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Tectonics and Conductivity Structures in the Southern Washington Cascades

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The tectonic setting of the southern Washington Cascades has been studied with the aid of magnetotelluric (MT) and other geophysical data. The main feature of interest in the geophysical data is a broad high-conductivity anomaly mapped with MT and geomagnetic variation (GMV) data. This anomaly is located roughly within the triangle formed by the volcanoes Mount Rainier, Mount St. Helens, and Mount Adams but exceeds beyond Mount Rainier to the northwest. We interpret the cause of the anomaly to be conductive rocks with resistivities of 1–4 ohm m and thicknesses possibly greater than 15 km. These conductive rocks are found 2–8 km beneath the overlying less conductive volcanic and sedimentary rocks at the surface. Two aeromagnetic lows follow the trend of the conductivity anomaly, and linear belts of strike-slip seismicity are coincident with both these magnetic lows. One of the aeromagnetic lows is coincident with the western margin of the conductivity anomaly. The geophysical data appear to outline a suture zone of probable Eocene age caused by accretion of a large seamount complex (Siletzia) and that may contain large thicknesses of compressed forearc basin and accretionary prism sedimentary rocks of Cretaceous to Eocene age. Part of the shallower conductive rocks may be associated with carbonaceous continental and transitional marine sedimentary rocks of the Puget Group. The contact between the hypothesized compressed basin and the accreted terranes to the west may localize the release of shear stresses in this region of oblique subduction. Several possible explanations for the conductivity anomaly are considered in addition to the compressed basin hypothesis.

INTRODUCTION

In this paper we describe results from a regional magnetotelluric (MT) survey of the southern Washington Cascades and discuss these data along with gravity, magnetic, and seismicity data in terms of geologic structures and accretionary tectonics. The geoelectrical models, as well as those derived from gravity and magnetic data, are quite complex because of the inherent geological complexity of the region. However, main features of the MT models and information in the magnetic and seismicity data provide important new information on the structures of the region and allow hypothesis of a paleotectonic model which includes the accretion of a major seamount complex in Eocene time and related tectonic compression of Eocene and pre-Eocene marine sedimentary rocks. The postulated suture zone involving the seamount complex, forearc basin rocks, and preaccretion continental crust will be discussed in terms of zones of seismicity associated with Mount St. Helens and Mount Rainier and possible controls on the location of these volcanos.

GEOLOGICAL SETTING

The southern Washington Cascades mountains include three Quaternary volcanos of the magmatic arc associated with the North America–Juan de Fuca convergent margin (Figure 1): Mount St. Helens, which has been active since the cataclysmic May 1980 eruption; Mount Rainier, the most massive of the Cascades volcanos; and Mount Adams, a volcano roughly equal in size and age to pre-1980 Mount St. Helens. The three volcanos are located at the apexes of a triangle. Most of the study area is covered by Tertiary and Quaternary volcanic flows; however, continental and transitional marine sandstones, shales, and coal beds of the Eocene Puget Group crop out in the region northwest of Mount Rainier and in scattered other localities in the study area. The continental units interfinger with and give way to strictly marine sandstones and shales of the Carbonado and McIntosh formations in the region west and southwest of Mount Rainier [*Buckovic*, 1979].

The study area is flanked on the east by flood basalts of the Columbia Plateau, on the north by the North Cascades complex of crystalline and metamorphic rocks, and on the west by Tertiary and Quaternary sedimentary rocks and basalts of the Eocene Crescent Formation and correlative units. The Miocene basalts of the Columbia Plateau are several kilometers thick and are underlain by Tertiary sedimentary and volcanic rocks covering pre-Tertiary basement of unknown lithology [*Stanley*, 1984]. The Crescent Formation basalts and related Siletz River basalts in Oregon are part of an accreted seamount complex [*Duncan*, 1982] mapped in the coast ranges of Oregon and Washington, which we lump together as a single accretionary unit called Siletzia [after *Jones*, 1985]. The seamount complex is roughly outlined by a gravity maximum, whose eastern margin is shown by the high gravity gradients in Figure 1. Magnetic data discussed below provide more detail on the boundaries of the seamount complex. In the Olympic Peninsula (Figure 1), Tertiary marine sedimentary rocks form a thick subduction complex or melange that is being thrust beneath the Crescent Formation basalts [*Tabor and Cady*, 1978].

RELATED GEOPHYSICAL RESEARCH

Weaver and Smith [1984] and *Weaver et al.* [this issue] have studied the seismotectonics of the southwestern Washington Cascades. Weaver and coworkers have defined the stress regime in the area with the aid of the seismic network installed after the Mount St. Helens eruption of 1980. They have provided convincing evidence of a northwest trending belt of right-lateral slip that they call the St. Helens zone (SHZ). The SHZ is perplexing in that no surface expression of any strike-slip faults appears at the surface. Most of the earthquakes in the SHZ occur in the upper 5–15 km. A reasonably well-defined seismicity pattern exists in the Mount Rainier

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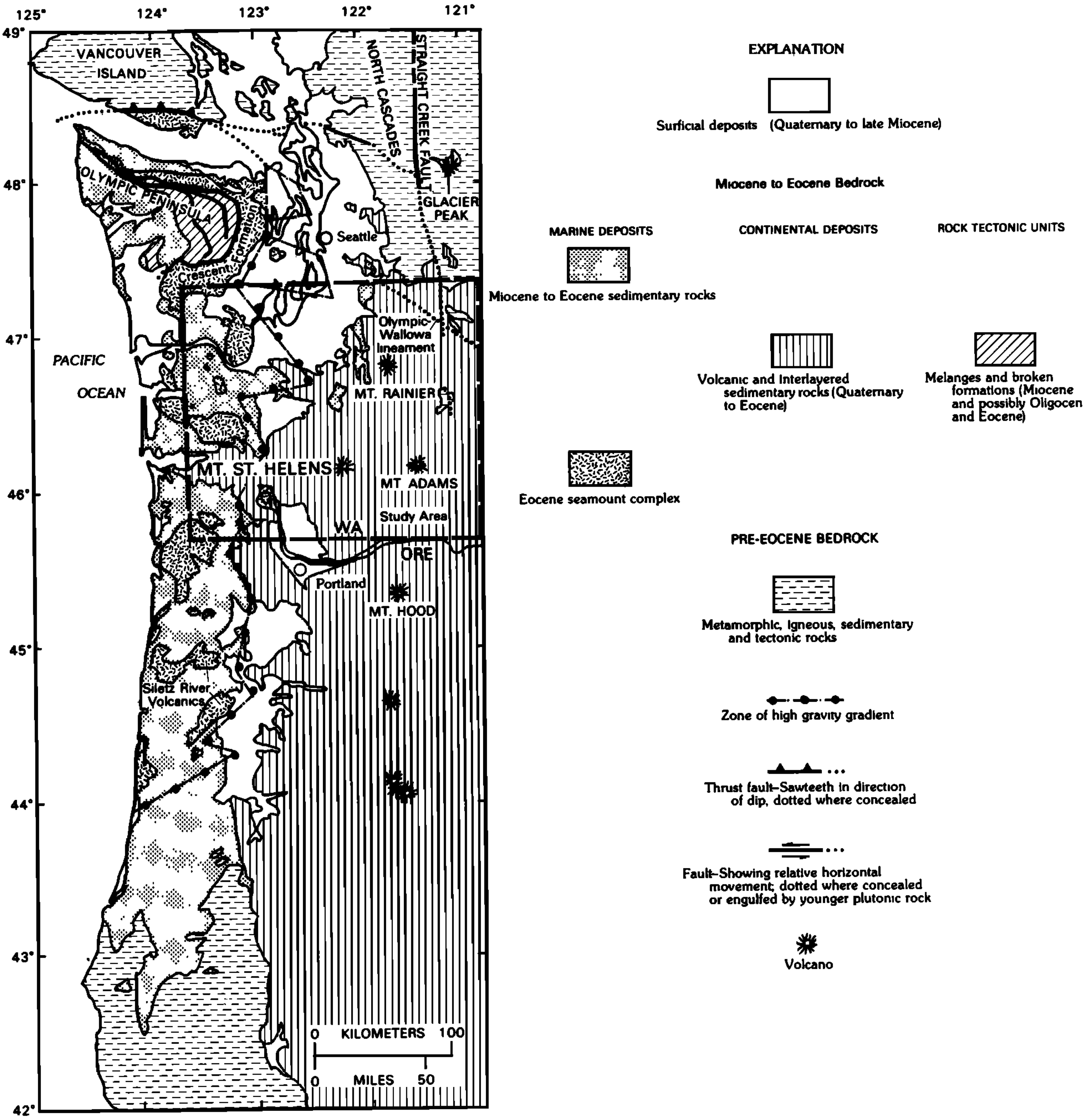

Fig. 1. Index map of Pacific Northwest showing Cascade Range and study area. Illustration modified from *Fox and Engebretson* [1983]. The zone of gravity gradients shown by the dot-dash line passing through the western part of the study area represents the eastern margin of a gravity high associated with an accreted seamount complex but partially due to density variations in the oceanic plate.

area (C. S. Weaver, written communication, 1986), but negligible seismicity has been associated with Mount Adams.

Law et al. [1980] and *Booker and Hensel* [1982] mapped a northwest trending geomagnetic variation (GMV) anomaly that extends from northeast of Seattle to near The Dalles on the Columbia River. On the basis of line current modeling of the GMV anomaly, *Law et al.* [1980] inferred that the conductive rocks causing the anomaly were in a belt 66 km wide and that the maximum depth to the conductive units was no greater than 25 km. *Booker and Hensel* [1982] call the GMV anomaly the Cascades Anomaly and interpret that the anomalous currents within the conductive units may be partially due to channeling of currents from Puget Sound. However, based upon MT sounding interpretations (profile AA′ indicated in Figure 2), *Stanley* [1984] interpreted that the GMV anomaly was probably caused by local induction in an east dipping wedge of conductive material.

Magnetotelluric Survey

Our initial MT study of the region between Mount Rainier and Mount St. Helens was sponsored by the U.S. Geological Survey geothermal program. A long profile AA′ (Figure 2) and the shorter BB′ were part of a regional study of the Cascade Range to map tectonic features that might provide information on geothermal resources in the Cascades. These initial MT profiles defined a thick, east dipping conductor shown on

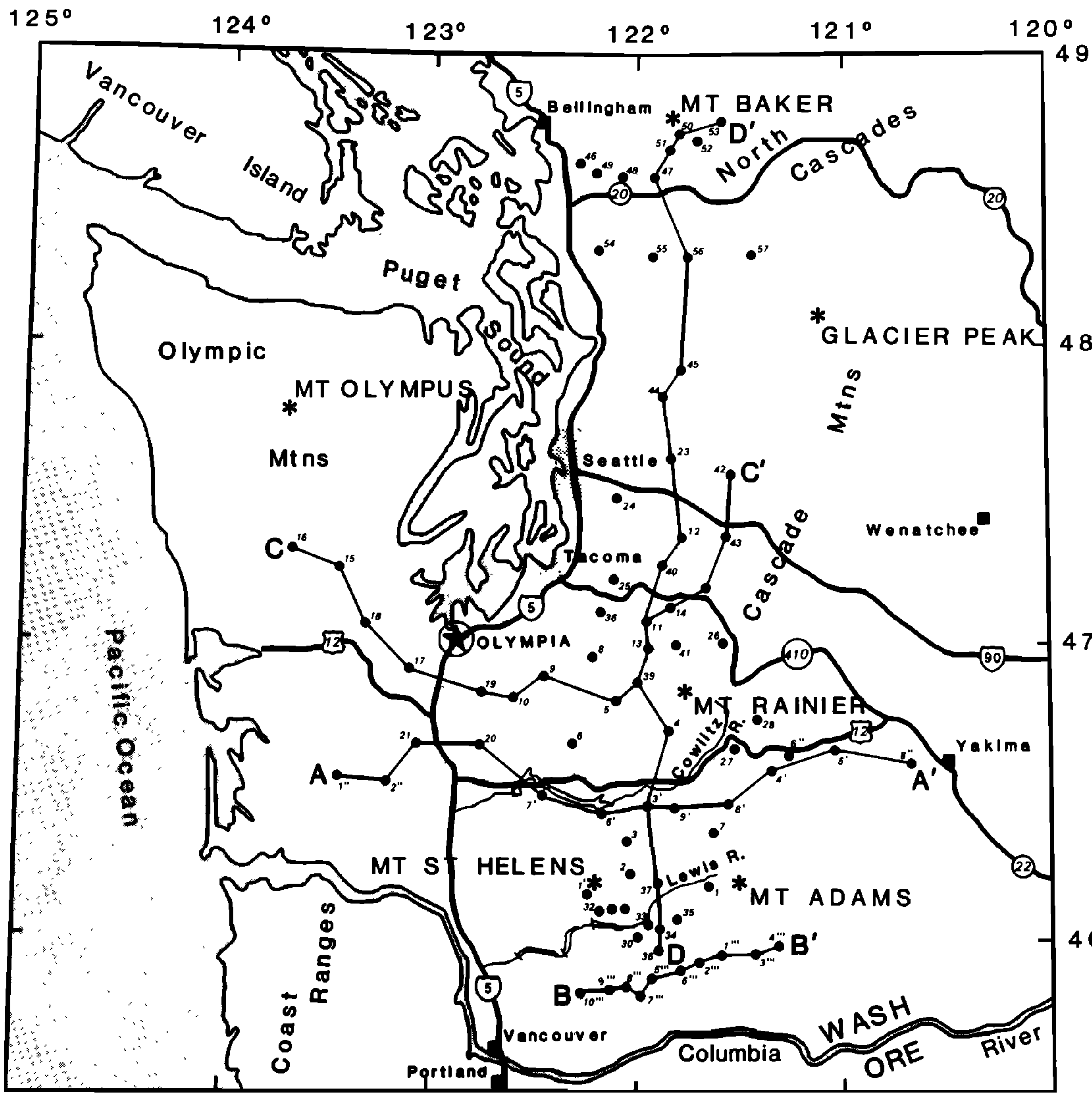

Fig. 2. MT sounding locations in western Washington.

the west end of profile AA′ in Figure 3 and led to additional surveys to map the regional extent of the conductor. We call the local conductivity structure on the central part of profile AA′ the southern Washington Cascades conductor (SWCC) and interpret that this conductivity structure is the cause of the "Cascade Anomaly" of *Law et al.* [1980] and *Booker and Hensel* [1982]. In our analysis, the conductivity structure and the associated geomagnetic anomaly are not an intrinsic part of the overall Cascade Range. J. R. Brooker (personal communication, 1986) has used the term "Cascade Anomaly" to refer to GMV anomalies which are present in the Oregon Cascades as well as in the Washington Cascades. We will use the term SWCC to refer to the conductive rocks mapped on section AA′ and the nearby region in southwestern Washington without regard to regional GMV patterns.

Our two-dimensional model for the portion of profile AA between soundings 7′ and 5′ is shown in Figure 4. The horizontal scale for this figure in the work by *Stanley* [1984] was misdrafted, and Figure 4 indicates the correct scale. Comparisons between computed vertical field transfer functions from our two-dimensional MT model of Figure 4 showed reasonably good agreement with the measured GMV parameters obtained by *Law et al.* [1980] on either side of the SWCC (KOS and WHI). Modeling of a more comprehensive GMV data set by J. R. Booker (personal communication, 1986) to the north of profile AA′ shows that major modifications of the two-dimensional model for AA′ are required to fit his observed data. MT data presented in this paper also require different structures to the north of AA′.

Additional MT soundings were completed in the area of the SWCC detected on profile AA′ to map its boundaries and to perform calibration measurements on a variety of rock units in western Washington. The data set is not as complete as desirable, but enough soundings have been completed and interpreted to locate the conductive unit boundaries approximately and to discuss is thickness and possible origins.

The overall set of MT sounding data was initially interpreted with one-dimensional models; however, the data from the

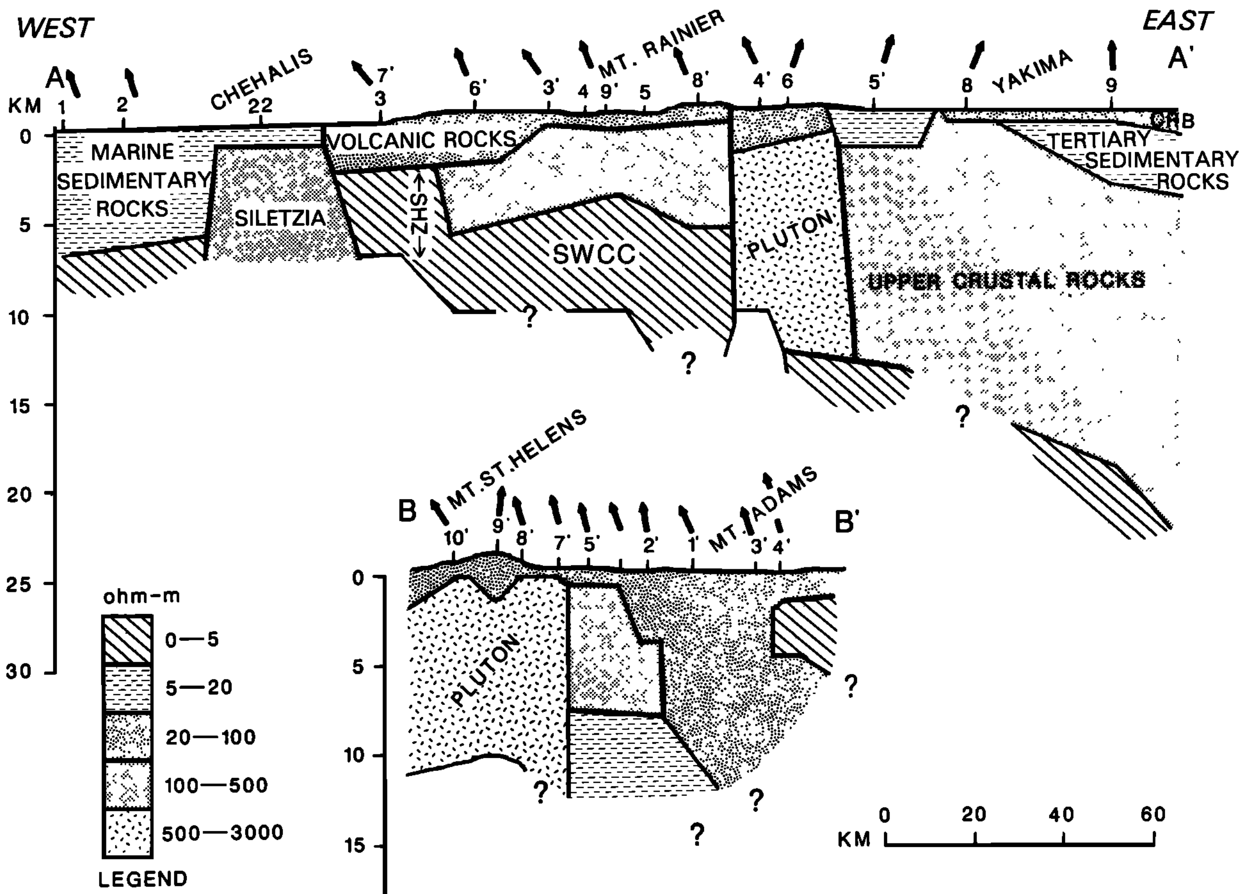

Fig. 3. MT one-dimensional model sections for profiles AA′ and BB′ [from *Stanley*, 1984]. The location of the Mount St. Helens seismic zone (SHZ) mapped by *Weaver and Smith* [1984] on the MT profile is also indicated between stations 7′ and 6′. CRB is Columbia River Basalt Group; SWCC denotes southern Washington Cascades conductor; and arrows above the sounding locations show the impedance strike in polar form (up represents north).

west end of profile AA′ and from profile CC′ have been modeled two dimensionally. The two-dimensionai model for the west end of profile AA′ did not differ greatly from the one-dimensional model but the more complicated geology encountered on profile CC′ required that more emphasis be given to the two-dimensional modeling. Only the two-dimensional model for CC′ will be discussed because it is significantly different from the one-dimensional model and more accurately represents the geology.

The two-dimensional model for profile CC′ is shown in Figure 5, along with residual gravity and magnetic profiles. The two-dimensional model was derived by forward modeling using a transmission line algorithm. The conductivity structure extends to model-space infinity on both ends and below the deepest horizon. No aesthenospheric structure was included in the model. It would be important to include aesthenospheric structure for modeling low-frequency magnetic transfer functions, but this was not the aim of the modeling; rather, the goal was to fit the MT results above 30-km depth.

Note that the thickness of the SWCC units was interpreted as being over 20 km. This interpreted thickness is based on the assumption that the 8 ohm m units west of sounding 9 did not continue underneath the portion of the profile from sounding 9 to sounding 14. If these 8 ohm m units were continued beneath the SWCC, then the 2 ohm m units in the SWCC could be made considerably thinner (less than 10 km), but merging into the conductive 8 ohm m materials. Sounding 15 (Figure 2) was adequate only for modeling the upper 5 km and is not represented in the data plots but was used to construct the initial two-dimensional model. The data for sounding 9 could not be fitted adequately with the two-dimensional model and the 1500 ohm m units beneath this sounding probably represent a Tertiary pluton that is of limited lateral extent and is not long enough to approximate a two-dimensional body. The grid size of the model was rather coarse, with cells of 1 km vertical and 2 km horizontal dimensions. We were able to model the observed MT data with this coarse grid size only by using an inhomogeneous surface layer that probably does not accurately represent the upper 1–2 km of the geology. However, the deep structures have been as adequately treated as appropriate within the limits of the data quality and three-dimensional effects.

Profile CC′ (Figure 2) does not form a straight line across the strike of the geology and thus our two-dimensional modeling efforts can be considered as only approximations, but we believe that the essential interpretation of greater than 10 km thickness for the SWCC units is a reasonable estimate of the true geological picture.

The complete data set for all the soundings indicated in Figure 2 is represented in Figure 6 in the form of a conduc-

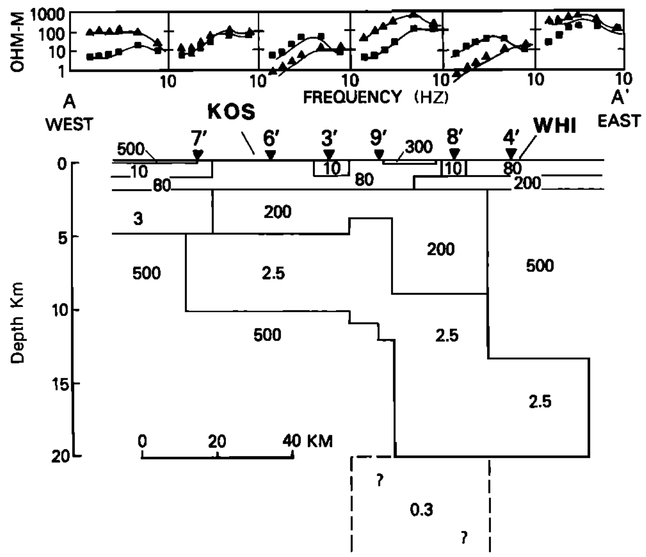

Fig. 4. MT two-dimensional model section for portion of profile AA' from *Stanley* [1984] with corrected horizontal scale (see text). The observed data for the MT sites 7'–4' are shown by the smoothed curves in the boxes in the upper part of the figure. The solid triangles and squares represent the computed transverse electric and transverse magnetic mode resistivities from the two-dimensional model. Numbers in the two-dimensional model are unit resistivities in ohm meters. KOS and WHI refer to original GMV stations from *Law et al.* [1980], who detected an anomalous conductor in this region.

tance map. Conductance contours were obtained from the models by summing the ratio of thickness to resistivity for model layers in the depth range 0–20 km. The map shows that the highest conductances are located in the triangle formed by the three volcanos and in the area to the northwest of Mount Rainier. Most of the models require the resistivity of the SWCC units to be 1–4 ohm m. The conductance contours can be converted to total thickness (in meters) by multiplying the conductance values by a specific interpreted resistivity. A value of 2 ohm m is generally an appropriate value for the interpreted resistivity of the SWCC models; thus the conductance contours can be converted to approximate (in meters) thickness by multiplying by a factor of 2.

Figure 7 is a contour map showing the depth to the 1–4 ohm m rocks. This map indicates that the conductive units are nearest to the surface in the area of Mount Rainier and appear to deepen to the southeast of Mount St. Helens.

Accuracy of Models

It is very difficult to assess the accuracy of the one- and two-dimensional models presented in the MT interpretations. *Stanley* [1984] discussed the accuracy of our one-dimensional modeling and pointed out the confirmation of depth to horizons in the Columbia River Plateau by subsequent drilling. We will not reiterate these one-dimensional based accuracy assumptions but instead will discuss possible problems with the two-dimensional models of Figures 4 and 5. As mentioned above, profile CC' crosses geologic strike in an arcuate manner and thus is not ideal for treating with two-dimensional modeling. In addition, the conductance contours of Figure 7 show that the structures change rapidly along strike, as do the two-dimensional models from profile AA' to profile CC'. This illustrates the inherent three-dimensional character of the geology in the region.

We have not yet attempted to model the data with three-dimensional models but intend to do so in the future. It will be very difficult to construct an adequate three-dimensional model for this region which is any more meaningful than the combined view provided by the two-dimensional models for AA' and CC'. One three-dimensional effect which has played the largest role in our cautiousness about the thicknesses implied by the two-dimensional models is the "static" effect of a tabular conductive body on the MT resistivities. The model provided by *Wannamaker et al.* [1984] illustrates that the MT sounding curves for a platelike conductor in a four-layered earth look quite isotropic for measurements made over the conductor but nonasymptotically approach apparent resistivities of much less than the actual values for the conductor. This effect is due to a constant bias on the electric field caused by the three-dimensional body. *Berdichevsky and Dimetriev* [1976] have presented simpler models which illustrate the same effect. To reassure ourselves that our intrepretations in the most conductive part of the SWCC did not suffer from this three-dimensional effect, key soundings were extended to nearly 1000-s period with the result that well-defined minima in the curves were developed that could be modeled with resistivities of 1–4 ohm m. This latter result negated much of our concern that the two-dimensional interpreted thicknesses in the most conductive part of the SWCC were biased to the high side by the "static".effect illustrated in the Wannamaker et al. and Berdichevsky models, but this matter will not be satisfactorily resolved until we have had time to construct an accurate three-dimensional for the SWCC region.

Possible Causes of the Conductivity Anomaly

We had earlier [*Stanley*, 1984] suggested that the east dipping conductive unit on AA' is composed mainly of sedimentary rocks because of the very low resistivities (1–4 ohm m) in the unit. In sedimentary rocks, pore fluid salinity and clay mineral content are the dominant factors in controlling resistivity [*Parkhomenko*, 1967]. Marine sedimentary rocks have highly saline pore fluids and higher percentages of shale facies and thus are usually much more conductive than nonmarine sedimentary rocks. However, nonmarine sedimentary rocks can have low resistivity if (1) they contain large amount of tuffaceous detritus, which easily converts to zeolites and layered clays, (2) they have high grade coals, such as anthracites or distributed organic matter with high grade coalification, or (3) they were deposited in closed lake basins or playas in which briny clays saturate the sediments.

The only sedimentary rocks tested by deep drilling in the survey region are units of the Puget Group [*Bukovic*, 1979]. Several deep oil wells have been drilled in the Puget Lowland to depths of nearly 4 km. Puget Group sedimentary rocks and interbedded volcanic rocks and coals have deep induction log resistivities in the range 12–60 ohm m. The lowest values in this range are about a factor of 3–10 greater than those measured in the main part of the SWCC. Farther to the west, in the Olympic Peninsula (Figure 1), in the Chehalis Basin, and in the coastal Gray's Harbor Basin, resistivities of the Eocene and post-Eocene marine sandstones and shales are very consistently in the range 4–6 ohm m. These values were obtained from deep induction logs at depth of up to 2 km. MT sound-

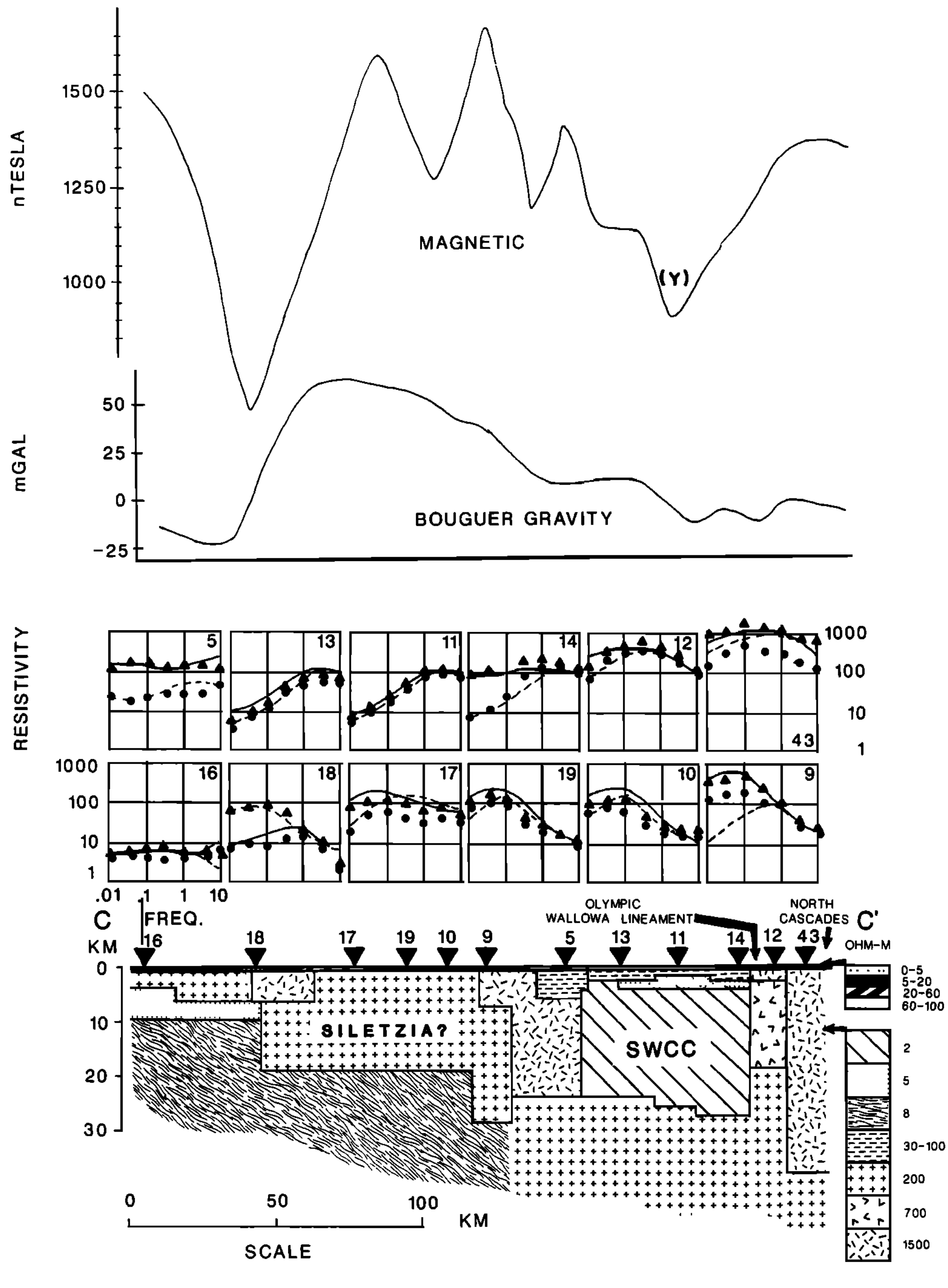

Fig. 5. MT two-dimensional model for profile CC′. Symbols for the resistivities of an inhomogeneous surface layer (1 km thick) are shown in the upper part of the pattern legend at the right of the two-dimensional model and the remainder of the model resistivities are indicated by the lower pattern legend (values all in ohm meters). The computed and observed MT resistivity amplitudes are plotted above the two-dimensional model, with the triangles and squares representing the observed parallel-to-strike and perpendicular-to-strike data. The computed data for the model is shown by the solid (parallel-to-strike) and dashed (perpendicular to strike) curves. The numbers in the upper right of the data plots refer to sounding numbers along the profile. The Bouguer gravity and aeromagnetic amplitudes are shown above the two-dimensional model for profile CC′. The linear anomaly discussed in the text in regard to Figure 9 is indicated by (Y).

ings completed in 1986 in western Washington and northwestern Oregon provide consistent interpreted resistivities of 3–5 ohm m at depths of 2–6 km for equivalent marine sequences. The consistent values are related to the regional formation salinities, and such consistent resistivities are not observed in continental rocks of the Puget Group.

A primary concern has been whether the marine rocks assumed to make up the SWCC can remain conductive at depths of 20 km, as our two-dimensional approximation to the MT data set implies. Previous studies which have mapped conductive rocks at mid-lower crustal depths in regions of high heat flow have invoked partial melting of the rocks as the conductivity mechanism [*Wannamaker*, 1986]. However, to investigate other mechanisms for deep conduction related to the SWCC we have made comparisons with a similar orogenic belt conductivity anomaly in the Carpathian Mountain region

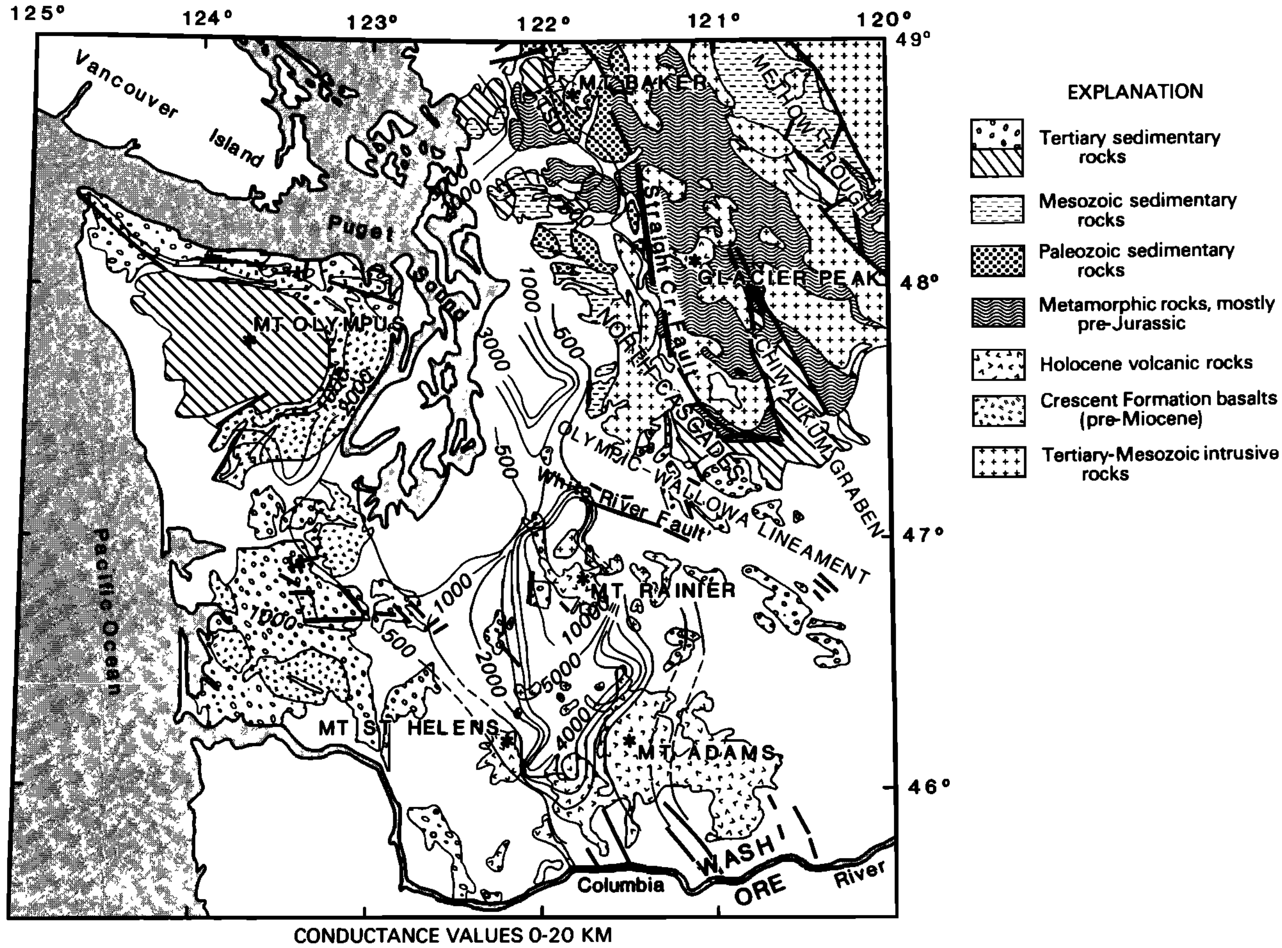

Fig. 6. Conductance contours derived from one-dimensional models in the depth range 0–20 km superimposed on generalized geology of western Washington.

of eastern Europe. Czechoslovakian geophysicists have studied a Tertiary suture zone between the Bohemian Massif and Carpathian Mountains in which compressed and partially subducted Mesozoic and Tertiary flysches and Tertiary mollasse occur to great depths. These rocks have been tested by drilling to nearly 8 km depth and two-dimensional MT models [*Cerv et al.*, 1984] show continuity of conductive flysch rocks with a 5–10 km thick dipping conductor (3 ohm m) that reaches over 20 km depth. Seismic reflection data have been obtained over the same region that verify the morphology of the conductor mapped with MT surveys [*Tomek*, 1986]. The maximum depth, resistivity, and morphology of the Carpathian conductor are quite similar to that of the SWCC on our profile AA′ [*Stanley*, 1986*b*].

In light of the Czechoslovakian results and our current research in Washington, we have investigated the physical property mechanisms for such deep sedimentary prisms. A compilation by *Hellwege* [1982] of rock properties for over 900 worldwide samples show that the porosity of Tertiary shales from the Po Basin and from Venezuela predictably approaches zero at depths of about 4 km. These data are for basin rocks which have not been horizontally compressed. If the assumed basin rocks in the SWCC have been horizontally compressed by accretion of Siletzia, then the approach to zero porosity may occur at shallower depths. These considerations have relevance both to the resistivity and density of the rocks. The density of shales and sandstones approach values of over 2.6 g/cm^3 at basin depths of about 4 km. Because the resistivity in marine rocks is controlled largely by the saline pore waters, a significant decrease in porosity will increase the resistivity at constant temperature and depth [*Parkhomenko*, 1967]. For a saline water system under 15–20 km lithostatic pressure, phase changes in the water and corrosion effects on the rock matrix make the prediction of rock resistivities complicated, but water in the rock system at depth is generally assumed to radically decrease resistivities [*Olhoeft*, 1981].

Other mechanisms may be at work to counteract the limited porosity and maintain low resistivities in the assumed sediments at the implied depths of 20 km. As mentioned above, partial melting of the rocks can generate the required low resistivities. In addition, evidence is being accumulated that electronic conduction mechanisms in deep shales may play an important role in decreased resistivities under limited porosity conditions. Mesozoic black shales in a large flysch basin in Alaska have been studied with MT surveys [*Stanley*, 1986*a*] and with laboratory geochemical and petrological methods. These shales have been mildly metamorphosed into argillites and have 3–5% carbon and large amounts of iron minerals. The carbon has been converted to high grade in fissile planes, and the MT data show that large sections of the shale have resistivities of 3–5 ohm m to depths of over 20 km. The carbon in the fissile planes is believed to dominate the conduction

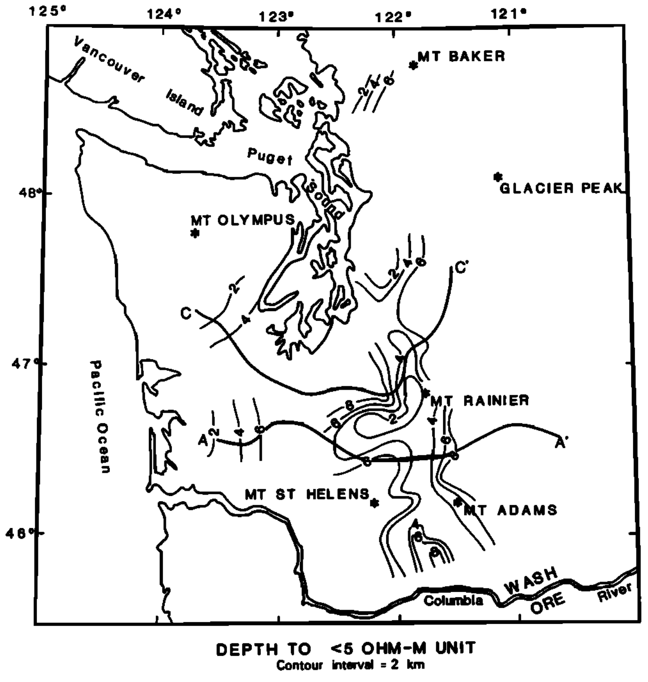

Fig. 7. Contours of depth to less than 5 ohm m units in western Washington.

mechanisms. Other thick conductive argillites have been mapped in the Proterozoic Belt Basin of Montana, and it has been established that the conduction mechanism there is pyrite-prrhyotite films [*Wynn et al.*, 1977]. We have collected samples of argillites from the Tertiary Kratigen flysch in Switzerland which show similar pyrite-prrhyotite films. Thus we propose that a consistent mechanism in the dewatering and metamorphosis of shales may be the transfer of the conducting minerals, either ore minerals or carbon, to films within fissile planes. These phenomena are proposed as mechanisms that could maintain the low resistivity of carbonaceous, iron-rich shales during deep tectonic emplacement by accretionary processes, counteracting the decrease in porosity which acts to increase resistivities. Enhanced conductivity caused by high grade coals or highly coalified distributed carbon in the Eocene Puget Group, which does contain large amounts of coals, is unlikely because the coals are all low in grade, typically subbituminous or bituminous [*Livingston*, 1974].

The occurrence of graphitic and/or mineralized schists of Paleozoic or older age is quite common in many areas of the world. Such rocks can have resistivities of a few ohm meters or even less than 1 ohm m in localized regions [*Ekren and Frischknecht*, 1967]. However, because of the youth of the crust in the study area [*Davis et al.*, 1978] it is unlikely that such schists are the cause of the SWCC.

Regarding the possibility that the SWCC units are volcanic, surface measurements and well log data show that the volcanic flow rocks in the region have resistivities generally greater than 40 ohm m and typically in the range 40–200 ohm m. The volcanic rocks at the surface over the SWCC are thick Eocene sequences of rhyodacite ash flows of the Ohanapecosh and Stevens Ridge formations and other near-vent andesitic facies such as the Northcraft and Tukwila formations [*Buckovic*, 1979]. Volcanic rocks can have very low resistivities when they contain large amounts of ash, which readily alters to a variety of clay minerals and zeolites. However, if we assume that volcanic rocks are a major component in the SWCC conductive units, they must be much more heavily altered (and lower resistivity) than the Northcraft, Ohanapecosh, and Steven Ridge formations, which were measured at the surface. There has undoubtedly been considerable hydrothermal activity in the vicinity of the Cascades volcanos that would increase the amount of clay minerals in both volcanic and sedimentary rocks of the region and decrease their resistivity, but we observed no surface correlation of the regional SWCC anomaly to any obvious areas of hydrothermal activity. Because of the position of the conductive unit in relation to the Cascades volcanos the effect of high heat flow must be considered. Heat flow values are not as high in southern Washington Cascades (about 63–71 mW/m^2 [*Blackwell and Steele*, 1983]) as in the Oregon High Cascades (>94 mW/m^2). Hot water in the intermediate depth formations could be a factor in decreasing resistivities significantly, possibly of the same order as the clay minerals content. Although zones of partial melt could contribute to low resistivities in the deeper part of the SWCC, no evidence exists for major magma bodies in the survey area. The eruption at Mount St. Helens is believed to have been triggered by a very local magma source [*Weaver et al.*, this issue].

In summary, the geoelectrical models and known geology suggest to us that possible lithologies of the conductive rocks of the SWCC can be ranked as follows in order of likelihood: (1) marine sedimentary rocks of early Jurassic to Eocene age, containing hypersaline fluids and possibly dominated by shale facies, (2) continental sedimentary rocks similar to those of the Puget Group and other nonmarine basin units of Tertiary age occurring in Washington and elsewhere in the Pacific Northwest, (3) thick, highly altered volcanic tuffs, either in primary flows or reworked into continental/marine sediments, and (4) carbonaceous/graphitic and/or mineralized schists, carbonates, or shales of pre-Mesozoic age in an exotic component.

PROBABLE AGE OF SWCC ROCKS

We suggest that the resistive section on MT cross section CC′ from soundings 9–18 represents a massive block of Siletzia crust. This hypothesis is based upon magnetic highs that are associated with this portion of CC′. We also hypothesize that the SWCC units on CC′ represent a more compressed version of the units on AA′ that we include in the SWCC. Siletzia crust may have been detected at sounding 20 on profile AA′ (Figure 3), but it is of lesser extent than on CC′ (Figure 5). The greater mass of the assumed Siletzia crust on CC′ may partially explain our hypothesized greater compression of the conductive units on CC′. Additionally, the North Cascades crystalline complex may have provided a more effective backstop for the assumed basin rocks on CC′ than was provided in the region east of the SWCC units on AA′. It is conceivable that the North Cascades represent more typical continental crust, and the region on the east end of profile AA′ underlying the Columbia Plateau represents more typically oceanic or transitional crust.

Armentrout and Suek [1985] presented paleoreconstructions of the accretion of Siletzia showing a pre-early Eocene forearc basin/accretionary prism complex preserved after the subsequent westward jump of subduction [*Armentrout and Suek*, 1985, Figures 19-21]. *Cowan and Potter*'s [1986] interpretation of an east-west transect passing through the region south

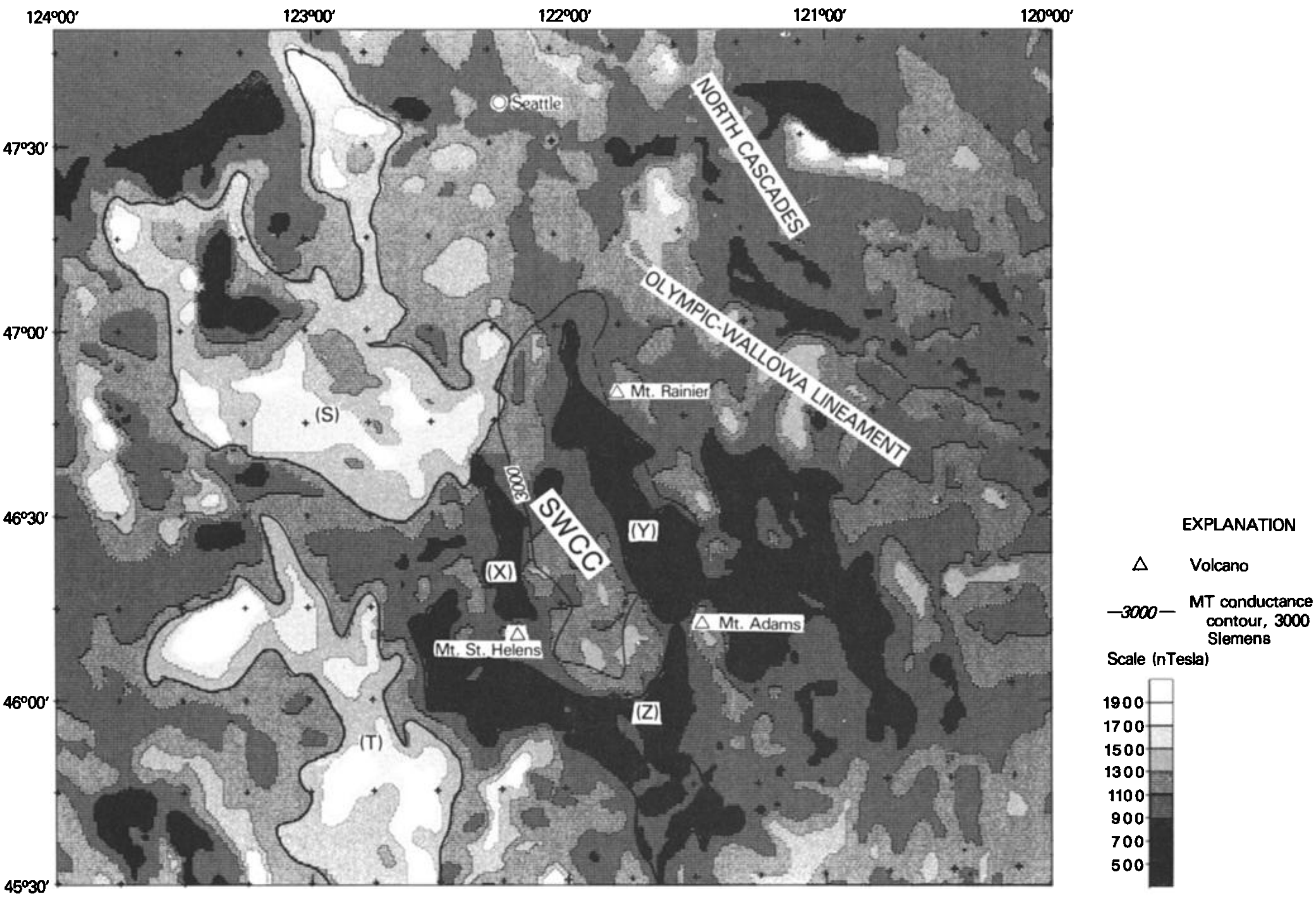

Fig. 8. Aeromagnetic map of study area. Anomalies (X), (Y), and (Z) are segments of aeromagnetic lows that appear to approximately enclose the conductivity anomaly. Anomalies (S) and (T) are interpreted to be caused by two distinct subunits of the accreted seamount complex (Siletzia). The 3000-S conductance contour for the SWCC is also shown.

of Mount Rainier hypothesizes the existence of imbricated slices of Mesozoic marine sedimentary rocks overlain by Tertiary sedimentary rocks such as might be formed by compression of a thick accretionary prism and/or forearc basin. Canadian MT and seismic reflection surveys have found structures on Vancouver Island similar to the west end of our cross section CC′ [*Yorath et al.*, 1985; *Kurtz et al.*, 1986]. These surveys have been interpreted to show Tertiary subduction complex units equivalent to the Olympic subduction complex that have underplated Vancouver Island crust at depths greater than 20 km.

The paleostratigraphy and structure prior to the Eocene accretion of Siletzia is poorly known from surface geologic mapping. There is no evidence for pre-Eocene marine sedimentary basin rocks in the immediate vicinity of the SWCC, but in the region north and south of study area a belt of Mesozoic forearc basins existed [*Dickinson*, 1976]. The nearest such forearc basins are the Nanaimo Basin [*Muller and Jeletsky*, 1970] mapped in the southeastern part of the Vancouver Island area, the Methow trough in north central Washington (Figure 6) and basins represented in the Mitchell and John Day inliers in north central Oregon [*Dickinson and Thayer*, 1978]. Thus it is reasonable to assume that Eocene marine rocks may have been prograded onto Mesozoic forearc basin rocks rather than directly on oceanic crust.

The paleoreconstruction of possible basin settings and types is complicated by the 150–200 km of dextral displacement postulated to have occurred since the Mesozoic in the region south of the Straight Creek fault (Figure 1) by *Davis et al.* [1978]. If this amount of strike slip has occurred since accumulation of the assumed sediments, then the original depositional location may have been south of the present Columbia River, nearer to where other Mesozoic forearc sediments have been mapped in Oregon. If this is the case, then the hypothesized basin complex and associated accreted components that compressed it could have moved together as a unit. Paleomagnetic constraints [*Simpson and Cox*, 1977] on rotation of the Coast Range of Oregon (cored with Siletzia rocks) do not either support or contradict the movement of Siletzia to fit this latter possibility.

RELATIONSHIP OF SWCC TO GRAVITY, MAGNETIC, AND SEISMICITY DATA

Magnetic and Gravity Data and Models

Aeromagnetic maps of the MT survey region (Figure 8) indicate several linear magnetic lows, which are interrupted locally by discrete highs and more intense lows. The westernmost linear magnetic low (X) in Figure 8 coincides with the SHZ and with the approximate western boundary of the SWCC (Figure 9). The SHZ and the magnetic low (X) cross MT profile AA′ between sounding 7′ and 6′ (Figure 3), where a

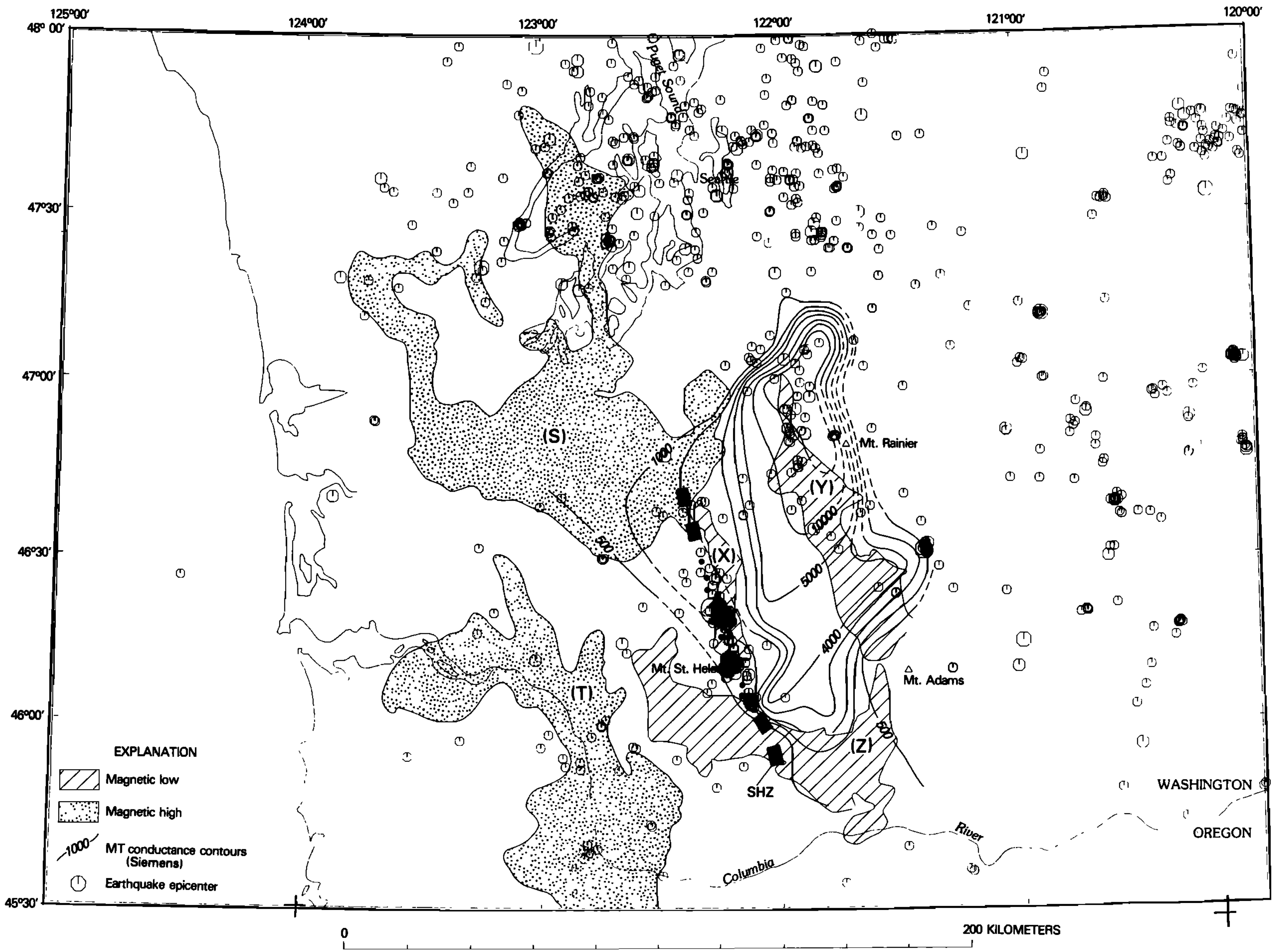

Fig. 9. Aeromagnetic anomalies from Figure 10 superimposed upon conductance contours and earthquake data supplied by C. S. Weaver. SHZ is the St. Helens seismic zone from *Weaver and Smith* [1984]. The earthquakes plotted are those deeper than 5 km and with magnitudes greater than $M = 2.0$.

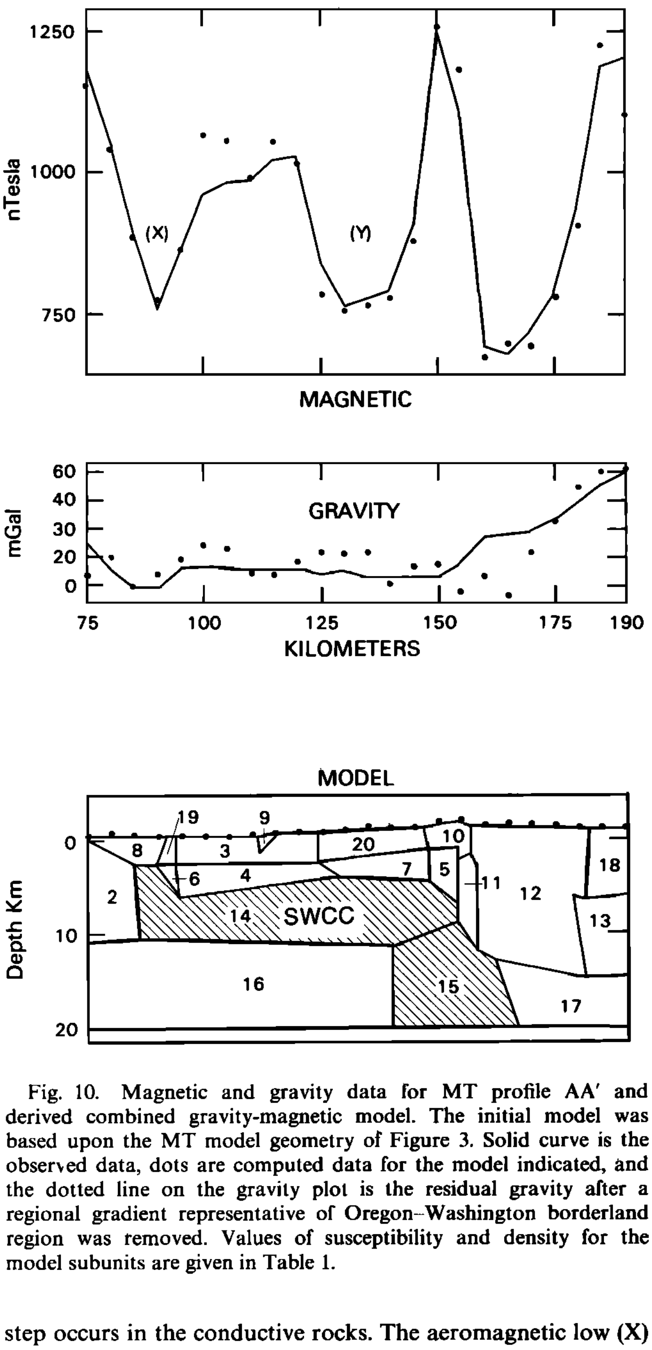

Fig. 10. Magnetic and gravity data for MT profile AA′ and derived combined gravity-magnetic model. The initial model was based upon the MT model geometry of Figure 3. Solid curve is the observed data, dots are computed data for the model indicated, and the dotted line on the gravity plot is the residual gravity after a regional gradient representative of Oregon–Washington borderland region was removed. Values of susceptibility and density for the model subunits are given in Table 1.

step occurs in the conductive rocks. The aeromagnetic low (X) is interrupted in the area of Mount St. Helens by a magnetic high believed to be caused by intrusive units [*Finn and Williams*, this issue]. The longer aeromagnetic linear, (Y), follows the trend of the SWCC but occurs approximately in the central part of the higher conductance section.

The connection between the western (X) and eastern (Y) magnetic low segments southeast of Mount St. Helens (anomaly Z) follows the southeastern boundary of the SWCC and is part of a larger northwest trending low that extends to the southeast as far as the Columbia River from the area west of Mount St. Helens.

We questioned whether the linear magnetic lows were intrinsic anomalies or just were lower-amplitude trends between several adjacent highs. A high due to basalt flows in the Indian Heavens area (southwest of Mount Adams) appears to be a factor in forming anomaly Z, but X and Y have inherent continuity into anomaly Z, and the correspondence of the conductivity anomaly edge with anomaly Z suggested to us that intrinsic factors might cause all of the lows. We considered also that the linear magnetic lows might be partially caused by destruction of magnetic minerals by hydrothermal alteration in the upper few kilometers of the surface. The hydrothermal alteration could have taken place mostly along the SHZ strike-slip fault and on boundaries of the SWCC, including the southern boundary. Hydrothermal fluids may rise from depth along the assumed boundaries of the sedimentary complex and along internal shear zones, especially where active slip is occurring, such as in the SHZ.

Comparison of the aeromagnetic anomalies (X) and (Y) with published and known geologic information showed no obvious relationship between the anomaly (X) and surface geology. However, anomaly (Y) appears to coincide with a set of anticlines documented by *Hammond* [1980], including the Skate Mountain anticline southwest of Mount Rainier and the Carbon River anticline northwest of Mount Rainier. Volcanic rocks are nonexistent in the Puget Group in the area of the Carbon River anticline and are probably thinner along the Skate Mountain anticline. If the volcanic rocks have higher magnetizations, then the thinning of volcanic rocks along the anticline could produce the magnetic low (Y). There are no corresponding structures associated with anomaly (X).

The magnetic data along profile AA′ (Figure 10) show the amplitude character of the regional magnetic anomalies somewhat more clearly. Figure 10 consists of a combined gravity-magnetic model based upon the MT model geometry. A $2\frac{1}{2}$-dimensional program that adjusts model geometry based upon fixed densities and susceptibilities was used to model both the gravity and magnetic data [*Webring*, 1985]. The model physical parameters are given in Table 1. The model geometry is different from the MT model in details but remains similar to the original starting model derived from the MT data. We have not recomputed the two-dimensional MT response of the gravity-magnetic model because the constraints from the gravity and magnetic data do not provide adequate reasons for altering the MT models.

We interpret that a magnetic high on the west end of the profile is caused by the oceanic basalts of Siletzia (unit 2).

TABLE 1. Densities and Magnetizations for Profile AA′ Gravity-Magnetic Model

Model Unit	Density, g/cm^3	Magnetization, A/m × 10^{-3}
2	2.70	6.00
3	2.47	3.50
4	2.63	3.77
5	2.63	4.00
6	2.64	0.00
7	2.60	0.03
8	2.38	2.74
9	2.49	0.002
10	2.43	4.40
11	2.7	2.40
12	2.59	0.429
13	2.84	0.712
14	2.63	2.79
15	2.72	0.00
16	2.85	0.00
17	2.93	0.00
18	2.59	3.97
19	2.43	0.00
20	2.55	0.00

Profile AA′ just crossed the southern end of magnetic high (S) on Figure 9, which we interpret reveals the outline of a main component of Siletzia. Anomaly (T) in Figure 9 outlines another magnetic high caused by the combination of Siletzia rocks, Goble volcanics [*Armentrout and Suek*, 1985], and Columbia River basalts. The magnetization of the Siletzia unit was modeled as 6.0 A/m, the highest value used for any units of profiles AA′ and CC′.

The magnetic low (X) can be produced by a zero magnetization unit extending to near the surface (units 6 and 19), although this mechanism for fitting the data is not unique. The magnetic low (Y) is produced in the model by using low magnetization units 7 and 20 in the upper 5 km. These units could represent the contrast between thin volcanic rocks (units 3, 4, 5, 10) and nonmagnetic sedimentary rocks (units 7 and 20) with resistivities of 100–500 indicated on the one-dimensional MT model of Figure 3. The magnetic high just east of (Y) is accounted for in the model by units 4, 5, and 11 with magnetizations of 4.0 and 2.7 A/m; unit 11 represents the nearby Goat Rocks pluton previously modeled in detail by *Williams and Finn* [1987]. The low on the east end of the profile was modeled largely with unit 12, with a low magnetization which we suggest may be related to outcrops of pre-Jurassic sedimentary rocks of the Russell Ranch Formation [*Ellingson*, 1972]. The magnetic high on the extreme east end of profile AA′ is caused by the basalt flows of the Columbia River Basalt Group. Note that the SWCC rocks have been given a substantial magnetization (unit 14) above 12 km depth. This magnetization was not required by profile AA′ data but was derived from analysis of profile CC′, which will be discussed below.

In order to model the part of the crust involved in the MT study a regional gradient characteristic of the northern Oregon–southern Washington Coast Ranges region was subtracted from the observed Bouguer gravity to produce the residual data plotted in Figure 10. The two-level nature of the residual gravity anomaly implies that we can at best determine the average density contrast between the eastern end of the profile (a relative high) and the western portion covering the SWCC (a relative low). The density of 2.61 used for the SWCC rocks above 12 km (Table 1) is compatible with measured values from *Hellwege* [1982] discussed above for Tertiary shales at depths greater than 4 km. With these densities the interpreted thick section of marine sediments below 4 km does not produce a major gravity anomaly but provides part of the contrast between the western and eastern portions of the profile.

A cursory investigation of the gravity field over the Methow Trough in northern Washington is also instructive. Several kilometers of Mesozoic continental and marine sedimentary rocks occur in the Methow, flanked by crystalline rocks of the Okanogan complex on the east and crystalline rocks of the North Cascades complex on the west. The only gravity low [*Society of Exploration Geophysicists*, 1982] in the Methow region crosses the Methow structure almost perpendicular to strike, indicating that the sedimentary rocks in the basin have densities that do not differ greatly from the surrounding quartz-rich crystalline rocks.

Other constraints from the gravity and magnetic data can be derived from profile CC′, which was modeled in the same manner as AA′. The magnetic and residual gravity data for CC′ is shown Figure 11. The geometric model configuration in

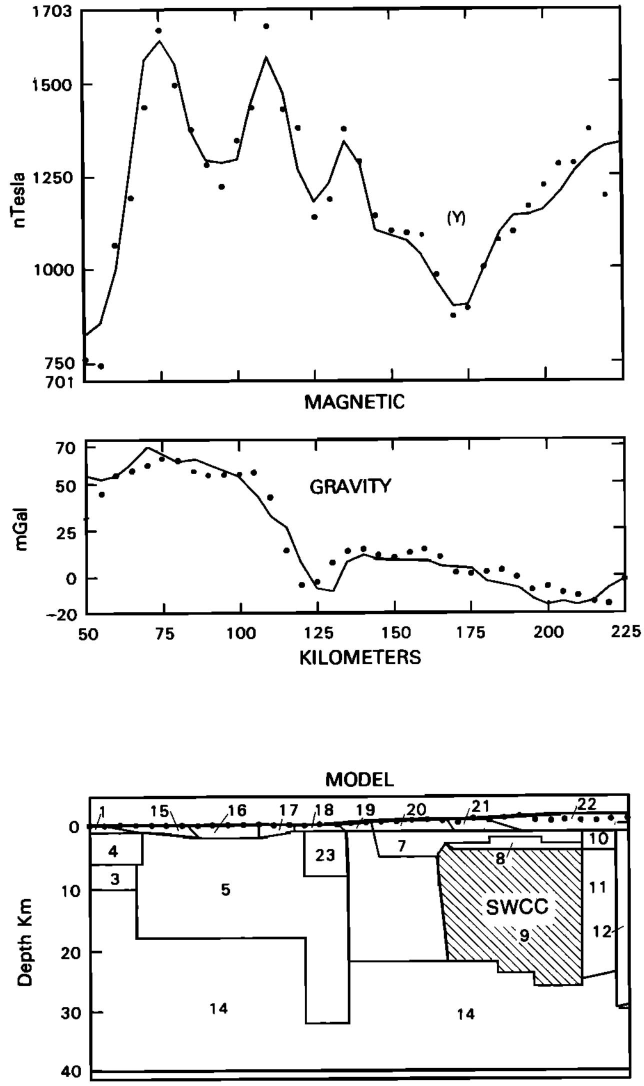

Fig. 11. Magnetic and gravity model for MT profile CC′. Model unit density and susceptibility values are given in Table 2.

the lower part of the figure is based upon the MT model of Figure 5, with only minor modifications to the electrical unit geometries required to satisfy the potential field data. The densities and magnetizations used to fit the gravity and magnetic data are given in Table 2.

The magnetization value of 6.0 A/m used for the hypothesized Siletzia crust (unit 5) on the profile CC′ model was transferred also to the model for AA′ to maintain consistency. Note that the gravity high on the west end of CC′ is modeled with denser rocks (unit 14, 2.85 g/cm^3) in the mid-lower crust where the MT interpretation showed conductive materials. It is also possible to fit the gravity data with the assumed Siletzia rocks making up much of the density contrast with assigned densities of greater than the 2.61 units indicated for unit 5. This shift of higher densities from unit 14 to unit 5 might be more appropriate to our arguments for electrical structures derived from the MT data, but we present the model in this manner to provide some feel for the range of possibilities in fitting the gravity data and to be consistent with the model for AA′. A density of 2.61 is used for the SWCC rocks. As noted previously, data from *Hellwege* [1982] amply illustrate that

TABLE 2. Densities and Magnetizations for Profile CC′ Gravity-Magnetic Model

Model Unit	Density, g/cm^3	Magnetization, A/m × 10^{-3}
1	2.42	1.45
3	2.48	0.00
4	2.48	1.00
5	2.7	6.00
6	2.61	4.00
7	2.59	4.45
8	2.59	4.40
9	2.63	2.79
10	2.57	4.41
11	2.67	4.08
12	2.67	4.24
13	2.85	0.00
14	2.85	0.00
15	2.11	4.98
16	2.2	0.00
17	2.0	6.00
18	2.15	1.26
19	2.56	6.50
20	2.47	0.890
21	2.33	0.00
22	2.52	4.69
23	2.48	3.29

density increases (and porosity decreases) rapidly in sandstones and shales with depth down to about 3–4 km where values typical of those used in our model for the SWCC occur. Of considerable significance is the fact that intermediate magnetizations (2.78 A/m, Table 2) were required to fit the magnetic profile in the area of the SWCC. These values suggest that the SWCC rocks are reasonably abundant in magnetic minerals in the area of profile CC′. This is a key piece of information that constrains possible lithologies in the conductive rocks of the SWCC.

The possibility that the SWCC units are volcanic was reconsidered in light of results from the magnetic modeling which required these rocks to have significant magnetizations. The resistivities of the SWCC rocks (1–4 ohm m) would require volcanic rocks to be highly altered, but highly altered volcanic rocks normally have low susceptibilities because of the destruction of magnetic minerals. Most sedimentary rocks have very low or negligible magnetizations, with the exceptions of black shales and slates. Many black shales are highly enriched in metal content, with iron minerals being a typical major constituent of such shales [*Vine and Tourtelot*, 1970]. Studies of black slates of the Allsbury Formation by *Ekren and Frischknecht* [1967] show them to be the cause of magnetic highs, even when surrounded by crystalline rocks, generally thought of as sources for magnetic anomalies. The slates were also very conductive. A more relevant study has been done of black shales of Paleozoic age in the Calico Hills area of Nevada by *Baldwin and Jahren* [1982], where it was found that nonmagnetic iron pyrites were converted to magnetite during hydrothermal alteration with the result that the black shales had average magnetizations of 3.89 A/m. *Jödicke* [1985] has found that metaanthracite bearing black shales in Germany have resistivities of less than 1 ohm m in some sections and low magnetic susceptibility. He discussed other pyrrhotite-rich black shales, however, that cause magnetic highs in the Lammersdorf region of Germany. We believe that the magnetic modeling results weight the possible SWCC lithologies toward black shales because of the very low resistivities and the significant magnetizations. Some carbonaceous shales occur in the lower, transitional marine part of the Puget Group in the Carbonado region northwest of Mount Rainier, and the Eocene marine McIntosh Formation mapped in the western part of the study area contains dark gray siltstone and claystones with interbedded tuff zones and carbonaceous layers [*Snavely et al.*, 1981].

Seismicity Patterns

A review of cumulative seismic activity for the years 1970–1978 [*Crosson*, 1983] reveals a clear separation of seismic patterns associated with the Puget Sound region and another pattern associated with the Mount St. Helens–Mount Rainier region. The aeromagnetic data discussed in the previous section have delineated significant magnetic anomalies that correlate with the seismicity and conductivity data (Figure 9). Dense concentrations of seismicity have been recorded at Mount St. Helens and at Elk Lake [*Grant et al.*, 1984], and the cumulative data set defines a northwest trending belt extending from southeast of Mount St. Helens to approximately 60 km northwest of Elk Lake, which Weaver calls the SHZ. These events occur at depths most typically of 5–15 km. The SHZ crosses MT profile AA′ between MT soundings 7′ and 6′ (Figure 3).

Another quasi-linear concentration of seismic events occurs to the northwest of Mount Rainier, following the axis of the aeromagnetic low (Y) and the trend of the conductivity anomaly (Figure 9). A large number of shallow earthquakes (2–5 km) have been recorded near Mount Rainier. These shallow events are probably caused by crustal loading of the large thickness of volcanic rocks in the Mount Rainier massif (C. Weaver, verbal communication, 1986) and the data base represented in Figure 9 has had earthquakes shallower than 5 km deleted. There is a gap in the MT data in the area of Mount Rainier National Park, so the exact trend of the conductivity anomaly in this area is not known. Contours are dashed to show this uncertainty, as they are in the region west of Mount St. Helens.

We suggest that the strike-slip zone active in the Mount St. Helens region (SHZ) is located at the western margin of the SWCC precisely because this postulated accretionary contact allows the slip component of oblique subduction to be accommodated most easily here. The step at the west margin of the SWCC between MT soundings 7′ and 6′ (Figure 3) may be either an imbricate zone or a normal displacement, but clearly it is a locus where slip motion occurs more easily than elsewhere in the general area. The linear belt of seismicity west of Mount Rainier occurs within the SWCC. The fact that the seismicity west of Mount Rainier appears to correlate with anomaly (Y) and the anticlines mapped by *Hammond* [1980] suggests that this may be an internal zone of compression in the basin rocks. Further investigations of the relationship of the seismicity to observed details in the other geophysical data will require more extensive surface observations and additional testing of possible mechanisms. However, in the absence of mapped surface faults that correspond to the seismicity patterns, the geophysical surface measurements offer the best clues as to the mechanisms behind the patterns.

LOCATION OF MOUNT ST. HELENS AND MOUNT RAINIER

The spatial arrangement of the three volcanoes, Mount St. Helens, Mount Rainier, and Mount Adams is interesting because of the fact that Mount St. Helens is located to the west of the general trend of the Cascades volcanoes as defined by the line formed by Mount Hood–Mount Adams–Mount Rainier (Figure 1). It is possible that magmatic activity at Mount St. Helens is localized by the same factors localizing the relief of slip stresses in the SHZ. *Weaver et al.* [this issue] point out that the deepest earthquakes beneath Mount St. Helens indicate that magma transport probably originated along a zone of weakness that is preferentially oriented with respect to the regional tectonic stress.

Although we had not previously obtained MT data in Mount Rainier National Park to enable study of the relationship of Mount Rainier to the SWCC feature, in the summer of 1986 detailed MT soundings were completed along an east-west profile just north of the park. These data have not been completely interpreted but do show that Mount Rainier is located on the exact eastern edge of the SWCC. Another 1986 profile completed south of Mount Rainier National Park shows that the SWCC is bounded on the east by the Tatoosh pluton complex just south of Mount Rainier. Thus we propose that there are fundamental tectonic controls of the location of both Mount St. Helens and Mount Rainier related to the accretionary history of the region.

Fox and Engebretson [1983] have interpreted Miocene through Holocene regional stress patterns in the Washington–Oregon region using fold orientations, basin-and-range structures and photoelastic modeling. The compressive stress trajectories for the North American plate–Juan de Fuca plate interaction derived by Fox and Engebretson show a remarkable agreement with the trend of the two linear seismic belts at Mount St. Helens and Mount Rainier. Their trajectories predict that right-lateral strike slip should turn from northwest to more northerly in the vicinity of Mount St. Helens and at Mount Rainier may even trend back to the east from north. When these predicted shear trajectories are coupled with our evidence for accretionary boundaries in roughly the same orientation, the preferential location of post eruptive seismicity does not seem surprising.

Summary and Conclusions

Conductive rocks responsible for a southern Washington Cascades conductivity anomaly may range over 15 km in thickness and extend to depths of as much as 25 km. On the basis of estimated resistivities (1–4 ohm m) and published paleotectonic models for the region we postulate that the low-resistivity rocks partially represent a compressed forearc basin/accretionary prism complex of Eocene or pre-Eocene age. The complex may have been trapped and compressed against the craton during accretion of Siletzia. We prefer to assume that the low-resistivity rocks represent a marine forearc basin/accretionary prism complex, with the high probability that some of the shallower units consist of post accretion marine sedimentary rocks and possibly carbon-rich continental sediments.

We have tried to give due consideration to other possible lithologies, and our order of preference for the probable lithologies is (1) marine sedimentary rocks of pre-Eocene and Eocene age, mostly shale facies, (2) Tertiary continental sedimentary rocks equivalent to the Puget Group, (3) thick sequences of highly altered tuffs, and (4) graphitic and/or pyritic slates, schists, carbonates, or argillites of pre-Mesozoic age.

Unknown amounts of strike-slip faulting that may have occurred since the Mesozoic cause large uncertainties in the reconstruction of the tectonic setting in which the conductivity anomaly formed. Magnetic anomalies and patterns of seismicity combine with the magnetotelluric interpretations to provide additional constraints on the region's tectonics and possible factors in controlling the location of Mount St. Helens and Mount Rainier.

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