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Earthquake Hazards in the Pacific Northwest of the United States

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TECTONICS OF THE WILLAMETTE VALLEY, OREGON

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Foreword

This paper is one of a series dealing with earthquake hazards of the Pacific Northwest, primarily in western Oregon and western Washington. This research represents the efforts of U.S. Geological Survey, university, and industry scientists in response to the Survey initiatives under the National Earthquake Hazards Reduction Program. Subject to Director's approval, these papers will appear collectively as U.S. Geological Survey Professional Paper 1560, tentatively titled "Assessing Earthquake Hazards and Reducing Risk in the Pacific Northwest." The U.S. Geological Survey Open-File series will serve as a preprint for the Professional Paper chapters that the editors and authors believe require early release. A single Open-File will also be published that includes only the abstracts of those papers not included in the pre-release. The papers to be included in the Professional Paper are:

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ABSTRACT

The Willamette Valley is a lowland separating the Oregon Coast Range from the Cascade Range. This report describes three separate basins within this lowland, the southern Willamette Valley south of 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 Willamette Valley sequence is similar to that 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-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 the Columbia River Basalt Group (CRBG) flowed through a lowland in the Cascade Range across the northern Willamette Valley and thence to the coast as intracanyon flows. The CRBG 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 degradation, 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. Most prominent of these early structures is the Corvallis fault, a low-angle thrust with horizontal separation estimated as 11-13 km. Faults and folds affecting the CRBG 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-Mt. 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.

Post-CRBG faults trend predominantly NW-SE and NE-SW, and folds trend predominantly east-west, compatible with the modern in situ stress field in which maximum horizontal compressive stress is oriented north-south. Limited evidence suggests relatively low slip rates in the range of 0.5 mm/yr. Individual faults are relatively short, but brittle crust may be as deep 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 (Figure 1). The lowland is 120 km long and extends north from Eugene, Oregon to about 30 km north of Vancouver, Washington. 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. 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 Miocene Columbia River basalt (Figure 2). The Tualatin Mountains (Portland Hills) separate the Portland 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 occupies the same structural position as the Puget Lowland, but the two lowlands are not connected. 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, with the upper part of the section containing a higher percentage of volcanic and volcaniclastic rocks, reflecting the proximity of the valley to Cascade arc volcanoes.

The first-order structure of northwestern Oregon is a broad, north-plunging anticlinorium centered over the Coast Range. The western flank of this anticlinorium, including the Oregon coast, contains strata coeval with those of the eastern flank dipping into the Willamette Valley. The strata continue their east dip across the Willamette Valley and into the western Cascades such that most of the pre-Columbia River basalt strata of the Willamette Valley are older than rocks of the western Cascades. 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). Second-order, smaller-scale structures include faults and dip reversals in both the Coast Range and Willamette Valley. Some of these second-order structures involve the Miocene Columbia River Basalt Group (CRBG) and younger strata, but other structures formed mainly in Eocene time.

The oldest exposed rocks of the region are the Siletz River Volcanics, tholeiitic and alkalic basalt flows and breccias of early and middle(?) Eocene age. The tholeiitic lavas are similar to ocean-ridge basalt and are interpreted as a product of rifting and extension of an elongate basin prior to the deposition of the Tyee Formation of middle Eocene age (Wells et al., 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 upper Eocene Yamhill Formation, largely fine grained, overlaps the Tyee Formation to rest directly on Siletz River Volcanics. It is the oldest formation in the Willamette Valley that grades eastward into volcanic rocks possibly related to the early western Cascades (Baker, 1988). In the northern Coast Range, the Yamhill is overlain by and possibly interbedded with the Tillamook Volcanics (Wells et al., 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 Oligocene-Eocene Eugene Formation and the marine and nonmarine Oligocene-early Miocene Scotts Mills Formation grade southeastward into volcanic rocks of the western Cascades, and rest unconformably on western Cascade volcanics. The equivalents of the Eugene and Scotts Mills formations on the coast are the Alsea and Yaquina Formations.

Around 16-14.5 Ma, the Columbia River Basalt Group (CRBG) flowed through a lowland in the Cascade Range between the Columbia River and the Clackamas River into the northern Willamette Valley (Beeson et al., 1989a). The N_2 Grande Ronde and Ginkgo flows have identical counterparts on the Oregon coast, indicating that these flows also crossed the Coast Range, probably as intracanyon flows (Beeson et al., 1989a).

Post-CRBG alluvial deposits are the oldest strata to be confined principally to the present lowland areas. These include the lacustrine Monroe Clay of late Miocene to early Pliocene age (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 last derived in large part from the ancestral Columbia River. In the late Pliocene to Pleistocene, the Boring Lava was erupted from vents in the Portland basin, Tualatin basin, and northernmost Willamette Valley (Allen, 1975). Some volcanic centers in the western Cascades are also of this age.

The Quaternary history is characterized by alluvial deposits and surfaces influenced by Cascade glaciation and base-level changes controlled by the Columbia River (P. McDowell, in press). Near the end of the Pleistocene, catastrophic glacial-outburst floods from the Columbia River repeatedly inundated the Willamette Valley as far south as Eugene and deposited the Willamette Formation (Allison, 1978; Balster and Parsons, 1969).

We have compiled and field-checked existing bedrock mapping in and around the Willamette Valley lowland except for the Portland-Vancouver basin, which is being described separately by the Oregon Department of Geology and Mineral Industries. The geologic map is included as Plate I. We mapped the subsurface geology of the lowland itself based on oil-exploratory wells (plotted on Plate I) and multichannel seismic lines that were part of an exploration campaign in the 1970's and 1980's together with a network of gravity stations, most of which were already in the public domain. Subsurface geology of the post-CRBG sediments is based largely on water wells and on boreholes drilled for engineering purposes by the Oregon Department of Transportation. Our work is on 1:100,000 metric-series maps and is shown as Plates I and II.

Responsibilities for individual portions of the map are: southern Willamette Valley, E. Graven; Corvallis fault, C. Goldfinger; northern Willamette Valley, K. Werner; Tualatin Valley, T. Popowski. A more detailed description of the geology is provided by Goldfinger (1990), Graven (1990), Werner (1990), and Popowski (1991).

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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 Patricia McDowell, and of Willamette Valley gravity data with Richard Couch, Bob O'Malley, and Gerry Connard. Marvin Beeson, Ian Madin, and George Priest reviewed the manuscript.

STRATIGRAPHY

GENERAL STATEMENT

Correlation of stratigraphic units (Figure 3) is based on radiometric ages, benthic foraminifera, and calcareous nannoplankton. Nannoplankton are referred to zones which are widely distributed in the North Pacific Ocean and are believed to approach time lines. A preliminary zonation for Paleogene strata based on coccoliths (Bukry and Snavely, 1988) shows some discordance with zonation based on benthic foraminifera. Benthic foraminiferal zones 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 foraminifera, hence the Kleinpell and Mallory benthic zones are the only ones available for biostratigraphy of most surface and subsurface sections.

SILETZ RIVER VOLCANICS

Oceanic basalts and interbedded basaltic sedimentary rocks dated as 50.7±3.1 to 58.1±1.5 Ma (Duncan, 1982) form the basement upon which the Tertiary rocks of the Coast Range and Willamette Valley were deposited. The formation was named by Snavely and Baldwin (1948) for exposures on the Siletz River and its tributaries in the central Oregon Coast Range. Snavely et al. (1968) recognized a lower unit consisting of submarine tholeitic 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 microfossils referred to the Penutian and Ulatisian benthic stages of Mallory (1959), Snavely et al. (1968), and McWilliams (1980), in general agreement with the radiometric ages. Coccoliths from the Coast Range west of the Willamette River are referred to Subzone CP 10, estimated as about 55.3-53.7 Ma in age (Bukry and Snavely, 1988).

The Siletz River Volcanics northwest of Corvallis belong mainly to the lower unit of Snavely et al. (1968). The volcanic rocks are overlain by and partly interbedded with up to 1000 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 et al. (1954). The Kings Valley Siltstone Member contains thin lenses of basaltic sandstone, a few thin layers of white tuff, and rare foraminifera 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 in age (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 et al., 1955). The top of the section contains medium- to dark-gray, calcareous, tuffaceous shale, siltstone, and sandstone (Brownfield and Schlicker, 1981a; Brownfield, 1982a).

The Siletz River Volcanics are found in the Gulf Porter 1 and Exxon Miller 1 exploratory wells in the southern Willamette Valley, where they contain interbeds of marine strata 3 to 30 m thick. In the northern Willamette Valley, the Finn 1 well contains 1110 m of Siletz River Volcanics, predominantly gray tuff, tuffaceous shale, siltstone, and sandstone with Ulatisian (including upper Ulatisian) microfossils indicating lower-middle bathyal to tropical inner neritic bathymtery (McKeel, 1984). Siletz River Volcanics in the Bruer 1 well consists of volcanic breccia and red and green tuff. Synthetic seismograms of the Bruer 1 and 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 discontinous, possibly due to constructional volcanic topography and erosion, as suggested for field exposures by Brownfield (1982a).

The base of the Siletz River Volcanics is neither exposed nor found in wells, so its thickness is unknown, although Snavely et al. (1968) proposed that its thickness exceeds 6 km. An east-west COCORP seismic line 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 et al., 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 et al., 1989). If this low-resistivity unit is not Siletz River Volcanics, the thickness of the Siletz River could be as low as 2 km.

The Siletz River Volcanics are correlative with basalts of the Roseburg Formation in southern Oregon, the Crescent Formation of Washington, and the Metchosin Volcanics of southern Vancouver Island (Snavely et al., 1968; Baldwin, 1974; Tabor and Cady, 1978); volcanics at the northern and southern end of the outcrop areas 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 et al., 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 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-ultramafic rocks marking the suture zone between Siletzia and North America (Johnson et al., 1990).

TYEE FORMATION

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 1200 m near Eugene, decreasing northward to 500 m west of Dallas, where mudstone and thin, graded sandstone and siltstone of the Tyee Formation impinge against a highland of 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 Exxon Miller 1 well. Strata in the Porter 1 well assigned to the Yamhill Formation may be a fine-grained equivalent of 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 to the Tyee Formation. The age of the Tyee is Ulatisian, or middle Eocene (Molenaar, 1985), and microfossils in the 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 50 to 52.5 Ma for the Tyee (Bukry and Snavely, 1988).

The Tyee 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 et al. (1964) suggested that the source of the Tyee sandstone was the Klamath Mountains of southern Oregon and northern California. Heller et al. (1985) subsequently found evidence of a Precambrian crustal component in Tyee sediments, 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 et al. (1955) for exposures in Mill Creek, a tributary of the South Yamhill River southwest of Sheridan. Here the formation consists of 150 m of tuffaceous siltstone and shale overlain by 150 m of basaltic sandstone and siltstone and 1050 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 exhibiting partial Bouma sequences (R. Thoms, pers. comm., 1991). The Yamhill thickens eastward across coeval normal faults to at least 932 m thick in the Bagdanoff 23-28 well, where it includes basalt and tuff.

The Miller sandstone member ("Miller sand" of Bruer et al., 1984), known only from the subsurface in the Willamette Valley south of Salem, is a sandy to conglomeratic volcaniclastic unit overlain by and interfingering northwestward with faintly-bedded micaceous siltstone and mudstone (Baker, 1988). The "Miller sand" decreases in thickness northwestward to zero, suggesting coeval displacement on the nearby Corvallis fault. The "Miller sand" increases in thickness southeastward at the expense of an underlying mudstone unit, 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 Porter 1 well penetrated 1055 m of volcaniclastic sandstone and siltstone and basaltic conglomerate, and the Ira Baker 1 well contains 1961 m of basalt, andesite, dacite, tuff, and minor tuffaceous mudstone, siltstone, volcaniclastic sandstone, and breccia probably equivalent to the Yamhill.

The "Miller sand" contains microfossils indicating shallow-marine deposition, whereas the overlying and underlying mudstone members 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 lower Narizian stage (D. McKeel, pers. comm., 1987; cf. McWilliams, 1980; Brownfield, 1982a). Foraminifera in the Bruer 1 and Finn 1 wells in the northern Willamette Valley are lower Narizian at the base of the Yamhill and Narizian for the remainder of the formation. Yamhill in the Bagdanoff 23-28 well yielded lower Narizian to upper Ulatisian foraminiferal assemblages (McKeel, 1984). In the Coast Range south of Eugene, the Elkton Formation and Lorane Siltstone have Ulatisian and lower Narizian foraminifera (Bird, 1967; Heller and Dickinson, 1985). 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 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 lower Narizian foraminifera in all three formations. The Yamhill changes facies eastward in the subsurface of the Willamette Valley to arc-like volcanic rocks (Baker, 1988), suggesting either that the Cascades arc began to develop earlier than the 41-43 Ma (cf. Lux, 1982; Priest and Vogt, 1983; Verplanck and Duncan, 1987; Taylor, 1990) or 35 Ma (Priest, 1990) age that is generally accepted based on surface geology, or that Clarno volcanism, 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 et al., 1983). The Yamhill is intruded by a sill of zeolitized gabbro with a K-Ar date on plagioclase of 43.2±1.8 Ma (L. Pickthorn in Bukry and Snavely, 1988). Strata with Narizian microfossils underlying the Cowlitz Formation in the Mist gas field are also referred to the Yamhill Formation by Bruer et al. (1984), but these beds contain upper Narizian microfossils and overlie the Tillamook Volcanics; they are described by Niem and Niem (1985) as the 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 "Hamlet formation" of the northern Oregon Coast Range, although no upper Narizian microfossils have been found in the Yamhill Formation.

TILLAMOOK VOLCANICS

The Gales Peak area west of the Tualatin basin is underlain by basalt correlated by Wells et al. (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 Klohs 1 well in the Tualatin basin, Refugian strata overlie zeolitized basalt that is interbedded with unfossiliferous marine siltstone, claystone, and minor sandstone; this basalt may be Tillamook Volcanics, Goble Volcanics, or basalt of Waverly Heights. Yamhill and Tillamook Volcanics may be interbedded in the Cooper Mountain 1 well between 945 and 2823 m well depth. The volcanics below 2124 m in the Barber 1 well may be Tillamook Volcanics.

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

BASALT OF WAVERLY HEIGHTS

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

SPENCER FORMATION AND ITS CORRELATIVES (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 upper Narizian stage. The Spencer is divided into two members (Al Azzaby, 1980; R. Thoms, pers. comm., Baker, 1988). 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 Hagg Lake to approximately 300 m of predominately clean arkosic sand south of Patton Valley (R. Thoms, pers. commun., 1991). In the Gath 1, Barr 1, Hickey 1, and Ira Baker 1 wells in the southern Willamette Valley, this member changes facies eastward to tuffaceous strata and interfingers and grades upward into volcanic rocks of Cascade origin. In the Wolverton 1 and Miller 1 wells 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 (Merrill 1 and Independence 1 wells) to 310 m (Wolverton 1 well).

The upper member consists of mudstone, siltstone, and subordinate sandstone, grading eastward to tuffaceous strata and volcanic rocks (Wolverton 1 and Porter 1 wells). Along the eastern edge of the valley (Gath 1, Hickey 1, Barr 1, and Ira Baker 1 wells), 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 upper Spencer mudstone and siltstone in the southern Willamette Valley were deposited in upper bathyal water depths deepening upsection to middle bathyal (McKeel, 1984, 1985). Thickness of the member in the southern Willamette Valley varies from 100 m in the M & P Farms 1 and Wolverton 1 wells to 178 m in the Porter 1 well.

Near the Corvallis fault, the Spencer Formation overlies the Tyee Formation directly with an angular unconformity of up to 90^0 difference in dip. The Spencer Formation, where it is in fault contact with Siletz River Volcanics along the Corvallis fault between Corvallis and Philomath, consists of fossiliferous tuffaceous, basaltic sandstone and conglomerate with clasts of Siletz River Volcanics up to 2 m in diameter.

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 Bruer 1 well to 45 m in the DeShazer 13-22 well. In the Tualatin basin, the Spencer Formation is 400 m thick near Hagg Lake. North of Forest Grove, strata correlative with the Spencer Formation are referred to the Cowlitz Formation, which rests unconformably on Tillamook Volcanics. The Cowlitz includes a lower unit consisting of a basal conglomerate overlain by siltstone ("Hamlet formation" of Niem and Niem, 1985), the C & W sandstone that produces gas in the Mist-gas field, and an upper siltstone member. The upper two members may be present in the Cooper Mountain 1 well.

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 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 et al., 1955) grading into the Yachats Basalt and the basalt of Cascade Head. Foraminifera are assigned to the upper Narizian Stage (W. Rau in Wells et al., 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 to 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 Fisher Formation (Vokes et al., 1951). This formation is 1680 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 equivalent to the Calapooya Volcanics and Colestin Formation of the southern Oregon Cascade Range (Wells and Waters, 1934, Peck et al., 1964). They comprise the T_5 map unit of Sherrod and Smith (1989), with age estimated as 45 to 35 Ma.

Fossil leaves in the lower Fisher Formation south of Cottage Grove (25 km south of Eugene) suggest a late Eocene age (R. Brown in Hoover, 1963). Radiometric ages from basalt and basaltic andesite near the top of the formation are 35-40 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 et al., 1951). The basalt flows dated by Lux (1982) were considered by Vokes et al. (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 Ira Baker 1 well 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 are notably free of volcanics. In the Gath 1 well, a 440-m-thick volcanic unit bracketed by strata with upper 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 (Phillips et al., 1989).

OLIGOCENE-EOCENE MARINE STRATA

North and west of the Tualatin basin, marine strata of Oligocene and Eocene age are mapped as the Keasey Formation and the overlying Pittsburg Bluff Formation (Wells et al., 1983). The Keasey Formation is predominantly thick, light gray tuffaceous claystone and siltstone with minor mudstone and sandstone; foraminifera are upper Narizian and lower Refugian (McWilliams, 1968, 1973; Brownfield and Schlicker, 1981a). North of Hagg Lake, the Pittsburg Bluff Formation consists of up to 1400 m of greenish gray to gray tuffaceous, glauconitic, and basaltic litharenite sandstone, siltstone, and minor conglomerate with foraminifera of the Refugian stage (R. Thoms, pers. 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 older unit. The Reichold Energy-Werner 14-21 well and the Oregon Natural Gas Werner 34-21 and DeShazer 13-22 wells 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, 1982a).

In the southern Willamette Valley, feldspathic, tuffaceous sandstone and siltstone of this age are called the Eugene Formation with Refugian foraminifera. The formation is 550 m thick near the Coburg Hills, including 343 m of strata penetrated in the Ira Baker 1 well, more than 800 m thick in the Lebanon area, including strata in the Hickey 1 well, and 780 m thick beneath the Salem Hills based on data from the Independence 1 and Merrill 1 wells. The formation is best exposed in the Coburg Hills, Peterson Butte, and the base of the Salem Hills. To the south, the Eugene Formation interfingers with the nonmarine Fisher Formation.

LITTLE BUTTE VOLCANIC SERIES

The Little Butte Volcanic Series (LBV) of Wells (1956) and Peck and others (1964) makes up the base of the exposed western Cascade sequence on the eastern margin of the southern Willamette Valley, where it overlies the Eugene Formation, and the northern Willamette Valley, where it is itself overlain unconformably by the Miocene-Oligocene Scotts Mills Formation and the Miocene Columbia River Basalt Group (Miller and Orr, 1988).

We subdivide the LBV 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 of the Coburg Hills northeast of Eugene (Walker and Duncan, 1989). The age range of the LBV is 35 to 17 Ma (Lux, 1982; Sutter, 1978; 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 LBV by Lux (1982) yield radiometric dates older than 35 Ma. Lux (1982) reported ages for the LBV as 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, LBV unconformably overlies the Oligocene and Eocene Fisher and Eugene Formations (W. Orr in Armentrout et al., 1983). On the other hand, Peck et al. (1964) found tongues of Eugene Formation interfingering with LBV south of Brownsville, Beaulieu (1974) noted similar relations to the north in Linn County, and the Gath 1 well in southwestern Marion County near Salem contains volcanic rocks interbedded with Eugene Formation. These volcanic rocks are more likely correlated to the Fisher Formation discussed above rather than LBV. The volcanic rocks are not found in the Merrill 1, Independence 1, and Schermacher 1 wells to the west. Following eruption, the LBV was tilted gently to the east and eroded prior to deposition of the Scotts Mills Formation in the northern Willamette Valley (see below). Peck et al. (1964) considered the volcanic sequence to be between 1300 m and 2600 m in thickness throughout most of the western Cascades. The volcanics appear to thin to the west. Near Washburn Butte, about 750 m of volcanic rocks lie between the Eugene Formation and Miocene-Pliocene andesite which probably overlies the LBV with angular unconformity. The Wicks 1 well, 10 km east of Silverton, penetrated 1830 m of volcanics, which may include units other than LBV.

Sedimentary formations correlative to the LBV include the Alsea Formation and Yaquina Formation near Newport and the Oswald West Mudstone of the northern Oregon coast. These formations are older than 25 Ma and thus fall within the time range of LBV. 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 are late Oligocene to early Miocene in age (Miller and Orr, 1988), thus within the time range of LBV. However, these formations overlie the LBV 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, Ti-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) by P.D. Snavely (in Clark, 1969). Other large intrusive bodes of similar lithology are found south of Philomath and at Bald Hills, Dimple Hill, Vineyard Mountain, Coffin Butte, Logsden Ridge, and Witham Hill (Snavely et al., 1980; Snavely and Wagner, 1961). The remanent magnetization of the Marys Peak sill is normally polarized (Clark, 1969), as are 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 in the vicinity of 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 WNW-striking Philomath fault that offsets the Corvallis fault, but intrusions were not found associated with other NW-striking faults offsetting the Corvallis fault.

Sills, presumably of the same 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 contact is found in the Porter 1 well and is marked by a high-amplitude reflector on a seismic line. Dikes are found 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 Miocene to Oligocene in age (Beaulieu, 1974; Walker and Duncan, 1989) and are presumably feeders for western Cascade volcanic rocks.

SCOTTS MILLS FORMATION

Marine and nonmarine strata of the Scotts Mills Formation of late Oligocene and early Miocene age are exposed in the Cascade foothills east of Silverton adjacent to the northern Willamette Valley. Miller and Orr (1988) divide the Scotts Mills Formation into the Marquam Member, 300 to 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 LBV on a surface with regional relief up to 100 m. The Marquam Member is marine and 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 consists of marine and nonmarine volcanic arkose, and the Crooked Finger Member consists of nonmarine volcanic conglomerate and mudstone. The three members comprise a prograding delta complex developed southwest of a volcanic headland underlain by LBV. The Scotts Mills Formation is found in two wells drilled in the Waldo Hills, the Wicks 1 well, which penetrated 239 m of volcanic rocks, claystone, siltstone, sandstone, and rare volcanic conglomerate and the Anderson 1 well which penetrated 140 m of an upward-coarsening sequence of sandstone, siltstone, and claystone with volcanic fragments. These strata overlie LBV in both wells. The absence of Scotts Mills Formation 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 meters 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 CRBG (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 CRBG (Miller and Orr, 1988). Fossil leaves in the Molalla Formation were dated as early Miocene (J. Wolfe in Peck et al., 1964). Radiometric ages of tuff beds in the Molalla are 15.9±1.0 Ma and 15.0±0.7 Ma (Fiebelkorn et al., 1983). Thus the age of the Molalla Formation ranges from perhaps as old as late Oligocene to middle Miocene. Conglomerate mapped as Troutdale Formation by Peck et al. (1964) in this area is part of the Molalla Formation.

SCAPPOOSE FORMATION

Fine grained shallow marine sediments interfingered with fluvial sandstone, coal-bearing mudstone and conglomerate comprise the middle Miocene Scappoose Formation (Van Atta and Kelty, 1985). The weakly consolidated strata are commonly exposed in steep slopes capped by resistant Columbia River Basalt. More than

275 m of Scappoose sediments disconformably overlie Keasey and Pittsburg Bluff Formations north of the Tualatin basin and at least 335 m overlie Pittsburg Bluff strata in the western flank of the Chehalem Mountains.

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

The Scappoose Formation is probably entirely middle Miocene in age, based on the occurrence of Grande Ronde Basalt clasts within the basal conglomerate and Columbia River Basalt flows overlying the unit. Partially 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 (CRBG) were erupted from fissures in eastern Oregon and Washington and western Idaho from 16.5 to 6 Ma. Some of these flows traversed the Cascades via the Columbia Trans-Arc Lowland, which extended from the Columbia River 60 km south to the Clackamas River (Beeson et al., 1989a) and reached as far as the present Pacific coast, where they are interbedded with marine strata. As noted by Beeson et al. (1989a), some of the broad folds and faults of the Oregon Cascade Range and Willamette Valley were active during CRBG emplacement. These include the Portland Hills-Clackamas River structural zone that limited some of the flows of the Grande Ronde Basalt and Wanapum Basalt to the Portland basin and the lower reaches of the Columbia River, and the Gales Creek-Mt. Angel structural zone, which formed a barrier to some flows of Wanapum Basalt. Only the R_2 and N_2 Grande Ronde basalt (about 16-15.6 Ma) and the Ginkgo, Silver Falls, Sand Hollow, and Sentinel Gap basalts of the Wanapum Basalt Formation (about 15.3 Ma; Beeson et al., 1985) crossed the Portland Hills-Clackamas River structural zone and entered the northern Willamette Valley.

The CRBG underlies nearly all of the Portland, Tualatin, and northern Willamette basins. Water wells penetrate more than 200 m of basalt beneath portions of the Tualatin basin (Popowski, 1991). 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 CRBG west of the Cascades, 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 volcanic centers in the lowland through which the Grande Ronde Basalt crossed the Cascades (Beeson et al., 1989a). Whereas the Grande Ronde Basalt blanketed most of the northern Willamette Valley, some of the Wanapum Basalt flow units tended to follow channels. One channel of the Ginkgo flow 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 et al., 1989a). Basalt on the Oregon coast near Newport is geochemically identical to the Ginkgo flow, suggesting that the Ginkgo flow continued across to the coast prior to most of the uplift of the Coast Range. Another Ginkgo flow passed north of the Willamette Valley such that the intervening northern Willamette Valley contains no Wanapum Basalt, only Grande Ronde Basalt (Beeson et al., 1989a; Tolan et al., 1989; Wells et al., 1989). Similarly, the Wanapum Basalt is absent in the Tualatin Basin. The Silver Falls and Sand Hollow basalts flowed southwest along the axis of the Waldo Hills, and the Sand Hollow basalt at Hungry Hills is the southernmost exposure of the CRBG in the Willamette Valley (Beeson et al., 1985; 1989a). The Waldo, Salem, and Eola Hills show a reversal in topography because they were a low area during the time of Ginkgo eruption. The CRBG is 100 to 180 m thick in the Salem Hills.

The CRBG rests with angular unconformity on older units: the Molalla Formation and Scotts Mills Formation east of the Willamette Valley and the Oligocene-Eocene marine sequence in the Salem and Eola Hills. Thus the east dip of the homocline comprising the western Cascades was in place prior to CRBG eruption (Priest, 1990).

SARDINE FORMATION

Volcanic and volcaniclastic rocks of the western Cascades erupted after emplacement of the CRBG were called the Sardine Formation by Peck et al. (1964). The volcanic rocks post-date 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 the Fern Ridge Tuff and the Rhododendron Formation and Outerson Basalt of Hammond (1979) and Hammond et al. (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 CRBG in the Waldo Hills, and volcanic and volcaniclastic rocks resting on east-dipping LBV 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). Volcanism was more calc-alkaline than that prior to eruption of the CRBG, consisting of lava flows and debris flows of intermediate composition with locally abundant basalt and basaltic andesite (Priest and Vogt, 1983). The basalt of Marks Ridge was dated as 4.5 $\pm$ 0.28 Ma (Episode 3 of Priest, 1990), and the basaltic andesite of Washburn Butte was dated as 11.9 $\pm$ 0.3 Ma (Verplanck, 1985; Episode 2 of Priest, 1990).

NONMARINE FINE-GRAINED SEDIMENTS

In the Portland, Tualatin, and Willamette basins, the CRBG and older rocks were deeply eroded, developing a topographic surface with up to 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 and A.R. Niem, personal commun., 1989). Deeply weathered fluvial and loessal silts interbedded with gravels dominated by CRBG clasts in the Tualatin basin were mapped as Helvetia Formation by Schlicker and Deacon (1967). The sediments 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 along with more locally-derived clasts suggests that the greater part of these sediments 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 sediments are known mainly from the subsurface, where they are known to water-well drillers as the "blue clay." In the northern Willamette Valley, the contact between the sediments and the CRBG is marked in some wells by a laterite. The sediments increase in thickness northeastward from 160 m in the Bagdanoff well and Werner 14-21 well to 265 m in the DeShazer well and 300 m in the Stauffer Farms well. In the northern Willamette Valley and Tualatin basin, the sediments are characterized on seismic lines by a lower sequence with low-amplitude reflectors and an upper sequence with medium- to high-amplitude reflectors.

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 et al., 1987) and is up to 100 m thick near the center of the valley. Core Hole 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 (Figure 4). Another corehole at Corvallis found a multicolored paleosol at the base of the clay unit. In Core Hole DH 14-90 between Sublimity and Stayton, Columbia River basalt is overlain by blue to dark-gray clay with intercalations of volcaniclastic sand and with paleosols with rootlets in growth position (Figure 5). Near Monroe, several coreholes penetrated a clay unit named the Monroe clay and dated as late Miocene on the basis of palynology (Roberts and Whitehead, 1984). Roberts and Whitehead (1984) interpreted the Monroe clay as lacustrine, in contrast to the fluvial interpretation for Highway Division core holes. Toward the center of the southern Willamette Valley, the clay is interbedded with sand and gravel that represent the main channel of the proto-Willamette River (Figures 6 and 7). This channel lies generally to the east of the present Willamette River and 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 second channel is found beneath the present Willamette River, west of the Salem Hills, but limited water-well data do not show the sand-and-gravel channel 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 lines in the northern Willamette Valley and Tualatin basin show a prominent series of reflectors midway in the sedimentary sequence which comprise 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.

TROUTDALE FORMATION

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 CRBG with significant percentages of exotic clasts such as quartzite and granite, indicating deposition by the ancestral Columbia River (ancestral Columbia River facies 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 from Boring Lavas and High Cascade lavas, with foreign clasts subordinant (Tolan and Beeson, 1984; Swanson, 1986). Correlative conglomerate in the southeast part of the Portland basin contain a dominance of clasts 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 LAVAS AND SNOW PEAK VOLCANO

Vents and flows of high-alumina, diktytaxitic, olivine-phyric basalt and basaltic andesite with subordinate pyroclastic rocks, breccia, and ash in the Portland basin were named Boring Lavas by Treasher (1942). These lavas intrude the Sandy River Mudstone and Troutdale Formation and form cones of interlayered cinders and lava (Mt. Sylvania, Mt. Scott) on an eroded surface of 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 Troutdale Formation (Lowry and Baldwin, 1952; Tolan and Beeson, 1984; 1989). The Boring Lavas are entirely 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 Columbia River basalt are interpreted as intrusions of Boring basalt. An intracanyon flow at Carver in the Clackamas River Valley southeast of Portland has a K-Ar age of 612 ± 23 ka (R. Duncan, pers. commun. to I.P. Madin, 1989); other K-Ar ages are as old as 5 Ma (Luedke and Smith, 1982; Swanson, 1986). Boring Lavas of the Oregon City plateau are dated as 2.6 Ma (Swanson, 1986).

Snow Peak, located just east of the study area, consists of nearly 1000 m of basaltic andesite flows and breccia with minor basalt (Beaulieu, 1974). These rocks were dated by Verplanck (1985) as 2.8 ± 0.3 Ma and 3.3 ± 0.6 Ma, equivalent in age to the Boring Lavas. The shield volcano is deeply dissected by U-shaped valleys carved by glaciers.

PLEISTOCENE TERRACE GRAVELS

Sediments younger than the Boring Lavas, Troutdale Formation, and the nonmarine fine-grained sediments are described by McDowell (in press). Gravels in the eastern parts of the Willamette Valley and Portland basin are glaciofluvial, derived from the Cascades, whereas gravels on the west side of these basins are fluvial, 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 to 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 (Figure 8). Roberts (1984) suggested that the high terrace gravels are the constructional top of his Monroe clay. Subsequent erosion was accompanied by development of deep 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 CRBG in the northern Willamette Valley.

The Linn gravels, at or below the present valley floor, were renamed the Rowland Formation and divided into two members by Balster and Parsons (1969) in the southern Willamette Valley: the Linn Member, predominantly silt, sand, and gravel, and the overlying Diamond Hill Member, predominantly sand and silt with a paleosol on top of it. 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 from the Cascades, a view supported by a surface morphology of coalescing alluvial fans recognized by Piper (1942). The North Santiam, South Santiam, Willamette, Mackenzie, 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 and continued past 28,500 years (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) founds that the Estacada Formation includes several terraces, and he has abandoned Trimble's nomenclature.

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 were named the Portland Hills Silt by Lowry and Baldwin (1952). 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 up to 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 Boring Lavas (Lentz, 1981).

CATASTROPHIC FLOOD DEPOSITS

The Willamette Valley floor as far south as Eugene is mantled by 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) named the Willamette Silt for light brown, homogeneous silt interbedded with coarser grained deposits. It contains erratics 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) changed the name to Willamette Formation which they subdivided 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 flooding events depositing silt in low-lying areas across much of the Willamette Valley. The coarse-grained equivalents of these silts in the northern Willamette Valley were called the River Bend Member by Roberts (1984), which consists 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 et al., 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 event (Allison, 1953). In the Portland basin, the flood deposits include boulder gravel, sandy gravel, and sand with a Columbia Basin provenance (Allen et al., 1986). The flood events 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 BP (Mullineaux et al., 1978; cf. discussion by McDowell, in press).

HOLOCENE DEPOSITS

During the Holocene, the Willamette River incised the main Calapooia-Senecal surface 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, in press). Holocene sand, gravel, silt, and clay are largely confined to channels and floodplains of major rivers and their tributaries.

STRUCTURE

GENERAL STATEMENT

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, with convergence rates decreasing and strike-slip component of subduction increasing from the Paleocene to the present (Wells et al., 1984; Riddihough, 1984). This has resulted in clockwise rotation of structural blocks, with the amount of rotation decreasing from Eocene to the present and from west to east.

In this report, we focus on deformation affecting the CRBG and younger deposits. Older structures are discussed only briefly; they are important because they serve in some cases as zones of weakness reactivated by younger faulting that may have seismogenic potential. Faults that cut Oligocene and older strata but with unknown age relations to CRBG and younger deposits are discussed by Graven (1990) and Werner (1990). Most faults are shown in Plate I and in Figures 9 and 10.

PRE-CRBG DEFORMATION

1.Coast Range anticlinorium

Present exposures of Siletz River volcanics commonly correspond to basement highlands that existed during the time Eocene strata were deposited. The Tyee Formation onlapped a highland of 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 affected isopachs of the "Miller sand" of the Yamhill Formation (Baker, 1988; Graven, 1990) and provided detritus to the upper Eocene Spencer Formation (Goldfinger, 1990). In the northern Willamette Valley, strata as young as the Scotts Mills Formation (Oligocene-Miocene) were tilted to the east prior to deposition of the CRBG, presumably reflecting uplift of the Coast Range. Yet the Coast Range was low enough that intracanyon flows of the CRBG were able to cross the range to the present-day coastline.

2.Corvallis fault

The NE-trending Corvallis fault is at least 50 km long, and for part of its length, it comprises 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 new gravity profiles show that the primary fault is a thrust that dips about 10^0 NW (Goldfinger, 1990). Dips in the hanging wall average 20^0 NW, and beds adjacent to the thrust in both the hanging wall and the footwall are overturned, 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 (cf. Yeats, 1988). Using a fault dip of 20^0, the horizontal shortening is calculated as 11-13 km. The fault was active in late Eocene time as based on isopachs of "Miller sand" parallel to and southeast of the fault (Baker, 1988) and on sedimentary breccia with clasts of Siletz River Volcanics 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, displaying left-lateral horizontal slickensides and mullion structure. The main fault trace is offset by several northwest-trending faults. Because the high-angle fault may displace Pleistocene sediments, it is discussed further below.

3.Eola-Amity Hills normal faults

A proprietary seismic line shows that the Siletz River Volcanics and the lower part of the Yamhill Formation in the Eola-Amity Hills are cut by two normal faults down to the east. This line 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 m to 1450 m. The Spencer Formation and the upper part of the Yamhill Formation are only slightly warped across the western fault.

POST-CRBG DEFORMATION

1.Coast Range anticlinorium and Willamette Valley synclinorium

CRBG flows can be traced to the western margin of the northern Willamette Valley where they are exposed in an east-dipping homocline. Flows and invasive flows identical to the flows mapped in the Willamette Valley are found on the Oregon coast from Seal Rock north to the Columbia River. The absence of CRBG 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 side streams. At Monroe, these sediments are dated by palynology as late Miocene to early Pliocene (Roberts and Whitehead, 1984), but contact relations with Boring Lavas as young as 0.6 Ma suggest that these sediments 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 Cascades underwent tilting (Priest, 1989). Beeson et al. (1989) recognized more than 1200 m of uplift of the Cascade Range near the Columbia River based on the structure of the CRBG and overlying Troutdale Formation.

2.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 to the Rowland Formation and the Willamette Formation dips 6^0 to 12^0 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 Parson (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 107 m, near the highest elevation at which Willamette Formation has been found (McDowell and Roberts, 1988). This contact is at an altitude of 68 m in the Willamette River channel east of the Mid Valley quarry. In addition, pre-Rowland overbank facies deposits of the proto-Willamette River similar to those present at and east of the Willamette River (Figure 4, 6, 7) 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 varying from a few centimeters to one meter in height is located on the trace of the Corvallis fault. It has the same sense of displacement as the main structure, steeply dipping with the southeast side down, as based on relations exposed in a hand-dug pit. This could be a slump rather than a fault. Low-sun-angle air photos show northwest-trending scarps that may be related to left steps on the Corvallis fault. These scarps occur in areas of outcrop of 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).

3.Owl Creek fault

The Owl Creek fault strikes N 10^0 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 (Figure 7). 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 such that Willamette Formation rests directly on Eugene Formation (Figure 7). Gravel in the Rowland Formation of Cascade 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 post-date all faulting.

4.Harrisburg anticline

A broad east-northeast-trending anticline between Corvallis and Eugene plunges east (Figure 9) and has about 100 m relief on the Eugene-Spencer contact. The axis of the channel of the proto-Willamette River is warped upward about 50 m where it crosses the anticline at the town of Harrisburg (Figure 11). There is no evidence of faulting associated with this anticline.

5.Jefferson anticline

A broad anticline north of Albany creates the concave-to-the-west map trace of the base of the Eugene Formation (Plate I). There is no evidence of stratigraphic thinning of Eocene strata across the structure, indicating that it developed later. Topography resulting from anticlinal growth may have diverted CRBG flows, particularly the Ginkgo flow, northwestward around the anticline. 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 6; Plate II), 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 (Figure 6). The Jefferson anticline may be a northeast continuation of the hanging-wall block of the Corvallis fault, in which Siletz River Volcanics are at the surface. The northwest-striking contact of Siletz River Volcanics with younger rocks is expressed as a positive gravity anomaly in residual gravity contours (Werner, 1990).

6.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 Cascades on the east. The gravel-filled channel of the proto-Willamette River does not follow the course of the present Willamette River west of the Salem Hills (Figure 6). Instead, the proto-Willamette River flowed east of the Salem Hills into the North Santiam basin (Figure 9) and exited through a modern water gap at the west end of the Waldo Hills now marked by an underfit stream, Mill Creek (Plate II, Figure 11). The axis of the proto-Willamette River is upwarped 55 meters at the subsurface extension of the Salem Hills, a structure here named the Shelburn uplift. The channel axis drops down nearly 100 meters into the North Santiam basin, then is upwarped 110 meters across the Waldo Hills at Mill Creek water gap. The water gap appears to be too narrow to have accommodated the Willamette River, but this may be due to preservation of only the base of the proto-Willamette channel after uplift and erosion. The age of the gravel-filled channel in the North Santiam basin with respect to the channel west of the Salem Hills is not known. However, the base of the Rowland Formation has more than 20 m relief in the western channel (Figure 6), suggesting that the western channel was still present at the time of Rowland deposition.

The minimum structural relief at the top of the CRBG in the North Santiam basin is 260 m, based on the maximum depth to basalt in water wells in the basin and the top of the CRBG in the adjacent Waldo Hills. Except for the Mill Creek fault discussed below, no faults have been recognized in this basin, but this may be due to the difficulty of correlating horizons in the post-CRBG sediments across the basin.

7.Mill Creek fault

The southern edge of the Waldo Hills is marked by a fault that displaces the CRBG approximately 100 m (Plate I). The base of the CRBG is exposed along the western end of the Waldo Hills near Turner, whereas the top of the CRBG 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.

8.Waldo Hills range-front fault

The northern range front of the Waldo Hills is marked by a pronounced northeast-trending photo lineation that is on trend with the Corvallis fault to the southwest. The contact between the CRBG and underlying marine strata is exposed near the range front southeast of Salem; several wells also penetrate this contact (Figure 12). Northwest of the range front, water wells reach the top of the CRBG, indicating vertical separation of at least 50 m. The fault may extend farther northeast than shown; vertical separation decreases toward the northeast. There is no clear evidence that the fault cuts strata younger than the CRBG.

9.Gales Creek-Mt. Angel structural zone

The Gales Creek-Mt. Angel structural zone is the southernmost of several northwest-trending, seismically-active linear features in northwestern Oregon and southwestern Washington. Both the Gales Creek-Mt. Angel structural zone and the Portland Hills-Clackamas River structural zone were active during deposition of CRBG. The Mt. Angel fault formed a barrier to three Silver Falls flows of the Wanapum Basalt (Beeson et al, 1989a).

Geological evidence exists for three segments: the Gales Creek fault, the Newberg fault, and the Mt. Angel fault, which have the same strike but are offset. The Gales Creek fault segment follows the Gales Creek valley between Gales Peak and David Hill, juxtaposing Tillamook equivalent (?) volcanics to the southwest with Columbia River Basalt on the northeast. The fault has been extended south toward Gaston, where seismic lines reveal a complex zone of deformation extending from Gaston to the base of the Chehalem Mountains. Modeling of a gravity line across this zone suggests three fault segments having a total vertical separation, largely earlier than the CRBG, of almost 3 km, down to the northeast (Jack Meyer, pers. commun., 1991). It is unclear whether this zone connects with the Newberg segment.

Werner (1990) mapped the Newberg fault on the basis of water-well data (Figure 13). North of the fault, the base of the CRBG is exposed on the south side of the Chehalem Mountains and dips northeast. South of the fault, the top of the CRBG is exposed in the Red Hills of Dundee and also dips northeast. CRBG is juxtaposed against Oligocene-Miocene marine strata along the fault, though the apparent sense of vertical offset is opposite that expressed in the Gaston area (Popowski, 1991). Gradient analyses of aeromagnetic and gravity data support the fault location. A seismic line across the projection of the fault zone between Newberg and Woodburn shows no displacement of the top of the CRBG (Werner, 1990).

The Mt. Angel fault was first mapped near Mt. Angel by Hampton (1972) based on water-well data. Based on seismic lines and water wells, we extend the Mt. Angel fault from the Waldo Hills northwest to Woodburn (Figures 14-18). Vertical offset of the top of CRBG increases to the southeast from 100 m in seismic section A-A' (Figure 15) to 200 m on seismic section B-B' (Figure 16), and at least 250 m on cross section C-C' (Figure 17). The presence of Frenchman Springs basalt at the top of Mt. Angel (M. Beeson, pers. commun., 1990) indicates that the top of CRBG would have been close to the present summit prior to erosion, constraining offset to approximately 250 m. A reflector within the overlying fluvial sequence is offset about 40 m, as based on seismic section B-B'. The dip of the fault is 60°-70° as based on seismic section B-B'. On the southwest side of the fault, the top of the CRBG is warped into a shallow syncline that increases in prominence northward as offset on the Mt. Angel fault decreases (Figure 13).

Evidence for the Mt. Angel fault is limited in the Waldo Hills, although a Ginkgo intracanyon flow of the CRBG in the Waldo Hills is offset right-laterally across the fault about 1 km (M. Beeson, pers. commun., 1990).

Six small earthquakes with m_c (m_c = coda-length magnitude) = 2.0, 2.5, 2.4, 2.2, 2.4, and 1.4 occurred on August 14, 22, and 23, 1990 with epicenters near Woodburn (Werner et al, 1990a). Routine locations were determined using the IRIS/OSU broadband seismic station in Corvallis (epicentral distance 68 km) and the Washington Regional Seismograph Network. Three events in 1980 and 1983 with $m_c < 1.7$ occurred at the same locality. The waveforms for the six events are so similar that the locations of all events are considered to be much closer than the scatter shown in Figure 15. The preferred focal mechanism (Figure 19) is a right-lateral strike-slip fault striking north-south and dipping steeply to the west with a small normal component.

10.Yamhill-Sherwood structural zone

This northeast-trending zone includes the Yamhill River fault of Baldwin et al. (1955) and Brownfield (1982a, b) which juxtaposes Nestucca Formation on the north against Yamhill Formation on the south (Plate I) with maximum vertical separation greater than 300 m (Baldwin et al, 1955). The fault may continue along the northern end of the Amity Hills based on a proprietary seismic line. Farther northeast, the Sherwood fault between Parrett Mountain and the Chehalem Mountains has 100 to 150 m of vertical separation of CRBG (Hart and Newcomb, 1965; Beeson et al., 1989a), 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 CRBG traversed the Cascade Range (Beeson et al., 1989a). 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).

11.Northern Willamette downwarp

The northern Willamette Valley trends roughly northeast, but the northern end of the valley is underlain by an east-trending downwarp in which the top of CRBG is as deep as -500 m. The downwarp cuts across the northern extension of the Mt. Angel fault but is most prominent east of it. The north flank is steeper than the south flank; this may be upwarping influenced by the emplacement of intrusions related to the Boring Lavas (Plate I). Post-CRBG sediments are warped to a lesser degree than the top of the CRBG, as shown by proprietary seismic data. This downwarp may be part of a western extension of the Yakima fold belt, as are other structures to the northeast as suggested by Beeson et al. (1989a).

12.Faults at Parrett Mountain, Petes Mountain, and in the adjacent northern Willamette Valley

Faults at Parrett Mountain and Petes Mountain were mapped by M. Beeson and T. Tolan (pers. commun. to I. Madin, 1990) based on juxtaposition of CRBG flows identified using geochemistry. Displacements are commonly tens of meters. To the south, seismic lines show that the top of the CRBG is faulted and has undergone upward bulging presumably related to emplacement of Boring intrusions (Werner, 1990). A fault, mapped by Glenn (1965) along the east bank of the Molalla River behind Swan Lake Farms near Canby, is shown in Figure 20. This fault dips steeply to the north. A mudstone bed beneath the unfaulted Willamette Formation is offset 1 m down to the north. The mudstone is correlated by Glenn (1965) to the Rowland Formation, although the characteristic paleosol at the top of the Diamond Hill Member is absent. Alternatively, the mudstone could be part of the pre-Rowland fluvial sequence which is exposed east of Canby.

13. Beaverton fault zone

Two faults striking N 45° E, constrained by seismic reflection lines and water wells, extend approximately 9 km northeast from the northern margin of Cooper Mountain. On the downthrow side of the eastern fault, north of Cooper Mountain, CRBG at -260 m elevation dips south, whereas CRBG is exposed at 100 m elevation on the upthrown side on the northern flank of the mountain. A data-gap in the seismic line prevents precise location of the fault. Five kilometers northeast, the eastern fault offsets the top of CRBG 70 m down to the northwest. Vertical separation at the northeastern end of the western fault is 30 m down to the northwest, while near Cooper Mountain, the sense of offset is reversed and the vertical separation is 75 m, down to the southeast.

The Beaverton fault zone continues southwestward into the Chehalem Mountains, where a series of northeast-trending faults is interpreted on the basis of aeromagnetic data and water wells, in agreement with previously mapped faults (Schlicker and Deacon, 1967). Contact relations across the Beaverton fault zone are consistent with either normal faulting or left-lateral strike-slip displacement.

14. Helvetia fault

The northwest-trending Helvetia fault offsets the Columbia River Basalt Group from the confluence of Rock and Beaverton Creeks near Orenco northwestward to the McKay Creek Valley and possibly into the Tualatin Mountains. Separation is down to the southwest. At Orenco, the top of CRBG may be separated 110 m, though possible Boring intrusions visible on seismic lines complicate the structure. Seismic reflection data show reflectors in the upper part of the overlying sediments to be offset approximately 20 m. Water wells west of Helvetia suggest up to 100 m of vertical separation.

Undulation of the top of CRBG in the northern Tualatin basin suggest similar faults may extend southeastward from the valleys containing the East and West Forks of Dairy Creek, though the data are inconclusive.

15. Tualatin basin

The CRBG 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 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 portion of the basin is complicated by the apparent intrusion of Boring stocks. Cooper Mountain and Bull Mountain, in the center of the basin southwest of Beaverton, are underlain by CRBG folded into two east-trending, doubly-plunging anticlines.

The post-CRBG fill consists of mudstone, siltstone, and sandstone with lenses of pebbly sand and gravel. The abundance of quartz and mica in these sediments indicates a dominant source from the Columbia River, with a subordinate local source from the CRBG in highlands flanking the basin. The floor of the basin is downwarped with its axis 200-300 m deep, trending east-west. The thickest sequence of post-CRBG strata is 410 m near Hillsboro. Proprietary seismic data show that the post-CRBG sequence dips much more gently than the underlying CRBG.

DISCUSSION AND CONCLUSIONS

AGE OF THE WILLAMETTE VALLEY AND COAST RANGE

The Willamette Valley is commonly referred to as a forearc basin. However, this is true only for the late Cenozoic after emplacement of the CRBG. The pre-CRBG strata are part of a forearc basin, but this basin includes the Coast Range as well as the Willamette Valley. For the most part, sedimentary facies show a deepening westward across the Willamette Valley and Coast Range, as best documented for the facies boundary between the upper Eocene Spencer strandline deposits and Nestucca deeper-water deposits. There were basaltic highlands to the west, but these did not link up to form a throughgoing Coast Range.

The first-order structure of the Willamette Valley is an east-dipping homocline that developed after the deposition of the Oligocene-Miocene Scotts Mills Formation and prior to the emplacement of CRBG. The east dip of this homocline implies uplift of the Coast Range prior to the CRBG, but this is not clearly documented in facies changes of pre-CRBG sedimentary rocks. The flows of the CRBG passed through the Cascade Range via the Columbia Trans-Arc Lowland of Beeson et al. (1989a) and on to the coast as flows filling broad valleys in an incipient Coast Range. There was no marked tendency for CRBG flows to follow the north-south trend of the modern Willamette Valley.

The fluvial deposits of the proto-Willamette River and tributary drainages are the oldest strata to follow the present trend of the Willamette Valley. The top of the CRBG beneath these deposits is commonly deeply weathered, suggesting that a long time elapsed after CRBG emplacement before these deposits began to aggrade in the Willamette Valley. A channel cut to 150 m elevation 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, producing broad synclines and anticlines.

AGE OF INITIATION OF ARC VOLCANISM EAST OF THE WILLAMETTE VALLEY

The general view is that Cascade arc volcanism began about 42-43 Ma based on the age of volcanic rocks at the base of the exposed sequence in the western Cascades. 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 lower Narizian to upper Ulatisian foraminifera, suggesting an age of 45-48 Ma. Coccoliths from the Yamhill Formation of the Coast Range are referred to Subzones CP 13c and CP 14a, with estimated ages of 42.5 to 47 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 age estimated as 50 to 52.5 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 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 Cascades occur in an eastward-dipping homocline that strikes nearly north-south (Sherrod and Pickthorn, 1989). The outcrop belt is truncated at a low angle by the range front of the western Cascades such that the oldest sequence, dated 35-45 Ma, is truncated in the southern Willamette Valley south of Lebanon, and the next oldest, 25-35 Ma, is truncated against the Willamette Valley east of Salem. Facies boundaries between marine sedimentary rocks and volcaniclastic rocks of upper Eocene and Oligocene age strike north-northeast. This means that the outcrop belt of Eocene and Oligocene rocks cuts across the arc at a small angle such that the southern end of the outcrop belt consists of volcanic rocks and the northern end consists of sedimentary rocks (Fig. 21).

The southern and eastern edges of the Willamette Valley appear to be controlled by the facies boundary between erosionally resistant volcanic and erosionally weak non-volcanic rock. 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 near the eastern edge of the valley, including Peterson Butte and Bond Butte.

The western edge of the valley is controlled by the contact between erosionally-resistant sandstone of the Tyee Formation and 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 Eugene Formation. The outcrop belt is wide because of a decrease in east dip of the Eugene Formation accompanying downwarping of the Willamette Valley following emplacement of the CRBG. The strike valley underlain by Eugene Formation is a late Tertiary feature, because it is covered by fluvial deposits of the proto-Willamette River system.

STRUCTURAL CONTROL OF FAULT SYSTEMS

Western Oregon has undergone clockwise rotation from Eocene through at least the Miocene, with greater rotations in the Coast Range than in the Cascades (Wells, 1984; Wells and Heller, 1988). This led to the development of faults with major displacement as early as the Eocene, with the greatest measured displacement 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 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 (Jack Meyer, pers. commun., 1991) and has been reactivated since middle Miocene time.

Werner et al. (1990b) compared in situ stress orientation in western Oregon based on 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 approximately north-south, confirming earlier studies based on less data. The fault patterns in the Willamette Valley are predominantly NW-SE and NE-SW, and folds involving the post-CRBG section commonly strike E-W, in agreement with a north-south maximum horizontal compressive stress.

EARTHQUAKE HAZARD FROM CRUSTAL FAULTS IN THE WILLAMETTE VALLEY

The fluvial deposits of the proto-Willamette River and its tributaries are cut by several faults with vertical separations up to 250 m. In addition, these deposits are warped into broad folds which 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 Boring Lava as young as 600 ka (I. Madin, pers. comm., 1990). Roberts (1984) suggested that the deeply-weathered high terrace gravels of the southern Willamette Valley are the constructional top of the proto-Willamette sequence, and that this sequence is as young as Pleistocene.

Post-CRBG deposits 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 possible Boring stocks (Popowski, 1991). The Owl Creek fault 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 Rowland Formation, the Corvallis fault zone has undergone at least 40 m of vertical separation since deposition of the Rowland Formation.

The Willamette Formation, dated as later than 15 ka to 13 ka, shows no evidence of offset by faulting, including the Owl Creek fault. However, seismicity on the Mt. 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 vertical slip rate of 0.5 mm/yr, a maximum figure. If the NW-SE and NE-SW trending faults are predominantly strike-slip, the rate of 0.5 mm/yr would be a minimum. However, the Mt. Angel fault, with a maximum vertical offset of the top of CRBG of about 250 m, has a lateral offset of a Ginkgo intracanyon flow of only 1 km. 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, 6 km, the Owl Creek fault, 15 km, 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^{-2}.

It is premature to estimate the earthquake potential from crustal faults in the Willamette Valley for the following reasons. First, we do not know how much of a mapped fault would rupture in a single earthquake. Second, 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) and on the Portland frontal-fault structure (Yelin and Patton, 1991), but we do not know if larger earthquakes are possible. Finally, we have no direct paleoseismological information about past recurrence history on crustal faults in western Oregon.

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FIGURE CAPTIONS

Figure 1. Plate boundaries of the Pacific Northwest and location of study area. Major stratovolcanoes shown by open triangles.

Figure 2. Physiographic features of the Willamette Valley and Tualatin Basin, northwest Oregon.

Figure 3. Stratigraphic correlation chart for Tertiary rocks of western Oregon. Symbols correspond to formations on Plates I and III and are identified on Plate ID. Foraminiferal stages from Kleinpell (1938) and Mallory (1959). Modified from Armentrout et al. (1983).

Figure 4. Graphic log of DH 13-88 drilled on the southeast side of Corvallis just east of the intersection of Highway 34 and 99W (Plate IIB; Figure 7).

Figure 5. Graphic log of DH 14-90 drilled 1.4 km west of Sublimity at Highway 22 north of Mill Creek on the southern edge of the Waldo Hills

Figure 6. Structure contour map of the base of the Pleistocene Rowland Formation of Balster and Parsons (1969), including subcrop map of the underlying unnamed fluvial sediments. Location of boundary between proto-Willamette River channel facies and overbank facies is approximate due to interfingering. H-H' locates cross section shown in Figure 7.

Figure 7. Structural cross section constrained by water wells, engineering bore holes, and petroleum-exploratory wells showing channel facies and overbank facies of proto-Willamette River, high terrace gravels, late Pleistocene outwash deposits of Rowland Formation, and catastrophic flood deposits of Willamette Formation.

Figure 8. Schematic post-Miocene history of the southern Willamette Valley, modified from Roberts (1984).

Figure 9. Tectonic map of the southern Willamette Valley. Areas underlain by post-CRBG alluvial deposits are unshaded, areas underlain directly by bedrock are shaded. Faults shown in heavy lines. Abbreviations: 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; SU, Shelburn uplift; TF, Turner fault; WHRFF, Waldo Hills range-front fault; WHU, Waldo Hills uplift.

Figure 10. Tectonic map of the northern Willamette Valley. Shaded areas, faults are as in Figure 8. Abbreviations of topographic features: AH, Amity Hills; CM, Chehalem Mountains; PAM, Parrett Mountain, PEM, Petes Mountain; RHD, Red Hills of Dundee. Abbreviations of faults: 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.

Figure 11. A: Longitudinal profile of the modern Willamette River; south is to left. B: Profile along proto-Willamette River showing deformation of the axis of the main stream channel. Dashed line follows axis of channel marked by gravel deposit, including a course east of Salem Hills through Mill Creek gap. Dotted line follows axis of a second channel west of the Salem Hills in which gravel deposits are not common.

Figure 12. a. Cross section across the Waldo Hills range-front fault based on water wells and surface geology. Symbols correspond to those in Plate I. Although the range front is linear, it is not known if the fault cuts the unnamed nonmarine fine-grained sediments. b. Map locating cross section and exposures of Oligocene and Eocene sedimentary rock from Hampton (1972).

Figure 13. Buried trace of the Newberg fault at Newberg, juxtaposing marine strata on the northeast against CRBG on the southwest. Post-CRBG sediments do not appear to be faulted. Symbols as in Plate I.

Figure 14. Structure contour map on top of basalt, primarily top of CRBG except near exposures of Oligocene-Miocene basalt (MO_b). Other abbreviations: MO_s, Miocene and Oligocene sedimentary rock; Mb_c, Columbia River Basalt Group; PMf, Pliocene and Miocene fluvial and lacustrine sediments; Qu, Quaternary sediments, undifferentiated.

Figure 15. Epicenters of earthquake near Woodburn and location of seismic and water-well cross sections. Formation abbreviations same as Figure 13.

Figure 16. Seismic section A-A', located on Figure 15. A, uninterpreted section; B, interpreted section. Four strands of Mt. Angel fault are recognized. Prominent reflector within PMf is higher on northeast than on southwest side. Symbols as in Figure 14.

Figure 17. Seismic section B-B', located on Figure 15. A. uninterpreted section; B. interpreted section. Symbols as in Figure 14. Top of basalt offset a greater amount than PMf reflector.

Figure 18. Cross section C-C', located on Figure 15, constrained by water wells. Only those parts of wells with useful well logs are shown. Symbols as in Figure 14. Base of Mb_c is not shown. Gravel intervals are shown by horizontal lines. Dip on fault is based on seismic section B-B' (Figure 17).

Figure 19. Composite focal mechanism for the August, 1990, earthquake sequence at Woodburn, Oregon, from J. Nabelek, pers. commun., 1990. Open circles indicate dilatation, filled circles indicate compression. Larger circles indicate a stronger first motion. Three separate focal mechanisms based on wave-form analysis are indicated by solid, dashed, and dotted lines; dashed focal mechanism is preferred. These are compatible with first-motion solutions.

Figure 20. Swan Island fault exposed in bank of Molalla River. Unit I may correlate to the Rowland Formation as described at River Bend, near St. Paul; it is downdropped to the north. Unit II, the Willamette Formation, is unfaulted. View to NE. Photograph by Glenn (1965).

Figure 21. Sketch map showing outcrop belts of western Cascade volcanic rocks (after Sherrod and Pickthorn, 1989) and NNE-trending facies boundary between volcanic and sedimentary rocks. Facies boundary controls the position of the eastern edge of the Willamette Valley between erosionally-resistant volcanic rocks to the ESE and erosionally-weak sedimentary rocks, principally Eugene Formation, to the WNW beneath the valley.

Plates

Plate 1. Geology of the Willamette Valley with structure contours on the top of the Spencer Formation (southern Willamette Valley) or on the top of the Columbia River Basalt Group (northern Willamette Valley and Tualatin basin). Contours in the Tualatin basin are queried where uncertain, due to possible Boring intrusions. A. southern sheet; B. central sheet; C. northern sheet; D. explanation

Plate II. Structure contours of the base of unconsolidated sediments. A. southern sheet; B. central sheet

Plate III. Cross sections A-A' through F-F'

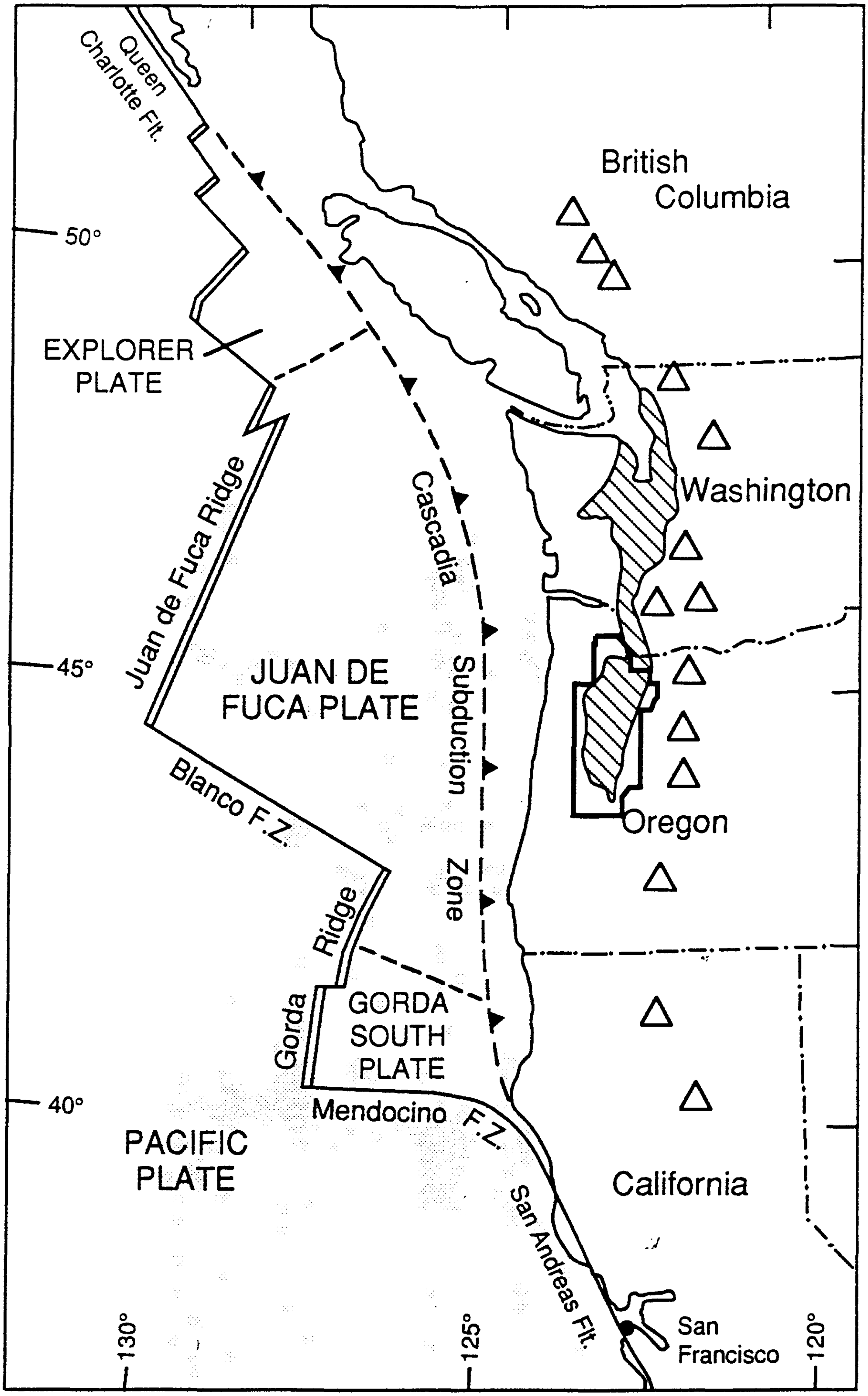

Queen Charlotte Flt.
British Columbia
50°
EXPLORER PLATE
Juan de Fuca Ridge
Cascadia Subduction Zone
Washington
45°
JUAN DE FUCA PLATE
Blanco F.Z.
Oregon
Gorda Ridge
GORDA SOUTH PLATE
40°
Mendocino F.Z.
PACIFIC PLATE
San Andreas Flt.
California
San Francisco
130°
125°
120°

Figure 1

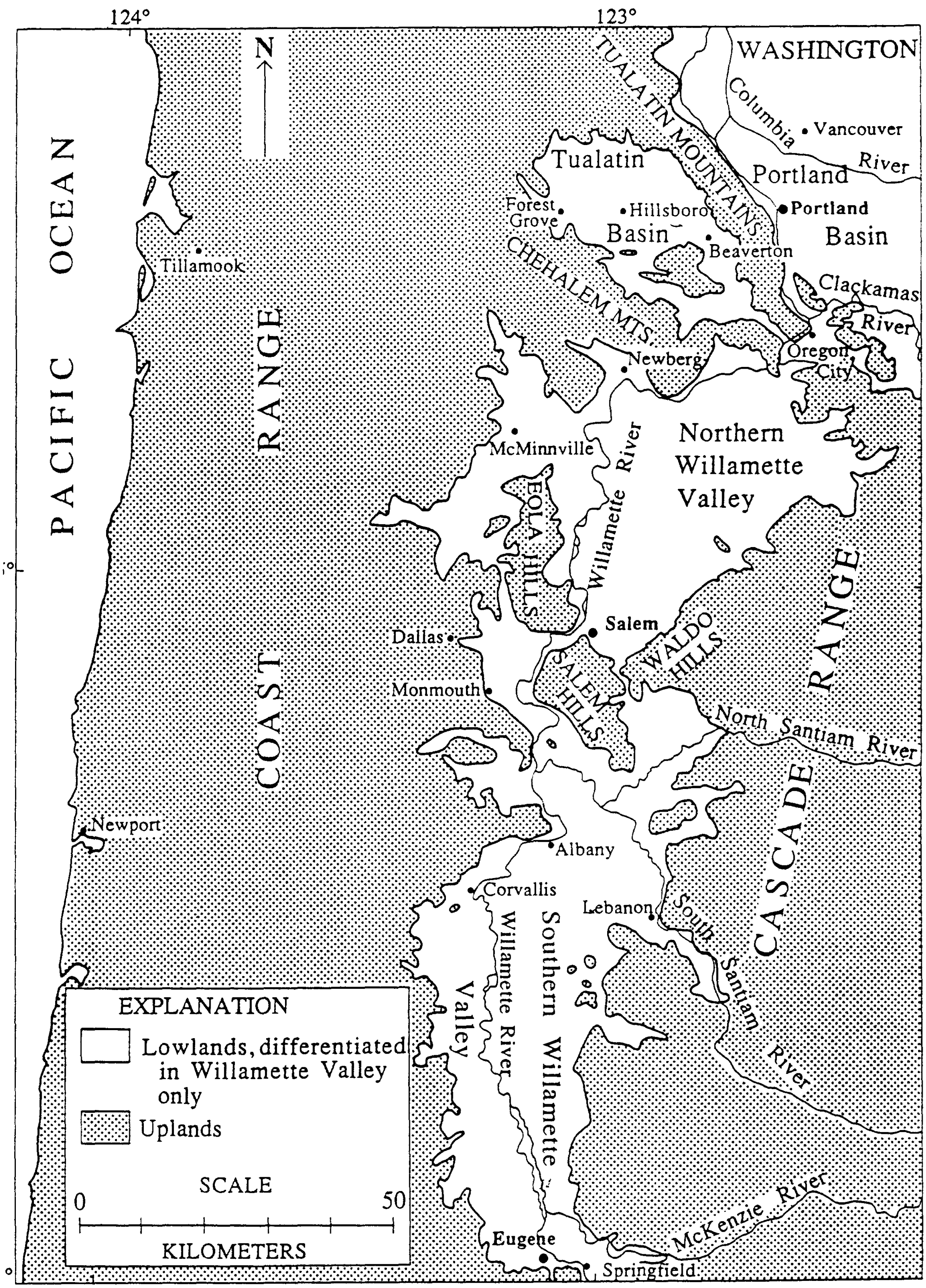

124°
123°
N
WASHINGTON
Columbia
Vancouver
River
PACIFIC OCEAN
TUALATIN MOUNTAINS
Tualatin
Portland
Forest Grove
Hillsboro
Portland
Basin
Basin
Beaverton
Tillamook
CHEHALEM MTS
Clackamas
River
Oregon City
Newberg
COAST RANGE
McMinnville
Northern
Willamette
Valley
Willamette River
EOLA HILLS
Salem
Dallas
WALDO HILLS
SALEM HILLS
Monmouth
North Santiam River
CASCADE RANGE
Newport
Albany
Corvallis
Lebanon
South Santiam River
Southern Willamette Valley
Willamette River
EXPLANATION
Lowlands, differentiated in Willamette Valley only
Uplands
SCALE
0
50
KILOMETERS
Eugene
Springfield
McKenzie River

Figure 2

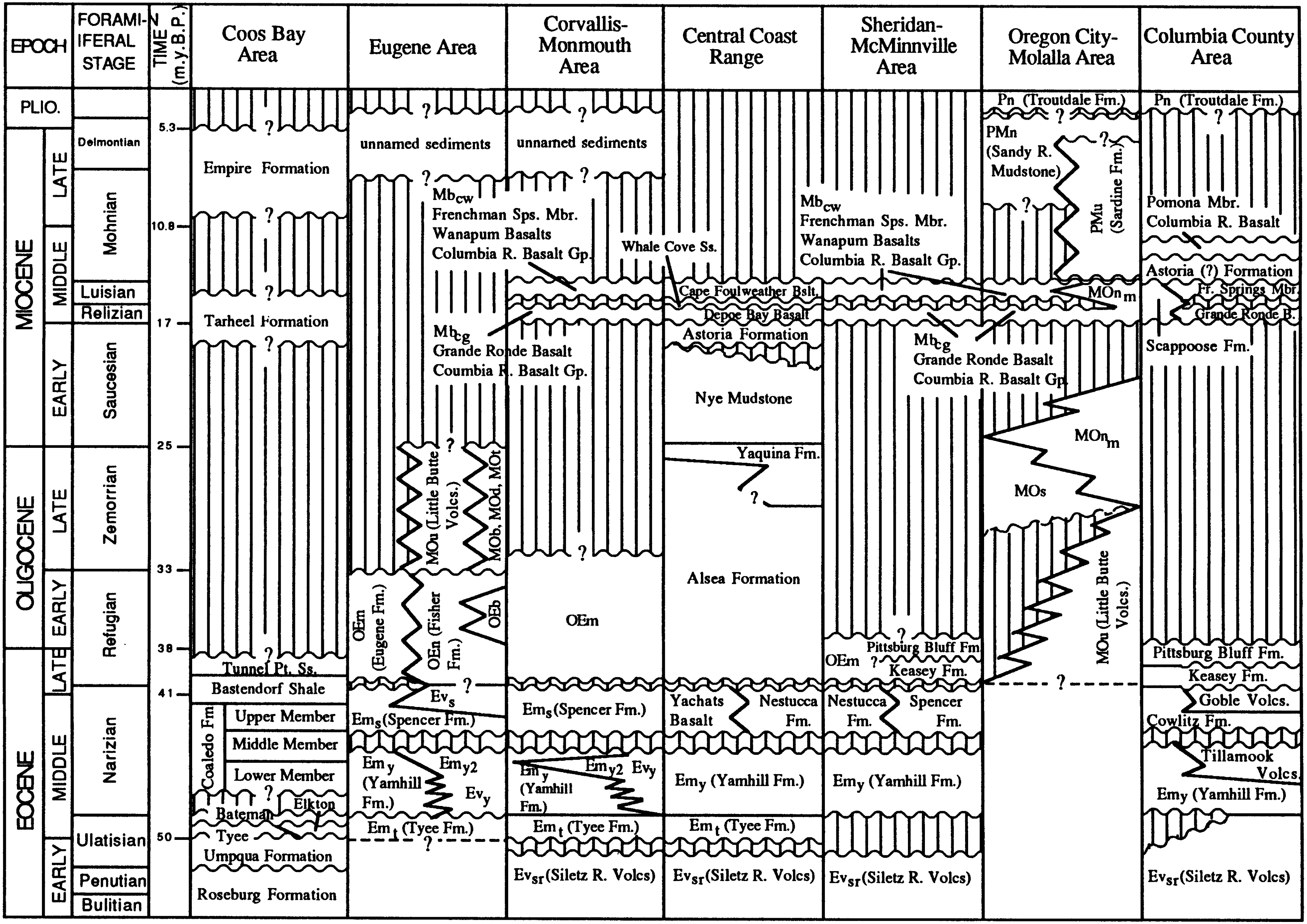
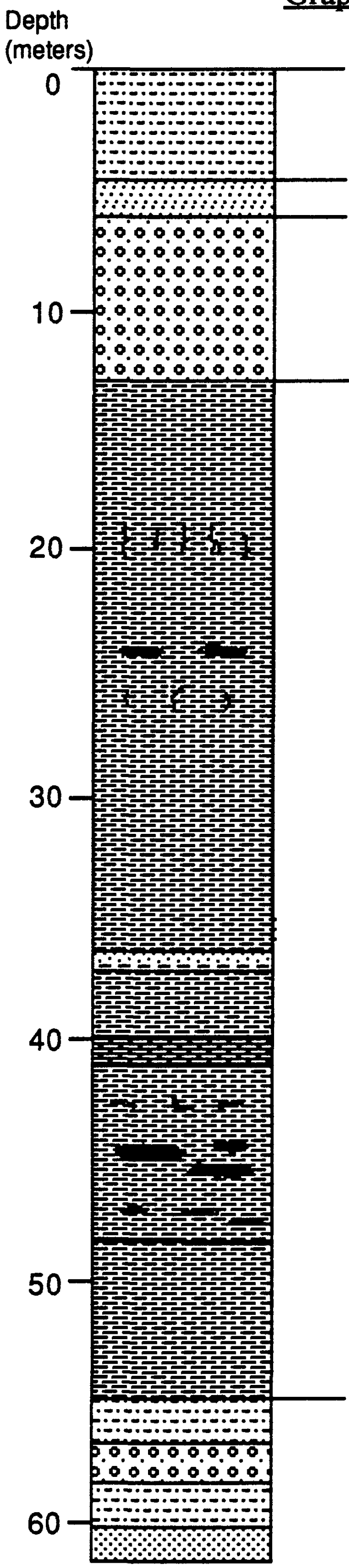

EPOCH
FORAMINIFERAL STAGE
TIME (m.y.B.P.)
Coos Bay Area
Eugene Area
Corvallis-Monmouth Area
Central Coast Range
Sheridan-McMinnville Area
Oregon City-Molalla Area
Columbia County Area
PLIO.
MIOCENE
OLIGOCENE
EOCENE
LATE
MIDDLE
EARLY
Delmontian
Mohnian
Luisian
Relizian
Saucesian
Zemorrian
Refugian
Narizian
Ulatisian
Penutian
Bulitian
5.3
10.8
17
25
33
38
41
50
Empire Formation
Tarheel Formation
Tunnel Pt. Ss.
Bastendorf Shale
Coaledo Fm.
Upper Member
Middle Member
Lower Member
Bateman
Elkton
Tyee
Umpqua Formation
Roseburg Formation
unnamed sediments
Mb_{cw}
Frenchman Sps. Mbr.
Wanapum Basalts
Columbia R. Basalt Gp.
Mb_{cg}
Grande Ronde Basalt
Coumbia R. Basalt Gp.
MOu (Little Butte Volcs.)
MOb, MOd, MOt
OEm (Eugene Fm.)
OEn (Fisher Fm.)
OEb
Ev_s
Em_s (Spencer Fm.)
Em_y (Yamhill Fm.)
Em_{y2}
Ev_y
Em_t (Tyee Fm.)
OEm
Ev_{sr} (Siletz R. Volcs)
Whale Cove Ss.
Cape Foulweather Bslt.
Depoe Bay Basalt
Astoria Formation
Nye Mudstone
Yaquina Fm.
Alsea Formation
Yachats Basalt
Nestucca Fm.
Pittsburg Bluff Fm
Keasey Fm.
Spencer Fm.
Pn (Troutdale Fm.)
PMn (Sandy R. Mudstone)
PMu (Sardine Fm.)
MOn_m
MOs
Pomona Mbr.
Columbia R. Basalt
Astoria (?) Formation
Fr. Springs Mbr.
Grande Ronde B.
Scappoose Fm.
Pittsburg Bluff Fm.
Goble Volcs.
Cowlitz Fm.
Tillamook Volcs.

Figure 3

Graphic Log of DH13-88



Willamette Fm.: Brown, micaceous, clayey silt with some fine sand and a trace of organics.

Diamond Hill Member, Rowland Fm.: Grey micaceous fine grained silty sand.

Linn Gravel Member, Rowland Fm.: Grey to brown sandy gravel and gravelly sand; many clasts > 3 cm, predominantly basalt.

Unnamed fluvial sediments: Blue green to grey clay with faint laminations and some organic material; abundant slickensided fractures.

Small rootlets in growth position.

Large wood fragments (>3cm).

Small rootlets in growth position.

Interlayered dark green to grey clayey sand.

Dark brown organic clay.

Large wood fragments; some > 6 cm thick (logs or roots).

Spencer Fm.: Green grey siltstone; gradational contact w/overlying clay.

Basaltic sandy gravel.

Dark grey sandstone and siltstone.

Figure 4

Graphic Log DH14-90

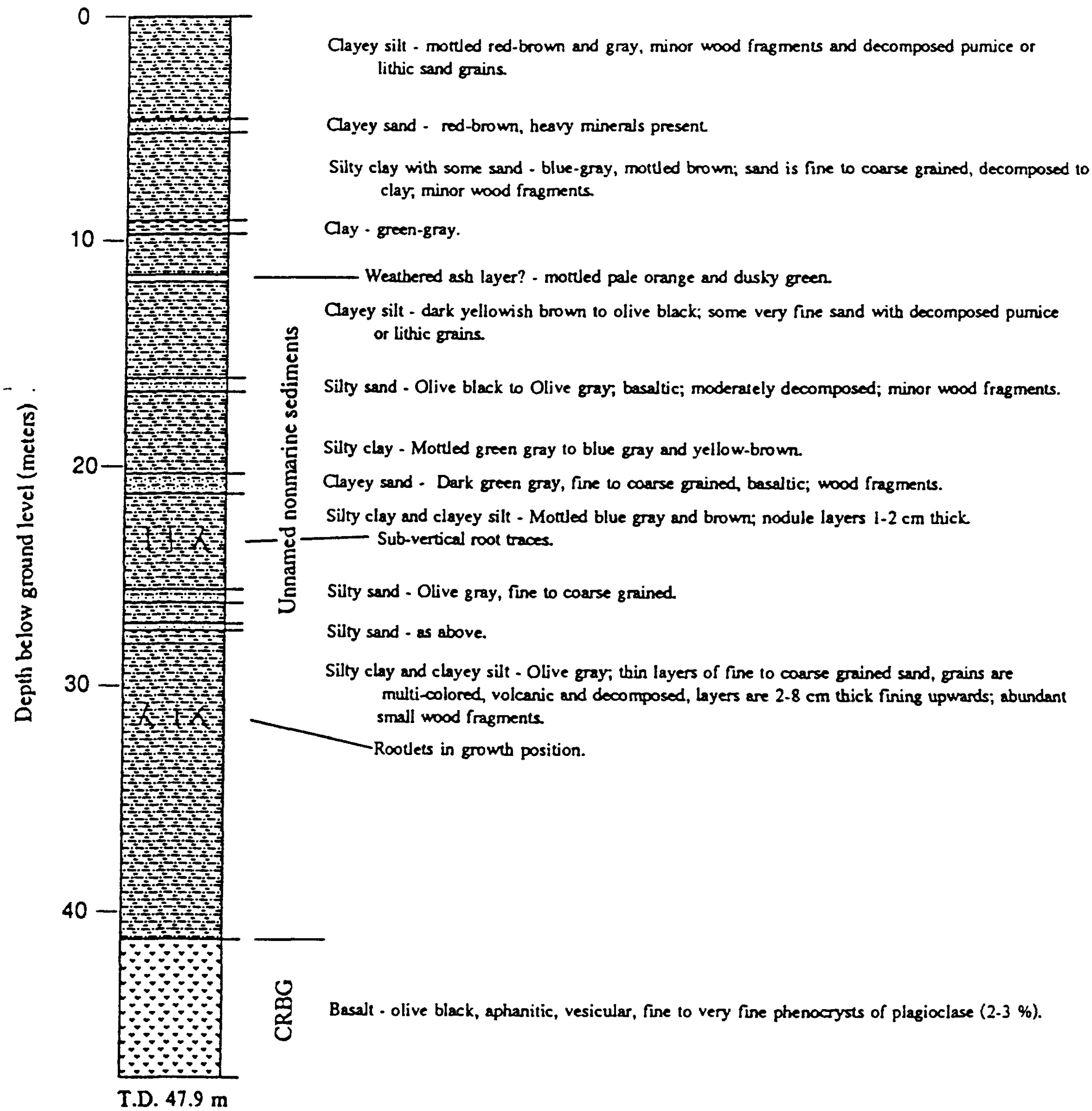
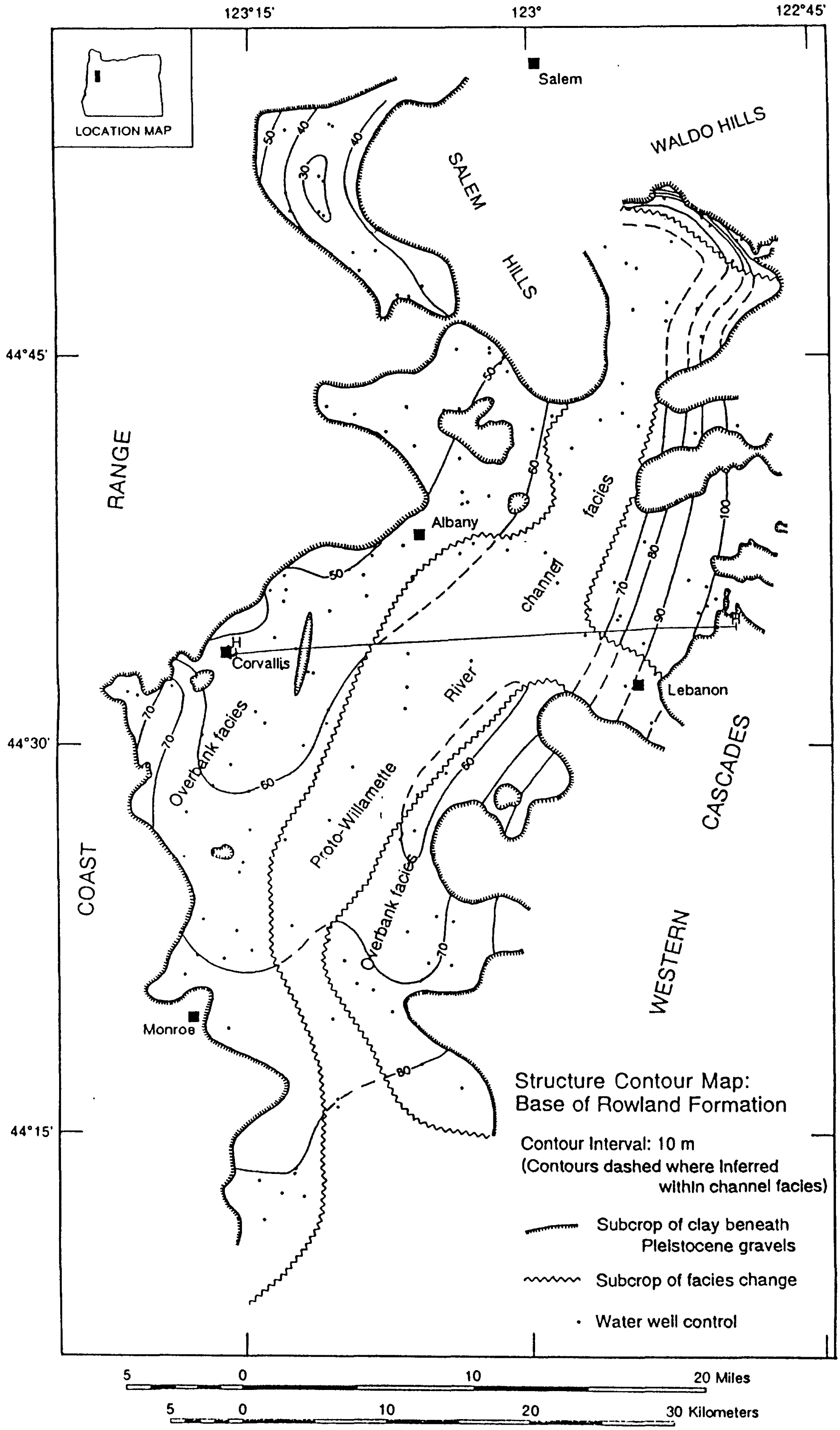


Figure 5



123°15'
123°
122°45'
44°45'
44°30'
44°15'
LOCATION MAP
Salem
WALDO HILLS
SALEM HILLS
Albany
Corvallis
Lebanon
Monroe
COAST RANGE
WESTERN CASCADES
channel facies
Overbank facies
Proto-Willamette River
Structure Contour Map:
Base of Rowland Formation
Contour Interval: 10 m
(Contours dashed where inferred within channel facies)
Subcrop of clay beneath Pleistocene gravels
Subcrop of facies change
Water well control
5 0 10 20 Miles
5 0 10 20 30 Kilometers

Figure 6

Cross Section H-H'

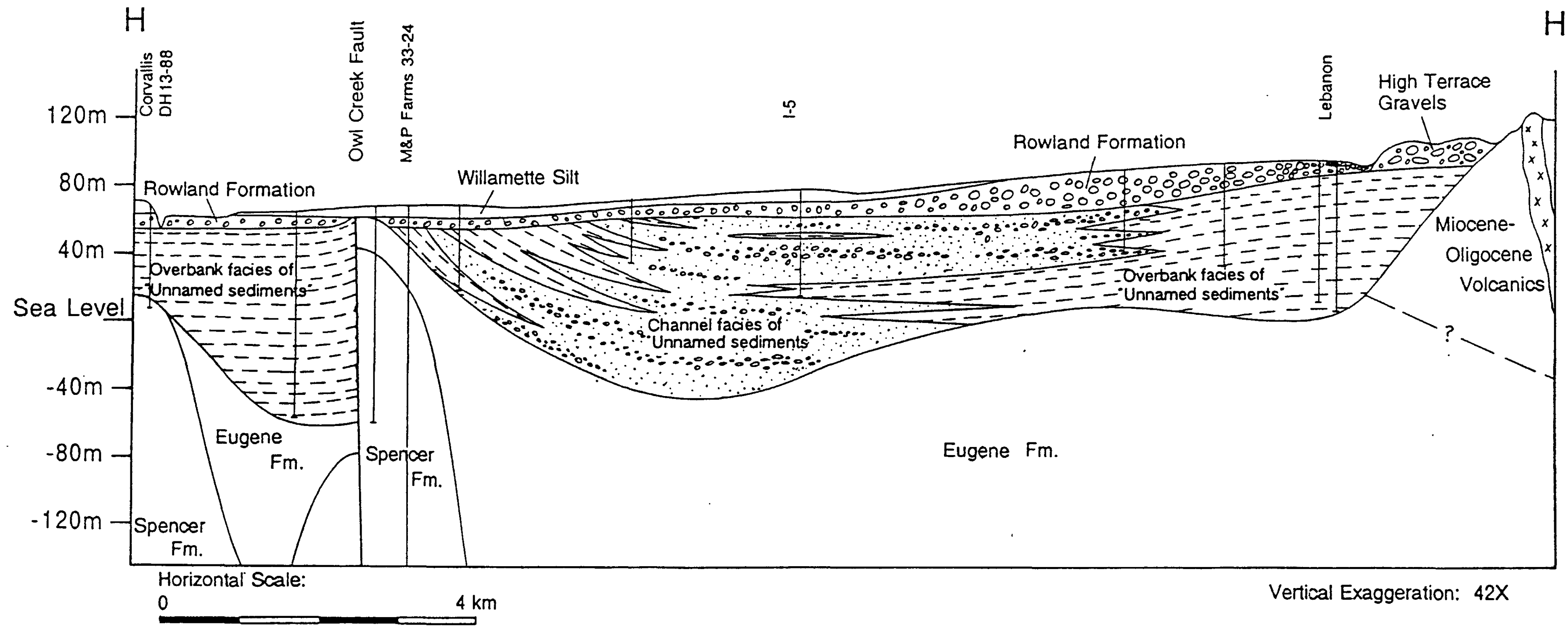


Figure 7

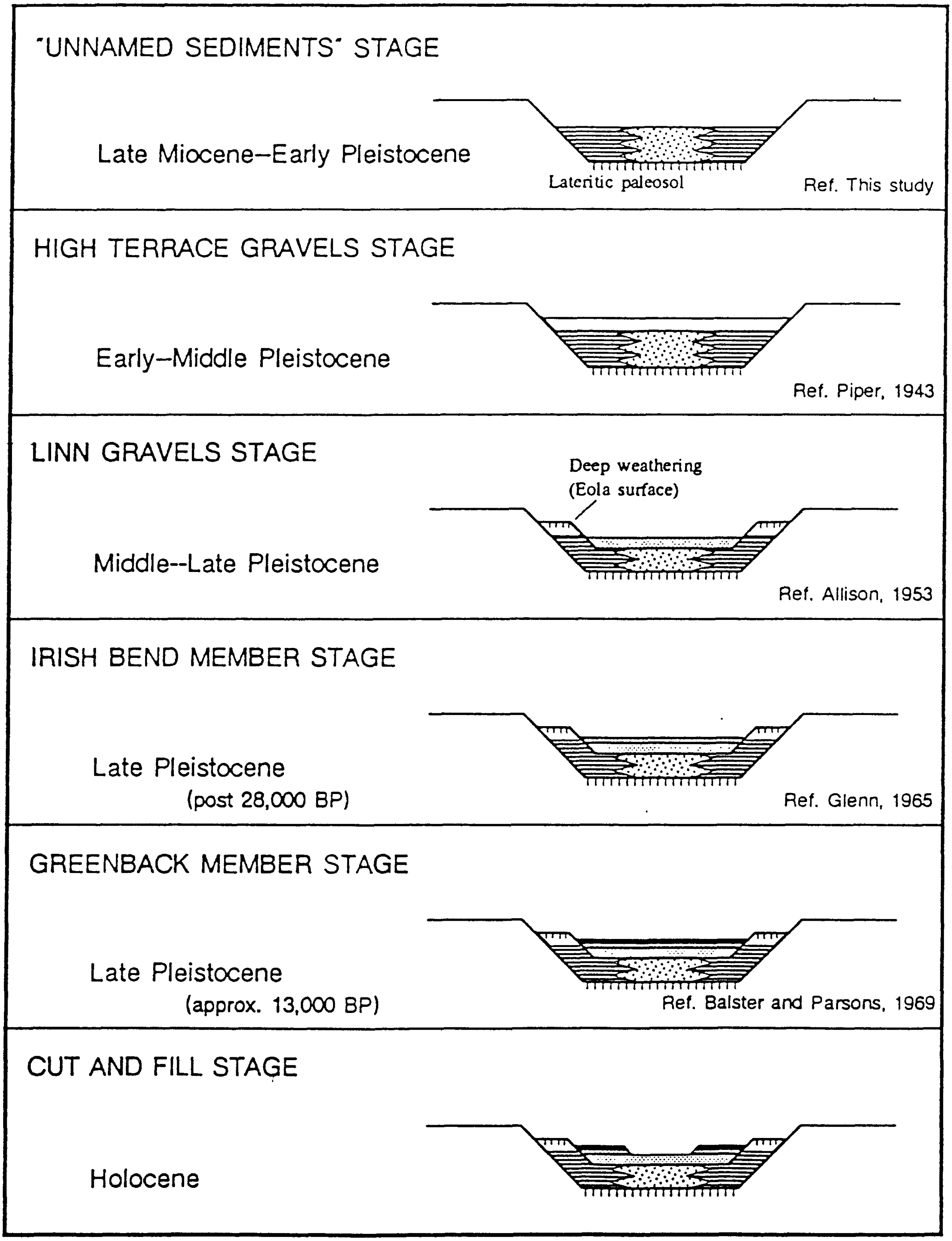

'UNNAMED SEDIMENTS' STAGE
Late Miocene–Early Pleistocene
Lateritic paleosol
Ref. This study
HIGH TERRACE GRAVELS STAGE
Early–Middle Pleistocene
Ref. Piper, 1943
LINN GRAVELS STAGE
Deep weathering
(Eola surface)
Middle--Late Pleistocene
Ref. Allison, 1953
IRISH BEND MEMBER STAGE
Late Pleistocene
(post 28,000 BP)
Ref. Glenn, 1965
GREENBACK MEMBER STAGE
Late Pleistocene
(approx. 13,000 BP)
Ref. Balster and Parsons, 1969
CUT AND FILL STAGE
Holocene

Figure 8

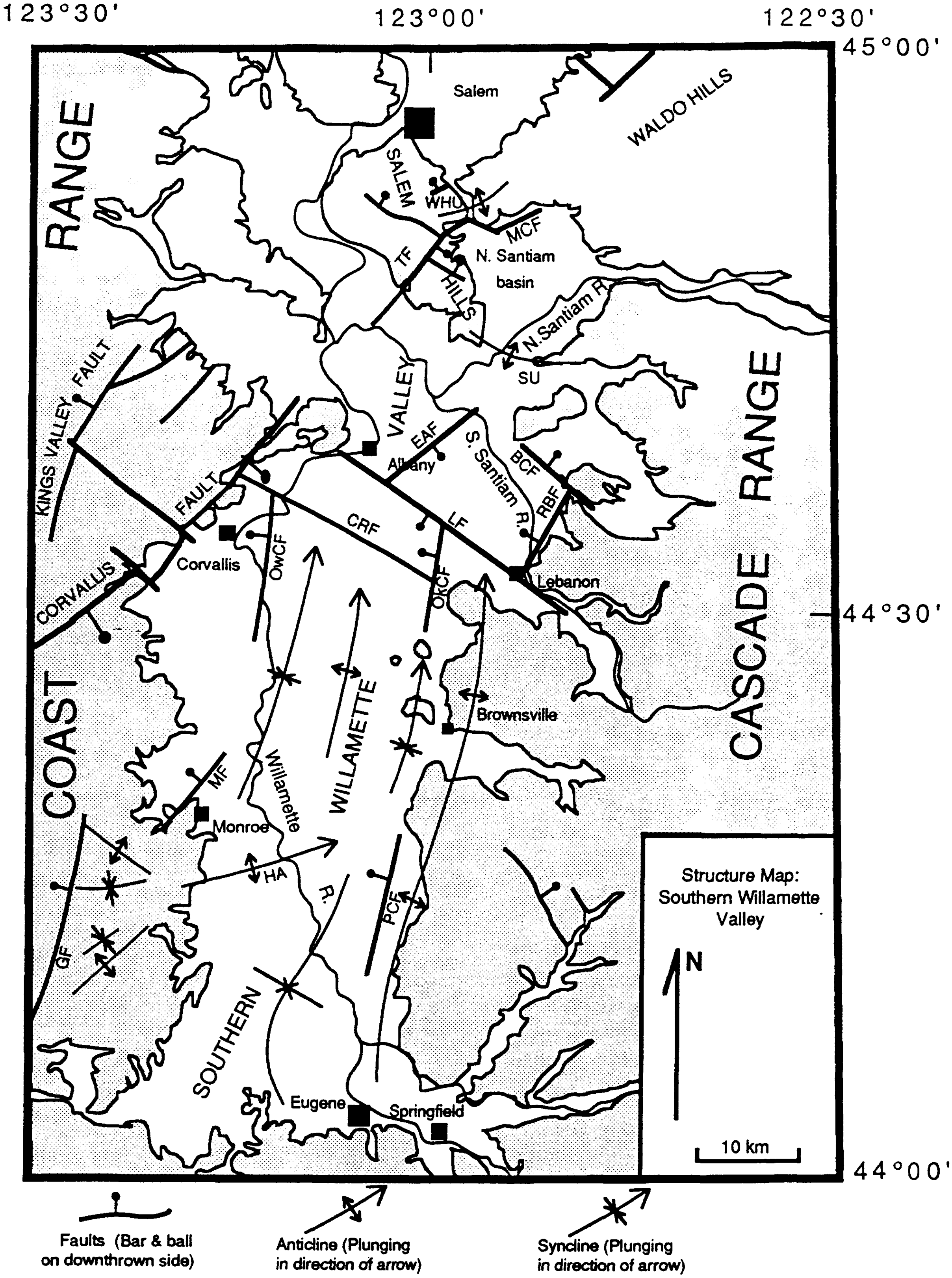
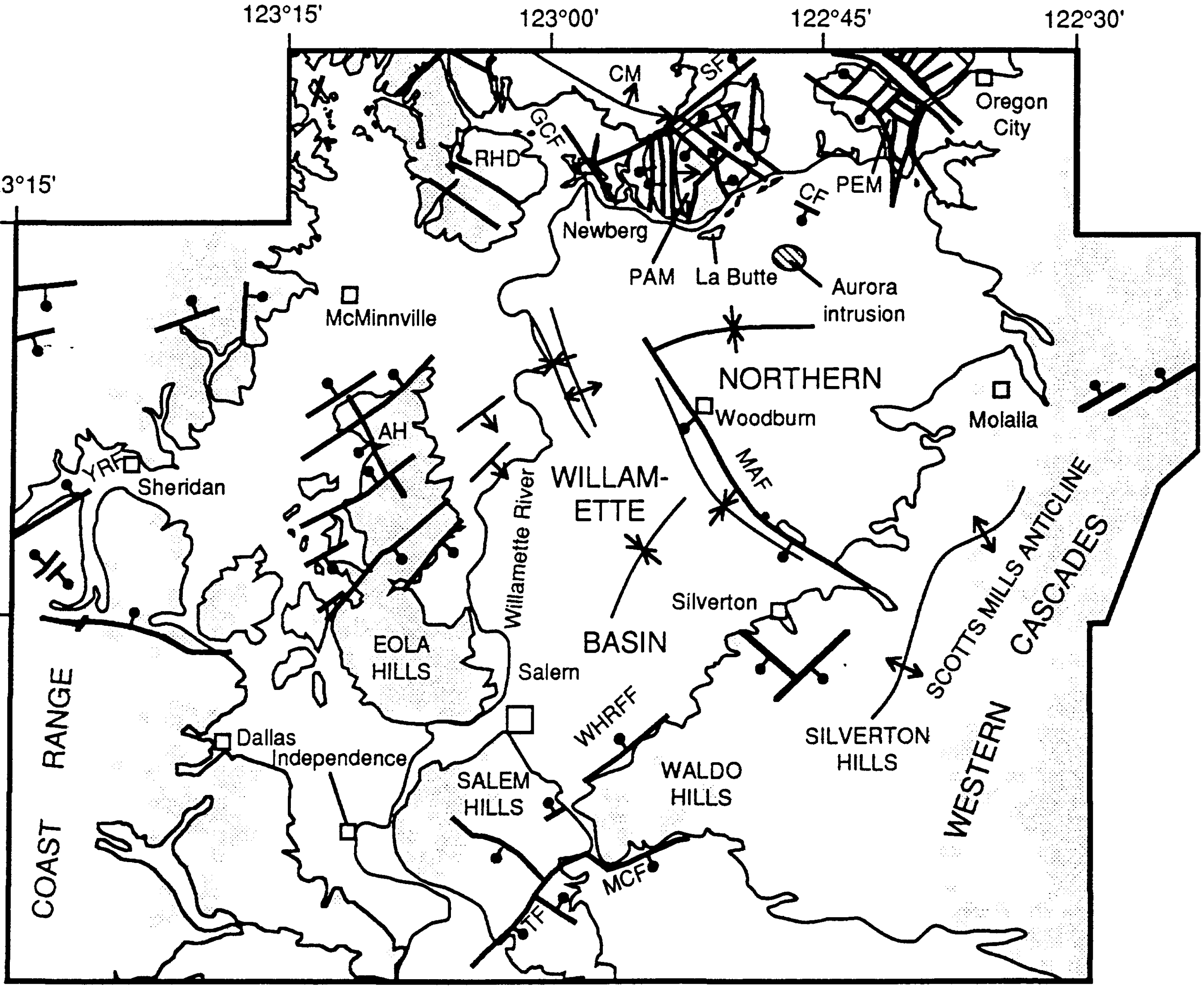

123°30'
123°00'
122°30'
45°00'
44°30'
44°00'
Salem
WALDO HILLS
RANGE
SALEM
WHU
MCF
TF
N. Santiam
basin
HILLS
N. Santiam R.
SU
KINGS VALLEY FAULT
VALLEY
EAF
Albany
S. Santiam R.
BCF
RBF
CASCADE RANGE
FAULT
CRF
LF
Corvallis
OwCF
OkCF
Lebanon
CORVALLIS
COAST
WILLAMETTE
Brownsville
MF
Willamette
Monroe
HA
R.
PCF
GF
SOUTHERN
Eugene
Springfield
Structure Map: Southern Willamette Valley
N
10 km
Faults (Bar & ball on downthrown side)
Anticline (Plunging in direction of arrow)
Syncline (Plunging in direction of arrow)

Figure 9



123°15'
123°00'
122°45'
122°30'
123°15'
45°15'
45°00'
CM
SF
GCF
RHD
Newberg
PAM
La Butte
CF
PEM
Oregon City
Aurora intrusion
McMinnville
NORTHERN
WILLAM-
ETTE
BASIN
Woodburn
Molalla
MAF
AH
YRF
Sheridan
Willamette River
Silverton
EOLA HILLS
Salem
WHRFF
SCOTTS MILLS ANTICLINE
CASCADES
WESTERN
SILVERTON HILLS
WALDO HILLS
SALEM HILLS
Dallas
Independence
COAST
RANGE
MCF
TF

Figure 10

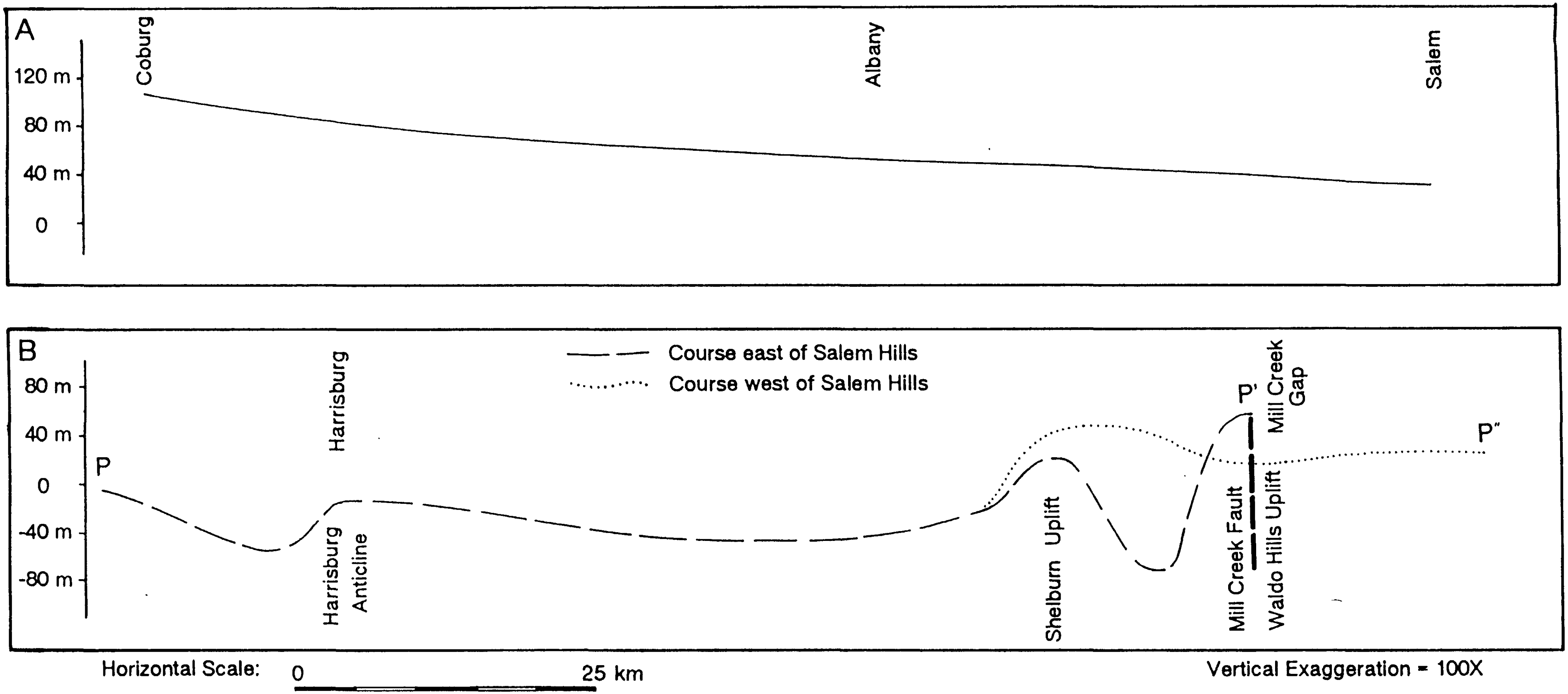
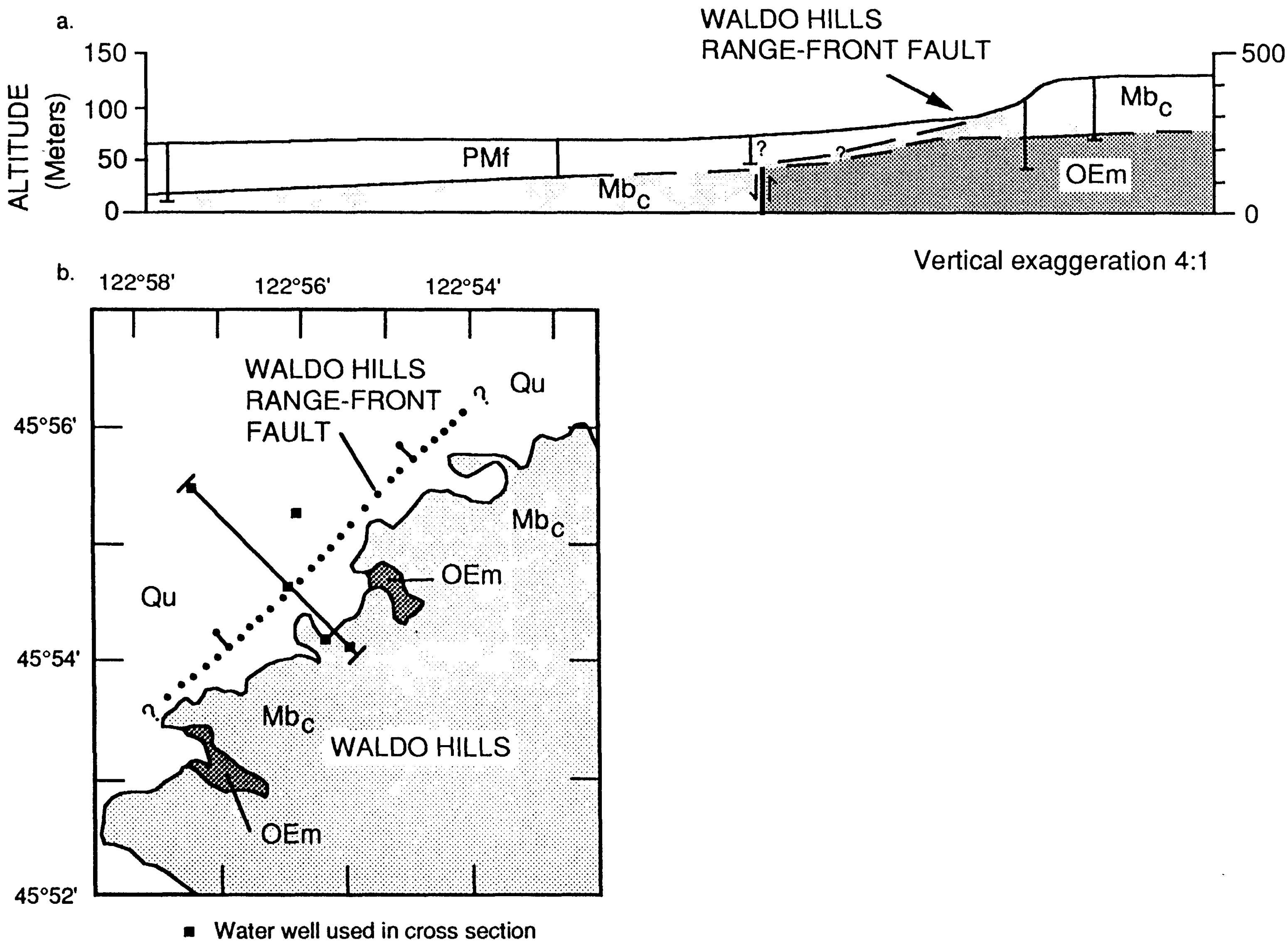

A
120 m
80 m
40 m
0
Coburg
Albany
Salem
B
80 m
40 m
0
-40 m
-80 m
P
Harrisburg
Harrisburg Anticline
Course east of Salem Hills
Course west of Salem Hills
Shelburn Uplift
P'
Mill Creek Gap
Mill Creek Fault
Waldo Hills Uplift
P"
Horizontal Scale:
0
25 km
Vertical Exaggeration = 100X

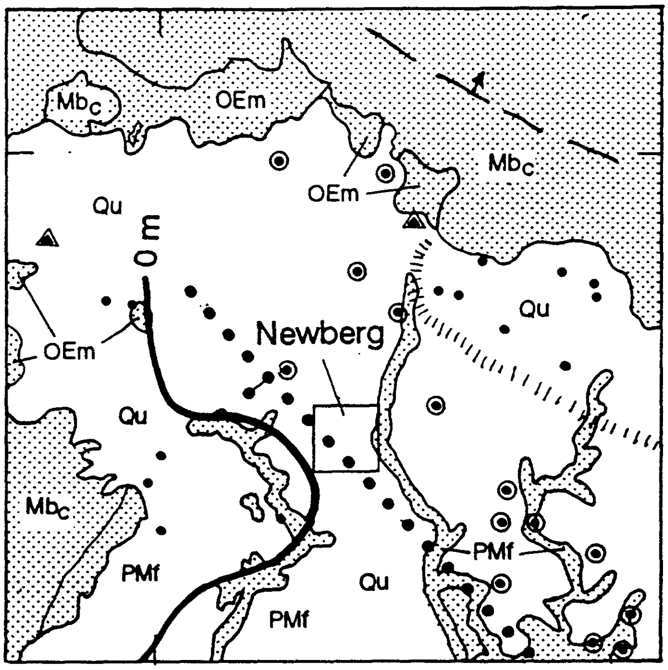
Figure 11



a.
ALTITUDE (Meters)
150
100
50
0
500
0
WALDO HILLS RANGE-FRONT FAULT
PMf
Mbc
OEm
?
Vertical exaggeration 4:1
b.
122°58'
122°56'
122°54'
45°56'
45°54'
45°52'
WALDO HILLS RANGE-FRONT FAULT
Qu
Mbc
OEm
WALDO HILLS
Water well used in cross section

Figure 12

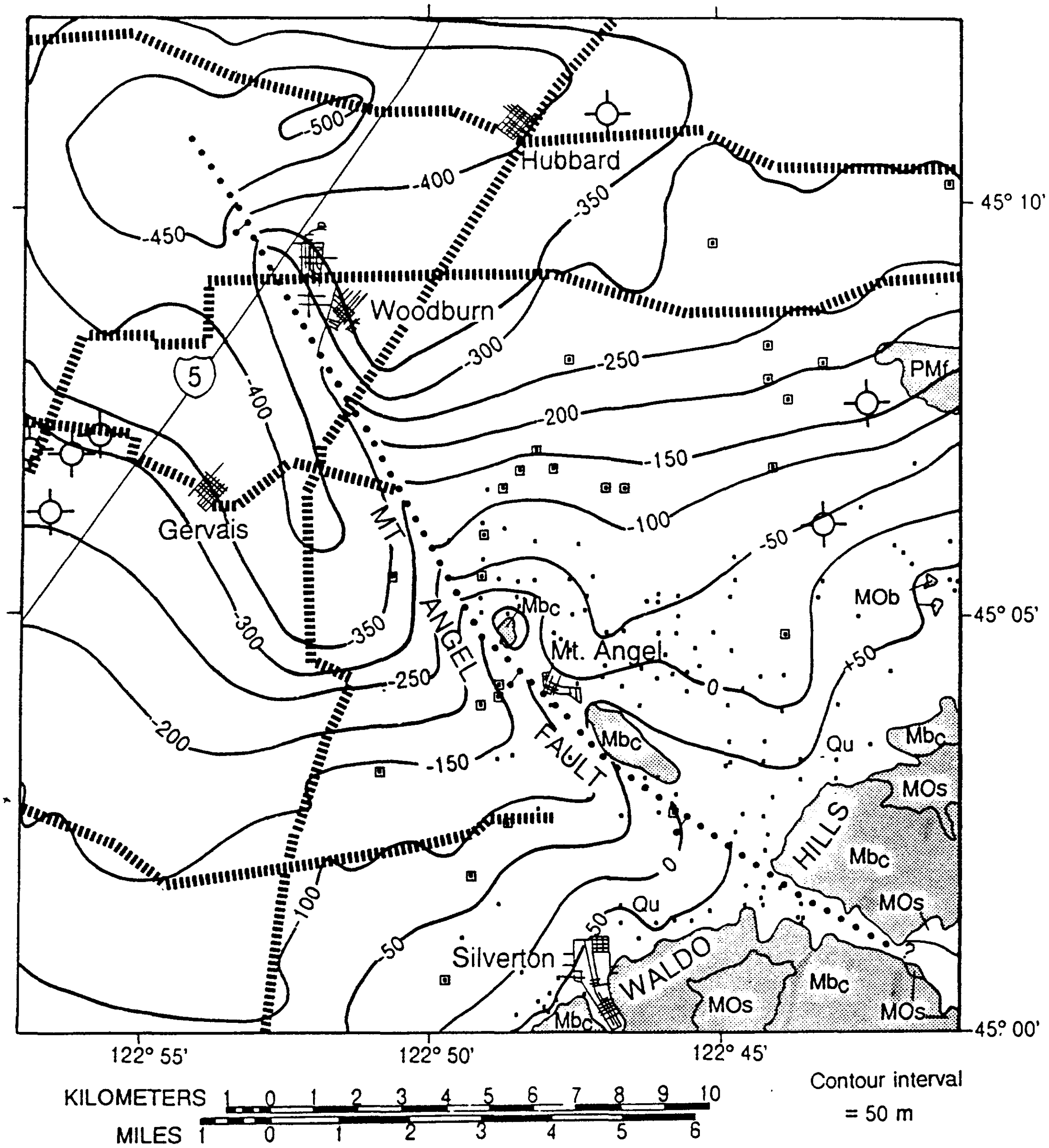
123°00'



EXPLANATION

Symbol: ball-and-bar line	Concealed fault; ball and bar on downthrown side.
Symbol: line with arrow	Homocline, arrow shows direction of dip.
Symbol: heavy solid line	Altitude to the top of Columbia River basalt.
Symbol: hachured line	Columbia River basalt - Oligocene and Eocene sedimentary rock subcrop.
Symbol: dot	Water well - reaches Columbia River basalt, located to quarter-quarter section.
Symbol: dot	Water well - Constrains altitude of contoured horizon, located to quarter-quarter section.
Symbol: triangle	Water well - Constrains altitude of contoured horizon, accurately located based on Ground-Water Report.

Figure 13



EXPLANATION

Geologic contact.

Concealed fault. Ball and bar on downthrown side.

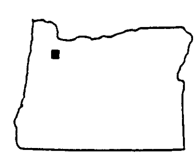
-50 Contoured altitude of the top of basalt (meters).

Seismic reflection control.

Petroleum exploration well.

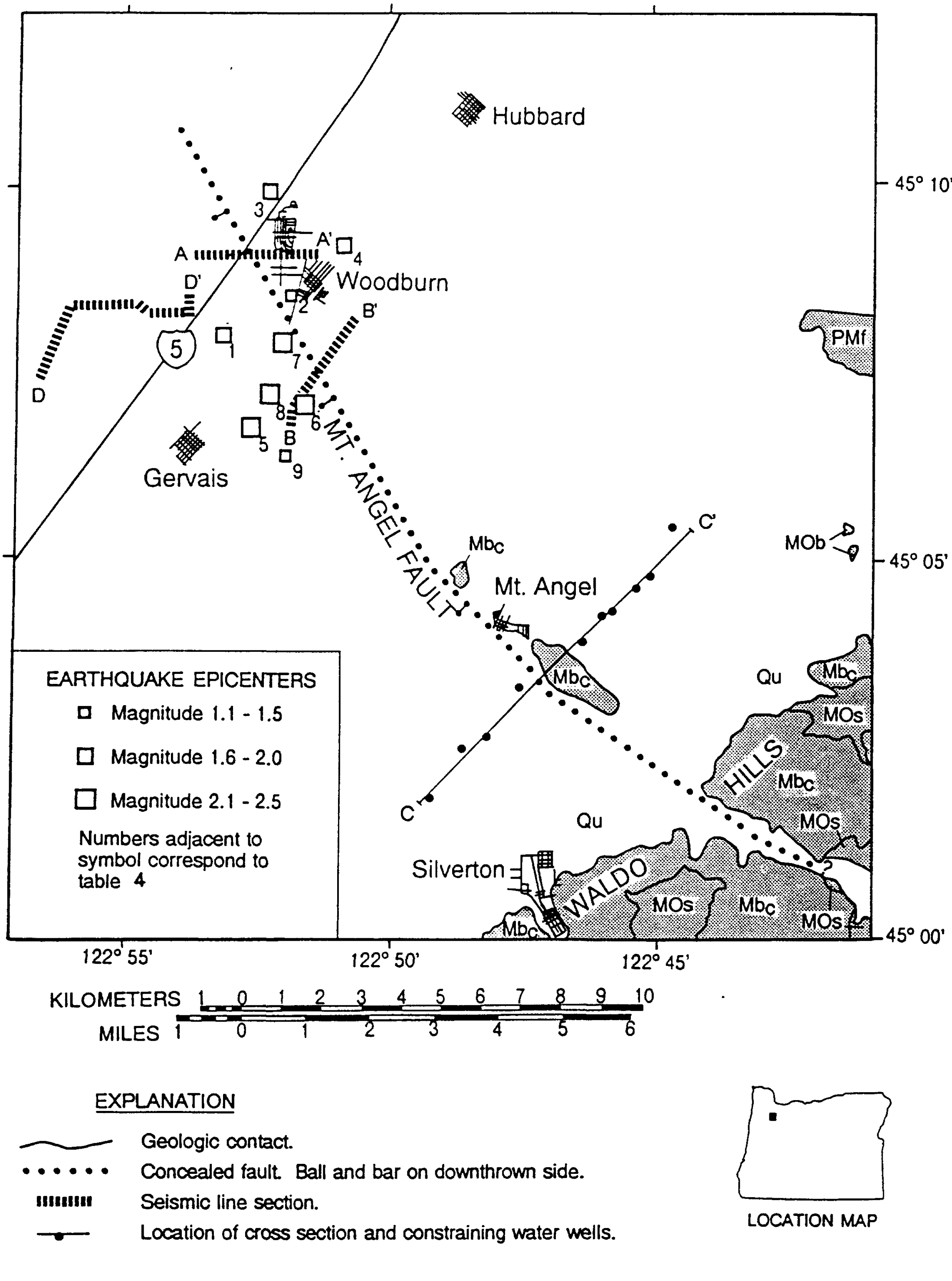
Water well which reaches basalt.

Deep water well which does not reach basalt.



LOCATION MAP

Figure 14



Hubbard
45° 10'
A
A'
D'
Woodburn
B'
5
PMf
D
Gervais
B
MT. ANGEL FAULT
C'
MOb
Mbc
45° 05'
Mt. Angel
EARTHQUAKE EPICENTERS
Magnitude 1.1 - 1.5
Magnitude 1.6 - 2.0
Magnitude 2.1 - 2.5
Numbers adjacent to symbol correspond to table 4
Qu
MOs
HILLS
C
Silverton
WALDO
45° 00'
122° 55'
122° 50'
122° 45'
KILOMETERS
MILES
EXPLANATION
Geologic contact.
Concealed fault. Ball and bar on downthrown side.
Seismic line section.
Location of cross section and constraining water wells.
LOCATION MAP

Figure 15

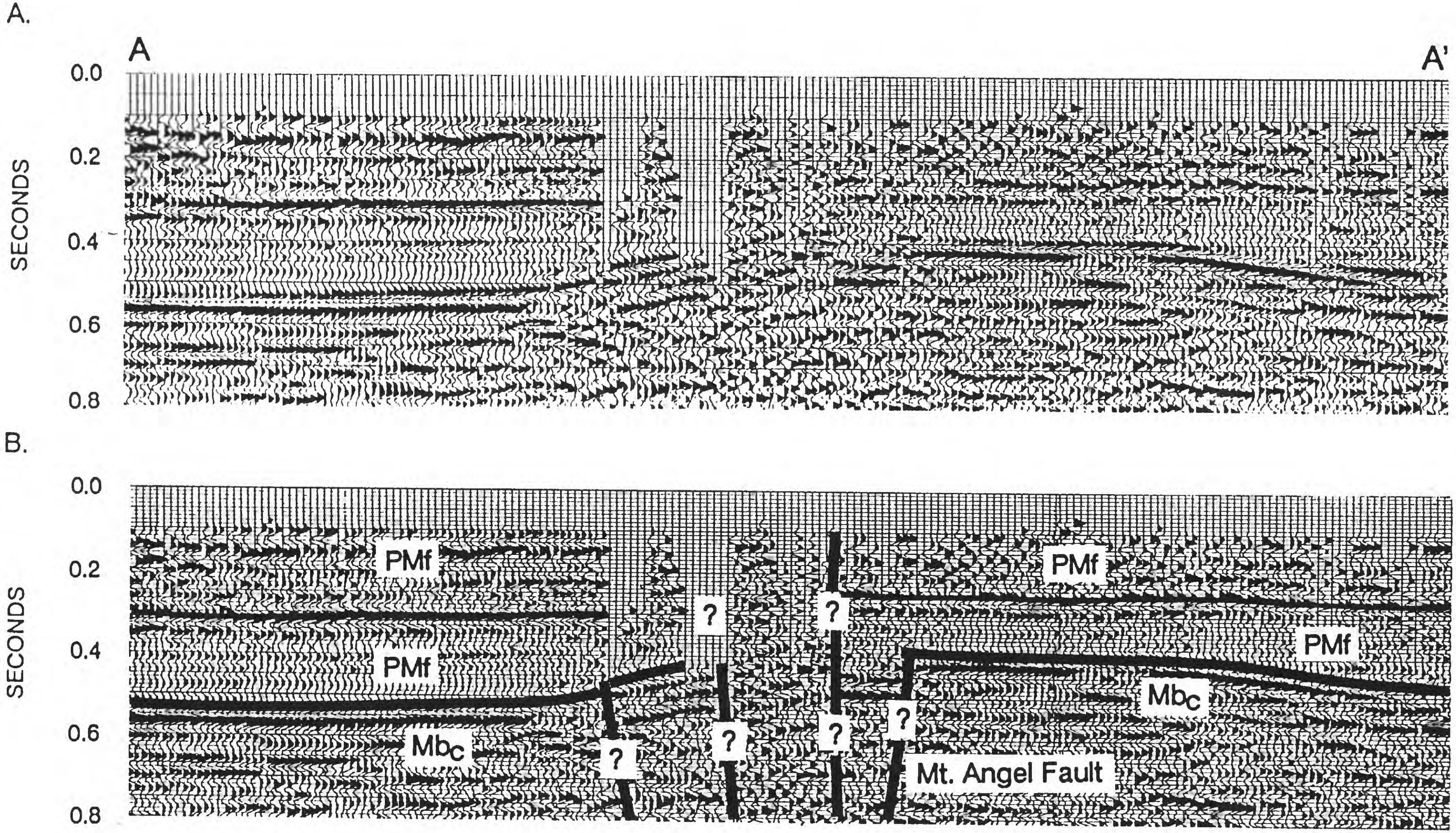

A.
A
A'
0.0
0.2
0.4
0.6
0.8
SECONDS
B.
0.0
0.2
0.4
0.6
0.8
SECONDS
PMf
PMf
PMf
PMf
Mbc
Mbc
?
?
?
?
?
Mt. Angel Fault

Figure 16

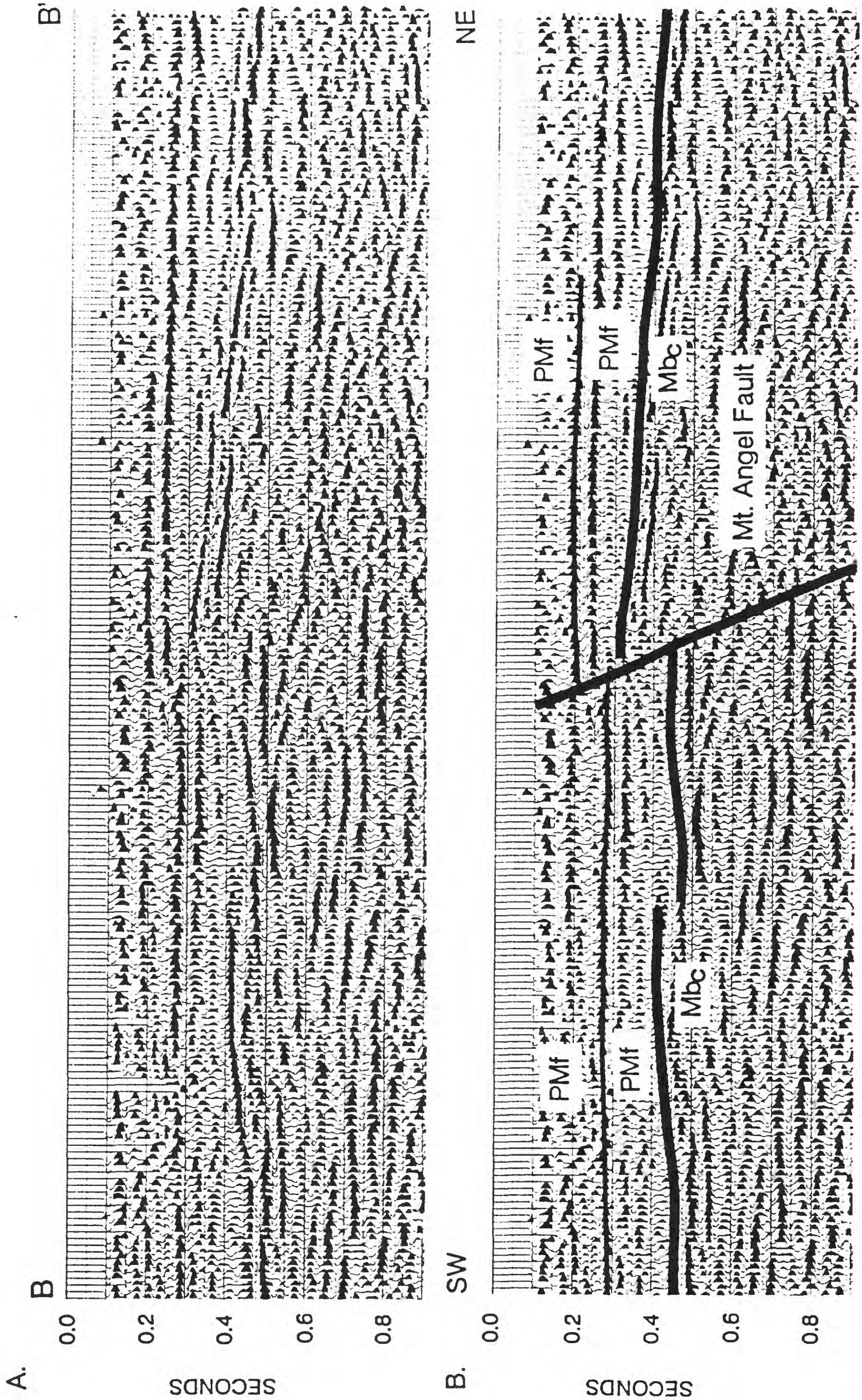


Figure 17

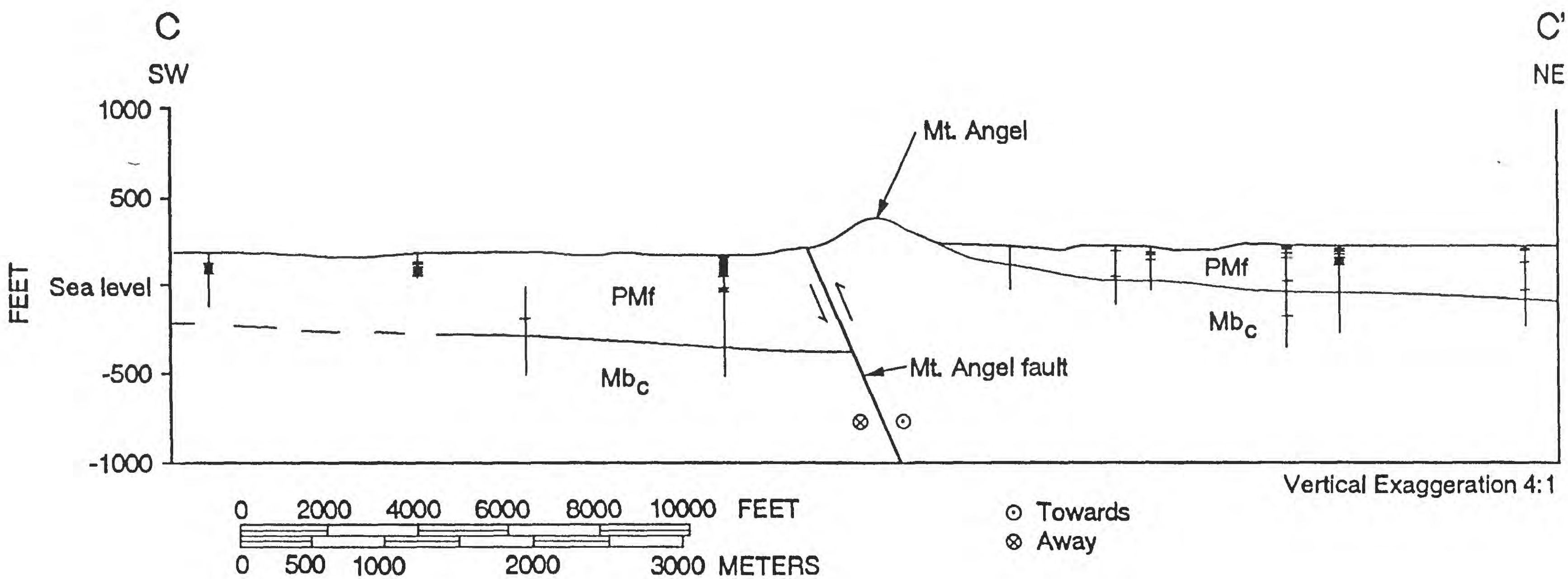

C
SW
C'
NE
1000
500
Sea level
-500
-1000
FEET
Mt. Angel
Mt. Angel fault
PMf
Mbc
PMf
Mbc
Vertical Exaggeration 4:1
0 2000 4000 6000 8000 10000 FEET
0 500 1000 2000 3000 METERS
⊙ Towards
⊗ Away

Figure 18

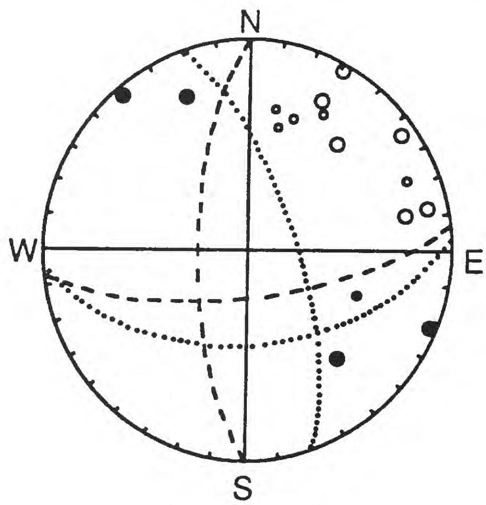


Figure 19

Figure 20

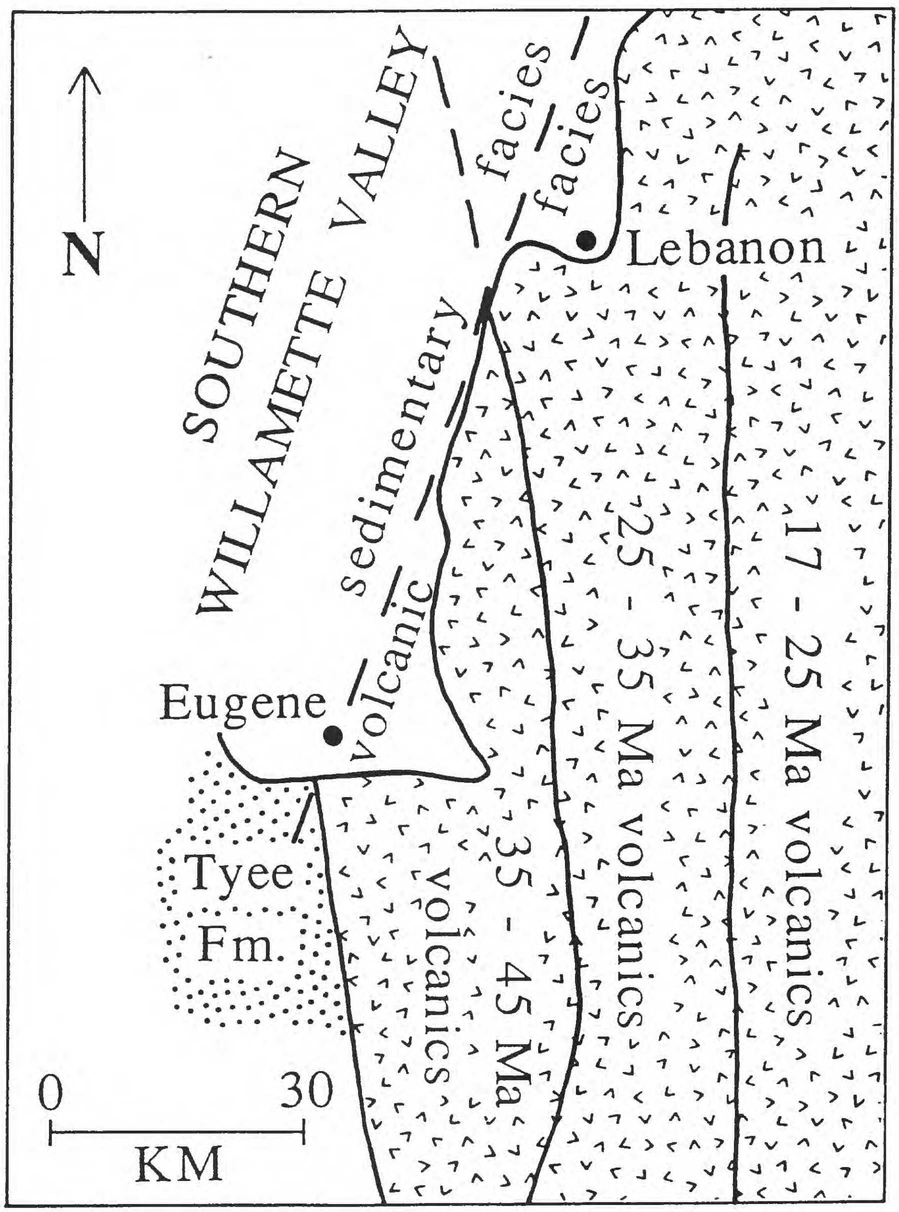

N
SOUTHERN WILLAMETTE VALLEY
volcanic facies
sedimentary facies
Lebanon
Eugene
Tyee Fm.
35 - 45 Ma volcanics
25 - 35 Ma volcanics
17 - 25 Ma volcanics
0
30
KM

Figure 21