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ARE HYDROCARBON SOURCE ROCKS BURIED BENEATH VOLCANIC FLOWS IN THE SOUTHERN WASHINGTON CASCADES?

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ABSTRACT

Geophysical studies in the southern Washington Cascades have outlined a possible, previously unrecognized sequence of sedimentary rocks. These postulated sedimentary units are interpreted as corresponding to at least the upper section of a low-resistivity package of rocks at depths of 1 to 10 km and with thicknesses up to 15 km that we call the southern Washington Cascades conductor (SWCC). The upper surface of this conductive package correlates in some places with anticlinal structures that bring Tertiary marine rocks near the surface. Subsurface details of these anticlinal structures have been imaged with deep reflection surveys. The conductive rocks have also been traced to the surface west of Morton, Washington, where they correlate with marine shales of the lower Eocene McIntosh Formation. We interpret that the conductive package is largely related to such Eocene, and older, marine sedimentary rocks, although other possible lithologies for the conductive package have been considered in detail. We favor marine sedimentary rocks as the primary constituent of the SWCC, but recognize that parts of the conductive section may be composed of nonmarine sedimentary rocks like those in the upper part of the Puget Group, a deltaic sequence, or those in nearby pull-apart basins. Geothermal fluids may be a contributing factor to low resistivities in the deeper parts of the conductive section (greater than 6-7 km). Another possible candidate for the conductive units is a thick section of highly-altered volcanic flows. Also, the possibility exists that the anomalous rocks are composed of pre-Tertiary, carbonaceous, metamorphic rocks.

The geometry of the conductive rocks consists of a east-dipping, low-angle wedge that thickens to the north and with an undulating upper surface corresponding to the mapped anticlines. The conductive

wedge may be related to an Eocene and older forearc basin/accretionary prism or to similar age marine rocks in a pull-apart structure. In either case, the conductive units may represent hydrocarbon source rocks. In addition, the seismic and MT results show that a possible anticlinal trap may exist near the leading edge of the hypothesized sedimentary sequence. However, high crustal-heat-flow caused by Oligocene to Holocene magmatic arc activity probably has left most of the proposed sedimentary sequence in an advanced state of thermal maturity.

INTRODUCTION

The Pacific Northwest states of Oregon and Washington encompass a region of complex geological settings in which petroleum exploration has been largely unsuccessful because of a variety of geological factors and the low quality of typical seismic data. The system of late Tertiary sedimentary basins west of the Cascades (Fig. 1) has been interpreted as containing largely immature source rocks, but with some good reservoir rocks (Armentrout and Suek, 1985). These basins formed on basement consisting of oceanic basalts of the Coast Range province, and are filled with 3-5 km of marine sandstones, shales, and minor volcanic rocks. The only producing field with ongoing development in the Pacific Northwest is the Mist gas field, west of Portland, Oregon (fig. 1).

Eocene to Miocene sedimentary units in the Olympic Peninsula appear to contain good source rocks (Snavely, 1987) and some oil has been produced from the coastal zone of the Peninsula and in the Grays Harbor basin to the south (Braislin and others, 1971). Methane is venting from a fault zone on the north side of the Olympic Peninsula (Kvenvolden and others, 1985). Organic geochemical analyses by Kvenvolden and others (1985) suggest that the deep parts of the Olympic melange assemblage are mature for oil and gas, and Snavely (1987) suggests that the highest potential for oil and gas generation in the western Washington region occurs in the thick, accretionary melange-wedges of the Olympic Peninsula.

Drilling in the Puget Lowland of Washington has not resulted in production (Fig. 1), but many wells have produced shows of oil and/or gas. Gas seeps in the Black Diamond, WA area (Mullineaux, 1970) and elsewhere in the Puget Lowland are believed to derive from coal bed methane at shallow depths. Testing of the Phillips State No. 1 well drilled east of Tacoma (Fig. 2) extracted a measurable quantity of high-paraffin oil at depths of 7060-7120 feet (Brown and Ruth Laboratories, 1982).

Extensive hydrocarbon exploration has been carried out in the Columbia River Plateau (Fig. 1), based upon initial, non-commercial, gas discoveries by Shell Oil Co. (Northwest Oil Report, 1983). This gas appears to have come from Tertiary nonmarine sediments in which flow is restricted by porosity-plugging authigenic minerals derived from volcanic clasts. Much speculation has developed concerning the possibility that the Plateau is underlain by Mesozoic sedimentary rocks similar to those that crop out in the Blue Mountains, Oregon (Kleinhaus and others, 1984; Miller, 1989).

The U.S. Geological Survey and Department of Energy have carried out geophysical and geological studies in the southern Washington Cascades region over a several year period to study anomalous features that might be associated with petroliferous formations in the region. A large region of low electrical resistivity (highly conductive) called the southern Washington Cascades conductor (SWCC, Fig. 1) was mapped using magnetotelluric (MT) surveys (Stanley and others, 1987). The overall geometry of this conductive package and correlation of its upper surface with anticlinal structures involving Eocene transitional marine rocks suggested to Stanley and others (1987) that the conductor might represent an accretionary prism/forearc basin system that was compressed during accretion of an extensive seamount assemblage that forms the core of the Coast Range in Washington and Oregon. In this paper we will consider new information on this anomalous conductor, including recently acquired deep seismic-reflection data, and discuss possible lithologies and tectonic models. After a discussion of various lithologic and tectonic possibilities, we will discuss the thermal history of the system and investigate possible traps indicated in the geophysical and geological data.

MT AND SEISMIC-REFLECTION DATA AND PHYSICAL PROPERTIES

Physical Properties

The ability to interpret lithology from the MT and seismic data sets is dependent upon our understanding of the electrical and acoustic properties of rocks under the temperatures and pressures encountered in the Cascade Range and surrounding region. The following, short discussion of rock properties is included to provide a background for statements concerning lithological correlations of various MT and seismic models in this paper.

Electrical resistivity vary over an extremely large dynamic range, with common rock resistivities typically ranging from 1 to 10,000 ohm-m. Rock-forming minerals are normally very resistive at surface pressures and temperatures, with the exception of metallic minerals and graphitic carbon, which are very low in resistivity. For most rocks, resistivity is controlled by ionic conduction through fluids in pore spaces or intergranular coatings, rather than electronic conduction through the mineral matrix. This ionic-controlled resistivity is a function of salinity of the pore fluids, temperature, and pressure, and is important for sedimentary and other rocks with connected porosities of greater than a few tenths of a percent. Ionic mobility increases and resistivity decreases as temperature is increased, but the effect on resistivity reaches a maximum at temperatures around 200-250°C for depths of a few km.

As porous rocks are buried to depths greater than a few km, porosities are decreased due to lithostatic loading until the rocks normally become highly resistive. In shales, ionic conduction also occurs in trapped water in clays and zeolites; as a result, the resistivity of shales will be low (1-20 ohm-m) and varies less than other sedimentary rocks as porosity decreases. As shales are metamorphosed, both porosity and layered clays are destroyed, but low resistivities can be maintained due to formation of carbonaceous or iron mineral films along fissile planes in the metashales. Intrusive rocks have very low porosity and thus are normally very resistive, typically in the range of 500-20,000 ohm-m. Fracture porosity and intense alteration of intrusive rocks can lower their resistivity well below this range. Unaltered volcanic rocks have very high resistivities when pore waters are very fresh; however, as volcanic rocks increase in age, development of authigenic minerals (clays and zeolites) dramatically decreases their resistivity. Typical values for tuffaceous-rich (non-welded tuff and ash alters very fast) flows and volcaniclastic rocks of Tertiary age in the Oregon Cascades are less than 20 ohm-m. Metamorphism of crustal rocks beyond zeolite facies generally increases resistivities, except for metamorphosed shales in which carbonaceous and/or metallic-mineral coatings may develop. Another exception to high resistivities in metamorphic rocks occurs upon dehydration of greenschist or amphibolite facies minerals in the rocks, as demonstrated by Lee and others (1983); their laboratory measurements on high-grade metamorphic rocks at temperatures up to 300°C and pressures of 0.4GPa indicated lowered resistivities that they attributed to high-pore-pressure fluids from mineral dehydration. As temperature and pressure increases, partial melting may occur, leading to a decrease in resistivity of the rocks by up to two orders of magnitude if there is sufficient interconnection between intergranular melt films. The range of resistivities and typical median values for geologic formations in the study area are indicated in the stratigraphic chart of Figure 3.

Accuracies in the MT models are influenced largely by data quality, selection of strike direction, frequency-independent shifts of curves due to near-surface complexities (similar to weathering problems in seismic reflection surveys; Sternberg and others, 1989) and oversimplified model geometry.

Seismic compressional-wave velocities in crustal rocks vary over a much narrower range than do resistivities, typically ranging from 2-7.4 km/s. Velocities for Tertiary sedimentary rocks are typically 3-5 km/s. Compressional velocities for Cascades volcanic rocks range from 4-6 km/s, controlled by porosity, weathering, and proportion of mafic minerals. The velocity of intrusive rocks is influenced by the proportion of mafic to quartz minerals in the rocks, with felsic rocks such as granite having velocities of about 5-6 km/s and intermediate to mafic intrusive rocks ranging higher than 6.3 km/s. Approximate velocities for the formations of interest to our study determined from acoustic logs, stacking velocities, and analogy with similar geologic units are given in Figure 3. The recording of reflections from geologic formations is dependent upon sufficient acoustic contrast and favorable geometry of the reflecting surfaces (Anstey, 1977).

The seismic reflection data outlines two key pieces of structural information: (1) folding corresponding to mapped anticlines and synclines and (2) basal dipping reflectors on the west and east ends of a long profile through the study area. Migration of the reflection data has only been done for the western part of this long profile because poor data quality for much of the profile did not warrant migration of the whole data set. Interpretation of unmigrated data will not affect general structural analyses for the anticlinal structures, but use of unmigrated data for the dipping reflectors on the west and east ends of the profile had to be handled cautiously. Because no wells were available along the reflection profiles, velocity information from wells in the nearby Chehalis basin, in combination with stacking velocities were used to aid processing and interpretation of the data. Approximate depth conversions used in the subsequent discussions and figures assume average velocities of 5 km/s above 3 s two-way travel time and 6 km/s for larger travel times.

GEOLOGY OF WESTERN WASHINGTON

The SWCC occurs partially within the Cascade Range that extends from northern California to British Columbia; volcanos of the Cascades (Fig. 1) represent the magmatic arc associated with post 36 Ma subduction of the Juan de Fuca plate and its predecessors. The Cascades magmatic arc may have begun to develop about 44 Ma with andesitic dikes that intruded the Crescent Formation (Snavely, 1987) and certainly was well established by 36 Ma at the time of eruption of the thick Ohanapecosh Formation volcanic flows near Mt. Rainier (Fig. 3). Pre-Tertiary crust in the region is composed of Mesozoic and older accreted terranes, volcanic arcs, and underplated magmatic rocks. This older accreted crust is exposed in the North Cascades (Fig. 1) of Washington and in the Blue Mountains and Klamath Mountains of Oregon.

A key feature of the geology of the Pacific Northwest margin is a terrane of oceanic basalts (Fig. 1), called "Siletzia" by Irving (1979), that forms the basement in western Oregon and Washington. Several models have been proposed for the origin of these oceanic basalts, including (1) accretion of a seamount-bearing oceanic plate during subduction (Snavely and MacLeod, 1974), (2) accretion of hot-spot-generated aseismic ridges or seamount chains (Duncan, 1982), (3) accretion of seamounts erupted along leaky fractures or transforms, or (4) in situ eruption of basalts in a dextral pull-apart structure along the continental margin (Wells and others, 1984; Snavely, 1984). Throughout this paper we refer to pull-apart basins as rifts or graben structures caused by the effects of differential movement on strike-slip faults. Other terms roughly synonymous with pull-apart structures are "rhombochasm" (Carey, 1958) and wrench grabens (Belt, 1968); terminology and a review of tectonic aspects of this type of structure is given in Mann and others (1983). The oceanic basalt assemblage is represented by the Siletz River Volcanics in Oregon (Snavely, MacLeod, and Wagner, 1968), Crescent Formation in Washington (Cady, 1975), and Metchosin volcanics on southern Vancouver Island (Muller, 1977) and is estimated by Duncan (1982) to have a volume of 250,000 km^3. Gravity and magnetic data have been analyzed by Finn (1989) who, along with Stanley and others (1987 and 1989), interpret that the Siletzia units extend underneath the region between the Black Hills and Mount Rainier (Fig. 1). For purposes of this paper, we infer that after Siletzia formation, models (1), (2), and (3) were identical to model (4) in mechanical response important to subsequent tectonism.

In the middle Eocene, feldspathic-quartzose sediments of the deltaic Puget Group (Armentrout and Suek, 1985) prograded across Oregon and Washington, filling the gaps between the seamounts. Isolated, but active volcanic centers developed within the prograding delta system, leading to eruption of the andesitic Tukwila and Northcraft Formations (Fig. 3). Marine shales and siltstones of units such as the McIntosh Formation (Snavely and others, 1958) formed the basement for this deltaic system. The Cascades magmatic arc was the source of voluminous felsic lavas and ash flows of Oligocene age like the Ohanapecosh Formation that filled a continental depression in the area of the present Cascades and eastern Puget Lowland (Fig. 3). The Miocene Columbia River Basalt Group (Fig. 3) erupted from 17 to 6 m.y.b.p. (McKee, Swanson, and Wright, 1977), flooding the continental-sediment-filled, backarc basin east of the Cascades.

Paleomagnetic data document significant block rotations of the Coast Range (Simpson and Cox, 1977; Globerman and Beck, 1979; Magill and others, 1981; Wells, 1989). There is agreement among these various authors that the Coast Range has undergone a relative clockwise rotation with respect to the North America craton of about 25° in the north and up to 75° in the south. There have been several models proposed by Simpson and Cox (1977) and Wells (1989) to explain this rotation. The most current analysis by Wells (1989) includes paleomagnetic data from the Black Hills (outcrops of Siletzia) near Olympia, Washington (fig. 1); this information indicates that much of the overall rotation of the Coast Ranges was taken up in individual block rotations, probably associated with dextral shear.

Horizontal translation by dextral-slip must also be considered in paleotectonic reconstructions. Western Washington lies at the southern end of a belt of dextral slip related to oblique convergence of the

Juan de Fuca plate and its predecessors, such as the Kula and Farallon plates. From several hundred to several thousands of km of strike slip have been postulated for the borderland terranes of British Columbia, the Yukon Territories, and Alaska in post-Cretaceous time (Irving, 1983; Irving and others, 1980; Jones and others, 1977). Active strike slip appears to be occurring in the Mount St. Helens area where Weaver and Smith (1983) have mapped a right-lateral slip zone with active seismicity that they call the St. Helens zone (SHZ, Figs.1,2). Stanley and others (1987) suggested that the SHZ is located on the boundary between Siletzia and the hypothesized sedimentary sequence of the SWCC.

Misch (1977) and Davis and others (1978) postulated that the Straight Creek fault (Fig. 1) might have about 190 km of right-lateral displacement. Price and others (1985) suggest that the Fraser Fault (northern extension of Straight Creek fault) had about 70 km of offset since the mid-Cretaceous. Motion on the fault system must have ceased by time of intrusion of the Chilliwack batholith in Oligocene time (Price and others, 1981). Detailed study of the southern end of the Straight Creek fault by Tabor and others (1984), found a Tertiary history of dominantly vertical movement. However, they interpret that horst-and-graben structures and en-echelon fold axes in the Eocene Swauk Formation suggests early Eocene right-lateral shear along the Straight Creek fault. Johnson (1984a) has inferred a major, transcurrent strike-slip fault (the Puget fault) that extends through the Puget Lowland and bends into thrust faults in southern Vancouver Island as part of a system of strike-slip faults that caused pull-apart structures in central and western Washington in which thick accumulations of nonmarine sediments accumulated (Johnson 1984a, 1984b, 1985).

The focus of hydrocarbon exploration in western Washington has been largely upon Eocene to Oligocene marine sedimentary systems. The rocks in these basins are mostly too thermally immature to be hydrocarbon sources (Armentrout and Suek, 1985). The search for other sedimentary systems with mature source rocks has brought us to investigate the possibility that proposed sedimentary rocks in the southern Washington Cascades conductor (SWCC) constitute such viable source rocks. In order to evaluate the SWCC as a possible location for hydrocarbon source rocks, it is necessary to evaluate the available constraints upon lithology, thermal history and paleotectonics of the SWCC. We will attempt these tasks in the following sections, and discuss the details of recent seismic reflection data as they relate the SWCC anomaly.

DETAILS OF SWCC STRUCTURE

Magnetotelluric Models

Three regional MT model cross-sections are shown in Figure 4 and a detailed model of the Morton area in Fig. 5 (locations of profiles in Fig. 2). These profiles represent one-dimensional (layered) interpretations of MT soundings done in the region of the SWCC, but two-dimensional interpretations of profiles AA' and CC' have also been completed, as described in Stanley and others (1987). The two-dimensional models provide more accurate constraints on deeper structures, such as the base of the conductive SWCC units (2-5 ohm-m resistivities) on profiles CC' and AA', but the upper surface configuration of the SWCC is more accurately determined on the one-dimensional models. In two-dimensional modeling using finite-element algorithms, it is impractical to model all aspects of the geology in the upper few kilometers because of the requirement for a very large model-grid; thus, most of our discussion will center around details of the one-dimensional models as they relate to structure on the upper surface of the SWCC.

Units of 30-500 ohm-m from the surface to depths of 5 km on the model for profiles AA' and BB' (Fig. 4a,b) largely correspond volcanic rocks (Fig. 3) of the Eocene Northcraft Formation the Oligocene Ohanapecosh Formation and the Miocene Stevens Ridge Formation (Vance and others, 1987). Very thick units with resistivities of 100-500 ohm-m, averaging about 150 ohm-m on the west ends of profiles AA' and CC' correspond to gravity and magnetic highs and were interpreted by Stanley and others (1987) to be made up of Siletzia seamounts or other oceanic basalts. Wannamaker and others (1989) interpreted that equivalent oceanic basalts in the Oregon Coast Range had resistivities of about 100 ohm-m or slightly less. Rocks with resistivities of 500-5000 ohm-m that reach within 2 km of the surface on the east end of profiles AA', BB', and CC' correspond to Tertiary plutons and North Cascades crystalline rocks. It is not clear what high resistivity units beneath soundings B55 to B39 on profile CC' signify; they may represent intrusions connected with Siletzia or younger intrusions, probably of Oligocene or Miocene age. The most significant feature of the three MT profiles is the thick, conductive section with resistivities of 1-5 (averaging about 3) ohm-m. The top surface of this conductive package (SWCC) occurs at depths of only 1-3 km near the axis of the Carbon River (profile CC', station 47), Skate Mountain (profile BB') and Morton (profile AA', stations 3 and 7, and profile EE') anticlines. The conductive rocks also appear to crop out west of Morton in the Bear Canyon area where they are represented by shales of the McIntosh Formation (Fig. 2) crop out. Because of the large thickness and low resistivity of the conductive section, all of the MT soundings did not penetrate to its lower boundary, but enough did so to enable approximate modeling of the lower surface. Resistivities beneath the conductive section are poorly determined, but must be greater than 100 ohm-m. It is apparent from the MT sections of Figure 4 that the SWCC units are thicker and less laterally extensive on profile CC' than to the south on profiles AA' and BB'; this geometry is interpreted to be due to greater horizontal compression on the north end of the proposed sedimentary sequence.

A layered model for detailed MT profile EE' is shown in Fig. 5. The thick conductive (3-6 ohm-m) section on the west end of the profile becomes shallower near Bear Canyon, where Eocene marine rocks of the McIntosh Formation crop out. The McIntosh Formation (Hedges, 1949; Snavely and others, 1951) is overlain by nonmarine Puget Group sedimentary units (20-80 ohm-m) and Northcraft Formation volcanic rocks (100-300 ohm-m). We interpret the section of conductive rocks (3-6 ohm-m) as contemporaneous with, and older than, the McIntosh Formation and equivalent to the 1-5 ohm-m section on the models of Fig. 4. The high-resistivity (>1000 ohm-m) units beneath sounding 13 may correspond to Oligocene to Miocene intrusive units that crop out 12 km west of Bear Canyon (Walsh and others, 1987) or may be an intrusion emplaced at the time of Siletzia formation. The relatively steep contact portrayed between the 1000 ohm-m unit and conductive (assumed McIntosh Formation) units, may reflect an intrusive contact, faulted contact, or tilted depositional contact.

Seismic Reflection Data

In order to study details of the SWCC, a deep reflection profiling program was initiated in the region. The survey was done in four segments (S1, S2, S3, S4 in Fig. 2) under contract to the U.S. Department of Energy using a 1000-channel, sign-bit system (Zoback and Wentworth, 1986; Gimlin and Smith, 1980). Five vibrators with a peak force of 27,240 lbs (12382 kg) were used with a modified downsweep from 8-32 or 8-48 Hz. Receiver group spacing was 30 m on segments S1 and 20 m on segments S2, S3, and S4; vibrator point spacing ranged from 40 m to 120 m. Data were stacked with a maximum of 256-fold coverage, with several passes of static corrections and deconvolution, including horizontal deconvolution. The latter technique is a predictive method to correlate events from trace to trace and produces a minimum numbers of artifacts when compared to the coherency filtering sometimes applied to poor-quality reflection data.

The stacked CDP (common-depth-point) record section from profile segment S1-2 is shown in figure 6 with the most evident reflections highlighted. The display of Figure 6 represents a decimation of CDP data by a factor of six to ten to make presentation of the results more visible at a small scale. An expanded section of a portion of the profile with all of the CDP data is shown in figure 7. Receiver-group spacing was 30 m on segment S1 and 20 m on segment S2 and S3. Details on the western and eastern ends of the profile are shown in Figs. 7 and 8 with the full CDP data set used.

The data were recorded to 15 seconds, but only the upper 5 seconds of data are shown in Fig. 6 because no coherent events were observed in the remainder of the record. The data quality is generally not adequate for interpretation at travel-times greater than 3-4 seconds. This degradation in data quality was caused by traffic noise, poorly-defined velocity functions, the presence of surface volcanics, structural complexity, and non-linear survey routes. Regardless of a lack of reflections below 3-4 seconds at increasing time, this survey represents the first reflection data suitable for intermediate-depth (down to about 8 km) structural interpretation from the Cascades. A standard exploration seismic profile across the central part of the Chehalis Basin was described by Ise (1985), but no published deep-reflection data exist for the Washington Cascades.

Comparison of MT, Reflection, and Geologic Data

A geologic cross-section through the region of the seismic reflection and MT profiles has been constructed by Phillips and Walsh (1989) as shown in Fig. 9 (location of profile GG' noted in Fig. 2). We have added the approximate location of key reflection sequence from FIg. 6. This was done only to show the interrelationships of reflection sequences in the context of the geologic cross-section. In addition, a magnetic data profile roughly coincident with the seismic profiles is shown above the geologic section. It is quite clear that the general character of the reflection data matches the presumed geological structure to depths of about 5 km; the Morton and Skate Mountain anticlines are the most dramatic features in the reflection data. Reflection sequence B (fig. 6) corresponds to the postulated base of the McIntosh marine units. Sequence E corresponds to the base of the combined Stevens Ridge-Ohanapecosh section of volcanic rocks, and sequence D to the base of Puget Group continental sedimentary rocks. The correspondence of sequence F to the geological cross-section is not clear, but is believed by us to represent volcanic flows, probably of the Northcraft Formation overlying the McIntosh Formation. High-amplitude, pseudo-horizontal reflection sequence C occurs within the SWCC.

The dipping reflection series A of 0.3-0.4 s span is believed to correspond to flows of the Crescent Formation and overlying reflective sedimentary units. Basement beneath the Chehalis Basin (that begins on the west end of the reflection profile) can be identified as the Crescent Formation from seismic reflection data obtained in the Basin (Ise, 1985); this basement rises to meet the area of the end of MT profile EE'. Magnetic and gravity data indicate that the Crescent Formation and underlying mafic crust extends beneath the SWCC (Finn, 1989). The complex reflectivity for series A may be due to flows and interbedded sedimentary layers. On the Olympic Peninsula, pelagic limestones have been mapped, interbedded with some of the oldest units (probably most distal) of the Crescent Formation (Snavely, 1987). In places arkosic sandstone, diorite conglomerate, and felsic tuff-breccia are interbedded with Crescent basalt flows (Snavely, Wagner, and Lander, 1980). This complex layering of Crescent volcanics and associated sedimentary rocks could provide the reflectivity observed in reflection sequence A. Migration of the seismic data has not been very effective because of poor data-quality below 3 seconds in the area of the Morton anticline. However, migration tests show that the eastward steepening of the reflection series A is probably real, as would be expected if these reflections represent oceanic crust near the frontal part of an accretionary prism. Although we prefer the interpretation that the reflection series A corresponds to the Crescent Formation and contemporaneous sediments, there is no well evidence on the reflection profile to confirm the hypothesis; other interpretations are certainly possible.

The magnetic-field low over the Morton anticline is caused by the absence of volcanic rocks on its crest. A smaller-amplitude magnetic low occurs over the Skate Mountain anticline. High magnetic-field amplitudes just west of the Morton anticline are caused by Northcraft Formation andesites in the subsurface and Stevens Ridge rhyolites and andesites at the surface.

The layered model for MT profile EE' (Fig. 5) can be approximately compared to the seismic data of Fig. 6 and 7. The conductive units on the model (Fig. 5) are 3-5 km thick and covered by 2-3 km of more resistive units that are interpreted to be Northcraft volcanic rocks and continental facies of the Puget Group. The thick low-resistivity section from the Morton anticline eastward lacks coherent reflections. Due to the large bends in profile S1-2, the common-depth-point (CDP) track is displaced substantially from the actual survey path. This displacement of the CDP track must be kept in mind when comparing the MT model and the reflection record section. High amplitude events of sequence C, deep within the core of the Morton anticline may represent a porosity anomaly. Because of their horizontal attitude, it is tempting to speculate that the sequence C may correspond to gas-liquid boundaries (Anstey, 1977); however, the amplitude anomaly may also be due to high-velocity volcanic layers, overpressured fluids or to acoustic focusing in the anticlinal structure. Questions about event C cannot be fully answered until full waveform analysis of this portion of the data has been completed.

On the eastern half of Fig. 6, the Skate Mountain anticline represents the most prominent feature in the data. A relatively high-amplitude, dipping set of reflections H on the east end of the profile extend to over 5 seconds, or approximately 14 km depth. These reflections tend to die out and change character near Packwood. A stacking velocity inversion occurs in the approximate horizontal midpoint of the event, suggesting the possibility of multiples. We interpret that the earliest event of (H) arises from the subvolcanic basement, and the later, subparallel reflections below H represent multiples. The multiples are probably generated as interbed multiples in Puget Group sedimentary rocks between relatively high-velocity volcanic flows of the Ohanapecosh Formation (bottom at sequence G) and high velocity basement. The events H are not recognizable west of Packwood, possibly because of loss of resolution due to complexities in the thick Ohanapecosh flows and modification of the conditions producing the strong multiples. The basement is probably composed of Mesozoic metasedimentary and igneous rocks such as those found just east of the end of seismic profile S3 in the Rimrock Lake area (Fig. 3). The Mesozoic units in the Rimrock Lake area, called the Tieton inlier (Ellingson, 1972) or Rimrock Lake inlier (Miller, 1989), comprise a Mesozoic tectonic melange of greenschist to amphibolite grade (Ellingson, 1972; Miller, 1989). These units have been intruded by Jurassic and Miocene plutons (Miller, 1989). Similar Jurassic and Cretaceous metasedimentary rocks are found along the western margin of the North Cascades (Fig. 1). The resistivity of the Rimrock Lake and similar North Cascades Mesozoic metasedimentary units is 200-600 ohm-m (Fig. 3); thus, these rocks are probably not the cause of the SWCC.

Well Information

The deepest well in the SWCC region is the Phillips State No. 1 (TD 12,920', Fig. 2) that was completed east of Tacoma (Fig. 2). The well penetrated alternating sequences of sandstones, siltstones, shale, and coals of the Puget Group, interpreted in a report by Brown and Ruth Laboratories (1982) to be marginal marine facies. The upper 7120 feet of the section contains about 50% sandstone/siltstone and 50% shale. From 7120 to 7660 feet, greenish-gray, volcanic rocks of the Tukwila Formation were encountered. Below 7660 feet shales dominate, traces of coal start to appear, and zeolites fill most of the fractures. Greenish-gray volcanic rocks were also noted at 9320-9540 feet. Below 12,560 feet to TD, the well section consists of 100% shale. The induction electrical log for the Phillips well indicates resistivities for the upper 7200 feet of 40-60 ohm-m. Resistivities decrease rather steadily below this point to 15-20 ohm-m at the bottom of the well. This pattern is to be expected from the changes in the ratio of sandstones to shale; zeolites below 7660 feet also contribute to lowered resistivities.

An organic geochemical study of core and cuttings from the Phillips well (Brown and Ruth Laboratories, 1982) showed that the upper 7800 feet of the well had vitrinite reflectances of approximately 0.4% to 0.6%, whereas the section below this depth had reflectances more typically near 1%. The vitrinite reflectance values of the section below 7800 feet reflect maturity of the organic material compatible with oil generation (Tissot and Welte, 1980). This increase in thermal maturity of the organic material may be due to a thermal pulse connected with the Tukwila volcanic center. Measurable quantities of a high-paraffinic oil were extracted from the interval 7060-7120 and probably migrated in from below the measured section, because the zone in which they were found is thermally immature. The high vitrinite-reflectance values below 7200 feet in the well may increase with depth so that underlying pre- and lower Eocene marine units may be increasingly mature, but this scenario is dependent upon whether the maturation recorded in the Phillips well is indeed due to volcanism from the Tukwila magmatic center (Eocene) and later Cascades plutonism and not just to deep burial. Walsh and Phillips (1983) present evidence from coal rank data for increased thermal maturation associated with the Oligocene to Holocene Cascades magmatic arc. The Phillips State No. 1 well is within 30 km of Mount Rainier, the largest volcanic center in the Cascades, and the combined thermal effect of this volcano, earlier Cascades vents, and the Tukwila volcanic center was just enough to put the rocks at depths greater than 7200' in the oil window. This observation suggests that the thermal maturation problem must be evaluated carefully.

Oil and gas shows have been documented in other drill holes in the area northwest of Mount Rainier. Mullineaux (1970) describes a large number of oil and gas shows from drilling on the Black Diamond anticline, a small structure sub-parallel to the Carbon River anticline (Fig. 1). Mullineaux states that wells in the area of the Black Diamond anticline produced oil and gas shows from all parts of the Puget Group. A 6000' hole on the anticline produced oil shows virtually all the way to the bottom (Mullineaux, 1970). A gas well drilled at Flaming Geyser on the Black Diamond anticline produced salt water and continues to produce open flow of minor amounts of methane, although this gas has been thought to be produced largely from coal beds (pers. comm., T. J. Walsh, Washington Dept. of Natural Resources). In addition to hydrocarbon shows from wells in the region, a small oil seep has been noted in the Bear Canyon (Fig. 2) area (Hedges, 1949).

Snavely and others (1958) report on a drillhole of 6000' depth in the Tenino area (Fig. 2) that penetrated the complete section of Puget Group rocks and an extensive section of the McIntosh Formation.

No information is available on hydrocarbon shows in the well, but it is safe to assume that there were no producible horizons. This well is important because of the stratigraphic information recorded on the McIntosh Formation, to be discussed in a subsequent section. A 10,820' TD well completed in the Chehalis Basin, the Shell Thompson No. 1 (Fig. 2) penetrated 7300 feet of coal-bearing, marginal marine clastic rocks of the Eocene Skookumchuck Formation (Fig. 3) and 3500' of Northcraft volcanic rocks.

A 8200' depth drillhole was completed in September, 1989 by Meridian Oil Company just north of Glenoma (Fig. 2), roughly between soundings 43 and 44 on MT profile BB' (Fig. 4). Information from this hole is still proprietary, but it is likely that the drill was still in volcanic rocks, because the interpretation of MT profile BB' indicates resistivities of about 150 ohm-m to depths of 3-4 km in the vicinity of the drillhole. In addition, the geologic map of Walsh and others (1987) indicates that the well was drilled in a syncline where it would encounter thick Stevens Ridge or Ohanapecosh Formation volcanic rocks.

LITHOLOGY OF ROCKS IN THE SWCC

We hypothesize that the conductive units of the SWCC are composed largely of marine sedimentary rocks based upon several observations:

(1) Interpreted resistivities of the SWCC units are about 2-5 ohm-m in most locations. These resistivity values are very typical of marine shales and shaley sandstones, as evidenced in MT soundings and well logs from Tertiary basins to the west of the SWCC region. Resistivities of nonmarine and transitional-marine sedimentary units are in the range 15-60 ohm-m in the few deep wells in the SWCC region, including the Phillips State No. 1 and Shell Thompson wells. Even some shales, such as the marginal-marine Raging River Formation in the bottom of the Phillips State No. 1, are not as low in resistivity as Tertiary marine units found further to the west (Cowlitz Formation, for example), as determined by wells logs and MT soundings in the Mist gas field and Chehalis basin. We assume this is due to the fact that the Raging River Formation is a brackish facies and the Cowlitz Formation is a more distal marine unit having higher formation salinities.

(2) Shallow depths to the conductive rocks correlates well with the location of anticlines cored with transitional marine facies of the Puget Group and marine units such as the McIntosh Formation. In addition, the conductive rocks appear to surface near Bear Canyon (Figs. 2,5) coincident with outcrops of the McIntosh Formation. The basal part of the Puget Group is transitional from marine to continental; considering that regional uplift was occurring in the Eocene, it is reasonable to assume a prior interval of marine deposition to that recorded in the McIntosh Formation, possibly several intervals.

(3) Ise (1985) used reflection data from a profile paralleling the Toutle River in the Chehalis Basin to demonstrate approximately 11,000' of additional reflective rocks beneath the bottom of a deep (10,000' TD) well near Toutle. The well had bottomed in the McIntosh Formation. Ise interpreted these reflectors to be sedimentary rocks of the McIntosh and older formations, and assumed about 5000' of this unmapped section to be the McIntosh Formation and the remainder of the sections to be older units.

ALTERNATE LITHOLOGIES FOR SWCC UNITS

Nonmarine Sediments

North and east of the SWCC region, a number of fault-bounded basins are filled with thick nonmarine sediments (Johnson, 1985; Evans and Johnson, 1989). These fault-bounded, or pull-apart (Mann and others, 1983) basins are interpreted to have been caused by oblique slip on the Straight Creek, inferred Puget (Johnson, 1984a), Leavenworth, Entiat, and Eagle Creek fault systems (Tabor and others, 1984; Johnson, 1985; Evans and Johnson, 1989). Syntectonic fill of the Swauk, Naches, Roslyn, Chuckanut, and Chumstick Formations in these Washington pull-apart basins is up to 6 km thick and consists of conglomerate, sandstone, shale, fanglomerate, and ironstone (Tabor and others, 1982). Resistivities in these nonmarine sediments are believed to be greater, in most instances, than the 2-5 ohm-m measured for the SWCC and too high to be the cause of the low resistivities in the SWCC. The Swauk, Naches, and

Chumstick Formations are contemporaneous with the Puget Group, but strictly nonmarine. There is no surface evidence for marine sediments in any of these pull-apart systems, but older marine sequences related to such basins may form part of the SWCC.

Geothermal Fluids

It is highly probable that low resistivities in deeper parts of the SWCC are partially due to geothermal fluids. Increased ionic mobility due to high-temperature geothermal fluids can increase the conductivity of sedimentary rocks by several hundred percent. The behavior of resistivity with temperature and salinity is well documented (Olhoeft, 1985). Resistivities of porous rocks such as those of the Swauk and Chumstick Formations can be lowered to the 1-3 ohm-m range with formation salinities of 30,000 ppm or greater; such salinities might be present in these nonmarine units only if playa conditions existed during phases of basin development, but this is unlikely due to a documented humid, subtropical climate during the Eocene (Wolfe, 1978; Evans, 1988). For the porosities of less than 10% that would be typical for Swauk and Chumstick sandstones at depths of greater than 5 km, a combination of temperatures of about 250°C and salinities of 10,000 ppm would be required to produce the resistivities of less than 5 ohm-m measured in the SWCC. Shale-rich parts of the Puget Group such as the Carbonado and Spiketon Formations (Buckovic, 1979) would have to be influenced less by temperature or increased salinities to be relatively conductive (as required by the SWCC) due to presence of clay minerals in the rocks.

The effect of temperature on resistivity in the SWCC region has been considered thoroughly because of the presence of three major volcanic centers: Mount Rainier, Mount St. Helens, and Mount Adams. Heat flow in the Washington Cascades has been studied by Blackwell and others (1985), who found that temperature gradients in the region of the SWCC are about 30°C/km; thus, temperatures of 200-300°C might exist in units of the SWCC at depths of 7-9 km. On the east side of the SWCC region, near Packwood (Fig. 1), higher gradients of >50°C/km have been mapped by Barnett and Korosec (1989); thus, even higher subsurface temperatures are expected on this part of the cross-section. However, we believe that the correlation of highs on the top of the SWCC with anticlines that bring Tertiary marine units to shallower depths is an indication that the main cause of the upper part of the SWCC is lithologic in nature. The Phillips State No. 1 well is instructive to study, since it is located only about 30 km from Mount Rainier. Although the pervasive zeolitization of the lower section of the well probably indicates past geothermal activity, there is no evidence of abnormal formation temperatures in this 4.2 km hole. We believe the present thermal effect of the volcanos in the southern Washington Cascades is limited to the area very near them, as characterized by more extensive heat flow data from the Oregon Cascades volcanoes (Blackwell and Steele, 1983). The correspondence of the top surface of the SWCC to the structure of anticlines in the region argues against the concept of increased temperatures being the primary cause of low resistivities in the anomalous region, because we would expect low resistivities to become shallower to the east where subsurface temperatures are higher. However, resistivities in the deeper parts of the SWCC are very likely influenced by increased temperatures, especially in the area near Packwood and eastward where Barnett and Korosec (1989) have mapped high thermal gradients.

Stanley and others (1990) have discussed the role of similar high thermal gradients in the Oregon Cascades (where heat flow is even higher) in producing deep crustal conductors. Such conductors in Oregon are pseudo-horizontal and occur regionally at depths of 11-20 km. There is a clear association of this Oregon horizontal conductor with midcrustal seismic velocities of 6.4-6.6 km/s. This association and other factors were used to suggest the cause of the regional conductor as metamorphic fluids and partial melt. There is no way to distinguish such a thermally-related conductor from the conductor that occurs in the southern Cascades, except for the factors of morphology of its upper surface, correspondence to seismic reflectors, and relationship to tectonic features.

Authigenic Minerals

It is possible that deeper parts of the SWCC may correspond to altered volcanic rocks that are conductive due to development of authigenic minerals such as zeolites and smectites. We have earlier mentioned the presences of zeolites below 7200 feet in the Phillips State No. 1 well (Fig. 2). Volcanic flows with high percentages of ash generally become quite conductive when hydrothermally altered, because the high silica content and large surface-area of ash allows rapid conversion to zeolites and smectites. These authigenic minerals are highly conductive due to their ability to maintain high ion-transfer capability. Electrical geophysical studies in Newberry volcano, Oregon and Long Valley caldera, California, by Fitterman and others (1988) and Stanley and others (1976) show that tuffaceous volcanic flows can have resistivities as low as 2-8 ohm-m. These resistivities are approximately equal to those in the SWCC and although the Tertiary volcanic rocks studied electrically in the region have resistivities of about 30-500 ohm-m, this does not exclude older, more ash-rich flows at depth as a constituent of the SWCC. The development of zeolites and smectites can lower the resistivities of marine and nonmarine sedimentary rocks, as well as volcanic rocks. The extensive zeolites in the lower part of the Phillips State No. 1 lower resistivities, but not dramatically, probably because they mainly fill fractures; in ash-rich volcanic or sedimentary rocks where the ash is in depositional layers, the continuous, layered distribution of the authigenic minerals is more effective in lowering resistivities.

Pre-Tertiary Conductive Rocks

Conductive rocks older than Tertiary could be the cause of the SWCC, because unmetamorphosed marine shales and mudstones of any age are generally quite conductive (2-20 ohm-m) and graphitic metasedimentary rocks can be very conductive (1-5 ohm-m, Stanley, 1989; Stanley and others, 1990a). The only pre-Tertiary rocks mapped in the region of the SWCC are those in the Rimrock Lake inlier (Ellingson, 1972; Miller, 1989). The Rimrock Lake inlier (Fig. 2) consists of a Jurassic igneous complex of trondhjemitic to gabbroic rocks, some metamorphosed to amphibolite grade, and a Jurassic-Cretaceous tectonic melange of mainly arkose and mudstone. Somewhat similar rocks, generally occurring as phyllites, are found along the western margin of the North Cascades (Fig. 1). MT soundings on the melange portion of the Rimrock Lake inlier indicates high (>200 ohm-m) resistivities at depths greater than 0.5 km, suggesting these units are thin and are probably underlain by more metamorphosed versions of the melange or by intrusive rocks. On the western flank of the North Cascades, other Mesozoic metasedimentary units have resistivities of 200-600 ohm-m, thus are probably not a cause of the SWCC.

Summary of Lithologies

In the preceding discussion regarding lithology, we outlined reasons for our preferred interpretation that conductive rocks in the SWCC correspond to Eocene, and possibly older, marine sedimentary rocks. These marine sedimentary rocks could have been deposited as part of a forearc basin/accretionary prism or in a marine pull-apart structure. Slightly less probable for the proposed lithology of the SWCC units, in our view, is that of highly altered volcanic rocks. Ranking third in probability for the SWCC lithology is a section of nonmarine sediments beneath the lower part of the Puget Group. Of lowest probability for the SWCC lithology are Mesozoic metasedimentary units like those in the Rimrock Lake inlier or other older rocks. High temperature geothermal fluids and possibly even partial melt may play a role in reducing resistivities in the deepest part of the SWCC, but the distribution and attitude of the highly conductive rocks are such that we believe that these factors are less important than lithologic ones, at least for hydrocarbon exploration depths.

TECTONIC MODELS: SUBDUCTION OR PULL-APART?

Stanley (1984) and Stanley and others (1987) interpreted that the SWCC is related to a late Cretaceous to early Eocene subduction assemblage. However, others have suggested (S. Johnson, U.S.G.S., writt. comm.) that the SWCC could be related to a pull-apart basin such as the Swauk or Chuckanut basins, but containing mainly marine sedimentary rocks. In addition, Snavely (1987) and Wells and others (1984) interpret that the oceanic basalts of Siletzia erupted in a continental-margin, pull-apart structure. Under the assumption that the SWCC units do actually correspond to marine sedimentary rocks of late Cretaceous to Eocene age, we review tectonic scenarios that we currently believe are best supported by the geophysical data.

The regional setting is a key factor in evaluating possible tectonic models to explain the geophysical anomalies. There is little question that dextral slip played a key role in late Cretaceous to Eocene structural development in western Washington, driven by oblique convergence of the Kula plate with North America.

This oblique slip resulted in northward transport of terranes along the continental margin of North America. Nonmarine basins discussed by Johnson (1984a, 1984b, 1985) are prominent features of western Washington, but no marine-sediment-filled, pull-apart structures have been mapped in either Washington or Oregon. However, along the continental margin of British Columbia, including Vancouver Island, both Cretaceous forearc and post-subduction (after suturing) sediments, as well as marine and nonmarine rift sediments are found in the Queen Charlotte and Georgia basins (Yorath, 1987). The Cretaceous marine sedimentary units are part of a subduction and post-suture sedimentary sequence that extends from central California to Alaska, and probably also occurred in western Washington.

Up to 5 km of a Neogene rift assemblage, both marine and nonmarine, occurs in the Queen Charlotte Basin on top of unknown thicknesses of upper Cretaceous, post-suture marine and nonmarine sedimentary rocks (Yorath, 1987). The basin basement is formed by lower Cretaceous subduction units that have been thrust over Wrangellia (an accreted terrane that extends from Vancouver Island to southcentral Alaska; Jones and others, 1977). In the southern Georgia Basin, along the east side of Vancouver Island, about 3 km of upper Cretaceous to Paleocene, Nanaimo Group marine and nonmarine sedimentary rocks are overlain by 1 km of nonmarine Eocene Chuckanut sedimentary units (Muller and Jeletzky. 1970). Eisbacher (1985) interprets the Nanaimo Basin (southern part of Georgia Basin) as part of a forearc system dominated by strike-slip, and that coeval, distal trench deposits were removed by dextral slip or subducted beneath the continental margin. We envision that the mix of trench and marine/nonmarine pull-apart sedimentary units found in the Queen Charlotte and Georgia Basins may also occur in the SWCC, with the largest volume being marine.

We suggest that the SWCC developed in the tectonic scenario shown in Fig. 10. In (a) oblique subduction of the Kula plate beneath North America is portrayed with a typical accretionary prism and forearc basin. By Paleocene, the dextral-slip component of oblique subduction probably led to a pull-apart environment for the forearc region (b) The formation of pull-apart structures in the forearc region led to thick marine, rift sediments being deposited upon late Cretaceous-Paleocene accretionary sediments. Pull-apart structures may have interacted with one or more leaky transforms near the triple junction to cause a thick build-up of oceanic basalts and seamounts. Allochthonous terrane slices (shown as composed of Mesozoic rocks) may have been transported northward into contact with the rift/accretionary assemblage; remaining forearc sediments of late Cretaceous age migrated northward along with other margin components. (c) Mostly nonmarine Puget Group delta sediments and pull-apart sediments like the Swauk Formation covered the marine assemblages of late Cretaceous to early Eocene in age. Local volcanic centers erupted the Tukwila and Northcraft Formations. An accretionary prism/forearc basin system formed outboard of the seamount assemblage (d) Thick volcanic flows of the Ohanapecosh Formation signaled the establishment of the Cascades volcanic arc associated with the new subduction zone.

In Fig. 11 a cross-section based on the paleotectonic models in Fig. 10 was constructed with the MT and seismic reflection data used to constrain the morphology of units and structures. Some thrusting of the Paleocene-Eocene pull-apart sediments is shown, coupled with Oligocene and younger horizontal compression or transpression that caused folding in the Morton and Skate Mtn. anticlines. An intrusion in Siletzia on the west end of the section is shown, as indicated from MT profile EE' (Fig. 5); this intrusion may be related to the original development of Siletzia or may be a younger (Miocene-Oligocene) pluton. The eastward extension of Siletzia is compatible with gravity and magnetic models developed by Finn (1989). The cartoon portrays two possible fault components west of Morton. An east-dipping fault interpreted from the reflection data of Fig. 7 may be a detachment that merges with basement and could have been a key fault in Eocene pull-apart development. This would have required the fault to be part of a strike-slip system as indicated by the strike-slip symbols. The presently active SHZ to the south of the reflection profile is mapped as vertical from recorded seismicity (Weaver and Smith ,1983), but it may roll over into the fault of Fig. 7 and 11 west of Morton. Strike-slip zones may rotate from vertical to much lower angles over a short distance, as evidenced by the San Andreas fault in the Loma Prieta area (Dietz and Ellsworth, 1990). Oligocene-Miocene intrusions in the SWCC basement are strictly inferred and not evident in any of the geophysical data.

POSSIBLE HYDROCARBON POTENTIAL OF THE SWCC REGION

If the SWCC units are composed mostly of marine sedimentary rocks, then they may represent a possible source of hydrocarbons. An analysis of hydrocarbon potential of hypothesized sedimentary rocks involves evaluation of basin conditions, thermal history, reservoir units, seals, and traps.

Organic Content

The organic carbon content of the hypothesized pre-upper Eocene marine basin may be similar to forearc sediments in basins west of the Cascades in Oregon and Washington. Measured values (100 samples) of total organic carbon in Cenozoic marine sedimentary rocks in southwestern Washington were about 1% (Armentrout and Suek, 1985). A larger data set from western Oregon and Washington (Armentrout, 1985, reference to unpublished data) has similar mean values.

Total organic content of units in the Phillips State No. 1 well (Fig. 2) averages over 1%, with some broad intervals averaging closer to 2%. The largely fluvial clastics of the Puget Group penetrated are relatively high in total carbon, but the organic matter was severely oxidized and/or degraded during sedimentation (Brown and Ruth Laboratories, 1982). The degraded organic matter is depleted of hydrogen and has no hydrocarbon generating capacity. Coal beds in the Phillips well were deposited in a more anoxic environment, but hydrocarbon extract analysis shows that their hydrocarbon generating capacity is minor. As mentioned above, high-paraffin oil extracted from depths of 7060-7120 feet in the Phillips well was interpreted to have migrated from below.

A more favorable situation for hydrocarbon potential would require sedimentary rocks with several percent of organic carbon in an unoxidized state, but having reached thermal maturity. Anoxic conditions would be expected in a deep marine pull-apart structure or a forearc basin in the lee of a linear seamount assemblage. Thus, an environment promoting favorable amounts of unoxidized carbon could have existed under the scenario presented in Fig. 10.

Thermal History

Armentrout and Suek (1985) developed a time-temperature reconstruction for the northern Willamette basin, including the Mist gas field (Fig. 1). This analysis showed that rocks of the lower Cowlitz Formation, which the authors state is partially correlative (Walsh and others, 1987) to the McIntosh Formation, reached the oil generation window 33 m.y. ago. This window corresponds to burial depths of 3 to 5 km and temperatures of 90 to 130°C. A similar analysis has been completed for the Phillips State No. 1 well (Brown and Ruth Laboratories, 1982) in Washington (Fig. 2); however, the model was developed only for the upper 7200 feet of the well which had vitrinite reflectances below 0.6%. The model assumed a geothermal gradient of 27°C/km at the beginning of Oligocene times to an average present-day value of 21°C/km and accurately simulated the nearly linear, vitrinite-reflectance profile in the upper 7200'.

These models are useful, as they adequately represent the low maturity of most of the sampled units in western Washington and northwestern Oregon. The proposed SWCC sedimentary sections, which we interpret to include McIntosh Formation and equivalents, mostly occurs at depths greater than 5 km. Past heat flow has been high in the Cascades arc, as evidenced in the coal rank data from Walsh and Phillips (1983) and continues to be high in the eastern part of the study area (Barnett and Korosec, 1988). All of the proposed sedimentary section within the SWCC at depths greater than 5 km may be over-mature because of the long-term thermal effects from the Cascades arc. Assuming that most of the hydrocarbons were driven off from the deep parts of the proposed sedimentary system during Oligocene-Miocene and later, it is important to know if suitable reservoir rocks and sealed traps existed during the migration, and if these sealed traps have survived to the present time.

Traps

A possible structural trap (Fig. 12) involves the series of northwest trending anticlines including the Morton, Carbon River, and Skate Mountain anticlines. The reflection data indicate 2-3 km of relief on the Morton and Skate Mountain anticlines (Figs. 6,7,8,9), but the amount of closure is unknown. Structural evidence suggests that the Skate Mountain anticline is contiguous with the Carbon River anticline, with the latter structure emerging at the surface NW of Mount Rainier. Thus, there may not be any closure along strike of the Skate Mountain anticline. In addition, the Skate Mountain anticline is located over the probable axis of highest thermal activity where Oligocene volcanic centers, Miocene intrusions, and the present arc are centered. Hydrocarbons from the proposed SWCC sedimentary sequences would have migrated from beneath the Skate Mountain anticline to regions further to the west, such as the Morton anticline (Fig. 9); thus, the Morton anticline appears to offer more promise as a possible updip structural trap. These fold structures were probably caused by continued compression of Siletzia against North American or by transpression associated with region strike-slip motion, but most of the folding was post-Oligocene because volcanic rocks of the Ohanapecosh and Stevens Ridge Formations were involved in the folding.

Mullineaux (1970) interprets that folding in the Black Diamond and Renton areas occurred in middle or late Miocene time. This timing is important, for if the structures are considerably younger than Miocene, any hydrocarbons produced would not have been trapped during the main thermal event in Oligocene to Miocene time. In a negative sense, there is no support in the geophysical data for pre-Oligocene origin of any part of the Morton, Carbon River or Skate Mountain anticlines.

It is clear from the MT data that the axis of a narrow fold indicated in the seismic section (Fig. 6) under the Morton anticline occurs on top of the conductive units that we interpret as probable McIntosh Formation and older marine sediments. Stratigraphic traps may occur within the hypothesized marine pull-apart or forearc sequences (Fig. 12); one likely place might be between the McIntosh Formation (acting as a seal) and more permeable dipping units in the hypothesized older assemblage (Fig. 11).

Reservoir Rocks

Finding a suitable reservoir in the late Tertiary basins of western Washington and Oregon has been envisioned as the most difficult part of the exploration process (Armentrout and Suek, 1985; Olmstead, 1989). In the Mist gas field, production is largely from Cowlitz Formation sandstones. The Cowlitz Formation is an eastern-sourced, deltaic facies partially correlative with the lower part of the Puget Group. Reservoir sandstones of the Cowlitz Formation have favorable porosities and permeabilities in the Mist gas field, in contrast to most Tertiary sandstones of western Washington and Oregon, that are typically low in porosity due to a component of altered volcanic clasts (Galloway, 1974). The McIntosh Formation might contain highly porous sandstone units like those found in the partially-correlative lower Cowlitz Formation of the Mist gas field. In the lower Cowlitz Formation high values of porosity and permeability of the reservoir sandstones are attributed to a lack of volcanic clasts by Armentrout and Suek (1985) and a corresponding lack of pore-filling authigenic minerals; they suggest that the lack of volcaniclastic grains in the lower Cowlitz Formation is due to a combination of factors including deposition away from middle to late Eocene volcanic centers (like the Northcraft and Tukwila) in a high-energy depositional environment, probably in a volcanically quiet period during subduction zone reorganization (Fig. 10). Shales in the upper Cowlitz formation serve as the seal for the lower Cowlitz Formation reservoir rocks in the Mist field.

Snavely and others (1951) have characterized the McIntosh Formation in the Tenino, Washington (Fig. 2) area as chiefly consisting of well-indurated tuffaceous siltstone, shale and claystone, suggesting low formation porosities. This characterization of the McIntosh Formation would seem to be negative evidence for porous sandstone reservoirs like those in the lower Cowlitz Formation, although Snavely and others (1951) also state that the upper part of the McIntosh Formation in the Tenino area consists of 250 feet of a arkosic sandstone. In the Morton coal field, located within the Morton anticline, McIntosh Formation rocks (Snavely and others, 1951) include dark gray siltstone and shale interbedded with massive arkosic sandstone and coal beds. Near Bear Canyon (Fig. 2) McIntosh Formation outcrops consist of gray siltstone (Snavely and others, 1951). Thus, sparse, but largely negative information exists on the possibility for a analogue to the reservoir-seal system in the Mist gas field. However, scenarios involving either a restricted-circulation (on the backside of an linear seamount assemblage) marine forearc or pull-apart basin probably produced quite different sandstone petrology than that of the western Washington and Oregon, late Tertiary forearc systems.

The potential carbon content and reservoir potential of the proposed marine sedimentary rocks in the SWCC is undefined, and even if these factors could be assumed to be promising, thermal data suggests that most of the rocks should be over-matured. Figure 12 summarizes the probable maturation state of the SWCC and nearby basins, along with deep migration paths. In order to have served as structural traps, it is essential that the anticlines presented as possible exploration targets were formed prior to Miocene time when maturation was accelerated by increased magmatic activity; most indications are negative for this favorable timing. Stratigraphic traps may occur at dip unconformities between units such as the McIntosh Formation and hypothesized older pull-apart and accretionary prism units (Fig. 12); such traps may also occur within the Morton area as suggested in Fig. 11.

SUMMARY AND CONCLUSIONS

Deep MT surveys in Washington State have been used to map a conductive section of the earth's crust in the southern Washington Cascades and surrounding region that we call the SWCC. Analysis of key features of the SWCC lead us to believe that it may represent unmapped marine sedimentary sequences in a conventional forearc assemblage, trapped by an accreting seamount assemblage (Siletzia), or deposited in a Paleocene to early-Eocene pull-apart basin. The upper part of these conductive units correlates closely with mapped marine units at the base of the Puget Group, such as the McIntosh Formation, and maximum thicknesses of up to 10 km of the conductive units occur in the eastern part of the system near Packwood and west of Mount Rainier. Study of nearby forearc/pull-apart marine sedimentary sequences in the south Georgia (or Nanaimo) Basin is instructive for use as a possible analog to the SWCC feature, in terms of both lithology and structural evolution. Detailed consideration of other possible lithologies for the SWCC units caused us to rank marine sedimentary rocks as the most probable lithology, but highly altered volcanic rocks and/or nonmarine rift clastics are also possible lithologies. It is less likely that the SWCC units correspond to pre-Cretaceous rocks.

Using the assumption that the SWCC represents unmapped marine sedimentary rocks, we conducted a cursory analysis of hydrocarbon exploration factors. Organic content, maturation, traps and seals for an anticline near Morton were discussed using wells in Washington and data from the Mist gas field in Oregon. Based upon coal rank data and geothermal drilling, we conclude that the proposed sedimentary sequences of the SWCC would be over-mature below 5 km depth. Effective organic carbon content could be favorable because of anoxic conditions postulated for the proposed basin, but there is little information about potential reservoir rocks and seals. Our models for the SWCC will require stratigraphic drilling to answer most of the key questions. The complexity of western Oregon and Washington region has led largely to frustration in the search for hydrocarbons. We offer a new tectonic model for consideration in hydrocarbon exploration in the Pacific Northwest.

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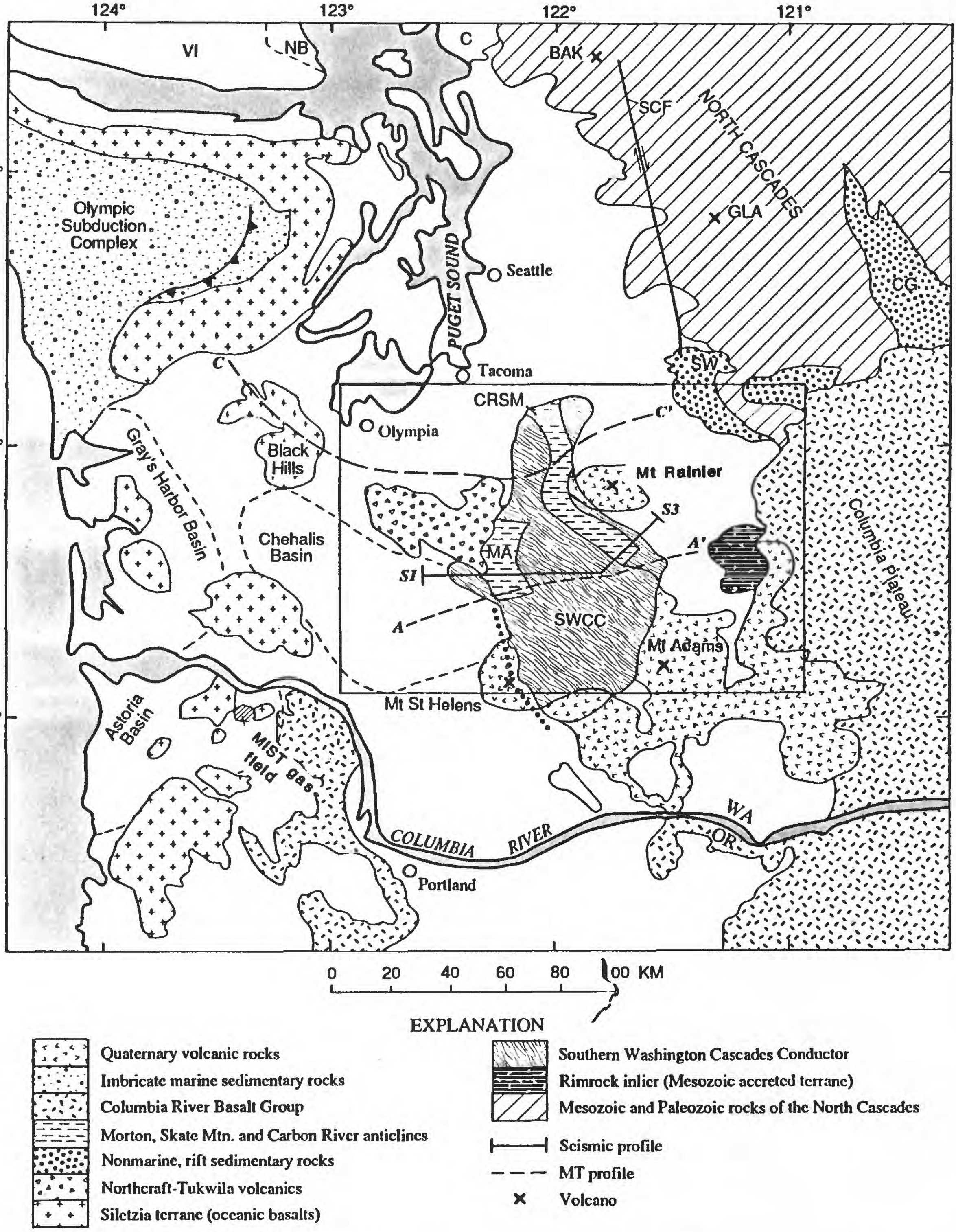

Figure 1-Index geologic map for parts of Washington and Oregon. Among the key features noted are: the main late Tertiary basins of the region, outcrops of the basalt flows of Siletzia (accreted seamount complex), thick conductor mapped with MT surveys (SWCC), Mesozoic inlier (Rimrock inlier), anticlines in SWCC region (wide dotted lines, CRSM and MA), location of Mist gas field (in NW Oregon), MT (bold dashed lines, AA' and CC') and seismic (bold solid line, S1-S3) profiles. Area of detail shown in Fig. 2 is outlined by the box. SCF=Straight Creek fault, SWCC=southern Washington Cascades conductor, AST=Astoria Basin, GH=Grays Harbor Basin, VI=Vancouver Island, NB=Nanaimo basin, CG=Chiwaukum graben, SW=Swauk basin, C=Chuckanut basin, R=Rimrock Lake inlier, BAK=Mount Baker,GLA=Glacier Peak, PS=Puget Sound, MA=Morton anticlines, CRSM=Carbon River and Skate Mountain anticlines,SHZ=St. Helens seismic zone (bold line near Mt. St. Helens), SILZ=Siletzia, TUK=Northcraft and Tukwila Formations, CRB=Columbia River basalt Group, HV=Holocene volcanic rocks.

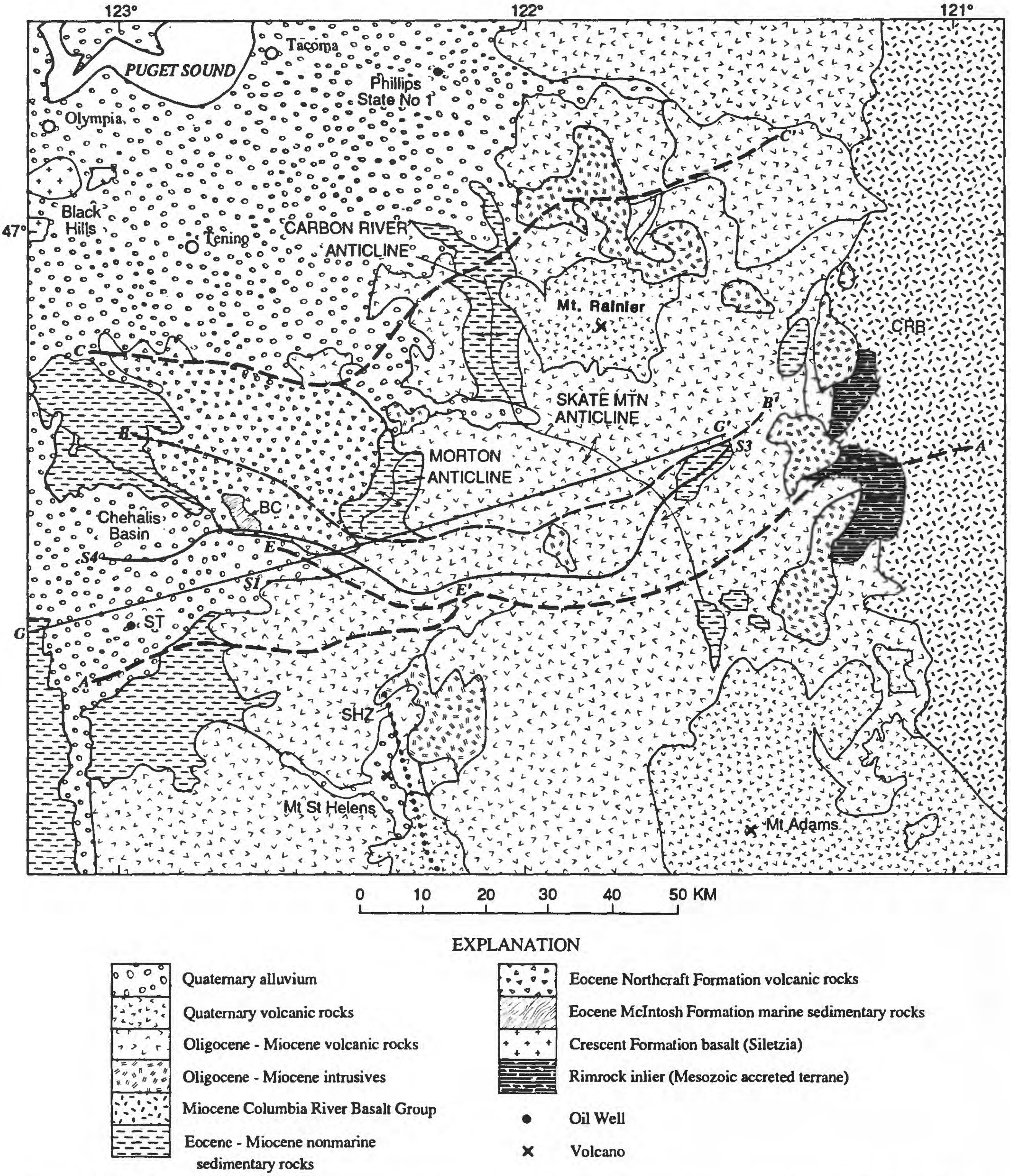

Figure 2-Details of geology in the southern Washington Cascades conductor (SWCC) study area. The location of wells discussed in the text; seismic (bold solid line, S1-S4) and MT profiles (dotted solid lines, AA',BB',CC'EE') are also shown. A geological transect from Walsh and others (1987) is indicated by a thin, solid line (GG'). GL=Glenoma well drilled by Meridian Resources, ST= Thompson State well; CRB=Columbia River Basalt Group, Qal=Quaternary alluvium, Qva,b=Quaternary volcanics (andesite, basalt), Eva=Eocene volcanic rocks (Northcraft and Tukwilla Fms), Ec1,2=Puget Group nonmarine sedimentary rocks, MOi=Miocene-Oligocene intrusive rocks, Ova=Oligocene volcanic rocks (Ohanapecosh Fm and other), KJml =Cretaceous-Jurassic melange (Rimrock Lake/Tieton inlier), Mb=Miocene basalt (Columbia River Basalt Group), Em=Eocene marine (McIntosh Fm. at Bear Canyon, BC).

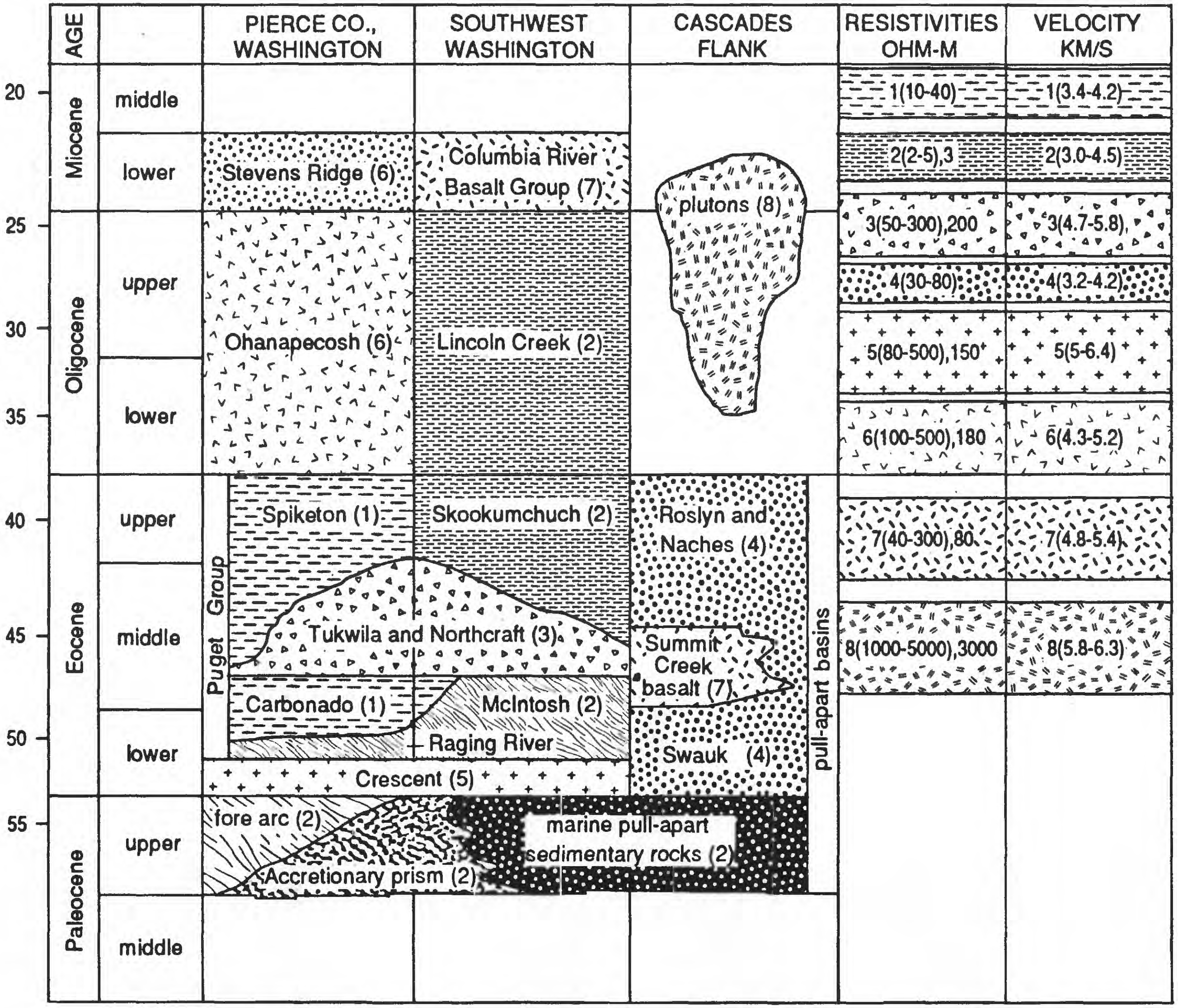

Figure 3-Stratigraphic chart for Cenozoic of western Washington and northwestern Oregon (adapted from Buckovic (1979), Vance and others (1987), and Walsh and others (1987). Patterns correspond to those used in other figures where possible. Resistivity ranges from MT soundings and well-logs for the various formations are indicated in the right-hand column in parentheses; median values (where enough values available) are indicated after range. Approximate seismic velocities for the formations in the rightmost column.

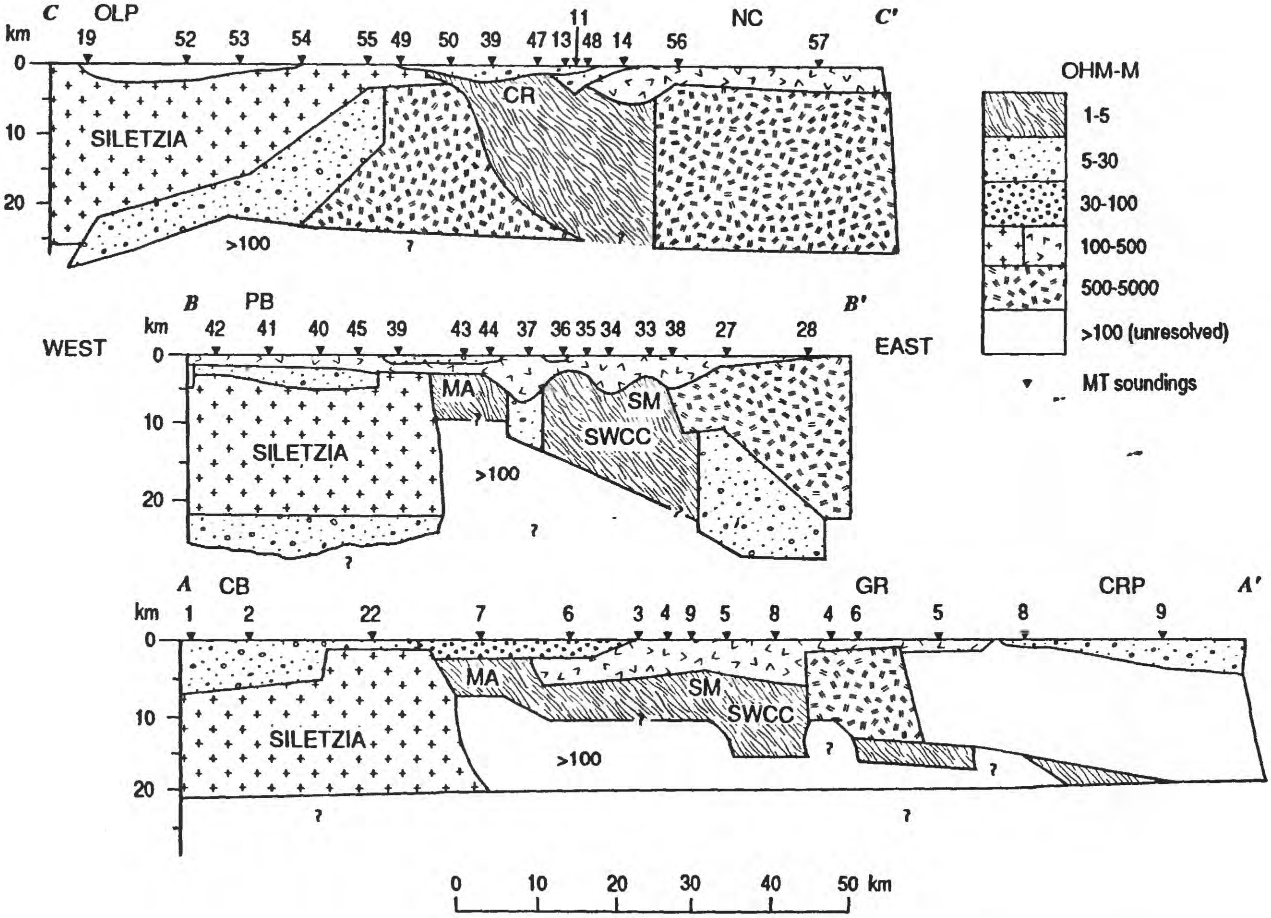

Figure 4- MT model sections based upon one-dimensional modeling for profile AA'(a), BB'(b), and CC'(c) (locations in Fig. 3). Interpreted resistivities for the various model layers are indicated by the patterns in the explanation. OLP=Olympic Peninsula, CR=Carbon River anticline, NC=North Cascades, PB=Puget Lowland Basin, MA=Morton anticline, SM=Skate Mountain anticline, CB=Chehalis Basin, GR=Goat Rocks pluton, CRP=Columbia River Plateau. Numbered, inverted triangles are MT sounding locations. Vertical exaggeration is 1:1.

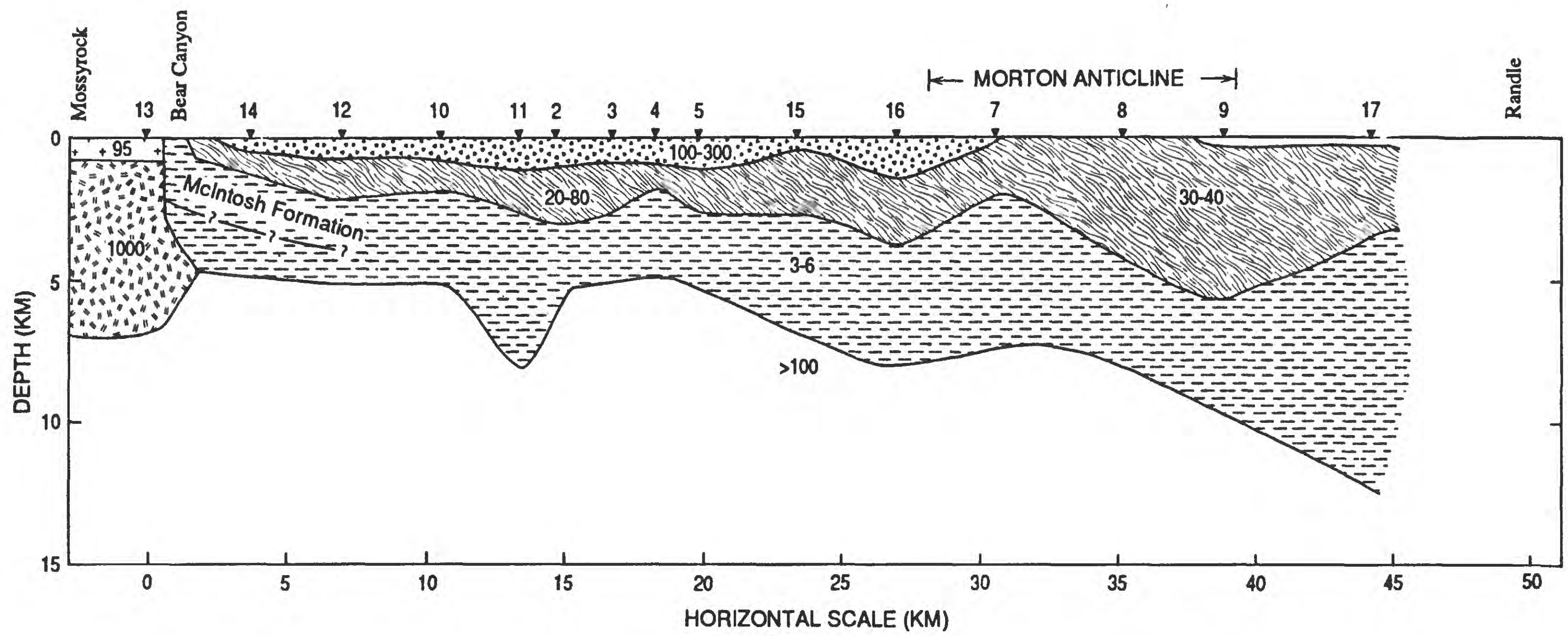

Figure 5-Magnetotelluric 1D-model cross-section EE' (Fig. 2). Numbers in the cross-section are interpreted resistivities for the model layers and numbered, inverted triangles are MT sounding locations. Vertical exaggeration is 1:1. Location of profile shown in Fig. 2.

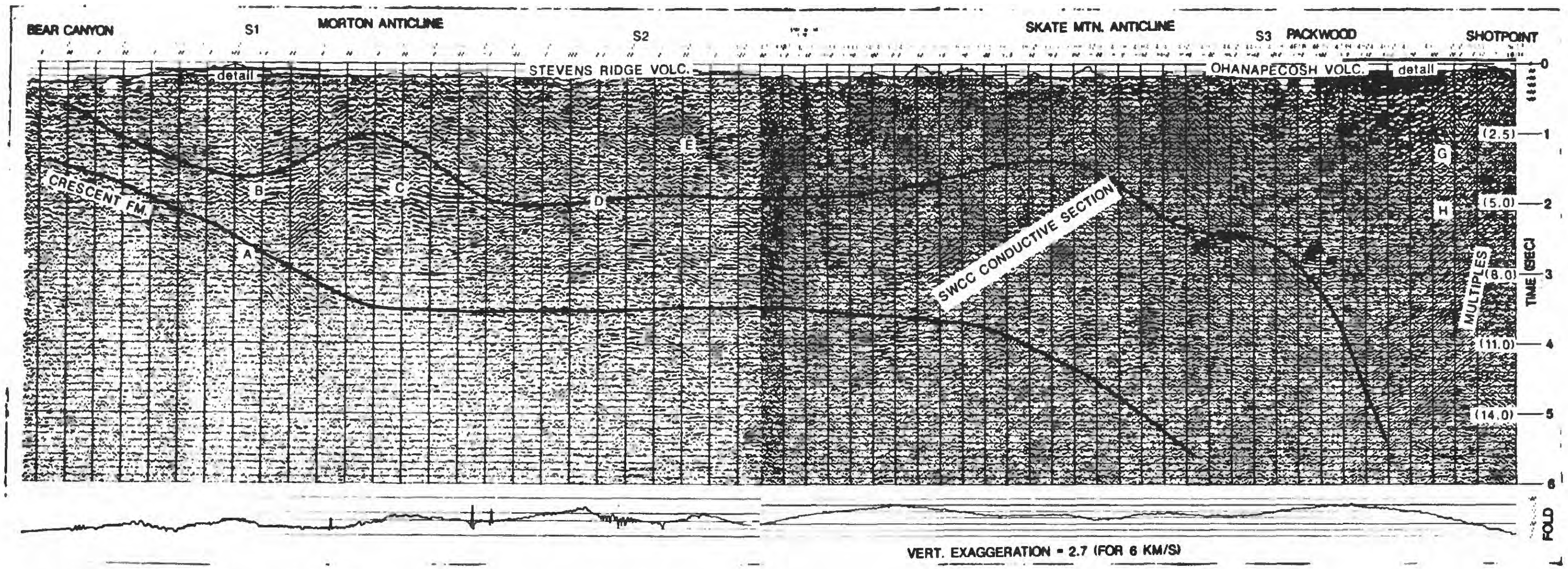

Figure 6-Unmigrated CDP section for seismic reflection profile S1-2-3 (Fig. 2 for location). Numbers above the plot represent shotpoints (upper row) and CDP points (lower row). The full CDP data set has been decimated by a factor of six for the western half of the plot (up to shotpoint 1427) and by 10 for the eastern half (shotpoint 1427 to 5230 at extreme right). Detail of shotpoints 407 to 715 (bold line near Morton anticline) is shown in Fig. 7 and detail of shotpoints 4740 to 5230 (extreme east end) is shown in Fig. 8. Scale on right sidie of plot indicates two-way travel time with approximate depth in km in parentheses. Depths were calculated by using a constant velocity of 5 km/s for the upper 2 s and 6 km/s below 2 s two-way travel time. Letters indicate key reflection sequences discussed in text and subsequent figures. Vertical exaggeration is approximately 1:1 for a velocity of 6 km/s. The solid lines represent an attempt to correlate the upper and lower surfaces of the SWCC conductive units on Fig. 4(a) with horizons in the reflection data. Multiples discussed in text are labelled east of Packwood. The line at bottom of display represents the stacking fold, ranging from 1 to 256.

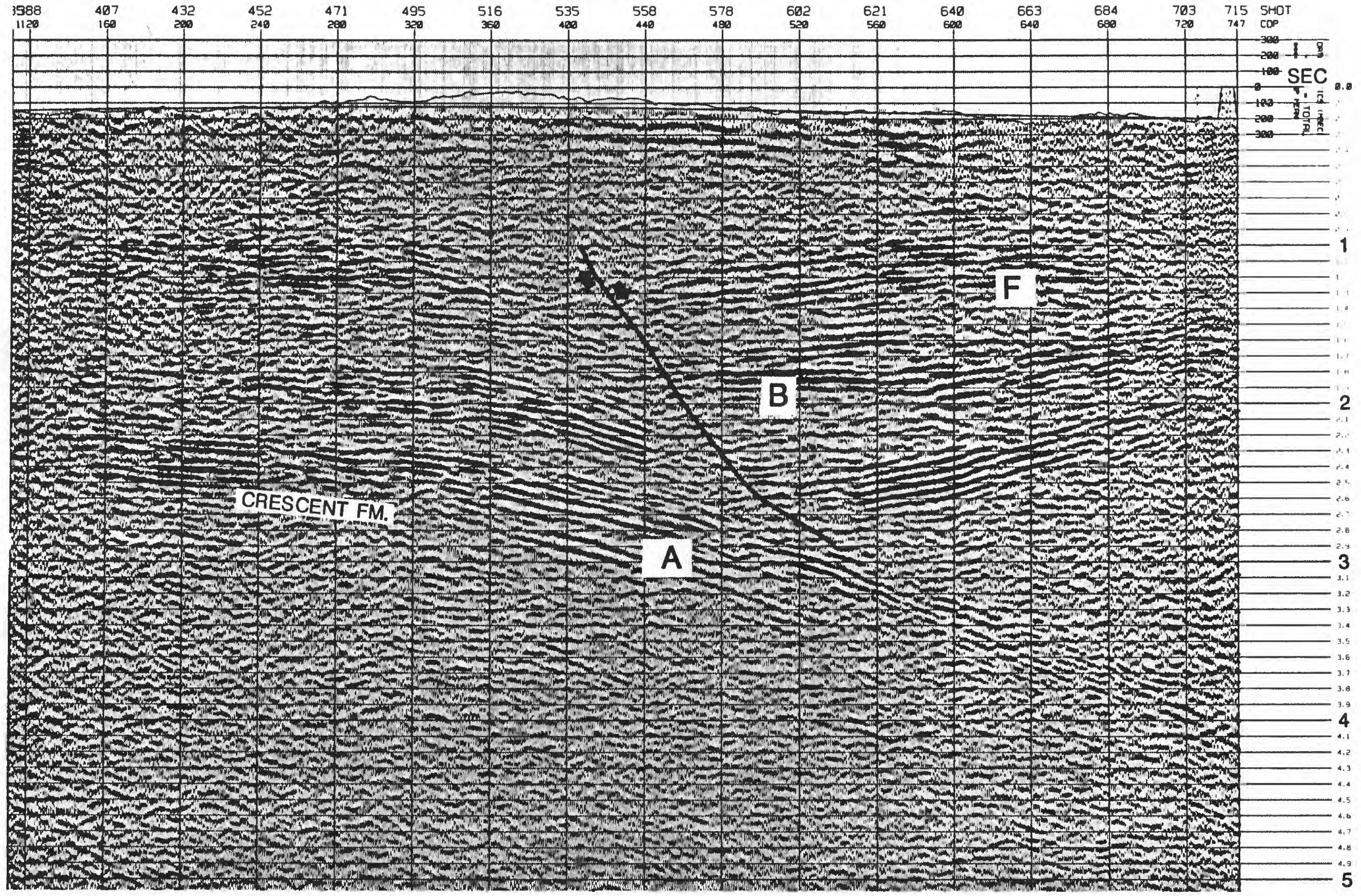

Figure 7-Detail of portion of seismic profiles S1-S2, involving shotpoints 407-715. All of the CDP data is plotted, in contrast to the decimated data of Fig. 6. Letters correspond to reflection sequences as in Fig. 6. Scale on right is two-way travel time in seconds. A normal fault is interpreted to occur between shotpoints 516 and 640.

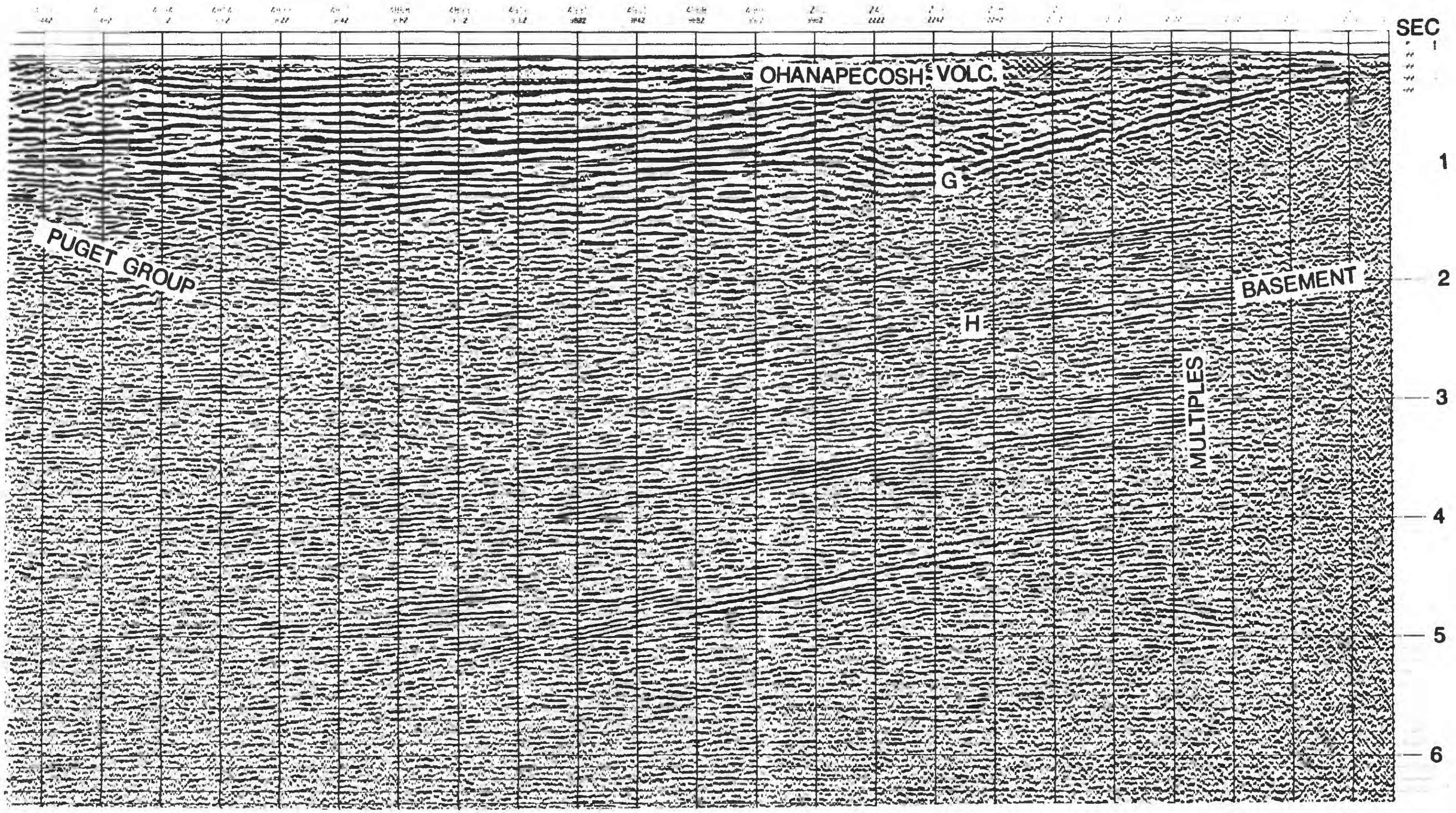

Figure 8-Detail of portion of seismic profile S3, involving shotpoints 1427-5230 (see extreme right of Fig. 6). All of the CDP data is plotted. Letter correspond to reflection sequences as in Fig. 6.

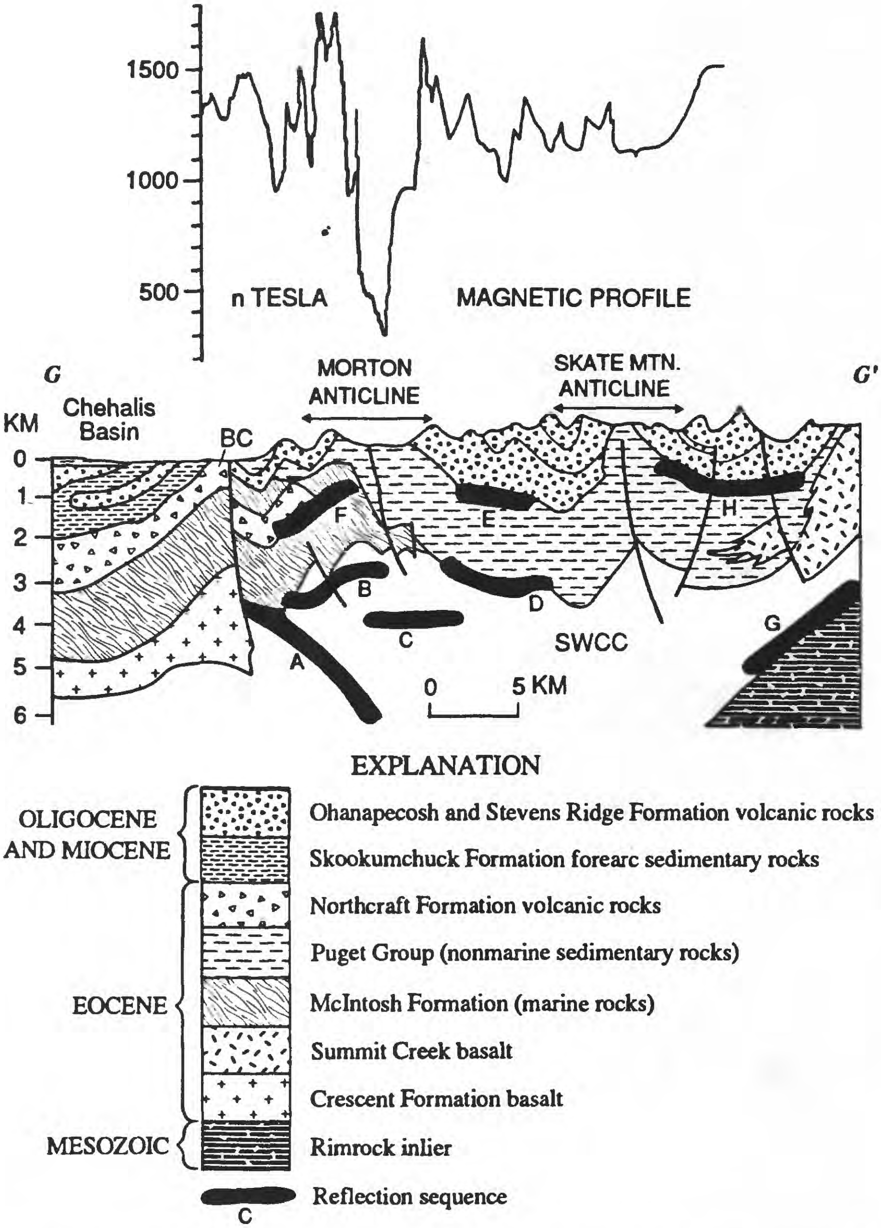

Figure 9-Geologic cross-section compiled by Phillips and others (1989). Added for purposes of this paper are main seism reflection events (bold dotted lines, A-H) from figure 6. We have added Crescent Formation basement beneath t Chehalis Basin according to our interpretation and that of Ise (1985). Faults (bold solid lines) are from Phillips and othe (1989). An aeromagnetic profile flown approximately along the seismic profile S1-S3 is shown in the upper part of t figure.

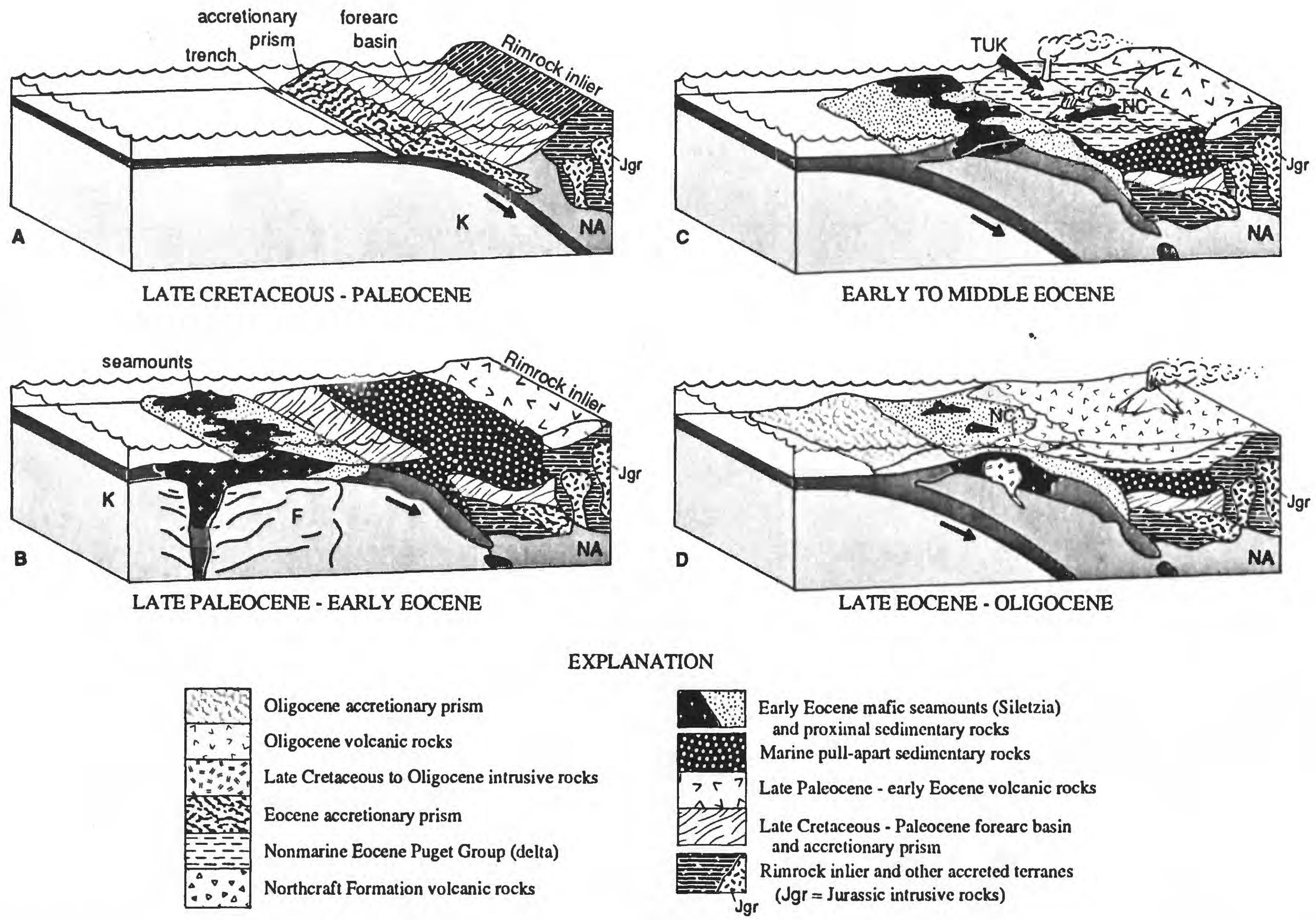

Figure 10-Our interpretation of tectonic development of western Washington from late Cretaceous to Oligocene adapted from Armentrout and Suek (1985), Ise (1985), Snavely (1987), Eisbacher (1987), and Johnson (1987). See text for explanation.

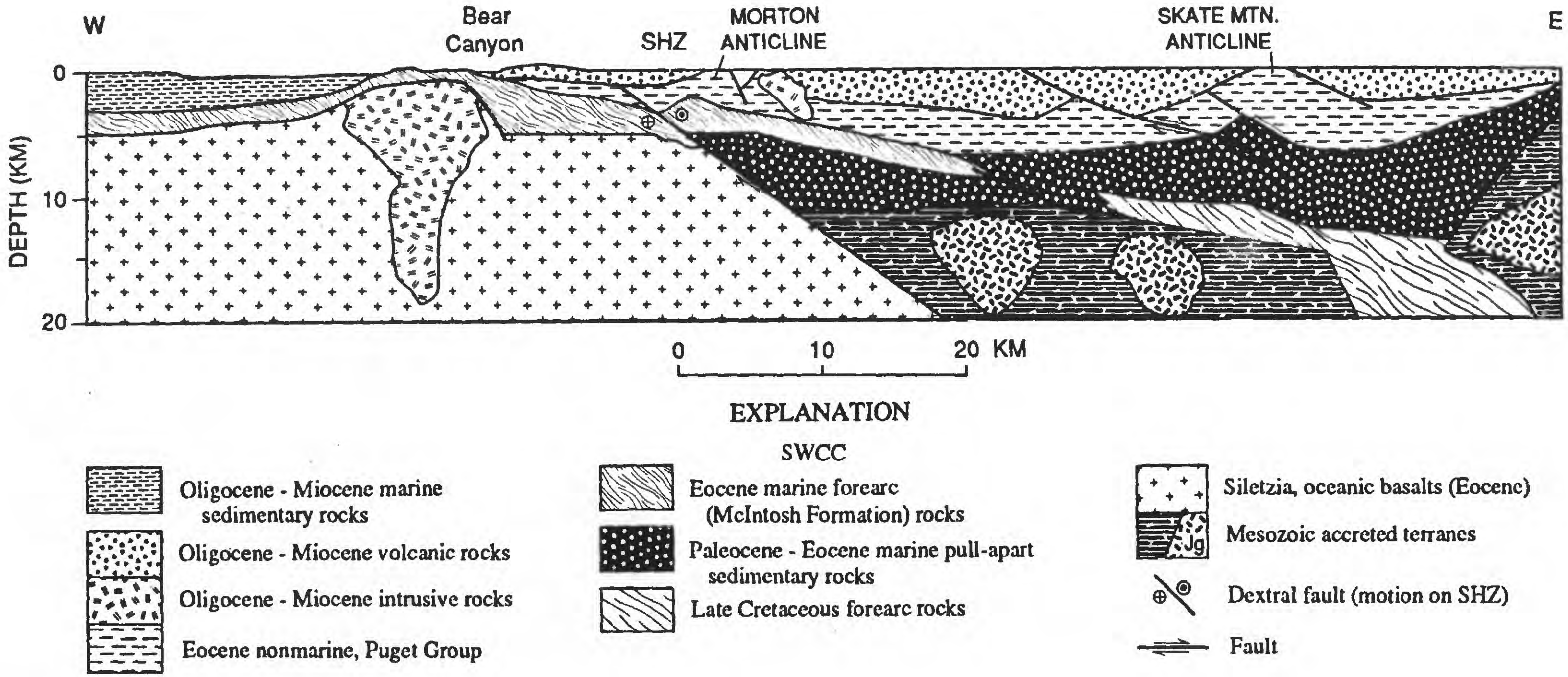

Figure 11-Interpretive cross-section along seismic profiles S1-S2-S3 for tectonic scenario of Fig. 10 with details from geophysical models. The inferred normal (detachment) fault from Fig. 7 is shown extrapolated deeper into the cross-section and strike-slip symbols indicate that this fault may have been part of dextral system active during pull-apart development in Eocene.

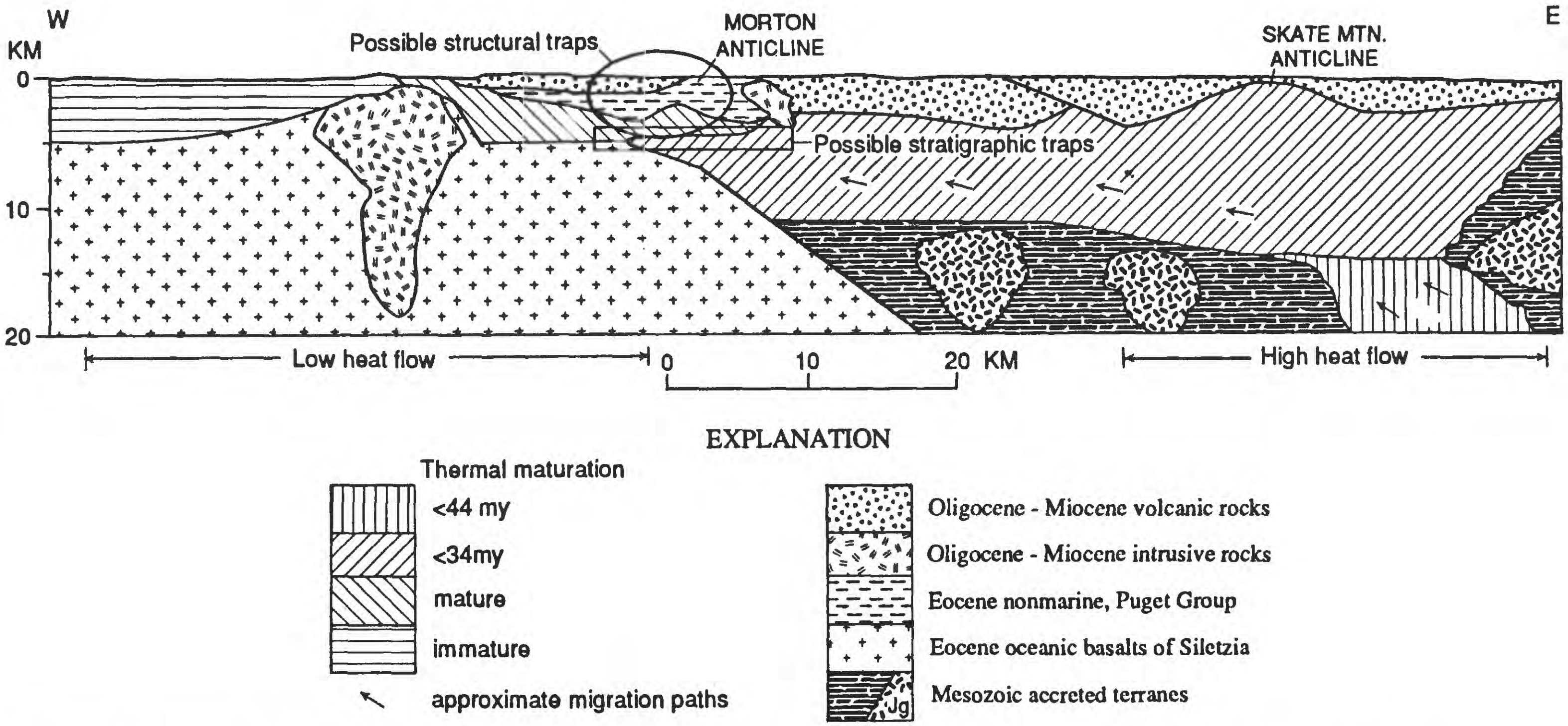

Figure 12-Source, migration, trap scenario for SWCC, using cross-section of Fig. 10 as base. See text for explanation.