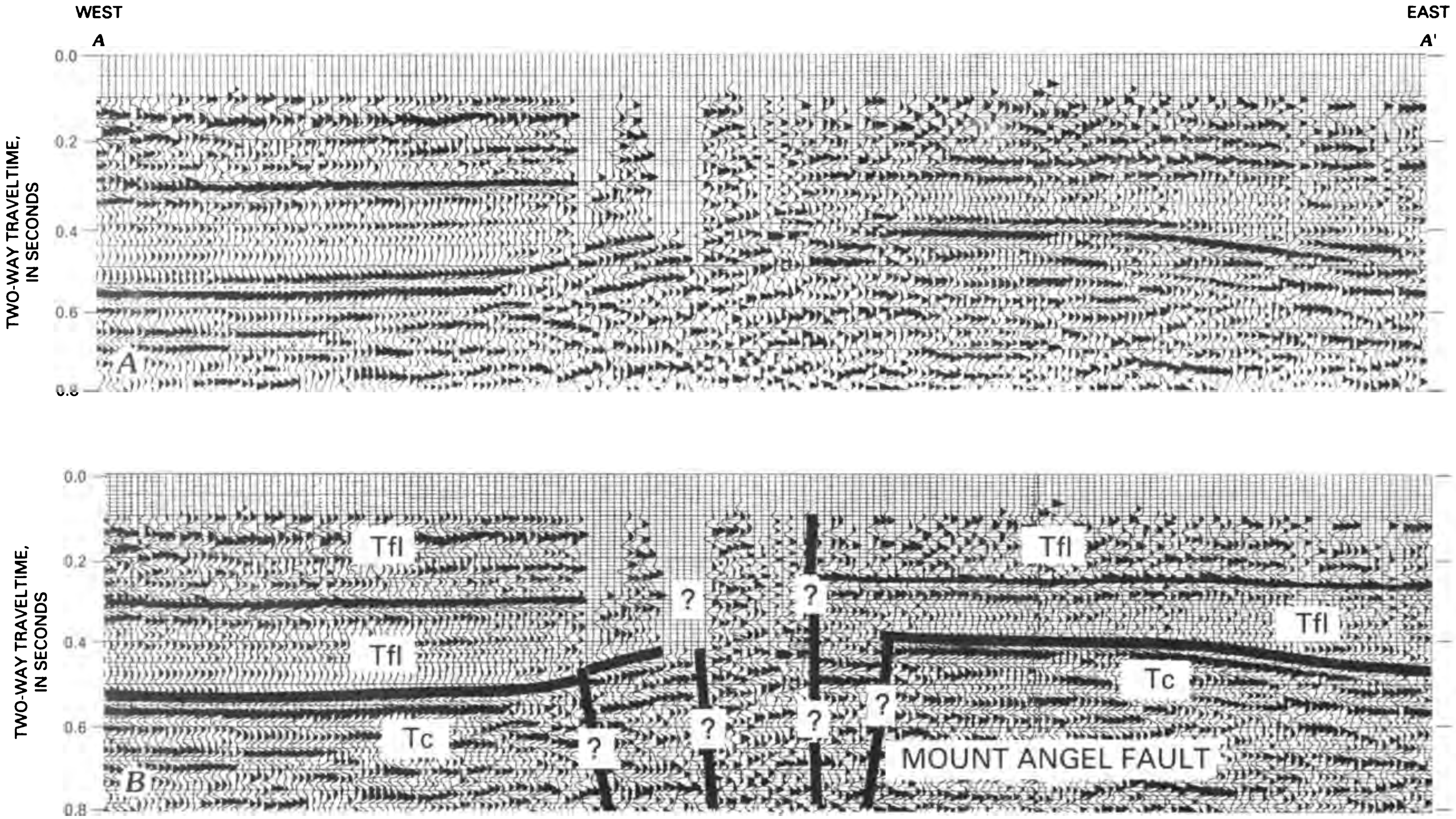


Figure 91. Seismic section *A–A'* across the Mount Angel fault, Willamette Valley, Oreg. *A*, uninterpreted section; *B*, interpreted section. Four strands of the Mount Angel fault are recognized. The prominent reflector within unit Tfl is higher on the northeast than on the southwest side of the fault. Queries denote possible faults. Map-unit symbols are same as in figure 89. Line of section is shown in figure 90.

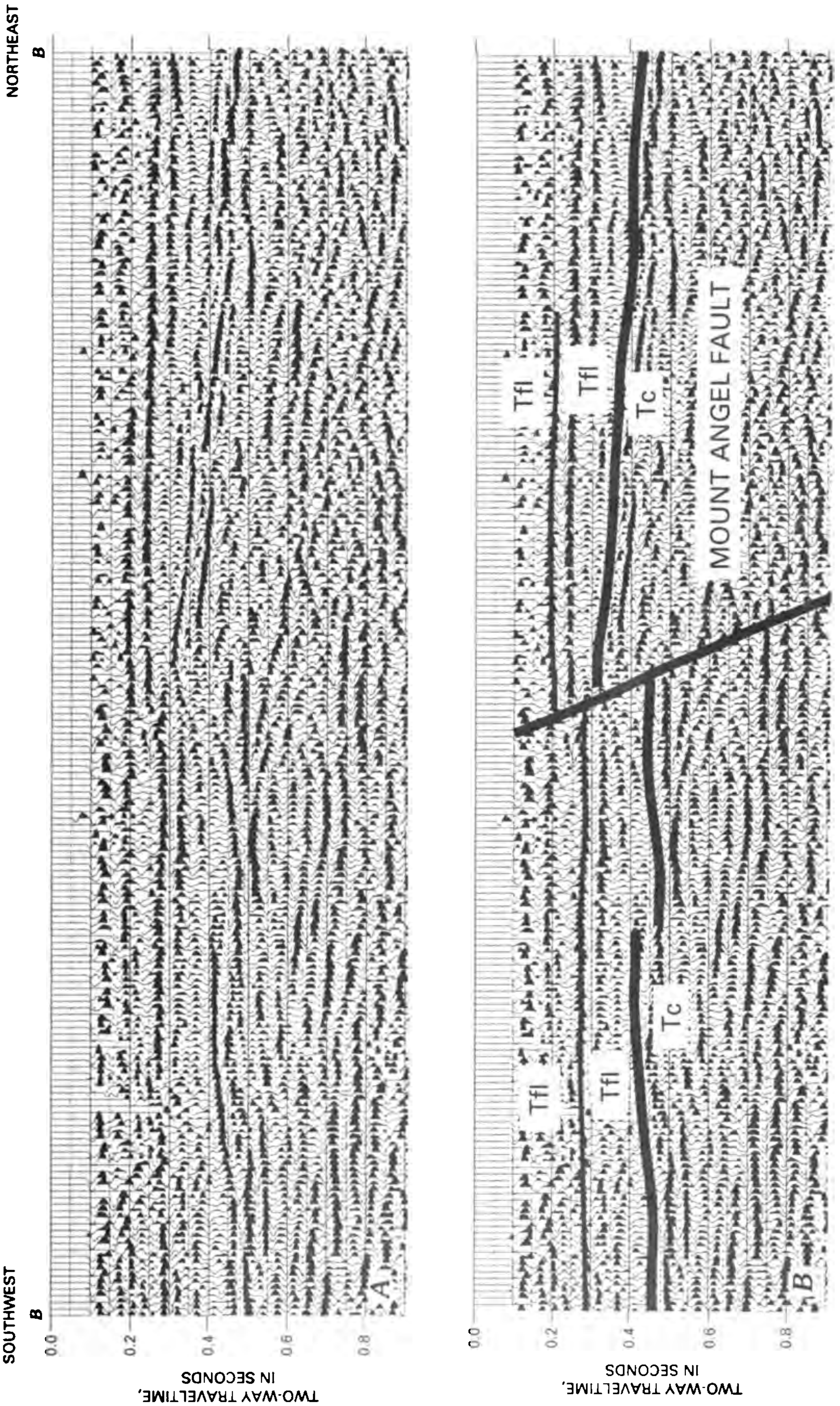


Figure 92. Seismic section *B–B′* across the Mount Angel fault, Willamette Valley, Oreg. *A*, uninterpreted section; *B*, interpreted section. The top of the basalt (unit Tc) is offset a greater amount than the unit Tfl reflector. Map-unit symbols are same as in figure 89. Line of section is shown in figure 90.

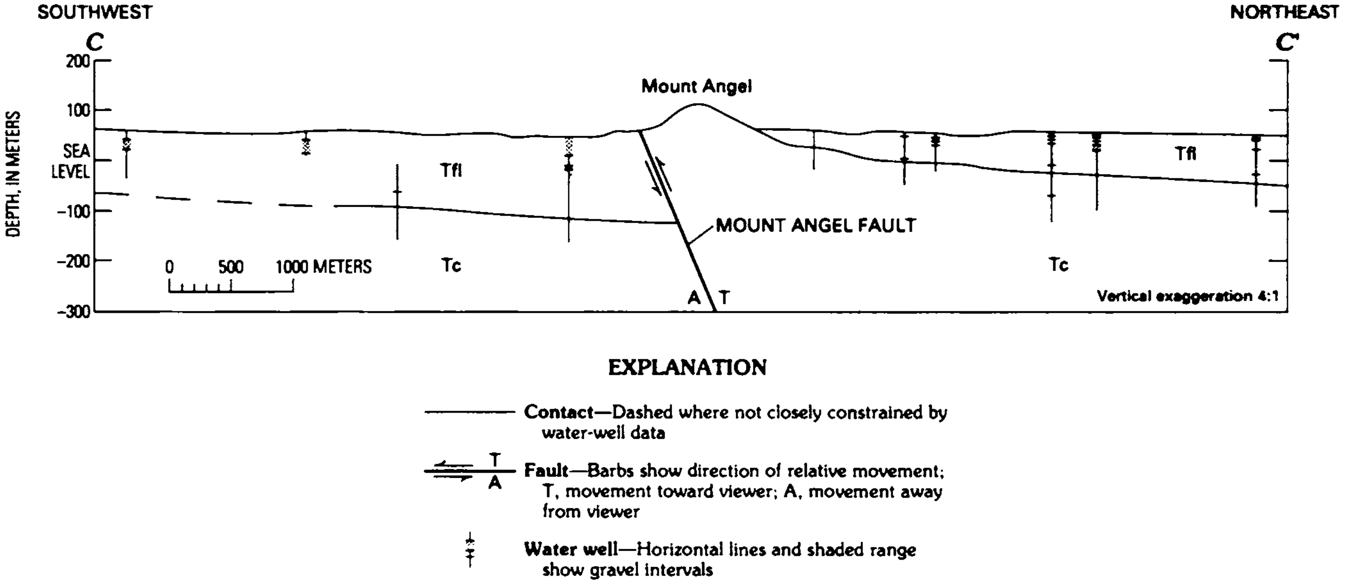


Figure 93. Cross section *C–C'* of the Mount Angel fault, Willamette Valley, Oreg., constrained by water wells. Only those parts of wells with useful well logs are shown. Base of unit Tc is not shown. The fault dip is based on seismic section *B–B'* (fig. 92). Map-unit symbols are same as in figure 89. Line of section is shown in figure 90.

faulted and has undergone upward bulging presumably related to emplacement of intrusions of the Boring Lavas (Werner, 1990). A fault (fig. 95), mapped by Glenn (1965) along the east bank of the Molalla River behind Swan Lake Farms near Canby, dips steeply to the north. A mudstone bed (fig. 95, unit I) beneath the unfaulted Willamette Formation is offset 1 m down to the north. The mudstone was correlated by Glenn (1965) with rocks now known as the Rowland Formation, although the characteristic paleosol at the top of what is now called the Diamond Hill Member is absent. Alternatively, the mudstone could be part of the pre-Rowland Formation fluvial sequence that is exposed east of Canby.

BEAVERTON FAULT ZONE

The Beaverton fault zone extends from beneath downtown Beaverton about 14 km westward along the northern flank of Cooper Mountain and the hills north of Farmington. The fault zone was originally mapped as a single fault with separation down to the north by Madin (1990) utilizing water wells. Proprietary seismic-reflection data and recently acquired aeromagnetic data (Snyder and others, 1993) show two separate traces in the area north of Cooper Mountain with a net vertical separation of 285 m down to the north. Beneath Aloha, the approximately horizontal flows of the Columbia River Basalt Group are offset 75 m down to the south; basalts of this age are south dipping at 260 m below sea level north of Cooper Mountain, whereas north-dipping flows are exposed at 100 m elevation on the northern flank of Cooper Mountain. A data gap in the seismic profile prevents precise location of the southern trace of the fault.

The westward extent of the fault zone is poorly constrained due to the paucity of deep water wells in the area north of Farmington but is interpreted to extend still farther along the northern flank of the Chehalem Mountains. Several(?) northeast-trending faults extending from the Chehalem Mountains to the Beaverton fault zone, interpreted on the basis of aeromagnetic data and water wells, are apparently truncated by the fault zone.

ELMONICA FAULT ZONE

Two subparallel faults, constrained by seismic-reflection profiles and aeromagnetic data, extend westward at least 11 km from Elmonica to the confluence of Rock and Beaverton Creeks south of Orenco (pl. 2A). The westward extent of the fault zone is unknown due to the paucity of deep water wells in the center of the basin, but interpretation of aeromagnetic data suggests the faults terminate east of Sewell.

The net vertical separation of the Columbia River Basalt Group is between 85 and 110 m down to the north. Separation on the northern trace increases westward, from about 10 m near Elmonica to 110 m south of Orenco, though possible intrusions of the Boring Lavas visible on seismic profiles complicate the structure. Seismic-reflection data show that folding of the reflectors in the upper part of the overlying sedimentary deposits increases westward; the reflectors are offset about 20 m near the mapped western end of the fault. Where the southern trace crosses seismic profiles, the vertical separation is about 75 m, and the reflectors in the overlying sedimentary deposits are not visibly offset.

HELVETIA FAULT

The northwest-trending Helvetia fault (pl. 2A) offsets the Columbia River Basalt Group from the McKay Creek valley southeastward to north of Orenco, based on water-well data. Separation is down to the southwest. The fault may extend northwestward into the Tualatin Mountains. Water wells west of Helvetia suggest as much as 100 m of vertical separation. The Helvetia fault has little aeromagnetic expression.

Undulation of the top of the Columbia River Basalt Group in the northern Tualatin basin suggests that similar faults may extend southeastward from the valleys containing the East and West Forks of Dairy Creek, though the data are inconclusive.

TUALATIN BASIN

The Columbia River Basalt Group is folded and faulted into a northwest-trending, fault-bounded, flat-bottomed basin southwest of the Tualatin Mountains and north of the Gales Creek and Newberg faults. The northeast-trending Sherwood fault (fig. 85) terminates the basin to the southeast, and the Helvetia fault and an unnamed fault on the flank of the Tualatin Mountains bound the basin to the northeast. The structure of the eastern part of the basin is complicated by the apparent intrusion of stocks composed of the Boring Lavas. Cooper Mountain and Bull Mountain, in the center of the basin southwest of Beaverton, are underlain by the Columbia River Basalt Group folded into two east-trending, doubly plunging anticlines.

Fill postdating the Columbia River Basalt Group consists of mudstone, siltstone, and sandstone with lenses of pebbly sand and gravel. The abundance of quartz and mica in these sedimentary deposits indicates a predominant source from the Columbia River, with a subordinate local source from the Columbia River Basalt Group in highlands flanking the basin. The floor of the basin is downwarped, and its axis is 200–300 m deep trending east-west. The thickest sequence of strata that postdates the Columbia River Basalt Group measures 410 m, near Hillsboro. Proprietary seismic data show that this dips much more gently than the underlying Columbia River Basalt Group.

DISCUSSION AND CONCLUSIONS

AGE OF THE WILLAMETTE VALLEY AND COAST RANGE

The Willamette Valley is commonly referred to as a forearc basin. However, this statement is true only for the late Cenozoic after emplacement of the Columbia River Basalt Group. Strata that predate the Columbia River Basalt Group are part of a forearc basin, but this basin included the Coast Range as well as the Willamette Valley. For the most part, sedimentary facies deepen to the west across the Willamette Valley and Coast Range, as best documented by the facies boundary between the upper Eocene strandline deposits of the Spencer Formation and deeper water deposits of the Nestucca Formation. There were basaltic highlands to the west, but these did not join to form a continuous Coast Range.

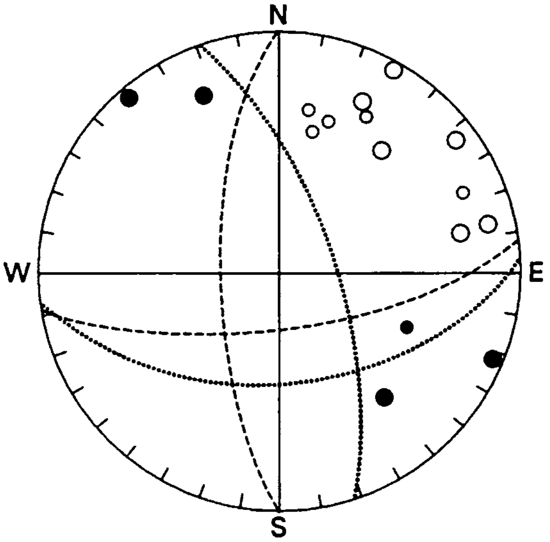


Figure 94. Composite focal mechanism for the August 1990 earthquake sequence at Woodburn, Oreg. (J.L. Nabelek, Oregon State University, written commun., 1990). Circles indicate dilatation and dots denote compression. Larger symbols indicate a stronger first motion. Three separate focal mechanisms based on wave-form analysis are indicated by solid, dashed, and dotted lines; the dashed-line focal mechanism is preferred. These mechanisms are compatible with first-motion solutions.

The first-order structure of the Willamette Valley is an east-dipping homocline that developed after the deposition of the Oligocene and Miocene Scotts Mills Formation and prior to the emplacement of the Columbia River Basalt Group. The east dip of this homocline implies uplift of the Coast Range prior to the emplacement of the Columbia River Basalt Group, but this uplift is not clearly documented in facies changes of sedimentary rocks that predate the group. The flows of the Columbia River Basalt Group passed through the Cascade Range via the Columbia trans-arc lowland of Beeson, Tolan, and Anderson (1989) and continued to the coast as flows filling broad valleys in an incipient Coast Range. There was no marked tendency for these flows to follow the north-south trend of the modern Willamette Valley.

The fluvial deposits of the Willamette River and tributary drainages are the oldest strata to follow the present trend of the Willamette Valley. The top of the Columbia River Basalt Group beneath these deposits is commonly deeply weathered, suggesting that a long time elapsed after the emplacement of the group before these deposits began to

Figure 95. Swan Island fault exposed in the bank of the Molalla River, Willamette Valley, Oreg. The mudstone labeled unit I may be correlative with the Rowland Formation as described by Glenn (1965) at River Bend on the Willamette River, 5 km south-southwest of St. Paul; it is downdropped to the north. Unit II, the overlying Willamette Formation, is unfaulted. View to the northeast. Photograph courtesy of Jerry L. Glenn.

aggrade in the Willamette Valley. A channel cut to 150 m altitude between the Cooper and Bull Mountain uplifts and the Chehalem Mountains also suggests a substantial period of downcutting prior to sedimentation. Aggradation may have been a consequence of Coast Range uplift, raising the local base level for these fluvial sediments. Reactivation of the Gales Creek fault system and new faulting resulted in the deepening of the Tualatin basin. The Willamette Valley was downwarped, resulting in a flattening of homoclinal dips of older strata underneath the valley and, locally, a reversal of dip that produced broad synclines and anticlines.

AGE OF INITIATION OF ARC VOLCANISM EAST OF THE WILLAMETTE VALLEY

The general view is that Cascade arc volcanism began at about 43–42 Ma, based on the age of volcanic rocks at the base of the exposed sequence in the western Cascade Range. Data from wells in the Willamette Valley show that volcanic rocks of the Fisher Formation are underlain by the Yamhill Formation, which grades southeast from marine strata to volcanic and volcaniclastic rocks. The Yamhill Formation in the Willamette Valley contains early Narizian to late Ulatisian foraminifers, suggesting an age of 48–45 Ma. Coccoliths from the Yamhill Formation of the Coast Range are referred to Subzones CP 13c and CP 14a, with estimated ages of 47–42.5 Ma.

The underlying Tyee Formation shows no evidence of a nearby eastern volcanic source, suggesting that it predated the inception of a volcanic arc east of the Willamette Valley. Coccoliths from the Tyee Formation are referred to Subzones CP 12a and CP 12b, with an age estimated as 52.5–50 Ma. Thus, a volcanic arc was initiated later than 50 Ma, and arc volcanism occurred during deposition of the Yamhill Formation as early as 47 Ma. This 50–47 Ma age is coeval with the deposition of the Clarno Formation east of the Cascade Range, and the Yamhill-age arc volcanism may be part of the Clarno arc.

THE SOUTHERN WILLAMETTE VALLEY AS A BROAD STRIKE VALLEY

The older rocks of the western Cascade Range occur in an eastward-dipping homocline that strikes nearly north (Sherrod and Pickthorn, 1989). The outcrop belt is truncated at a low angle by the range front of the western Cascade Range such that the oldest sequence, dated at 45–35 Ma, is truncated in the southern Willamette Valley south of Lebanon, and the next oldest, dated at 35–25 Ma, is truncated against the Willamette Valley east of Salem. Facies boundaries between marine sedimentary rocks and volcaniclastic rocks of late Eocene and Oligocene age strike north-northeast. This discordance between strike direction and the western Cascade Range front means that the outcrop belt of Eocene and Oligocene rocks cuts across the arc at a small angle so that the southern end of the outcrop belt consists of volcanic rocks and the northern end consists of sedimentary rocks (fig. 96).

The southern and eastern edges of the Willamette Valley appear to be controlled by the facies boundary between erosionally resistant volcanic and erosionally weak nonvolcanic rocks. The southern edge of the Willamette Valley corresponds to the northward termination of the Fisher Formation near Eugene. Volcanic rocks of the Little Butte Volcanics change facies to sedimentary rocks at the eastern margin of the southern Willamette Valley. Intrusive plugs in the Eugene Formation form isolated hills, including Peterson Butte and Bond Butte near the eastern edge of the valley.

The western edge of the valley is controlled by the contact between erosionally resistant sandstones of the Tyee Formation and the Spencer Formation on the west and erosionally weak fine-grained strata of the Eugene Formation to the east. Most of the valley is underlain by the Eugene Formation. The outcrop belt is wide because of a decrease in the east dip of the Eugene Formation accompanying downwarping of the Willamette Valley following emplacement of the Columbia River Basalt Group. The strike valley underlain by the Eugene Formation is a late Tertiary feature because it is covered by fluvial deposits of the Willamette River system.

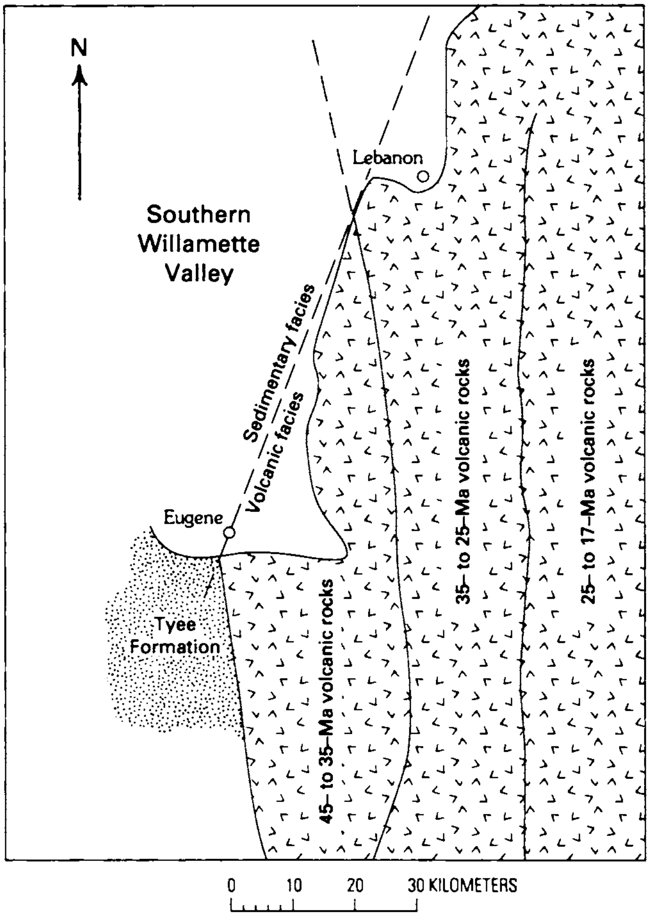


Figure 96. Map showing outcrop belts of western Cascade Range volcanic rocks (modified from Sherrod and Pickthorn, 1989) and the north-northeast-trending boundary between volcanic and sedimentary rocks (dashed line). The facies boundary controls the position of the eastern edge of the Willamette Valley; erosionally resistant volcanic rocks are to the east-southeast and weak sedimentary rocks, principally the Eugene Formation, are to the west-northwest beneath the valley.

STRUCTURAL CONTROL OF FAULT SYSTEMS

Western Oregon has undergone clockwise rotation from the Eocene through at least Miocene time, with greater rotations in the Coast Range than in the Cascade Range (Wells and Heller, 1988). This rotation has led to the development of faults with major displacement as early as the Eocene, the greatest measured displacement being on the Corvallis fault. Because these faults are zones of weakness, further movement is likely to reactivate them, even if their orientation is not parallel to the plane of maximum shear stress. The clearest example of this is the Corvallis fault, which was part of a low-angle fold-thrust system in Eocene time but was subsequently reactivated as a high-angle fault with a large component of strike slip (Goldfinger, 1990). The Gales Creek fault also had major vertical movement in Eocene time (H.J. Meyer, Oregon Natural Gas Corp., oral commun., 1991) and has been reactivated since middle Miocene time.

Werner and others (1991) compared the modern stress orientation in western Oregon using borehole breakouts with stress orientations based on earthquake focal mechanisms, alignment of volcanic vents, and orientation of conjugate faults. They found that the maximum horizontal compressive stress is oriented about north, confirming earlier studies based on less data. The fault-trend patterns in the Willamette Valley are predominantly northwest and northeast, and folds involving the section that postdates the Columbia River Basalt Group commonly strike east, in agreement with a north-south maximum horizontal compressive stress.

EARTHQUAKE HAZARD FROM CRUSTAL FAULTS IN THE WILLAMETTE VALLEY

The fluvial deposits of the Willamette River and its tributaries are cut by several faults with vertical separations as much as 250 m. In addition, these deposits are warped into broad folds that may be the surface expressions of faults at seismogenic depths. The fluvial deposits are poorly dated; paleobotanical evidence from fossil leaves and pollen favor a late Miocene to Pliocene age, and the deposits in the Portland basin are older than the Boring Lavas, which is as young as 600 ka (Ian P. Madin, Oregon Department of Geology and Mineral Industries, oral commun., 1990). Roberts (1984) suggested that the deeply weathered high-terrace gravels of the southern Willamette Valley are the constructional top of the sequence formed by the Willamette River, and that this sequence is as young as Pleistocene.

Deposits that postdate the Columbia River Basalt Group in the Tualatin basin are cut by the Beaverton fault zone and the Helvetia fault, though some of the deformation could be attributed to intrusion of stocks, possibly of the Boring Lavas (Popowski, 1995). The Owl Creek fault (pl. 2B) cuts the Rowland Formation, which is late Pleistocene in age, beginning earlier than 36 ka and continuing past 28.5 ka. If the gravels at the Mid-Valley rock quarry between Corvallis and Philomath are part of the Rowland Formation, the Corvallis fault zone has undergone at least 40 m of vertical separation since the deposition of the Rowland Formation.

The Willamette Formation, dated as younger than 15–13 ka, shows no evidence of offset by faulting, including by the Owl Creek fault. However, seismicity on the Mount Angel fault at Woodburn indicates that this fault is active.

Because the vertical offsets of the proto-Willamette River deposits are no greater than a few hundred meters for deposits that are older than 600 ka, slip rates on Willamette Valley faults are probably small. A displacement of 300 m in 600,000 years represents a maximum average vertical slip rate of 0.5 mm/year. If the northwest- and northeast-trending faults are predominantly strike slip, the rate of 0.5 mm/year would be a minimum. However, the Mount Angel fault, with a maximum vertical offset of the top of the Columbia River Basalt Group of about 250 m, has only a 1-km lateral offset of a Ginkgo intracanyon flow of the Frenchman Springs Member of the Wanapum Basalt. There is no evidence of the amount of horizontal offset of other faults.

Faults in the Willamette Valley are relatively short in length. The mapped length of the Mt. Angel fault is about 24 km, the Waldo Hills range-front fault about 6 km, the Owl Creek fault about 15 km, and the Corvallis fault at least 35 km. The seismic moment of an earthquake with a slip of 1 m on a fault 30 km long in a crust in which the brittle-ductile transition is at 30 km would be 2.7×10^{26} dyne cm, assuming a shear modulus of 3×10^{11} dyne/cm.

It is premature to estimate the earthquake potential from crustal faults in the Willamette Valley because we do not know how much of a mapped fault would rupture in a single earthquake and we do not know what the slip would be in a single crustal earthquake. Earthquakes of moderate size have been generated in this century on the St. Helens seismic zone (Weaver and Smith, 1983), on the Portland frontal-fault structure (Yelin and Patton, 1991), and on the Mount Angel fault (Thomas and others, 1993), but we do not know if larger earthquakes are possible. Finally, we have no direct paleoseismological information about recurrence history on crustal faults in western Oregon.

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