The Role of Volcanism, Inversion, and Neotectonics in the Puget-Willamette Lowland Petroleum System, Washington and Oregon

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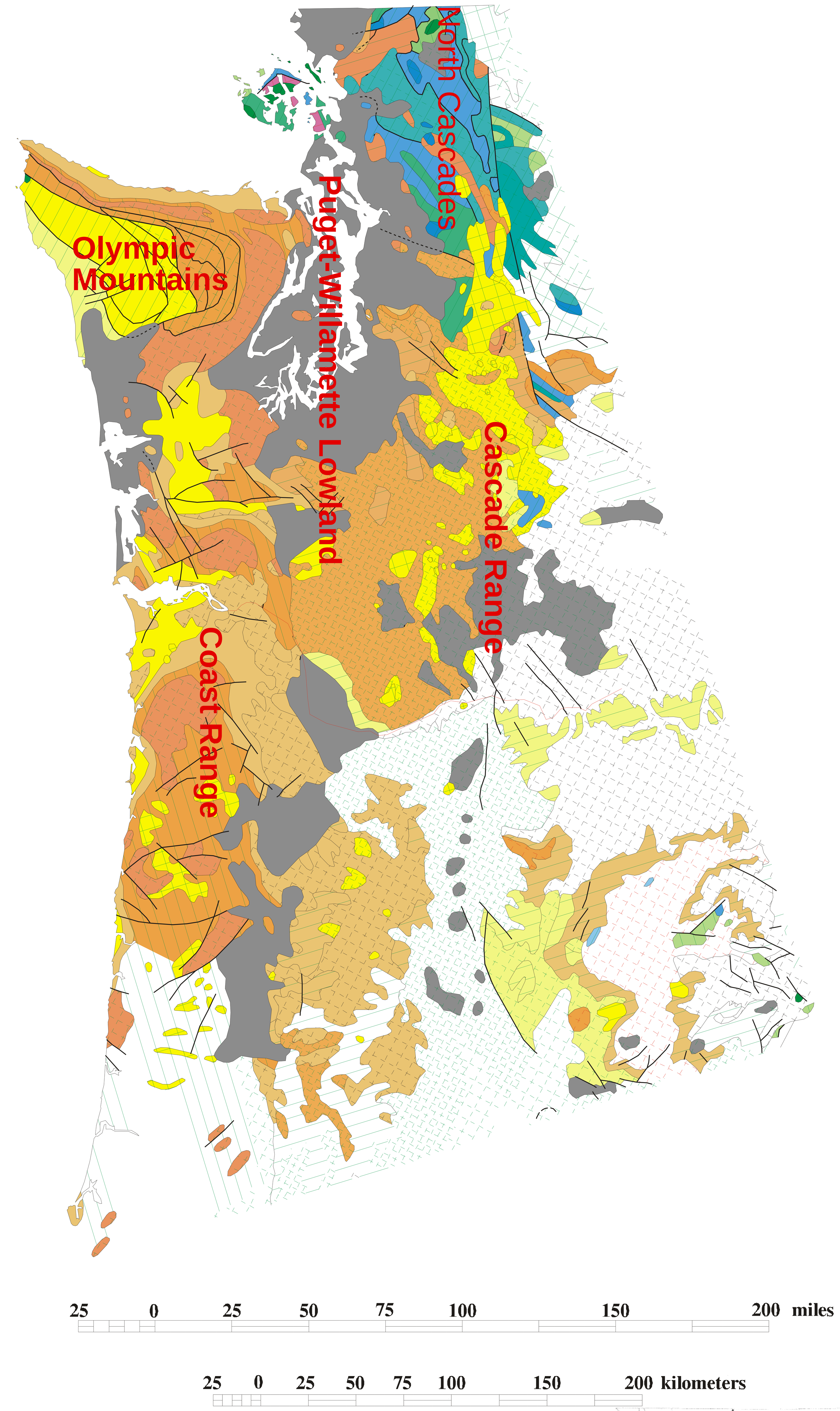


Abstract

Eocene sediments deposited west of an ancestral Cascade Range include a coal-bearing sequence covering much of the Puget-Willamette Lowland. The terrestrial deposits pass into marine deposits to the west. Syn-depositional normal faulting and strike-slip faulting are evident in several sub-basins, which are interpreted to represent a transtensional setting. Eocene volcanism locally effected sedimentation. Eocene fluvial sandstones overlain by intra-formation claystones are potential reservoir-seal couplets. Eocene coals and carbonaceous claystones represent a potential gas-prone source interval.

Locally preserved sediments indicate that subsidence continued into Miocene and Pliocene time, and was followed in the Puget Lowland by extensive Pleistocene glaciation. At present, active faulting affects the Lowland in several discrete zones.

Models of vitrinite reflectance data from wells located in the Lowland indicate that from the Eocene to the Present, the regional geothermal gradient ranged from 28 to 41°C/km. The eastern margin of the Lowland was bordered by the Cascade volcanic arc, and was subjected to advective heat flow.

In the southern Lowland, normal faults were modified by episodes of late Eocene and Miocene transpression, which resulted in mild inversion of older normal faults. In the northern Lowland, Holocene faulting is recognized in outcrop and is interpreted on seismic data acquired in Puget Sound.

Structures formed by early Miocene or earlier events may have trapped migrating hydrocarbons. Structures formed or modified by Holocene faulting very probably post-date hydrocarbon generation and migration.

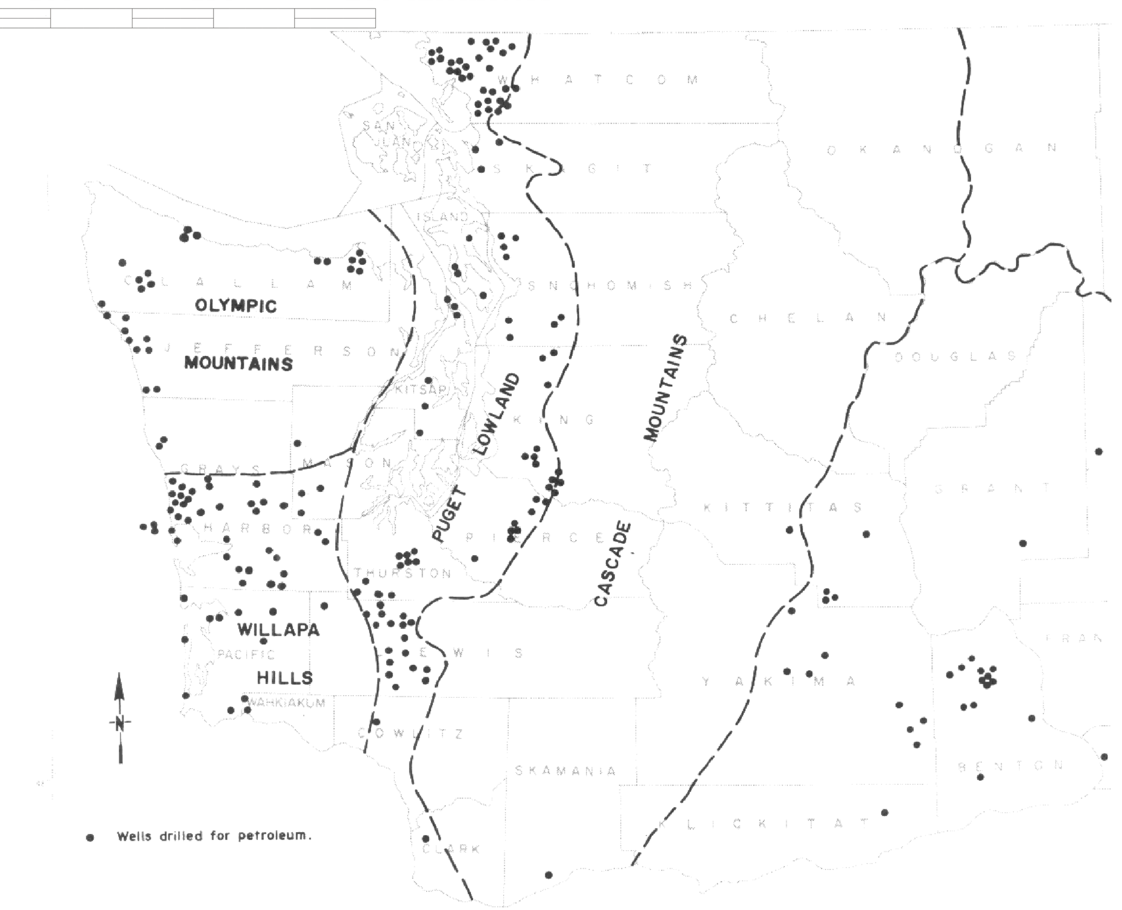
Introduction

The Puget-Willamette Lowland is located between the Cascade Range on the east and Olympic Mountains-Coast Range on the east. Exploration has been active in the region for over 100 years.

Exploration for oil and gas in Washington and Oregon commenced in 1890 with a well drilled near Everett. Oil shows were reported in the well, although it was abandoned due to mechanical problems. Over 700 wells subsequently drilled reveal the presence of Eocene and younger sediments in several basins distributed across the western and central portions of the states. One commercial gas discovery occurs in northwest Oregon at the Mist Field. Discovered in 1980, this field motivated an exploration boom in which failed to discover additional fields.

This poster describes aspects of the petroleum system that produced the Mist Field. It reports the results of heat flow modelling applied to published vitrinite reflectance data, and places these results in the context of Cenozoic volcanism. The structural histories of two cross-sections drawn in the southern Lowland are examined. An episode of inversion is inferred for both cross-sections. The region is subject to recurrent seismic activity. Reflection seismic data acquired in the northern Lowland is inferred to demonstrate the presence of faults that offset Quaternary units.

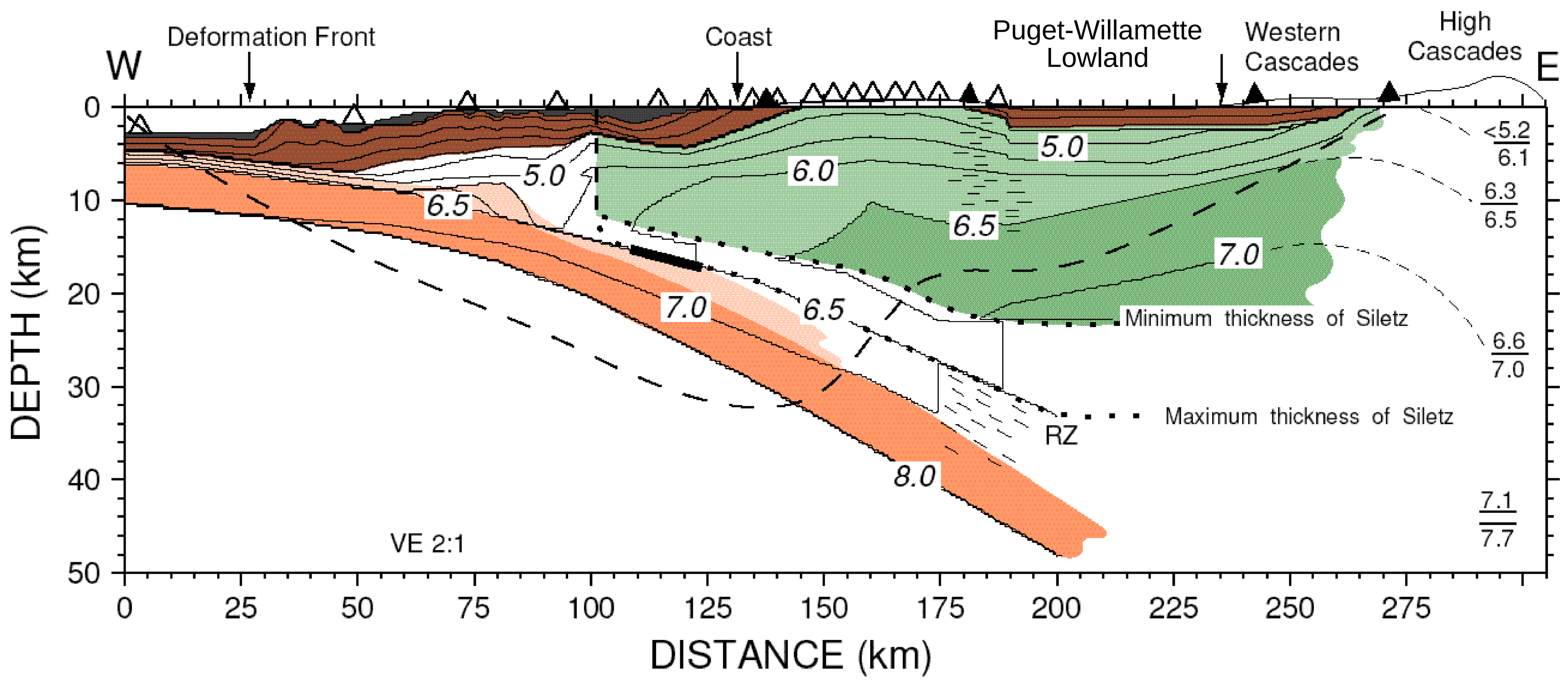
Explorations wells have been located in the Willamette-Puget Lowland, the margins of the Olympic Peninsula, and Southwest Washington on the flanks of the Willapa Hills.



McFarland (1983) page vi.

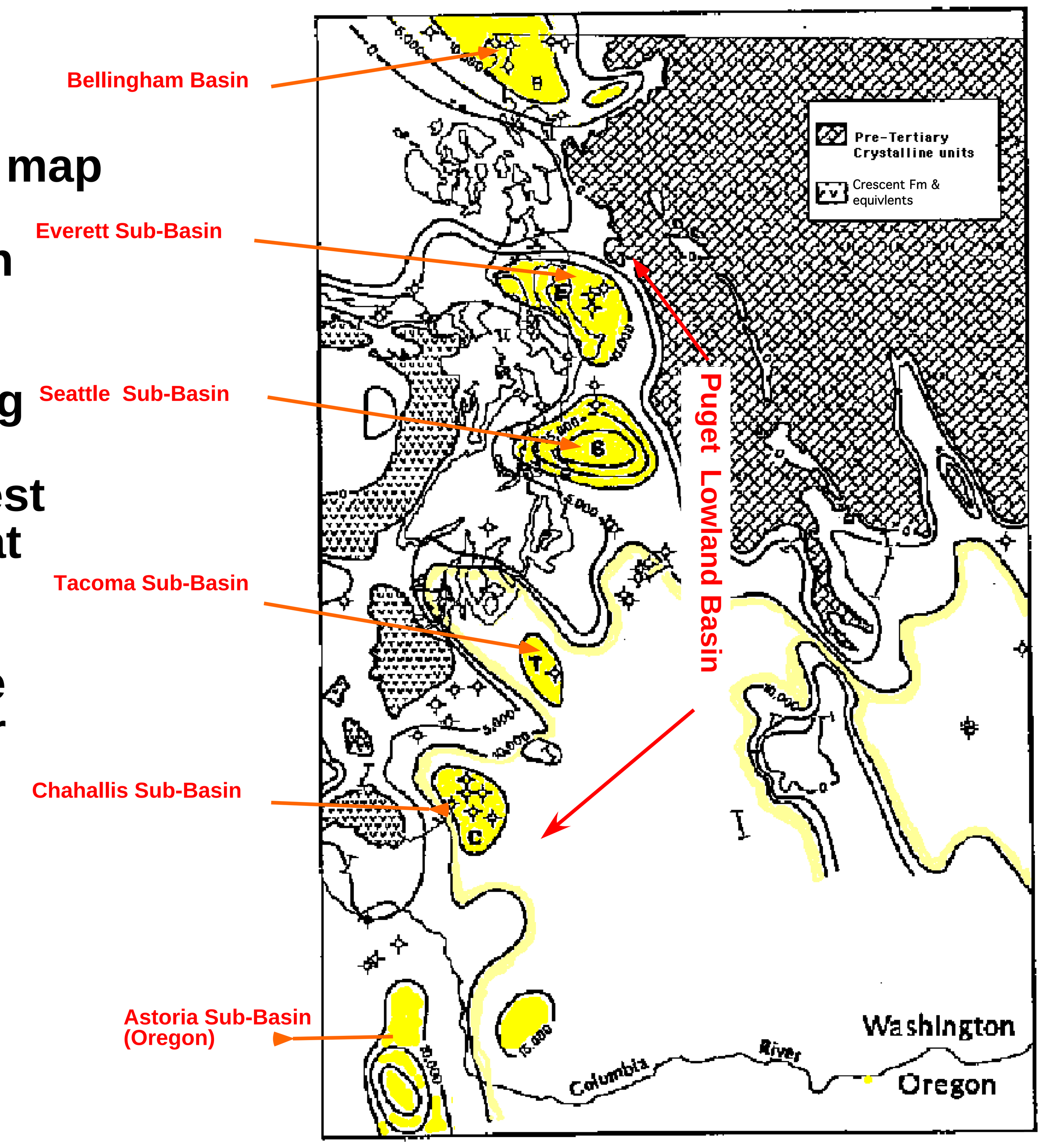
Regional Setting of Sedimentary Basins

Eocene and younger sediments occur in outcrops in western Washington and Oregon, and they have been encountered in the subsurface. These sediments are inferred to be deposited in a forearc basin located between the incipient Cascade volcanic arc and subduction zone of the descending Juan de Fuca plate. Changes in subduction geometry and relative motions between the Juan de Fuca and North American plates during the past 40 M A have modified the forearc basin.



Tehu et al 1996, Figure 4 The relabled profile is located in across the margin in northern Oregon, approximately across the southern margin of the study area.

Walsh and Lingley (1991) examined surface, well, and proprietary seismic data to compile an isopach map of the Eocene interval in Puget-Willamette Lowland. Their map indicates that the Puget Lowland Basin is divided into four sub-basins, some of which have strata exceeding 10,000 feet in thickness. The map also shows most of these basinal areas have northwest trending axes. Johnson (1985) indicates that the Bellingham Basin opened between northwest trending strike-slip faults, and suggests that this may apply to other Eocene basins in western Washington. Limited data in the south suggest that the coal bearing Eocene interval extends beneath the volcanic cover of the southern Washington Cascade arc.

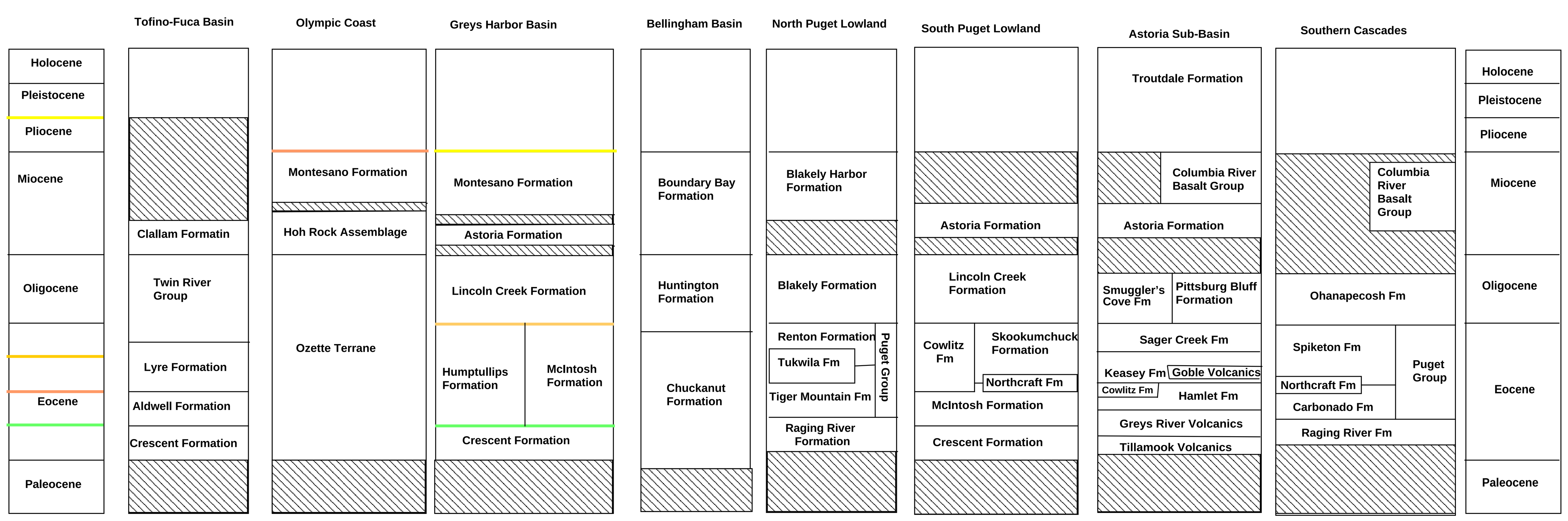


Modified from Figure 4, Walsh and Lingley (1991)

Isopach of Ulatisian and Narizian (Eocene) surface-accumulated rocks in western and central Washington. Thicknesses are from measured sections, drilled depths, and cross-sections.

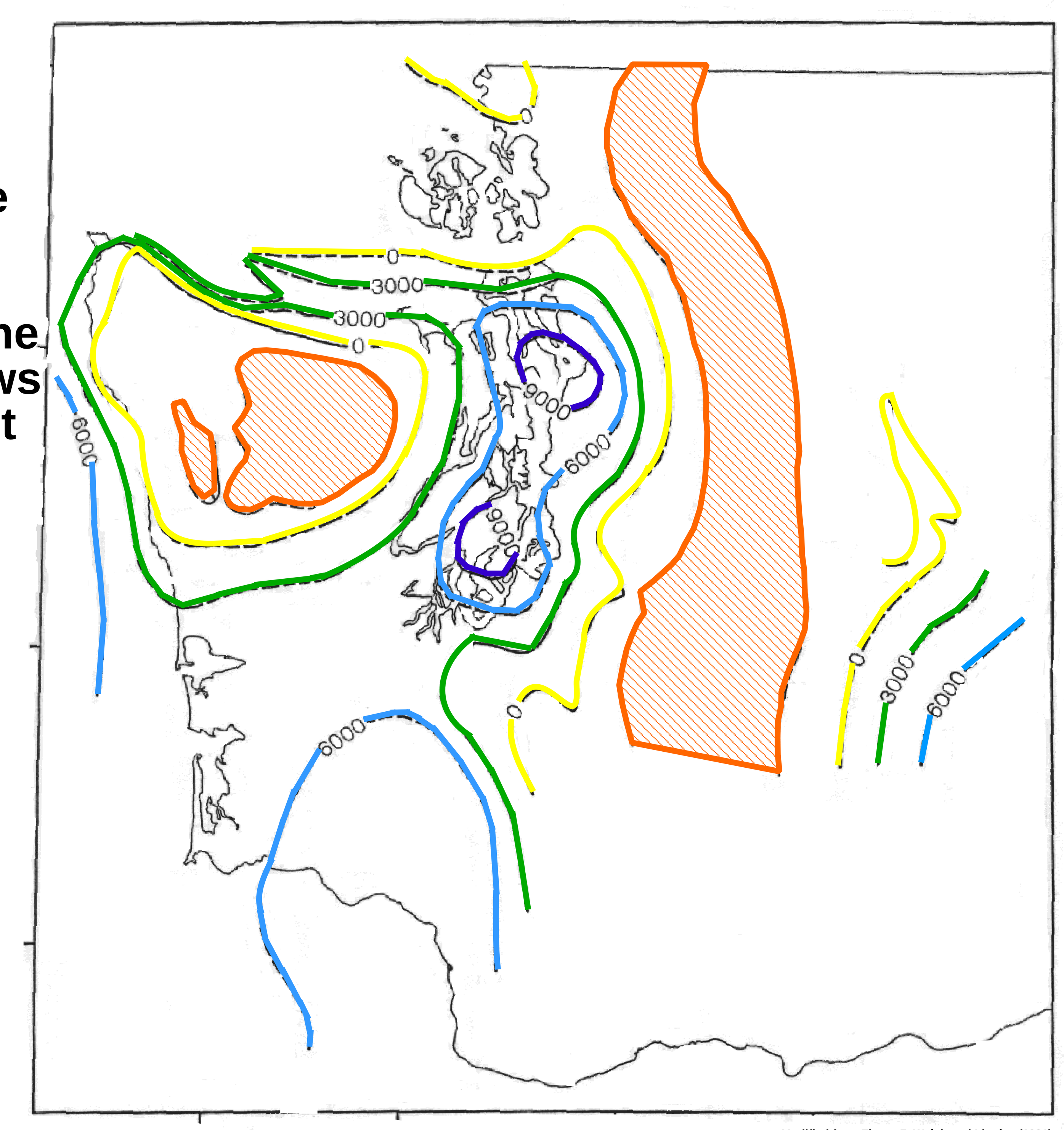
Lower Eocene volcanic units of the Crescent, Grays River, and Tillamook Volcanic Formations form the basement for subsequent sedimentation. Two Eocene coal bearing sedimentary basins are recognized east of the Cascade arc: the Bellingham Basin and the Puget-Willamette Lowland Basin. These pass into Eocene marine strata located to the west in the Georgia, Greys Harbor, and Astoria Basins. The Miocene is marked by episodes of deposition and erosion which vary across the region. Fluvial, marine, and glacial units occur locally.

Correlation Chart for Western Washington and Western Oregon



Modified from Figure 2, Johnson et alia 1997 and Figure 4 Niem et alia. 1994.

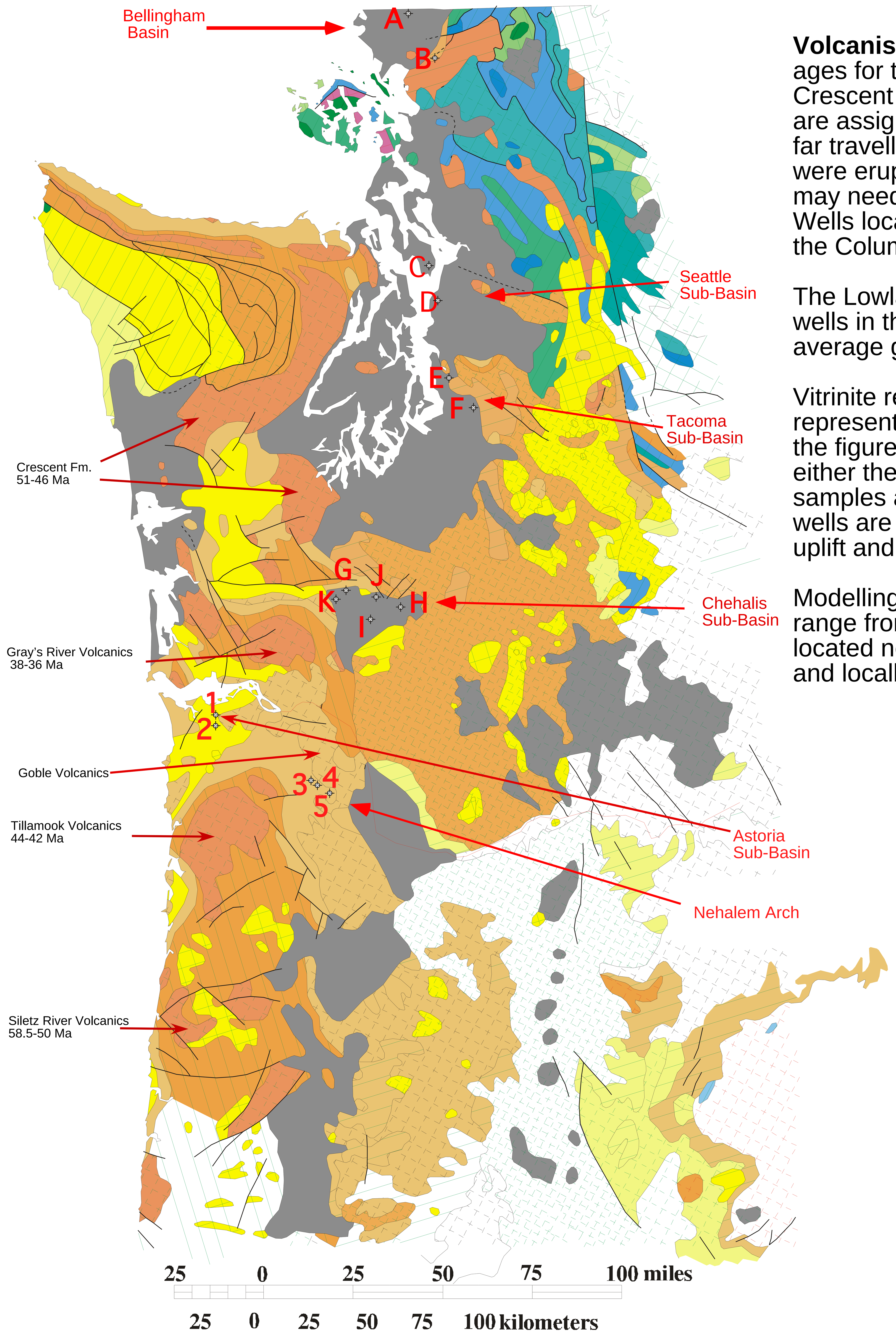
Well and outcrop data demonstrate that Eocene strata reach vitrinite reflectance values of 0.5 at depths ranging from outcrops located above sea level to depths greater than 9,000 feet below sea level. The 0.5 reflectance surface broadly dips to the west from the Cascade arc, and shows local deeps that are offset to the west of the sub-basin centers.



Modified from Figure 7, Walsh and Lingley (1991)

Contour map in depth (in feet) to vitrinite reflectance Ro=0.5%.

Volcanism, Heat Flow, and Vitrinite Reflectance Profiles



Modified from Geologic Map of the United States
Philip B. King and Helen M. Beikman

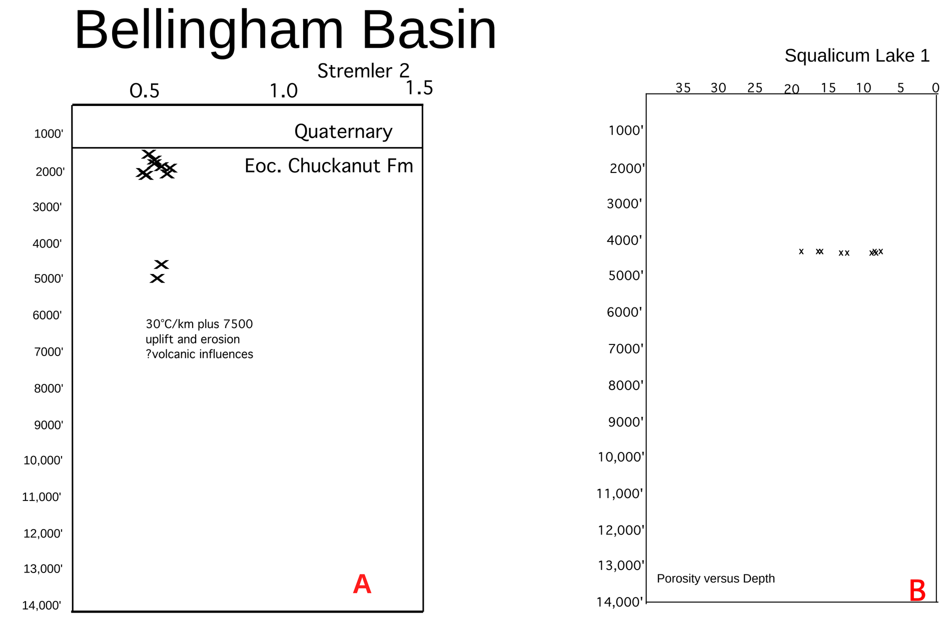
Volcanism in the Pacific Northwest The Siletz River Volcanics are the oldest igneous units found in western Oregon. Determining ages for these ocean island basalts is problematic, and biostratigraphic dating suggests 58.5 to 50 Ma (Haeussler et al 2003). The Crescent Formation comprises mid-ocean ridge basalts found in the Olympic Mountains and Black Hills of western Washington. These are assigned radiometric ages ranging from 51 to 46 Ma. Together these units form the Siletzia, a terrane which is not considered to be far travelled, although its southern sector has rotated clockwise 70° since its eruption. The Tillamook, Goble, and Greys River volcanics were erupted 44 to 36 Ma. The are encountered in a number of wells. Recent field work indicates the present nomenclature for these may need revision (Evarts 2001). The Cascade arc began to erupt 30 Ma, primarily in western Oregon and southernmost Washington. Wells located on the eastern margin of the Lowland may encountered these Cascade volcanic units. The Grande Rhonde member of the Columbia River Basalt Group flowed through the southern portion of the Lowland 25 Ma.

The Lowland is located in a fore arc setting, where a low geothermal gradient may be expected (Hunt 1981). A review of 15 exploration wells in the Lowland finds the uncorrected geothermal gradient ranges from 24 to 40°C/km, with an average gradient of 30°C/km. The average gradient, as well as the lateral variation in gradient are similar to those found in continental or rift settings.

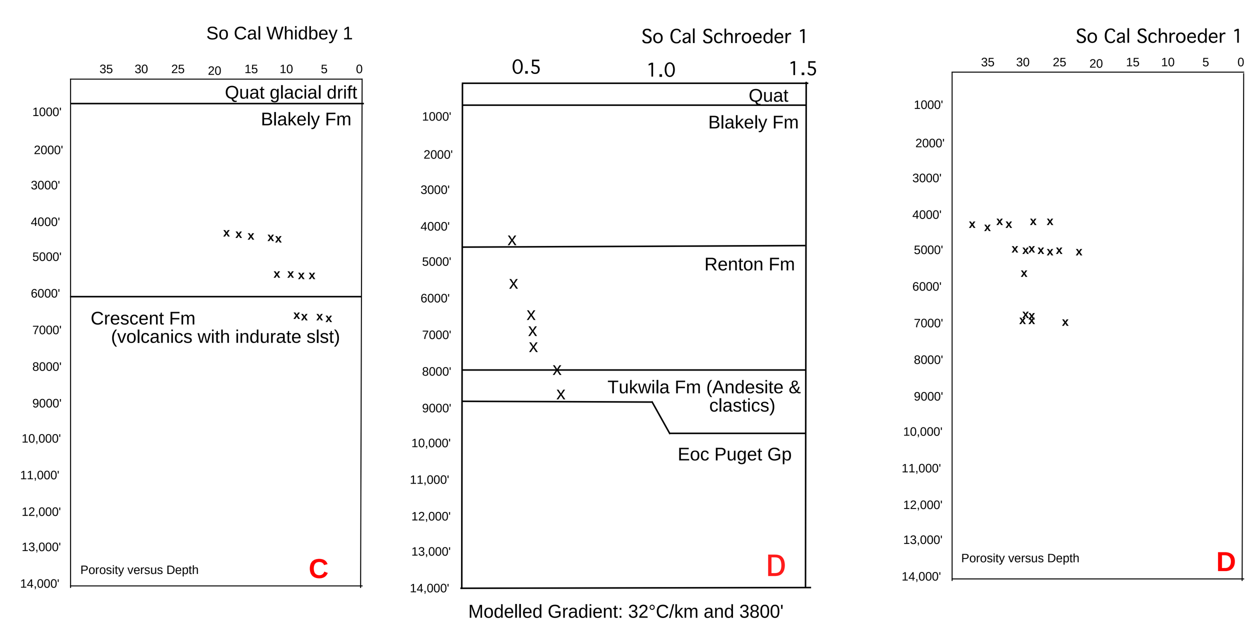
Vitrinite reflectance profiles from 11 wells were modelled using a program developed at Atlantic Richfield Company. These wells represent nearly all of the wells for which vitrinite reflectance data are publicly available. The results for each well are presented in the figures below. None of the Ro profiles intersects the surface at 0.2 percent reflectance. This is often interpreted to indicated that either the vitrinite is recycled from deeper horizons or that uplift and erosion has occurred at the well location. As nearly all of the samples are taken in coal bearing units, the possibility of vitrinite recycling may in most cases be dismissed. Core porosity data for three wells are also presented in the figures. These limited data do not suggest siginificant deeper burial for these wells. The possibility of uplift and erosion, possibly prior to Miocene time, is further addressed under "Inversion".

Modelling for these wells suggests that geothermal gradients were elevated prior to the period of uplift and erosion. The gradients range from 30°C/km to 41°C/km, with an average of 37.5°C/km. Igneous units are reported in several of these wells, and most are located near outcrops of Eocene volcanic units. An elevated geothermal gradient may occurred during the Paleogene in the Lowland, and locally volcanism may have contributed to advective heating of sedimentary pile.

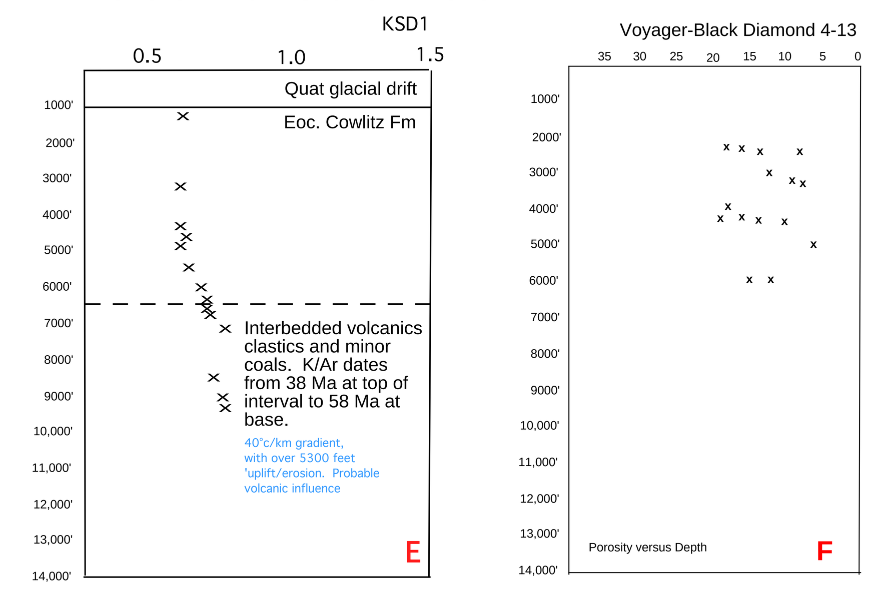
Bellingham Basin



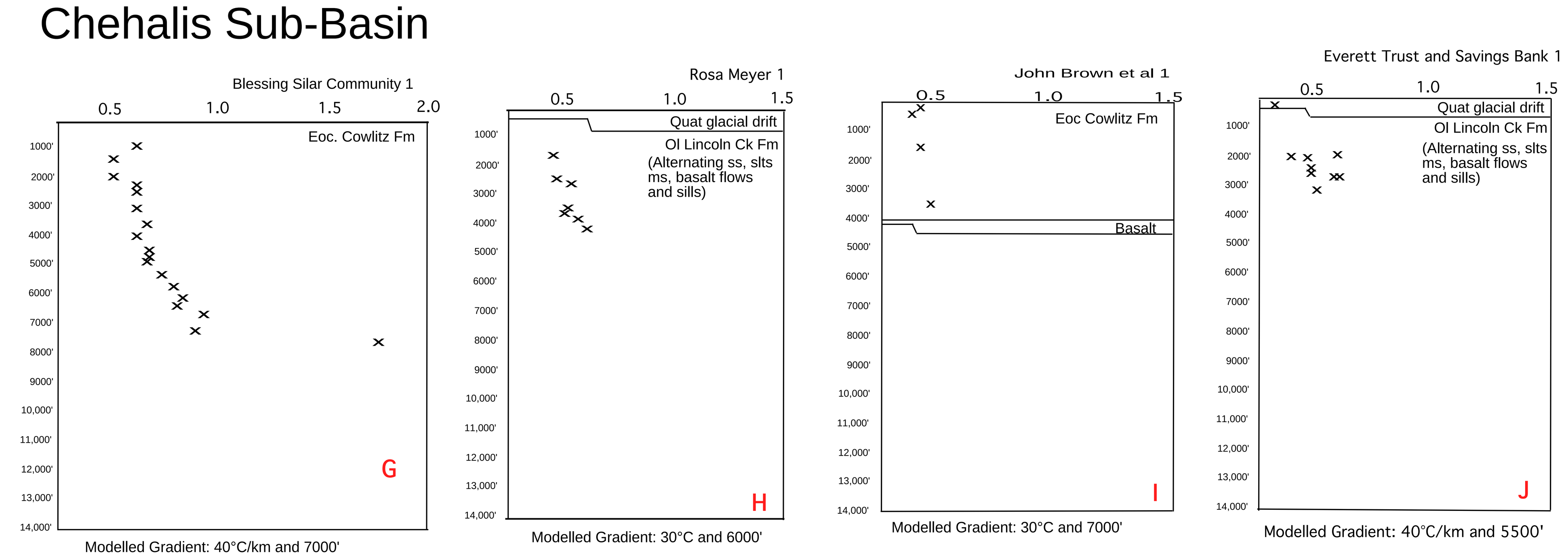
Seattle Sub-Basin



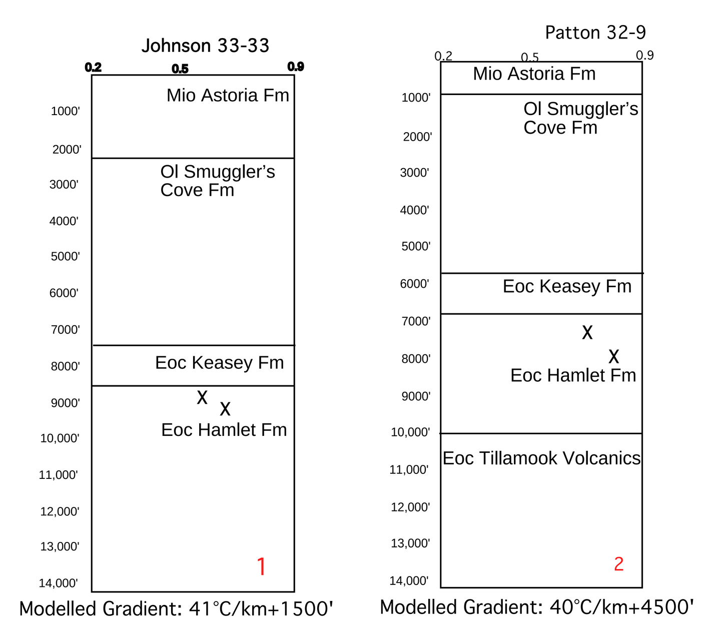
Tacoma Sub-Basin



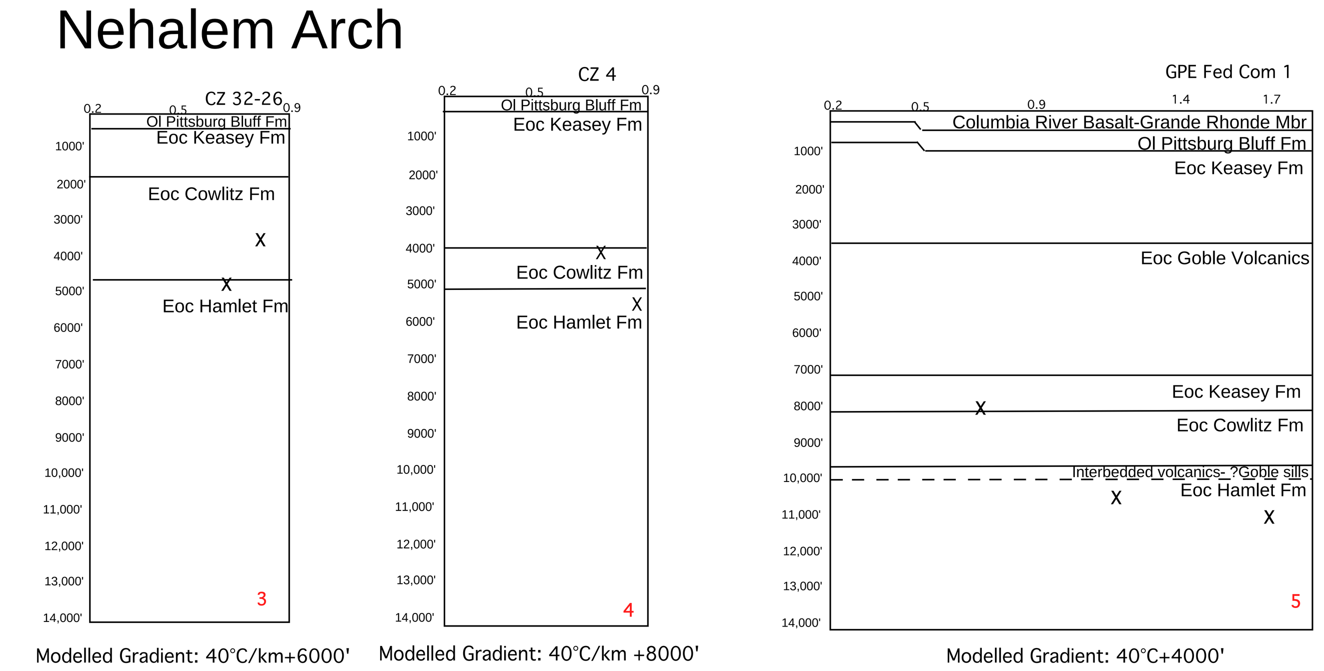
Chehalis Sub-Basin



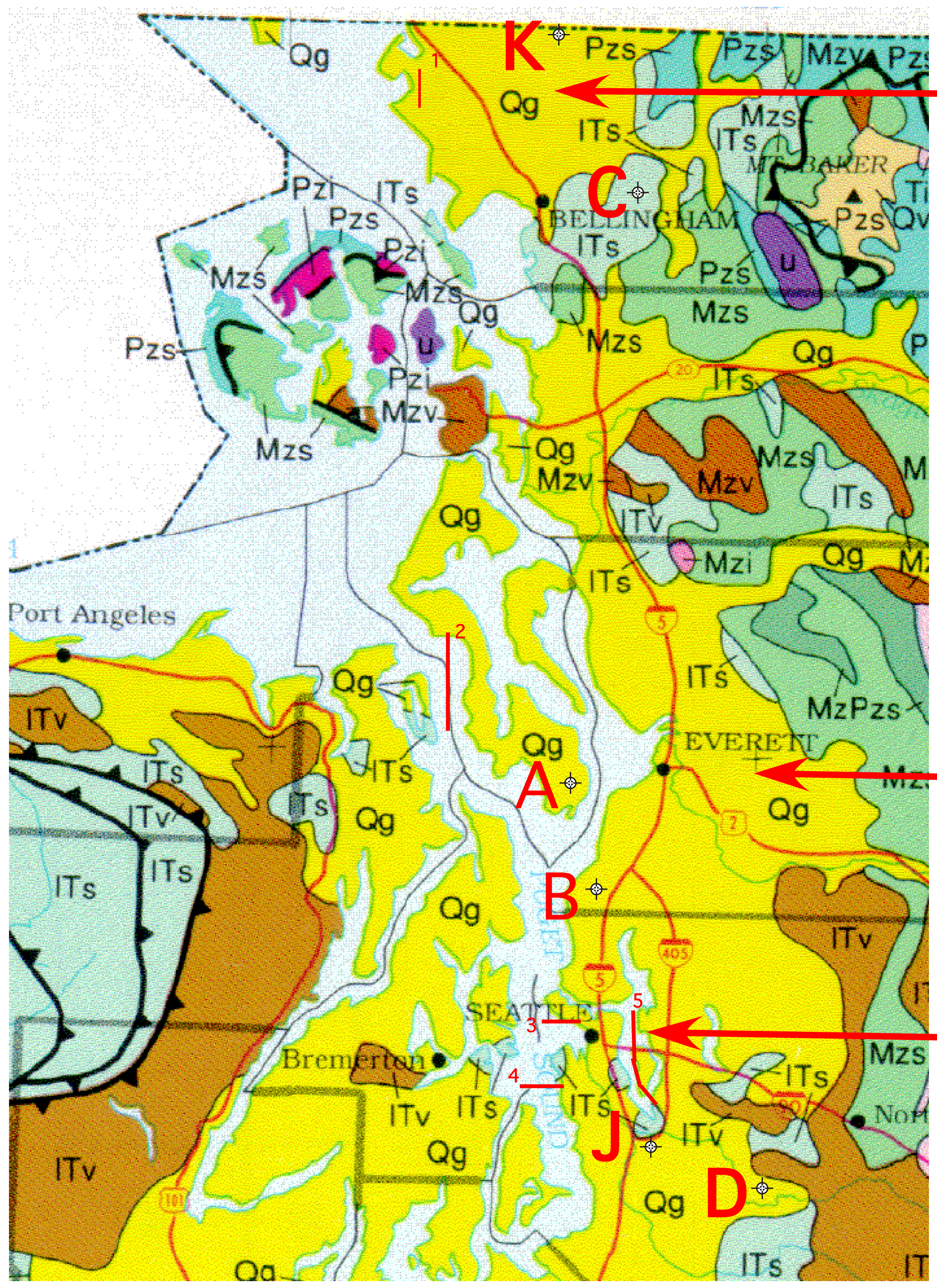
Astoria Sub-Basin



Nehalem Arch



Neotectonics in the Bellingham Basin and Northern Puget Lowland



The Pacific Northwest is a seismicly active region and experiences M 3+ quakes several times each year. The northern Puget Lowland and adjoining Bellingham Basin have above average seismicity, and so have been the subject of active seismic hazard evaluations by both US and Canadian groups. Seismic data acquired by these groups are publicly available and illustrate the location of several major active faults. These data have not, however, been referenced in resource assessments published by either the USGS or the Canadian Geological Survey.

A review of these data suggests that many unsuccessful exploration wells have been located on features that have been deformed by Recent movement on these faults. Some gas seeps have been reported in this region, especially in association with coal mines. Very few seeps have been reported along the trace of recently discovered Quaternary faults.

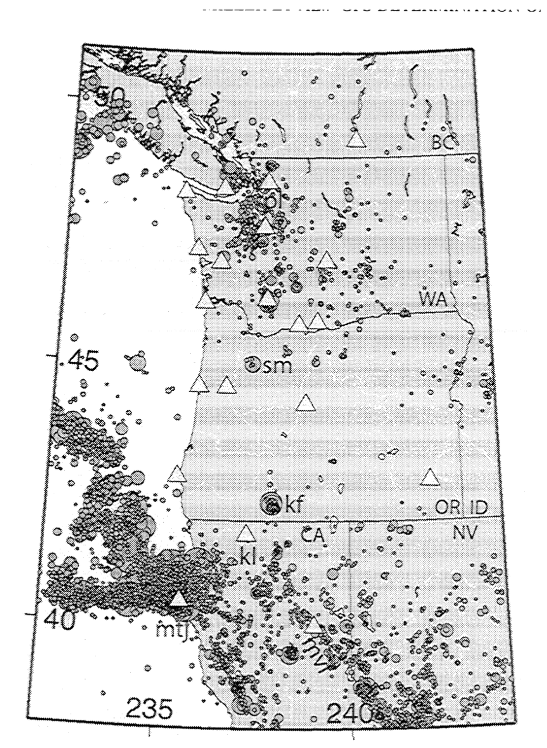
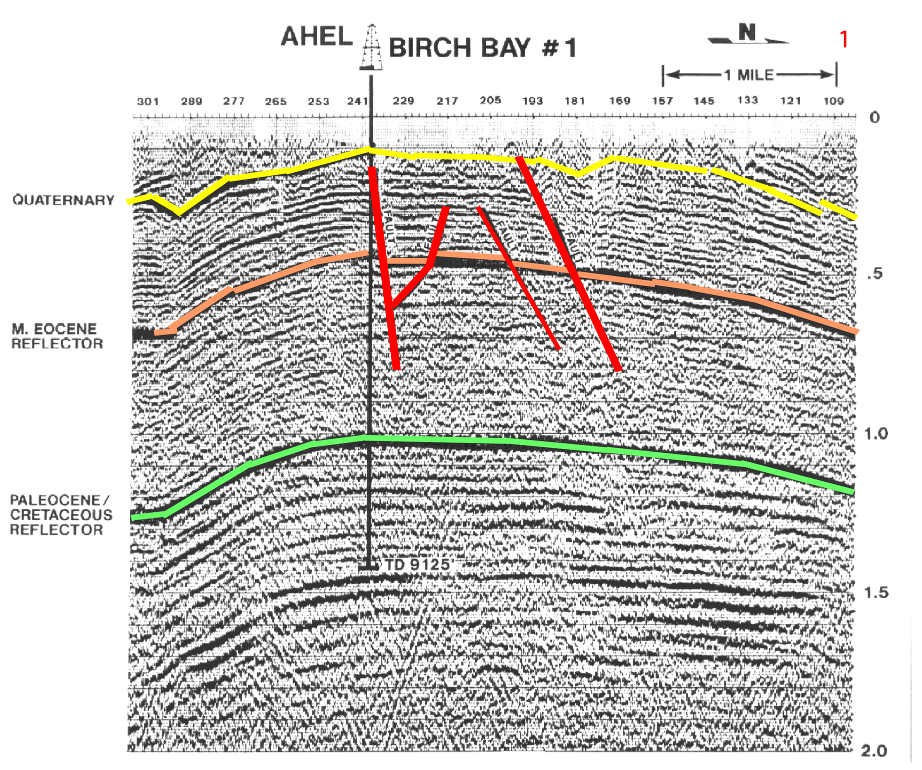


Figure 6. Regional seismicity in the Pacific Northwest. Seismic events with $M \geq 3$ from the Council of the National Seismic System catalog (1969 to 2000) are scaled by magnitude. Locations include: pl, Puget Lowlands; sm, Scott's Mills; kf, Klamath Falls; kl, Klamath Mountains; mtj, Mendocino triple junction; mvf, Mohawk Valley fault zone. Triangles show the locations of GPS stations (see Plate 1 and Figure 5 for velocities). Denser distributions of earthquakes occur in the areas where strain gradients are implied by GPS velocities, both in northern California and within the Puget Lowlands of western Washington. Diffuse seismicity also characterizes the back arc in central Washington. (Miller et al 2001)

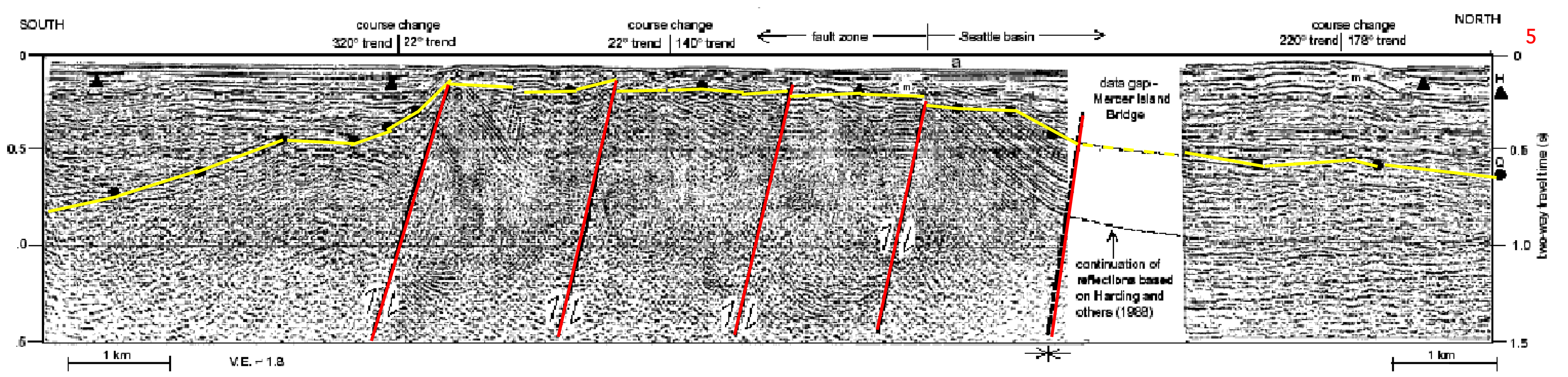
The **Bellingham Basin** has been the site of coal mining operations and over 90 exploration wells. Eocene coal seams are up to 15' thick, with high volatile C bituminus average coal rank. The total estimated reserves exceed 900 million tons. The Birch Bay 1 well tested 14 zones, and demonstrated that adequate gas reservoirs occur above -5000'. Wireline logs over several wells reveal the presence of claystones above potential reservoir sands. Onshore seismic data is not available in the public domain. Offshore data acquired to assess earthquake hazards show folding of Quaternary units above inferred blind thrusts, and displacement of Quaternary units by faulting. Viable gas prospects may require the presence of older structures unmodified by Recent tectonic activity. CBM projects appear to be viable, especially near existing gas pipelines.

The **Puget Lowland Basin** is divided into four sub-basins on the basis of Eocene isopach maps. The **Everett Sub-basin** is the northernmost, and it shares many features with the Bellingham Basin. Only 13 wells have tested this sub-basin, the most recent in 1972. There are no coal mines in the area.

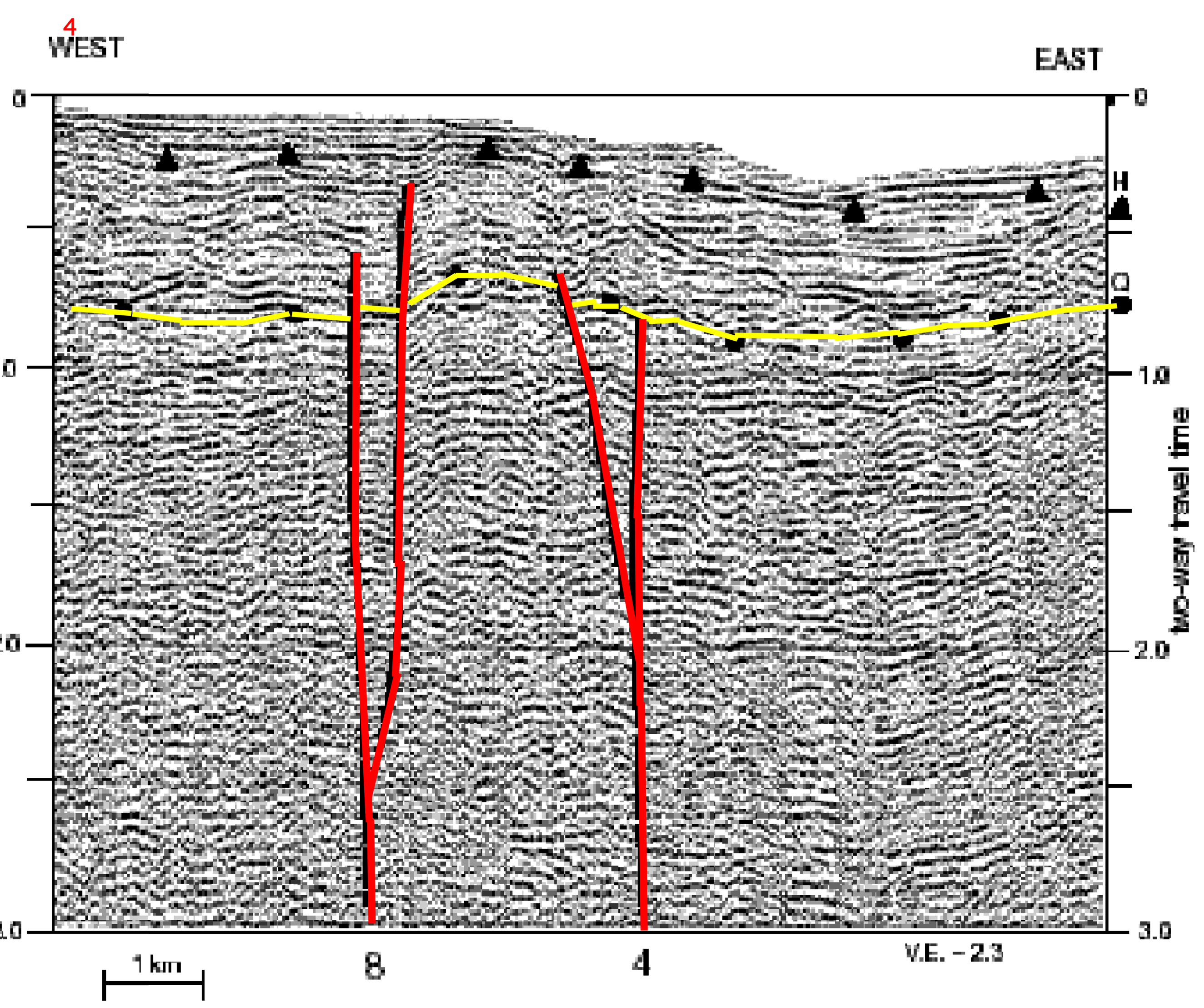
The **Seattle Sub-basin** has been tested by over 40 wells, and it is the site of two coal mining districts. Wells drilled after 1980 include several CBM tests. Eocene coal seams range from sub-bituminous to high volatile bituminous B rank. Coal reserves are estimated to exceed 900 million tons. The coal beds dip between 15 and 50 degrees in most mines. Seismic data acquired in Puget Sound show deformed Quaternary surfaces and faults that correlate with earthquake epicenters. Sandstone reservoirs within the Eocene interval appear to have adequate porosity above -9000. Wireline logs over several wells indicate the presence of claystones above potential reservoir sandstones. Most of the surface locations of wells drilled in the Seattle Sub-basin appear to be on young structural features. Successful gas exploration may need to test older structures not disturbed by Recent tectonic activity. Coal Bed Methane projects sited near existing gas pipelines appear to have the highest chances of commercial success.

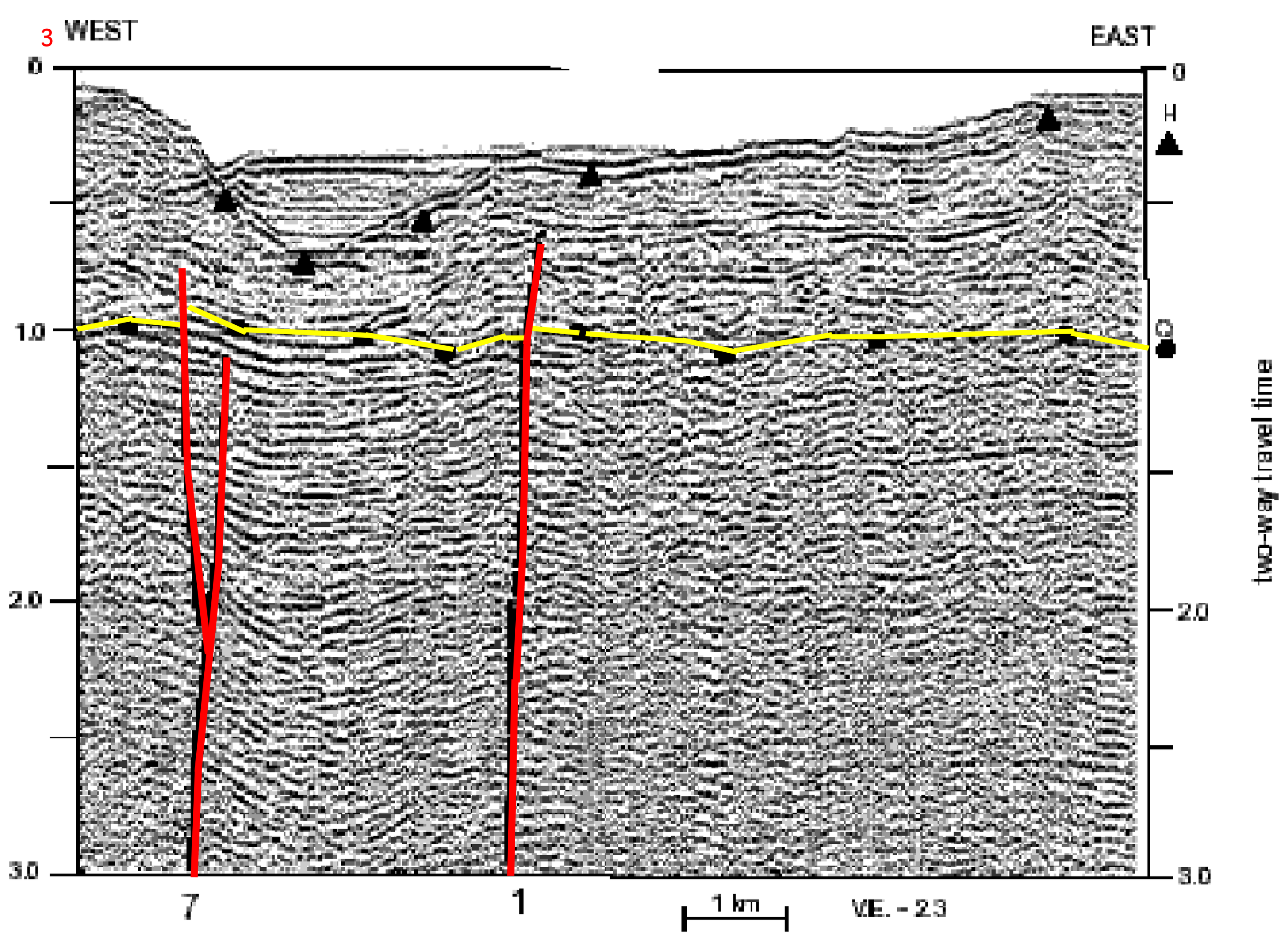


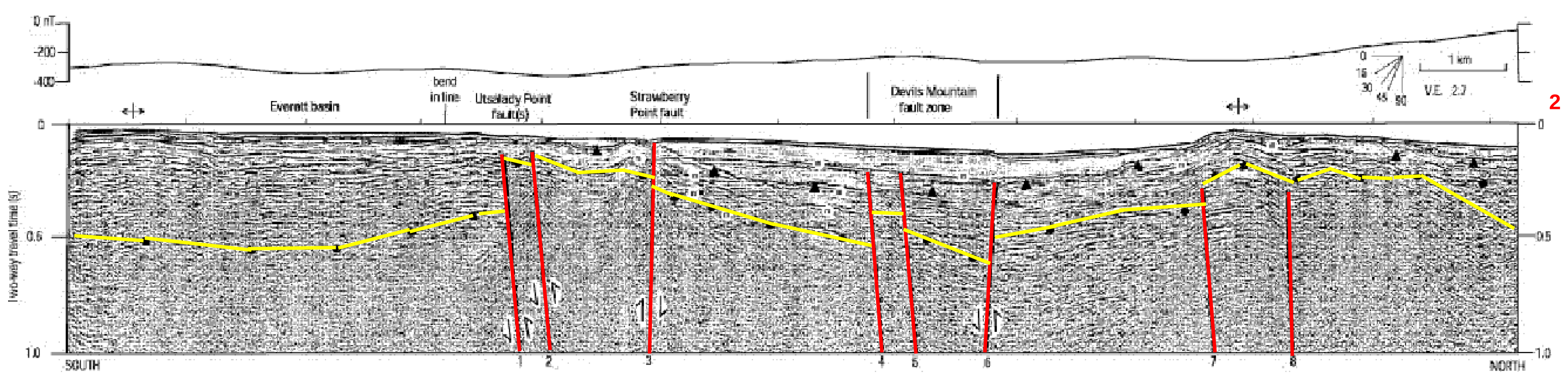
Seismic section through the Birch Bay structure. Modified from Figure 2 Hurst 1993.



USGS Profile Northern Puget Sound (Figure 5 Johnson et al 1999)

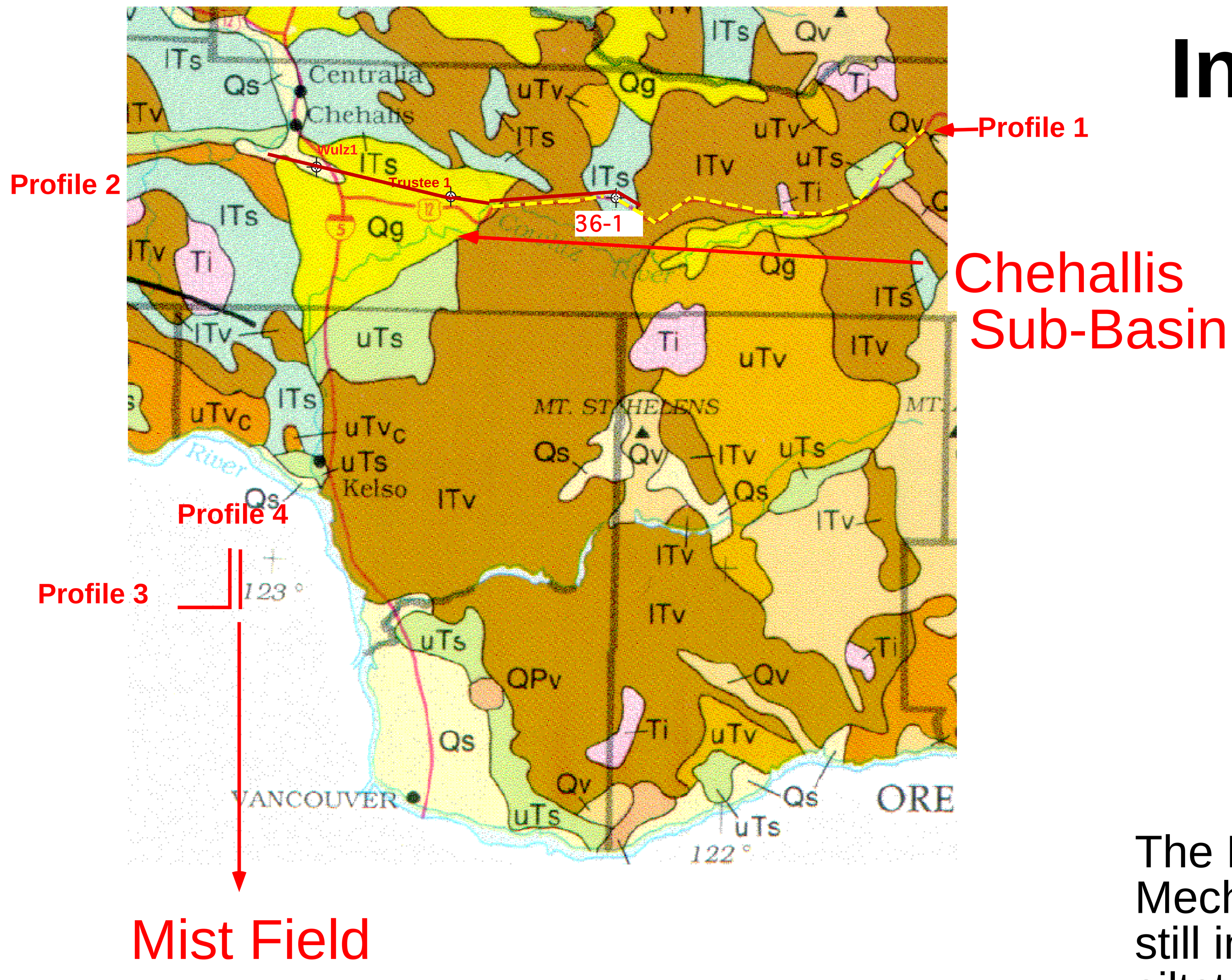






USGS Seismic profile and aeromagnetic profile northern Puget Sound (Figure 10A Johnson et al 2002)

Inversion in the Southern Puget-Willamette Lowland



The southern Puget Lowland sub-basins contain the thickest Eocene accumulations in Washington state. There are more coal mines here than elsewhere in the state (Beikman et al 1961).Estimated reserves in the Tacoma sub-basin are 360 million tons of bituminous coal, with seams ranging between 5 and 15 feet thickness. Surface mines typically encounter steeply dipping beds. Estimates in the Chehalis sub-basin exceed 3,700 million tons of sub-bituminous coal, with some beds 40 feet in thickness. Surface outcrops commonly show steep dips, and chevron folding is known in some mines. The only oil or gas production in the Northwest occurs at the Mist Field, Oregon to the south of the Chehalis sub-basin.

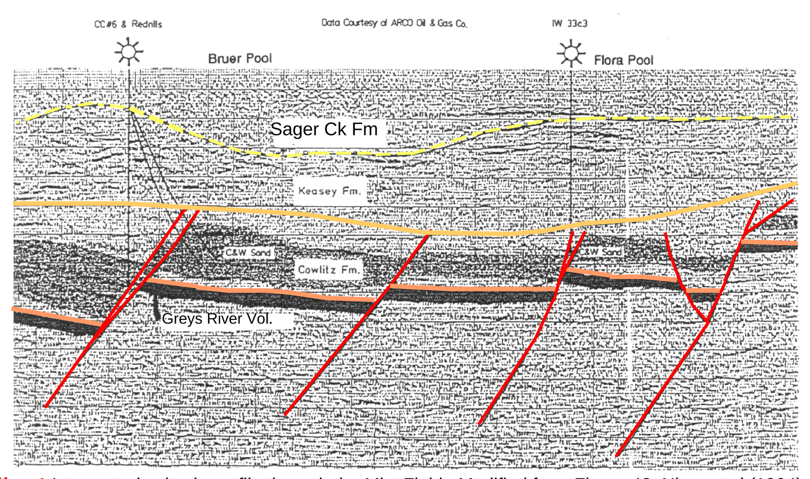
The Tacoma sub-basin shares many features with the Seattle sub-basin, including the risk associated with Recent tectonic activity. The Chehalis sub-basin appears less subject to active faulting and folding, and is thus considered the most prospective of the sub-basins.

The Chehalis sub-basin and the Southern Washington Cascades are underlain in part by the "Southern Washington Cascades Conductor" (SWCC), a feature first identified through a magnetotulleric survey. The region of low conductivity is interpreted to represent (?)Eocene marine sediments (Stanley et al 1992).

The Hunt Oil State 36-1 was drilled on the Morton Anticline as test of the SWCC model, with a prognosed depth of 15,000'. Mechanical problems at 10,341' left the well above the SWCC. Coals and sandstones were recovered at TD, indicating the well was still in the continental Eocene Puget Group. Hydrocarbon flourescence is noted on the completion log as "yellow flourescent cut from siltstones starting at 10,160 to TD".

Mist Field

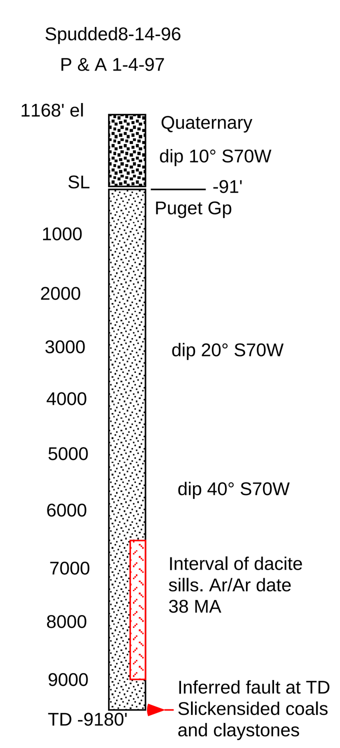
The Mist Field produces dry gas from the Eocene Clark and Lewis Sands of the Cowlitz Formation. The gas is considered to be from both biogenic and thermogenic sources (Armentrout and Suek 1985). The field occupies fault blocks, some mildly inverted, on the flank of the Nehalem Graben. Small fault blocks on the flank still produce, while the main field is now a gas storage site. Initial reserves are estimated at 70+BCF.

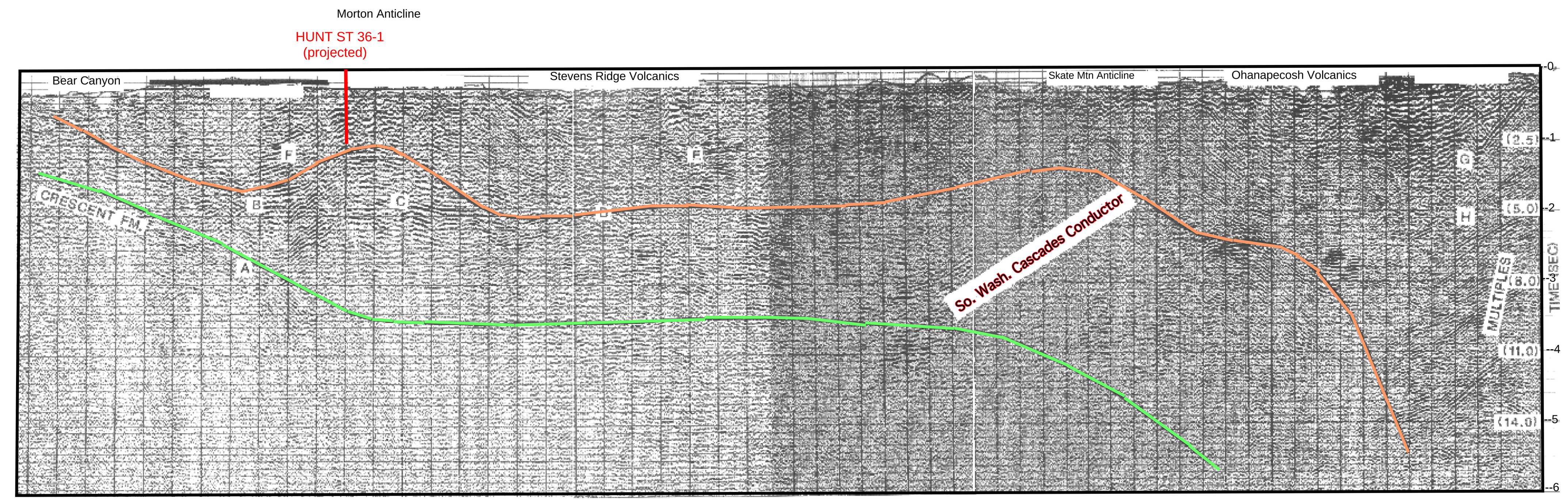


Profile 4 Interpreted seismic profile through the Mist Field. Modified from Figure 43, Niem et al (1994)

Data compiled from logs and drilling reports of Hunt State 36-1.

Hunt State 36-1



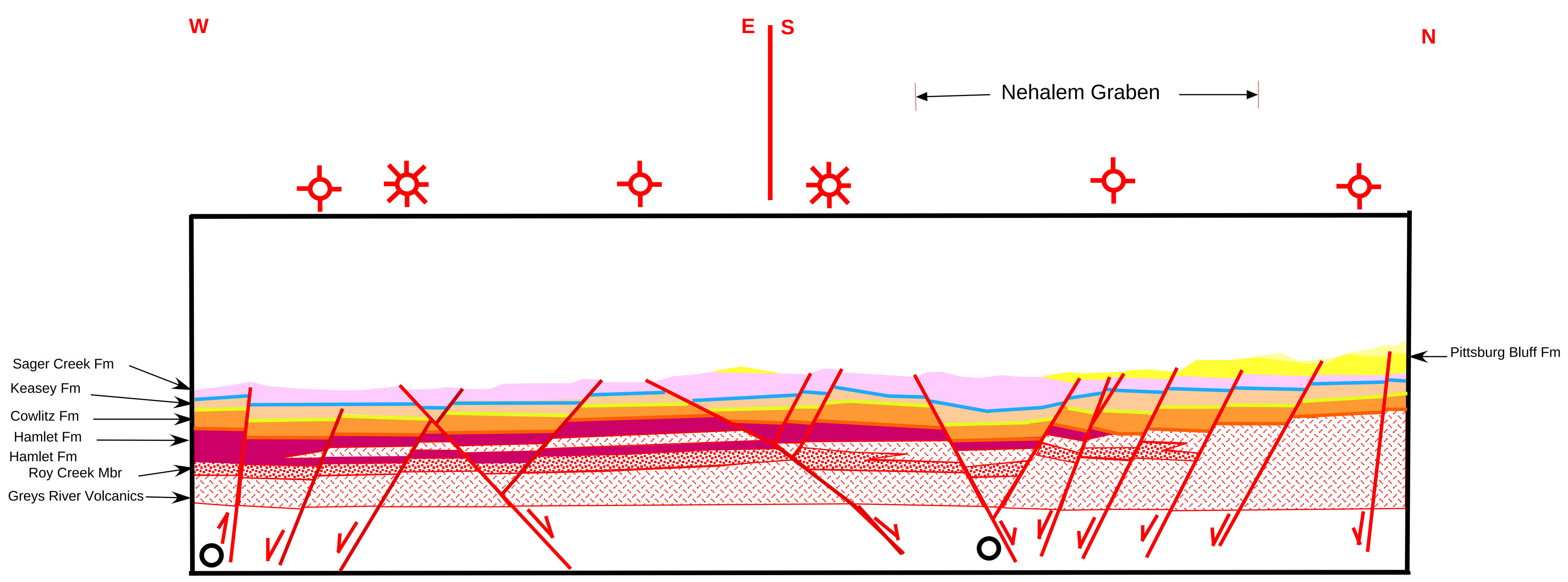


Profile 1

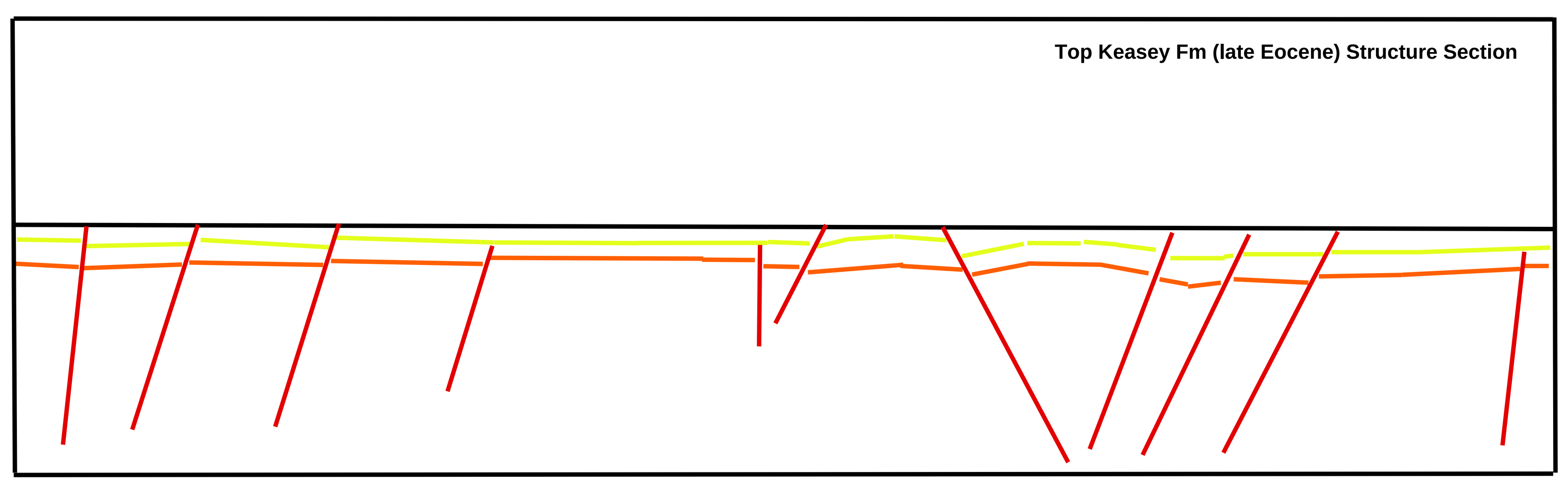
Modified from Figure 6 Stanley et al. 1992.

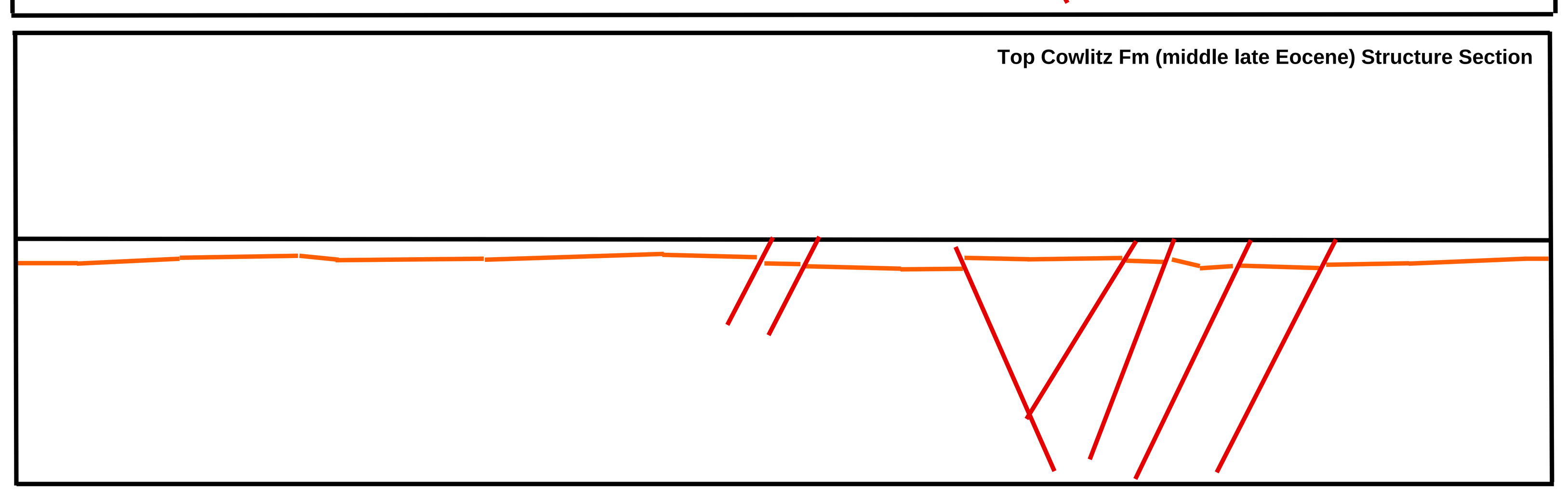
Unmigrated seismic profile across southern Washington showing flank of Chehalis Sub-basin and southern Cascades in region of Southern Washington Cascades Conductor (SWCC).

No wells have penetrated the orange horizon which is thought to be the top of the SWCC.



Profile 3 Cross section showing Mist Gas Field and Nehalem Graben. (Modified from Figure 36, Niem et al 1994)


Top Keasey Fm (late Eocene) Structure Section


Top Cowlitz Fm (middle late Eocene) Structure Section

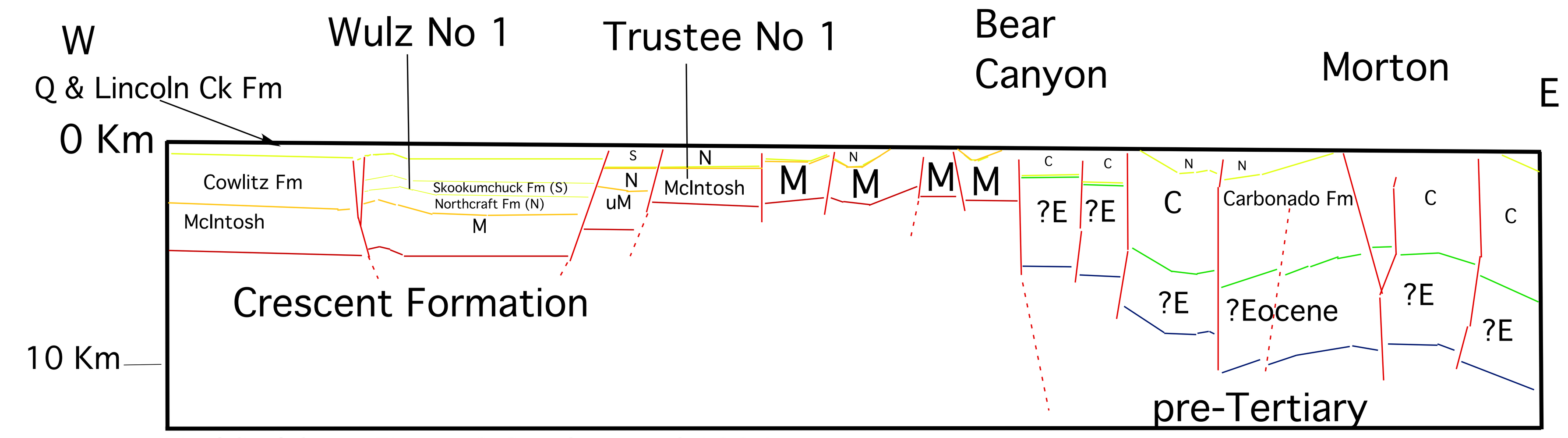
Top Hamlet Fm (early late Eocene) Structure Section

Structural deformation in the southern Puget-Willamette is interpreted to result from transpressive movements on strike-slip faults during post-Miocene time (Niem et al 1994, Stanley et al 1992, 1994). Field mapping in the Astoria Basin by Niem and colleagues has identified several zones of northwest trending faults with several kilo-meters of dextral displacement.

Structural reconstructions of the sections based on both seismic and well data suggest an earlier episode of deformation.

A reconstruction through the Mist field, shown on the left, suggests that inversion occurred in two episodes in the late Eocene and after deposition of the late Eocene Sager Ck Fm.

A reconstruction along the DOE line in southern Washington also suggests two episodes of inversion. The first occurred after deposition of the early Eocene Northcraft Fm. The second occurred after deposition of the late Eocene Cowlitz Fm. Interestingly, the SWCC may be inferred to occur within a ?Paleocene-Eocene graben that developed coevally with the ancestral Cascades.

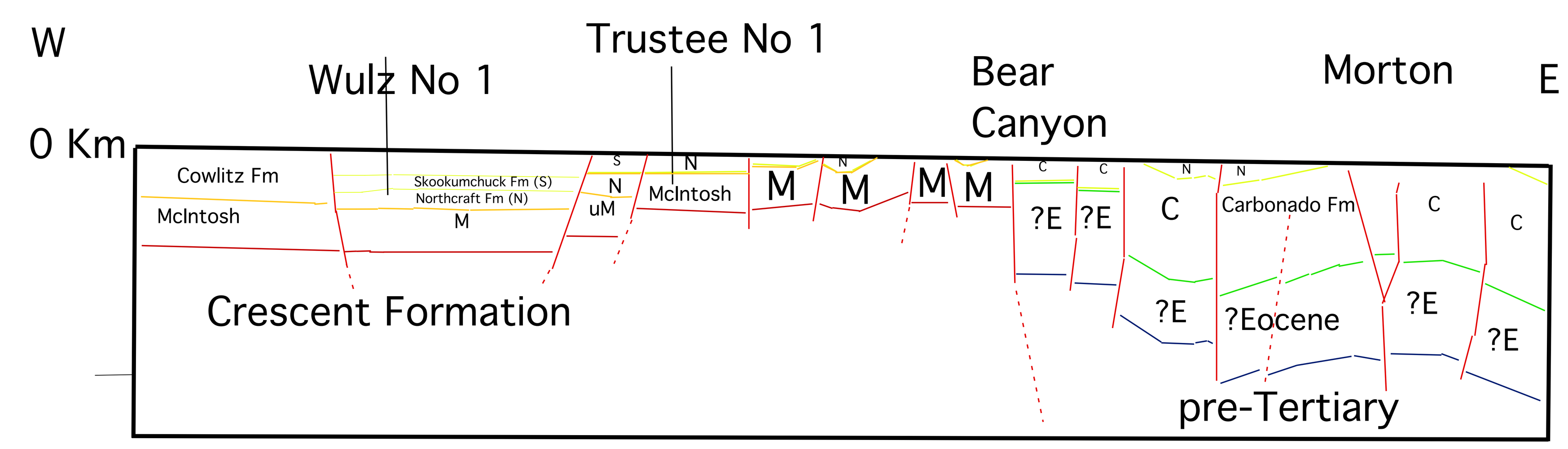


Modified from Figure 8 Stanley et al 1994

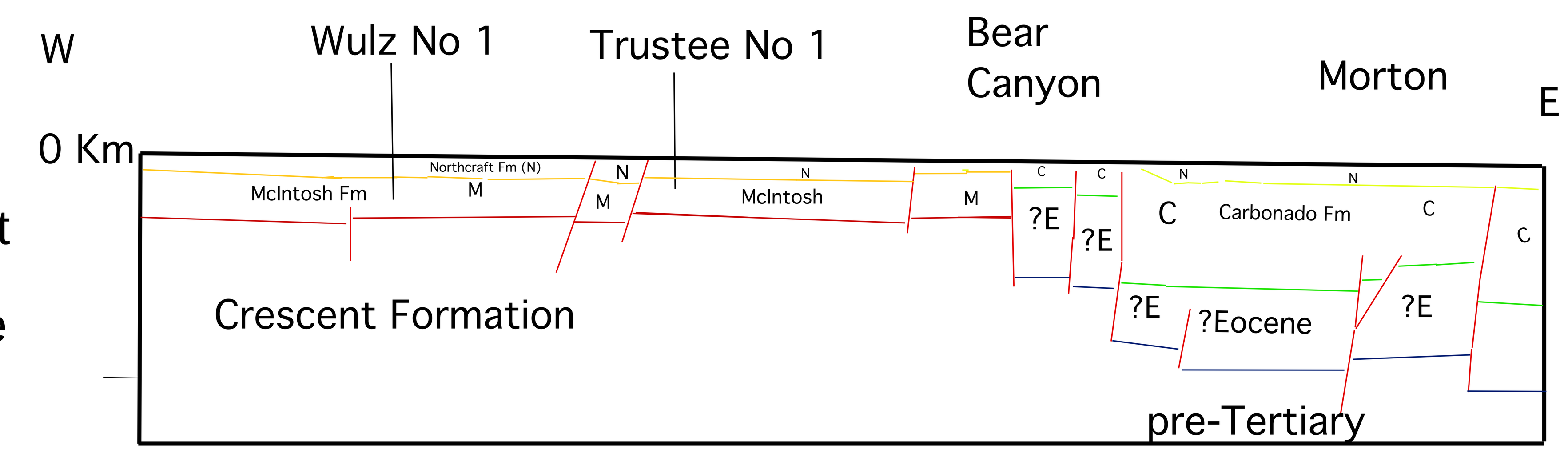
?Eocene -interpreted by Stanley et al as SWCC marine strata

Profile 2

10 Km



Top Cowlitz Fm (late Eocene) Structure Section



Top Northcraft Fm (middle Eocene) Structure Section

Petroleum System

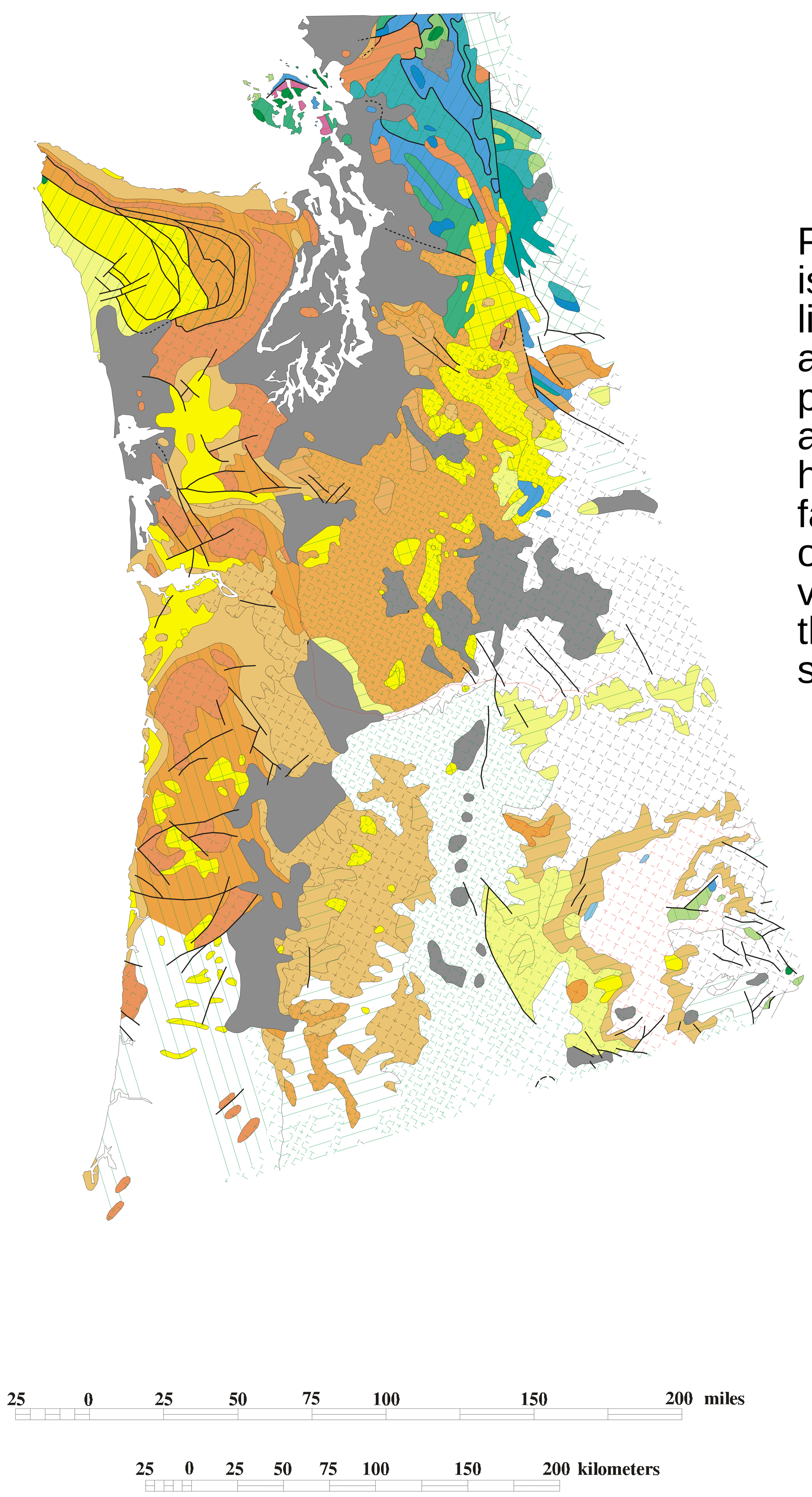
A wedge of Eocene continental and marine sediments deposited on an igneous basement occurs in western Washington and western Oregon. Coals occur on the eastern side of the sedimentary package and are inferred to be the principal hydrocarbon source interval. Fluvial and marine sands overlain by intra-formational claystones are considered likely reservoir-seal couplets.

The tectonic setting above a subducting slab has not lead to a low geothermal gradient. Intermittent magmatism commencing in the Paleocene resulted geothermal gradients more typical of rift or continental settings. Advective heating associated with volcanic centers is inferred to elevate the geothermal gradient locally.

A variety of structural styles may be identified on publicly available seismic data. Inversion, possibly associated with strike-slip faulting, is inferred to occur in southern Washington and northern Oregon. Occurring in ?Oligocene-early Miocene time, these movements likely are to precede hydrocarbon generation and migration.

Holocene faulting in the northern Puget Sound area has created structures that may post-date source rock maturation.

Resource Potential



Bellingham Basin: Coal-Bed Methane potential is medium to high throughout most of the basin, and low along the basin's margins. Conventional gas potential is medium to high in areas not subject to Recent faulting.

Puget Willamette Lowland Sub-Basins: Coal-Bed Methane potential is high along the eastern side of the the trough, especially along the limbs of synclines which are expected to be less deformed than the anticlinal areas where coal outcrops and coal mining occurs. Medium potential occurs over the center of the basin, and is limited by anticipated depth to the coal seams. The western portion of the basin has low CBM potential due to depth of burial and transition to marine facies within the Eocene interval. CBM in the northwest Oregon portion of the Lowland is low due to depth of burial beneath Miocene and younger volcanic deposits. Conventional gas potential is medium potential throughout the basin, with high potential for gas within the sub-basins not subject to Recent faulting.

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