PART I.

1. INTRODUCTION

A distinct middle Eocene mountain-building event has long been recognized in the Pacific Northwest (e.g., Misch, 1966). This orogeny included strong folding, widespread thrust faulting, and approximately 100-200 km of dextral slip on the Fraser-Straight Creek fault system, which is discordant to the preexisting structural fabric. The end of the short-lived event is marked by a pulse of extension in the northern Basin and Range, deep erosion to a profound regional unconformity, and establishment of the Cascade arc along a new north-south axis (Hammond, 1979).

In this review I argue that collision of an oceanic plateau, Siletzia, triggered the mid-Eocene orogeny in the Pacific Northwest (Figure 1). This idea is not strictly new: various scenarios for the formation and accretion of Siletzia and its effect on the Eocene landscape of the region have been offered and debated for many years (Heller et al., 1987; Simpson and Cox, 1977; Wells et al., 1984). Only recently, however, has the true nature of Siletzia become evident. At the same time, detailed structural and geochronological studies have largely disproved the paradigm that transtension dominated the entire Eocene history of the region. These developments are not widely appreciated, but they require reassessment of regional tectonic models.

This study began as an attempt to better understand the complex pattern of active structures in the region. The tectonics of Washington have previously been interpreted as resulting from strike-slip fault interactions: mostly transtensive in the middle Eocene and transpressive at present. Resolving the variously fault linkages, however, becomes awkward: roles of individual faults must be assigned on an ad hoc basis and are not regionally consistent (Johnson et al., 1994; Stanley et al., 1996). Both middle Eocene and neotectonic features, however, are consistent with distributed contraction across an oblique margin.

2. SILEZTIA: ORIGIN AND HISTORY

2.1. Nature of Siletzia

Siletzia includes a number of mainly basaltic units, their intrusive equivalents, and subordinate interbedded sedimentary rocks. Microfossils and Ar-Ar dates suggest that the terrane formed c. 62-49 Ma (Duncan, 1982), with dates of c. 55-51 Ma particularly well represented (Pyle et al., 1997). Siletzia is bounded below by thrust faults and structurally above, variously, by thrust faults, oblique/strike slip faults and an unconformity of early to middle Eocene age. The definition of Siletzia as a terrane specifically excludes younger volcanics of the Coast Ranges that can be shown to have erupted in a forearc setting, after accretion of the older basaltic basement (Wells and Heller, 1988). In contrast to interpretations that Siletzia formed in-place (Babcock et al., 1994), it also excludes most of the sediments overlying the basaltic basement, which are overlap assemblages. The cutoff is about 48-49 Ma, i.e. earliest middle Eocene (Garver and Brandon, 1994). A 45 Ma date emphasized by Babcock et al. (1994) for a sample from Hurricane Ridge Road on the northern Olympic Peninsula is anomalous and likely reset; if accurate it complicates but does not disprove the definition of Siletzia as a terrane.

Siletzia in Oregon is dominated by thick sections of pillowed flows and breccias shoaling upsection, locally culminating in subaerial basalts. The basalts are mostly subalkalic and silica-saturated, becoming alkalic high in the section (Snavely et al., 1968). Seismic refraction studies demonstrate that the crust is thick (20-30 km) and mafic (Shor et al., 1968), similar to the crust of the Ontong-Java plateau of the southwest Pacific (Trehú et al., 1994). This part of Siletzia presently seems to be translating northward as a more or less coherent block, but paleomagnetic and structural studies suggest it is moderately distorted and internally strained (Graven, 1990; Wells and Heller, 1988). Northeast-trending fold axes predominate (Graven, 1990); the Oregon Coast Range is a relatively young north-south anticlinorium (Beeson et al., 1989). In Washington the basaltic terrane appears to thin somewhat and is complexly folded about NW-SE, NE-SW (?) and east-west axes. It is also cut by a number of major faults into large blocks (Figure 2) that are themselves internally strained (Wells and Coe, 1985).

In the northeastern Olympic Peninsula the otherwise laterally continuous Crescent basalts are interrupted by a thick section of conglomerate and sandstone, in part basaltic. This section appears to represent a persistent paleochannel between two separate basalt sections (Babcock et al., 1994). The break is marked by a prominent gravity low; to the south the basalts become thicker and in part subaerial (Figure 2). The paleochannel is mapped as an upward continuation of the Blue Mountain unit, which generally underlies or is interbedded with the lower Crescent Formation around the entire "horseshoe" of the Olympic Peninsula (Tabor and Cady, 1978). The lower Blue Mountain unit has resisted dating, but is presumed to be Paleocene, and represents the seafloor sediments onto which the Crescent basalts erupted. Its basement is conspicuously missing, but may be represented by a prominent mafic wedge in the lower crust or upper mantle below Puget Sound and southern Vancouver Island (Clowes et al., 1987; Stanley et al., 1999).

Massey (1986) interpreted the Metchosin complex of Vancouver Island to be an incomplete but unusually thick ophiolite, analogous to Iceland. His "sheeted dikes" are very suggestive but perhaps not conclusive evidence of seafloor spreading. Muller (1979) earlier favored an Icelandic, “ridge-island” origin for the Metchosin, based on trace element geochemistry, the overwhelmingly marine character of the volcanics, and evidence for widespread emergence high in the section. Based on gravity surveys, the Metchosin complex is continuous below the Straight of Juan de Fuca with the Crescent basalts of the northern Olympic Peninsula, and is their probable source. The Crescent Formation seems to represent the progressively erupted margins of large edifices erupted elsewhere.

The thinner submarine basalts west of the Blue Mountain paleochannel are presumably the distal edge of the Metchosin complex, while the rather thicker and partly subaerial section of the eastern Olympics thickens southward and may be have been erupted from the south or east, perhaps the Bremerton area (Massey, 1986).

There is some consensus that Siletzia basalts were generated, at least in part, by a hot spot. All three possible eruptive settings discussed by Wells et al. (1984)--at a spreading center, along leaky transform faults, or in a marginal rift--involve a hot spot. Large ion lithophile element (LILE) and helium-3 enrichments (mantle plume signatures) increase steadily from the Metchosin southward to the Siletz River volcanics (Babcock et al., 1994; Pyle et al., 1997). The great thickness of Coast Range basalts, which also increases southward, appears to be mostly primary. Despite locally intense deformation (Baldwin and Perttu, 1980; Wells and Coe, 1985), pervasive structural thickening has not been demonstrated. A fairly consistent section 3-10+ km thick has been mapped around the Olympic Peninsula and on Vancouver Island (Massey, 1986; Tabor and Cady, 1978).

Siletzia appears to be an accreted oceanic plateau, although it may contain subordinate tracts of normal to transitional oceanic crust as well (Trehú et al., 1994). Most oceanic plateaus are flood basalts, which are more politely known as Large Igneous Provinces (LIPs). The largest flood basalt provinces appear to result not merely from the influence of a hotspot, but the initiation of one (Richards et al., 1989). Because they are so inaccessible and difficult to date, the significance of oceanic flood basalts was not appreciated as early as continental flood basalts. The huge volume and petrologic similarity of Siletzia basalts to the Miocene Columbia River basalts, however, had been noted much earlier (McKey, 1972). Babcock et al. (1995), in suggesting that Siletzia was a Large Igneous Province, considered that it formed in a forearc setting. Pyle et al. (1997), however, favored an open ocean setting.

The preserved area of Siletzia is somewhat greater than that of the Columbia River Basalt Group. Because they built up in deep water and were less free to flow, Siletzia basalts are generally thicker, and their volume substantially greater (the extrusive volume may be on the order of a million cubic kilometers). Furthermore, Siletzia appears to be sharply truncated on its seaward side (Brandon and Vance, 1992; Snavely and Wells, 1989; Trehú et al., 1995), so that it may have been rather larger. Davis and Plafker (1986) suggested that the Yakutat terrane, presently accreting to the soft underbelly of Alaska, quite likely originated at the latitude of Washington; its age and stratigraphy, so far as is known, are very similar in all respects to the Crescent Formation.

Numerous workers have noted that Siletzia may have formed over the Yellowstone hot spot, which in the early Eocene should have lain just west of what is now Cape Mendocino (Engebretson et al., 1985). The Yellowstone hot spot, however, may not have originated until 16-17 million years ago, marked by the Steens Mountain basalt-rhyolite sequence (Alt et al., 1988; Hooper et al., 2002). If the Siletzia hot spot is not the Yellowstone hot spot, the two should have distinct tracks within western North America. This is not clearly the case, and resurgence of a hot spot to form a second flood basalt remains an attractive and significant possibility. If the Siletzia and Yellowstone hot spots are one and the same, and the hotspot was fixed, Siletzia presumably migrated north several hundred kilometers latitudinally before and during accretion. Slight systematic flattening of paleomagnetic poles supports this, albeit not very conclusively (Beck, 1984).

2.2. Accretion of Siletzia

Siletzia is deeply underthrust both below rocks of the Klamath Mountains as well as those of southern Vancouver Island. In southern Oregon the suture appears to be a subduction zone that failed in the early to middle Eocene (Baldwin and Perttu, 1980; Heller and Ryberg, 1983). Accretion was partly accommodated by strike slip on the ENE-striking, dextral Canyonville fault, which Perttu (1976) suggested might bend northward and feed into the Straight Creek fault. This is probably not the case, because the Canyonville fault appears to be a little older than the Straight Creek fault, but the suggestion was a perceptive one. The Tyee Formation was deposited across the suture, with little subsequent displacement. Ages from fossils and laser Ar-Ar dates on detrital white mica show that the beginning of the Tyee deposition was 49-46 Ma (Heller et al., 1992); detrital zircons in the Tyee are as young as c. 45 Ma (Wooden et al., 1999).

On the north side of the Olympic Peninsula, coarse detritus of the Aldwell and Lyre Formations (late Narizian, c. 44-42 Ma) was mostly derived from terranes of southern Vancouver Island (Shilhanek, 1992). Underthrusting of the Metchosin complex beneath southern Vancouver Island appears to have caused uplift of the hanging wall and deposition in a foredeep (England and Calon, 1991; Garver and Brandon, 1994). Small igneous bodies, mostly quartz diorite, intruded rocks on both sides of the Leech River fault, the presumed suture, at about 43-39 Ma (England et al., 1997; Muller, 1979). The suture is beveled and overlain by Oligocene strata.

Younger strata obscure the eastern margin of Siletzia. Seismic refraction studies, however, suggest that the thickest part of the terrane extends well under the western Cascades of southwestern Washington and Oregon (Stanley et al., 1992; Trehú et al., 1994), forming a "shoulder" that seems to be echoed in arcuate magnetic trends inland (Figure 3). In southern Washington, middle Eocene forearc sediments interfinger with both hot-spot related Goble volcanics and the early Cascade-derived Northcraft volcanics (c. 39 Ma), so that accretion was largely complete by that time (Wells and Heller, 1988). The Grays River volcanics (Siletzia) are much more strongly deformed than the Goble volcanics.

In contrast to the moderate and fairly uniform rotations of the Goble paleomagnetic poles, those from the Grays River are much more variable and appear to define blocks bounded by major faults (Wells and Coe, 1985). These include north-striking fault zones that accommodated both dextral shear and contraction, and WNW-striking faults that Wells and Coe (1985) interpreted as sinistral R' shears.

The stratigraphy of the east side of the Olympic Peninsula and the Puget lowland suggests that as the Crescent basalt pile thickened, its height increasingly isolated it from continent-derived sediments. At about 52 Ma, however, the plateau submerged to mid-bathyal depths, and about 750 meters of Penutian and Ulatisian sediments accumulated unconformably upon it (Johnson et al., 1994). This likely represents approach and impingement of the plateau on the early Eocene trench. This trench appears to be defined by a wedge of late early to middle Eocene marine sedimentary and volcanic rocks between the gently dipping top of Siletzia and the pre-Tertiary basement of the Cascade Range (Figure 4). Where exposed, these rocks are similar to rocks of the Klamath-Roseburg suture: the older sandstones, deposited in deeper water, are very strongly deformed, while younger shallow marine and terrestrial deposits are progressively less deformed (Frizzell et al., 1984).

Seismicity and high-velocity crust typical of Siletzia continue to the western side of the Cascades and the end of the Seattle fault, suggesting that Siletzia dips gently to the east, about parallel to the Juan de Fuca slab (Figure 4, top). The reactivated backstop most apparent at Duvall appears to continue to the south under the western foothills of the Cascade Range (Figure 4, bottom). Stanley et al. (1988) suggested that the upper crust between the western Rainier and Saint Helens seismic zones, which has high conductivity and low density, might represent a late Cretaceous to early Tertiary accretionary wedge, and that Siletzia dipped gently underneath it along a failed subduction zone.

Originally it was thought that Siletzia either accreted in a "barn door" fashion from south to north, or accreted to a northwest-trending coast line, then rotated clockwise (along with the Blue Mountains) in front of the expanding Basin and Range (Simpson and Cox, 1977). Neither end-member model is entirely successful, and thus Wells and Heller (1988) proposed a model that included aspects of both but is dominated by distributed shear both during and after accretion. This hybrid accounts well for regionally varying clockwise paleomagnetic rotations, and is compatible with the geologic and paleomagnetic record. A somewhat surprising and critical constraint is a study of the paleomagnetism of the early and middle Eocene Clarno Formation in the Blue Mountains (Grommé et al., 1986), which seems to demonstrate that that the Clarno has rotated less than about 20°. Jurassic and Cretaceous batholiths in the Blue Mountains, in contrast, are rotated about 66° (Mankinen and Irwin, 1990). Apparently a significant proportion of the rotation of the Blue Mountains and extension of the Basin and Range province predates the Clarno Formation.

The Clarno Formation in fact appears to consist of two superficially similar volcanic sequences of distinctly different age (Bestland et al., 2001). The older, distinguished by dacites, yields familiar "Challis" dates of 53-51 Ma. The younger sequence yields dates similar to the Naches/Roslyn sequence: c. 43-39 Ma. According to Bestland et al. (2001), an unconformity separates the two sequences, but many details of structure and stratigraphy remain to be worked out. It is unclear which sequence is better represented in the data used by Grommé et al. (1986), who also underestimated the structural complexity and locally steep dips of Clarno rocks, which might permit a rigorous fold test. These problems aside, the paleomagnetic study appears sound, and it seems very likely that a little recognized episode of pre-Middle Eocene extension is largely responsible for the distorted structural pattern of the Cordillera of the western United States (Wise, 1963). Such an episode has been suggested by Hodges and Walker (1992), based on a number of independent studies showing mid-crustal attenuation faulting of broadly Sevier to Laramide age. Alternatively, if the older (53-51 Ma) Clarno rocks are not well represented in the paleomagnetic studies, much of the rotation of the Blue Mountains could be early-Middle Eocene (Grommé et al; Wells and Heller, 1988).

The terrane belts of Canada appear to end abruptly in northern Washington, forming a long west- or WNW-striking buttress (McGroder, 1991; Monger, 1984; Umhoefer and Miller, 1996). In contrast, the Eocene margin in Oregon appears to have trended northeast (partly corresponding to the Klamath-Blue Mountain lineament of Riddihough et al., 1986). The intervening wedge-shaped area is the Columbia embayment, which has generally been attributed to oroclinal bending. However it does not appear possible to fully “unfold” the Columbia embayment, or to completely straighten the Cretaceous coastline (Dickinson, 1976; Wells and Heller, 1988). Since the Blue Mountain trend appears to have been largely established by the middle Eocene, it seems likely that the early Eocene margin had a cuspate-lobate form. Subduction zone cusps are common, and appear to have some association with oceanic ridges of one sort or another. In this case the cusp might have been a triple junction (trench-spreading ridge-trench) between the North American, Farallon, and Kula Plates. Possibly the Columbia embayment formed progressively as "Baja British Columbia" moved northward and the proto-Basin and Range expanded behind its trailing edge (Figure 5). Or, if one does not believe in Baja B.C., the pattern may be attributable to steady ridge subduction at the Columbia embayment, with back-arc extension to the north and south. When Siletzia accreted it may have trapped a fragment of more normal oceanic crust along its inboard edge. This might help explain the prevalence of ultramafic xenoliths and the unusual, oceanic island-like chemistry of many of the volcanic rocks of the southern Washington Cascades (Leeman et al., 1990).

2.3. Discussion

The long-standing seamount vs. marginal rift debate over the origin of Siletzia is somewhat moot if Siletzia is mostly an oceanic flood basalt (Pyle et al., 1997; Trehú et al., 1994).

While the term "seamount" is a vague one, discussions of the origin of the Coast Range basalts carry the usual connotation of isolated, sequentially erupted volcanoes. Such volcanoes built on normal oceanic crust are somewhat subductable, and if accreted are typically strongly deformed and imbricated with accreted sediments. This may be somewhat applicable to basalts at the southern margin of Siletzia (Baldwin and Perttu, 1980), but not to the terrane as a whole.

Preliminary age dates of Coast Range basalts were somewhat symmetrically distributed, tending to be oldest (up to 62 Ma) in the north and south, and younger toward southwestern Washington. Duncan (1984) surmised from this that the basalts erupted from a hot spot under the Kula-Farallon spreading ridge, with plate motions carrying the older centers away from the hot spot. An analogy is the V-shaped pair of seamount tracks emanating from the Cocos ridge (Figure 6). Wells et al. (1984) thought that given the high rates of Kula-Farallon spreading, the resulting chains of seamounts would be too long to fit conveniently into the present outcrop belt.

More recent dating suggests that most of the Coast Range basalts are 55-51 Ma in age (Pyle et al., 1997), so that even the unusually rapid rates of Kula and Farallon plate motion were probably not sufficient to outrun the continuing effusive volcanism. Thus the geometric arguments of Wells et al. (1984) against collision of a long linear seamount chain are not strictly applicable. Flood basalts are so voluminous and erupt over such a wide area that the end result is not strongly dependent on plate tectonic setting.

The hallmark of an oceanic plateau is constructional volcanism that progrades more rapidly than plate motion. Ridges and transforms may localize volcanism, and almost certainly did in the case of Siletzia (Wells et al, 1984), but age progressions will not be as neat as originally envisioned. It should be noted that the timing of Siletzia basalt eruptions appears to have been very similar to that of the North Atlantic Tertiary Province, also a LIP (O'Connor et al., 2000). This implies that mantle plumes may have played a role in Paleocene-Eocene plate reorganizations.

While the exposed outcrops of Siletzia basalts are now rather linear, paralleling the active margin, geophysical surveys suggest an original distribution more reminiscent of a fried egg (Trehú et al., 1994; Wells et al., 1998). The thickest section is centered on the Siletz River volcanics in northwestern Oregon (see Figure 3). As with the Columbia River basalts it is not surprising that the younger, more evolved and less voluminous lavas should be mostly restricted to the center of the province, and as one moves outward one encounters older units until their base is reached. In the case of the Coast Range basalts, it seems possible that the oldest dates(c. 62 Ma) represent normal oceanic crust onto which the flood basalts erupted.

A pure marginal rift model for Siletzia, although popular, appears to be untenable. The basalt section is enormously thick, becoming alkalic and subaerial; rifts generally show the opposite trends. Based on analogy with the Andaman Sea, Brandon and Vance (1992) suggested that the early Eocene arc lay to the west, and that Siletzia formed in a back-arc setting. However, no evidence of west-derived arc detritus has been presented, and paleocurrent studies indicate transport was generally from the east or north (Shilhanek, 1992; Wooden et al., 1999). With the exception of the Blue Mountain paleochannel, there is in fact little sediment interbedded with the basalts, hardly typical of marginal basins. Direct evidence of rifting is conspicuously absent: there is no suggestion of fault controlled deposition of the Blue Mountain unit; nor have any large intrusive complexes been mapped crosscutting it (Tabor and Cady, 1978). The Blue Mountain unit itself was deposited in a deep marine setting, perhaps hundreds of kilometers from the coast. Voluminous latest Cretaceous and early Tertiary sediments on Vancouver Island and in northwestern Washington suggest that the sediment supply was considerably greater than today; like today a trench was unlikely to have presented an obstacle to the progradation of deep sea fans.

Feeder dikes for the lower Siletz River basalts trend mostly north (Snavely et al., 1968). Given paleomagnetic evidence for strong, post-accretion rotation of the Coast Range (Simpson and Cox, 1977), the original orientation was presumably northwest. This is not at all the orientation that would be expected for dikes in an oblique marginal basin. If similar to early Eocene dikes inland, these would have originally trended NNE and should now be oriented roughly east-west. Originally northwest-striking dikes are perhaps compatible with slab-pull forces in the Farallon plate.

A hot spot initiating through the Kula-Farallon slab window is a plausible alternative to an external origin for the terrane. It shares some of the apparent shortcomings of the pure rift model, but one can envision something like an Iceland forming above a hotspot and a subducting ridge. This might have occurred in a forearc setting, although a backarc setting would be more thermally favorable. Rapid extrusion of basalts could have formed platforms that diverted coarse sediments into major channels, allowing the more widespread accumulation of limestones and finer clastics.

The “rift plateau” hypothesis for Siletzia is the most viable alternative to the external plateau origin. It is not clear that there is good modern analogue, however, and the model seems somewhat contrived. An external origin for Siletzia is the simplest one. There are a number of examples of plateau collision, notably those involving the Ontong-Java plateau and the Caribbean platform. The process is not identical to continental collision, but capable of similar effects (Petterson et al., 1997). Given the prevalence of oceanic plateaus it should be quite common, and it has probably been a major contributor to the growth of continental crust (Condie, 1997; White et al., 1997).

Contrary to the assertion of Babcock et al. (1994), there is evidence in the form of regional scale melanges that the continental margin formerly lay inboard of Siletzia (Frizzell et al., 1987). There is no clear evidence that Siletzia was part of North America prior to the middle Eocene. The interpretation of Siletzia as an oceanic plateau obviates geometric arguments that it could not be an external terrane. Accretion of a relatively thick, buoyant oceanic plateau during rapid plate convergence might be expected to have dramatic structural consequences.

3. THE MIDDLE EOCENE EVENT

Geologists in the Pacific Northwest quickly recognized a major unconformity that beveled Eocene and older rocks, which are typically strongly folded and faulted. Much less deformed Oligocene and younger strata typically cap the unconformity. Mackin and Cary (1965) emphasized the regional significance of this unconformity, which is still preserved as gentle upland surfaces on the east flank of the Cascade Range. They called the beveled Eocene mountains the "Calkins Range" (Figure1). Growth of the Calkins Range is best recorded by an ESE-striking belt of Paleogene strata that stretches across southern Vancouver Island, northern Puget Sound and the Straits of Georgia, and the central Washington Cascade Range. This preserved belt of Paleogene rocks is offset by the partly coeval Straight Creek-Fraser fault system.

3.1 Central Washington Cascades

Deformation associated with the Straight Creek fault began about 49-48 Ma (see Evans, 1994 for discussion). Strong, rapid folding of the Swauk Formation, including the Silver Pass/Taneum volcanics (51-53 Ma) was followed in short order by eruption of the Teanaway volcanics. At first folding and dike emplacement were quite pervasive (Tabor et al., 1982). Near the Straight Creek and within the Olympic Wallowa line (OWL) the Teanaway volcanics were subsequently folded more or less concordantly with the older rocks, apparently reflecting the initiation and concentration of strain on throughgoing faults (Figure 7).

Near the Straight Creek fault zone folds are dragged and tightened, exposing windows of Easton schist and Chilliwack or Cultus equivalent rocks (Ashleman, 1979). Here the Cretaceous Shuksan thrust is itself tightly folded, suggesting that the mid-Eocene orogen is rather thick-skinned.

Dramatic folding across the OWL began after the Teanaway eruptions and persisted at least through deposition of the Roslyn Formation, the basinal continuation of the more volcanic-rich Naches (Figure 8). Fault fabrics within the Taneum Lake shear zone and the frontal Easton Ridge thrust suggest mostly reverse motion with a subordinate left-lateral component, as do the slightly oblique (left-stepping) folds associated with the faults (Figure 9). The Naches Formation and correlative units, deposited c. 43-41 Ma, are less deformed than the early Eocene strata. Although strongly wrenched, the Naches overlaps the trace of the Straight Creek fault with little apparent strike-slip offset (Vance and Miller, 1994), so that the orogeny was waning by this time.

The Chiwaukum basin is a compound syncline (Figure 7). Its basal strata are directly equivalent to the Swauk Formation (Cheney, 1994; Gresens et al., 1981). The basin has a cryptic early history perhaps dominated by extension (Evans, 1994). In the middle Eocene, during deposition of the bulk of the Chumstick Formation, the Chiwaukum basin was a dominantly contractional structure (J.E. Powell and R.D. Bentley, unpublished mapping, 1982). Basement-involved folds within the basin are parallel to the southwestern margin of the basin, defined by the Leavenworth fault, which is in turn perpendicular to the Teanaway dike swarm (Tabor et al., 1982). Slip on the Entiat fault, which strikes a little more northerly, appears to have been oblique (Evans, 1994), with a strong component of contraction. Cooling ages of the uplifted Entiat Mountains to the northeast are essentially identical to depositional ages of clasts derived from there, implying rapid uplift (Evans, 1994; Tabor et al., 1982). By the late middle Eocene, deposition outpaced slowing deformation, overtopping the east-facing Leavenworth fault scarp, and throughgoing, west directed drainage was reestablished (Evans, 1994). The overtopping strata of the upper Chumstick Formation appear to be equivalent to the Roslyn Formation, and may have been coextensive (Gresens et al., 1981).

Folds in the Columbia River basalts that are controlled by the Entiat, Eagle Creek, and Leavenworth fault zones all appear to bend southward near the Columbia River and parallel the Straight Creek fault (Tabor et al., 1982). Although this may reflect the interference of two intersecting fault systems, it also seems possible that the Entiat fault acted as a minor splay of the Straight Creek fault. In this case the Chiwaukum basin originated as a compressional step-over between the Straight Creek and the north-south striking faults.

3.2. Coast Mountains/North Cascades

In the Coast Mountains of British Columbia, the Fraser fault (the northern continuation of the Straight Creek system) cuts an extensional complex that appears to be offset from the Ross Lake fault zone in Washington; U-Pb dating of the complex suggests displacement on the Fraser fault is no older than 46 Ma (Coleman and Parrish, 1991).

In the Chelan block of the North Cascades of Washington the Straight Creek cuts gneisses with mid-Eocene cooling ages and lineated granitic dikes dated with U-Pb at c. 45 Ma. The gneisses display tight ductile folds, with northwest-trending fold axes and a strong stretching lineation parallel to the fold axes. The dikes are similarly lineated, but much less deformed, suggesting they are late kinematic with respect to uplift of the core but perhaps synchronous with initial displacement on the Straight Creek fault (Haugerud et al., 1991). Cooling dates from the Chelan block are in contrast with those from the rest of the North Cascades crystalline core, which generally cooled by the late Cretaceous to Paleocene. McGroder (1991) suggested that this portion of the crystalline core forms an anticlinorium that brought up rocks from mid-crustal depths as late as the middle Eocene.

Further east in the Chelan block, Miller and Paterson (2000) describe foliations and shear zones in greenschist to amphibolite facies rocks that were active between 48 and 46 Ma. Lineations in the shear zones are subhorizontal. Both dextral and sinistral fabrics are present, but the latter predominate. The authors suggest that strong NE-SW shortening and NW-SE extension rotated conjugate shear zones into parallelism. It should be noted that very strong shortening allows conjugate shears to form at low angles to one another (i.e. escape or "pumpkin-seed" tectonics). The dominance of left lateral fabrics implies some component of shear strain. Strain indicators in these rocks are not entirely consistent, and there is some suggestion that crustal thickening and collapse on similarly striking faults may have been synchronous (Miller and Paterson, 2000). Very dynamic and short-lived tectonism is implied.

Pseudotachylites and cataclasites in the structurally higher Chiwaukum schist of the Wenatchee Mountains are mostly left lateral in sense (Magloughlin, 1993). These northwest-striking, post-Paleocene fabrics may be R' shears antithetic to the Straight Creek fault, and would be consistent with distributed north-south dextral shear superimposed on the NE-directed compression. That the pseudotachylites are not associated with large throughgoing faults suggests a short-lived, unstable event.

3.3. Northwest Cascades

West of the Straight Creek fault, the lower Chuckanut Formation (Paleocene? -early Eocene) shows little evidence of fault-controlled deposition (Evans and Ristow, 1994). Higher in the section reversing and fault-parallel paleocurrents suggest initiation of motion on the Straight Creek fault and Darrington-Devils Mountain fault zone early in the Middle Eocene. Evans and Ristow (1994) demonstrate that deformation on the fault system was mainly 48-42 Ma. Similarly, Vance and Miller (1994) showed that major strike-slip on the Straight Creek was c. 48-41 Ma. The younger age limit is based on dates of the Barlow Pass volcanics (which are partly correlative with the Naches Formation and similarly overlap the Straight Creek fault with little offset) as well as two rough sedimentary pins. Upper Eocene kyanite-bearing sands on the west side of the fault are still adjacent to their source in the Chiwaukum schist on the east side of the Straight Creek, and conglomerates rich in clasts of Marblemount quartz diorite are not much displaced from that source.

Chevron-style folding and reverse faulting are ubiquitous in the lower-middle Eocene Chuckanut Formation (Misch, 1966). In several areas the deformed Chuckanut sediments are clearly detached from their basement along a gently dipping thrust fault (Dragovich et al., 1997; Misch, 1966). This is also the case east of the Straight Creek fault, where the basal Tertiary contact is typically faulted (Ashleman, 1979). In both areas the detachment locally cuts the early Eocene strata at high angles. This geometry is difficult to reconcile with a compressional origin, suggesting that the detachments may be reactivated normal faults. The Swauk and Chuckanut were deposited at the same time extensional core complexes in the Okanogan highlands were active, and the Swauk is interbedded with and unconformably overlain by intermediate to silicic igneous rocks very similar to those associated with extension in the Okanogan (Cheney, 1994; Fox, 1994).

Basement-involved Eocene folding west of the Straight Creek fault appears to be largely responsible for updoming of the Mount Baker window; similar fold interference patterns are much in evidence throughout the northwest Cascades-San Juan system. The apparent involvement of the late Cretaceous Nanaimo Group in the otherwise high pressure, mid-Cretaceous San Juan thrust system appears due to the much later Eocene thrusting of Nanaimo basin strata back over their source rocks in the Eocene (England and Calon, 1991).

Evans and Ristow (1994) suggest that the Darrington-Devils Mountain fault zone was primarily left lateral, antithetic to the Straight Creek fault, as did Whetten et al. (1980), based on offset of pre-Tertiary units. Fault patterns in northern Puget Sound suggest a very large component of sinistral slip (Mosher et al., 2000).

3.4. Vancouver Island

Strong contraction on southern Vancouver Island has been long known, and has been most thoroughly analyzed by England and Calon (1991), who used surface mapping, seismic reflection, fission track dating, and vitrinite reflectance studies. Their Cowichan fold and thrust belt includes strong NNE-SSW directed folding and listric thrust faulting that appears to have involved at least the upper 20km of crust. England and Calon estimate shortening of at least 20-30%, excluding the terrane-bounding Leech River fault. The orogen is dominated by pure contraction, without much dextral oblique or strike slip. There is some suggestion, however, of a left lateral component of motion on some faults, notably the west-striking San Juan fault (England and Calon, 1991) and the Leech River fault (Fairchild and Cowan, 1982). England et al. (1997) suggest that deformation was caused by accretion of Siletzia, here represented by the Metchosin complex. Based on a COCORP deep seismic reflection line, Siletzia appears to be underthrust to the north at least 30 km along the listric Leech River fault (Clowes et al., 1987), which bounds the Cowichan fold and thrust zone on the south. Fission track dates recording uplift and cooling appear to solidly date the Cowichan fold and thrust belt at 50-40 million years ago, with uplift culminating at about 45 Ma (England et al., 1997).

Fairchild and Cowan (1982) stated that motion on the Leech River fault is entirely younger than 39-40 Ma. This conclusion was based on limited K-Ar dates of metamorphic biotite, muscovite, and hornblende from the Leech River schist, a distinctive unit that records high temperature metamorphism culminating in garnet-staurolite-andalusite assemblages. K-Ar dates have since been shown to be unreliable indicators of age of metamorphism. The dates in this case probably record some combination of alteration, uplift, and cooling ending in the late Eocene. The dates are synchronous with the widespread suite of Mt. Washington intrusions, dominated by quartz diorite (England et al., 1997). In the Cowichan belt these intrusions did not apparently cause significant thermal metamorphism away from their immediate contacts with country rock, but they may be responsible for widespread quartz-ankerite alteration. Based on tentative correlation of the Leech River schist with the Tonga formation (Tabor et al., 1993) and Lookout Mountain unit (Miller et al., 1993), which have very similar patterns of high-T metamorphism and which occupy a similar structural position in the Cascades, I suspect that the highest grade metamorphism in the Leech River schist may be Mesozoic. However dramatic tectonites and tight folds near the Leech River fault, which were accompanied by recrystallization of biotite and locally hornblende, do suggest uplift from some depth and anomalously high temperatures in the Eocene (Fairchild and Cowan, 1982; Muller, 1979). Both the structures and cooling dates are consistent with major displacement on the Leech River fault, culminating in the late middle Eocene. It is possible that a progressive history of reverse, strike slip and perhaps normal faulting may be responsible for the complex structures and metamorphism associated with the Leech River fault.

The timing of deformation in the Cowichan belt is typical of the mid-Eocene event (c. 50-40 Ma; England et al., 1997). The uplift of the hanging wall of the Leech River fault is rather late, however. Syn-orogenic deposition on the northern Olympic Peninsula correlates with the Leech River uplift, not the earlier onset of Cowichan uplift (Garver and Brandon, 1994; Shilhanek, 1992). Perhaps the Cowichan belt was caused by subduction of the thickened Kula plate. As Siletzia migrated northward, the emergent Kula-Farallon Ridge (Metchosin complex) eventually collided with the margin, triggering rapid metamorphism and uplift of the Leech River schist. Prior to collision the Kula-Farallon ridge would have blocked southward sediment transport.

3.5. Summary

Strong, basement-involved compression from southern Vancouver Island to the east flank of the Cascades range occurred approximately 50-40 million years ago. The bulk of the100-200 km of right lateral motion on the Straight Creek fault system was 46-42 Ma (implying a slip rate of several cm/yr). Approximately coeval left lateral motion on west- or WNW-striking structures has been independently suggested by a number of geologists at locations throughout the Paleogene belt. Most major faults with this orientation, however, appear to have been dominated by late reverse motion, perhaps due to clockwise rotation into orientations more orthogonal to plate convergence. Some of these faults are very steep (>70°), which is consistent with a strike slip origin.

Although the principal strain axes implied by the middle Eocene event might not have been oriented much differently than those of the early Eocene, their magnitudes and the style of deformation appear to have been much different. In northern Washington and southernmost British Columbia the earlier Eocene record is dominated by strong NW-SE extension and margin-parallel transport on NW-striking right lateral faults. Many of the strike slip faults had been intermittently active since the Jurassic. In contrast, the Fraser-Straight Creek fault appears to have been a new break, across the structural grain, and is associated with very strong, deep-seated contractional wrenching. Such faults are typically found in collisional orogens, where they may form fairly low angles to antithetic structures. Left lateral motion on WNW- to west-striking faults such as San Juan and Devils Mountain faults, would be consistent with strong NE-directed contraction, indentation, and/or minor right lateral distributed shear parallel to the Straight Creek fault.

Motion on the Straight Creek fault system has previously been attributed to transfer of strike slip from the continental margin to the Rocky Mountain trench, allowing the core complexes of the Okanogan and perhaps a marginal basin to expand behind (Ewing, 1980; Price and Carmichael, 1986; Wells et al., 1984). However U-Pb age dates now suggest that the Straight Creek system largely postdated both the core complexes and eruption of Siletzia basalts (Coleman and Parrish, 1991; Fox, 1994; Parrish et al., 1988). While most of the Eocene record of the region was once interpreted entirely in terms of transtension, it now seems clear that there were two distinct orogenic events in Washington: an early Eocene episode dominated by extension and a middle Eocene episode dominated by contraction. Right lateral motions were important during both, but much of the deformation in both cases seems explicable in terms of pure shear. Sinistral faults appear to have been very important; the variety of orientations of these suggests unusually strong contraction as well as distributed dextral shear far into the interior.

4. EOCENE TECTONIC MODEL

4.1 Early Eocene

Engebretson et al. (1985) discussed various possible geometries of the Kula, Farallon and Pacific plate prior to the middle Eocene. Of these the "double transform" option, although somewhat peculiar in appearance, seems to best explain patterns of magmatism and terrane translation (Breitsprecher and Thorkelson, 2001), as well as the sudden onset of extension in northern Washington in the Eocene.

Regardless of the geometry preferred, by 51 Ma the large transforms would have been subducted and the Kula-Farallon spreading center would intersect the coast at about 48ºN latitude, extending under the Okanogan in the form of a wedge-shaped slab window. Voluminous early Eocene magmatism and extension inboard, becoming less pronounced toward the coast, is consistent with the notion that the extensional complexes of the Okanogan formed over the slab window. This was presumably in response to crustal coupling to the diverging Kula and Farallon slabs, and elevated temperatures above the slab window (Babcock et al., 1994). Another slab window may have lain under the Boulder and Idaho batholiths, and corresponds remarkably in outline to their area of outcrop (Breitsprecher and Thorkelson, 2001). These granites intruded in the late Cretaceous, but their rapid exhumation is early Eocene, accounting for the huge influx of muscovite-bearing sand into western Washington and Oregon (Heller et al., 1992; Wooden et al., 1999).

Siletzia at this point was immediately offshore and had begun to accrete. The Metchosin volcanics formed a large island straddling the ridge crest, but the main hotspot lay much further south. The young and vigorous hotspot, if typical, influenced an area at least 2000 km in diameter, thus perhaps explaining the coincidence in timing between the Siletzia flood basalts and the widespread, not entirely arc-like Challis volcanics and equivalents. These are dominantly felsic and occur both near the paleo-coastline (Taneum, lower Clarno) and far inland.

4.2. Middle Eocene

Accretion of Siletzia began somewhat earlier in the south than in the north. An arcuate Farallon subduction zone may have been more important than the orientation of Siletzia in determining the point of initial contact (Simpson and Cox, 1977). The slight obliquity of accretion may have caused the terrane to break into blocks. The Seattle fault and similar structures in Puget Sound appear to be steep; they may have originated as dominantly strike slip faults (Wells et al., 1984). Early deformation appears to include indentation. Rocks of the Klamath Mountains are strongly distorted and dextrally offset by the Canyonville fault and related structures. The Klamath-Blue Mountain lineament (Riddihough et al., 1986) is partly coincident with the Canyonville fault and may have carried dextral displacement far inland. Complementary indentation via sinistral shear may have occurred at the north end of the orogen, south of the Cowichan Belt.

Initial deformation in the Cascades began about 48 Ma, and seems to have been rather broadly distributed. Relatively rapid strain on numerous minor, somewhat irregular structures appears to characterize both shallow and deeper crustal levels. Rapid uplift and gravitational collapse may have been synchronous. Widespread diking suggests that initially the crust may have been able to laterally escape toward that part of the plate underlain by the Kula plate, but this seems to have been short-lived. After about 46 Ma strain became localized on and near major faults, notably the Straight Creek; magmatism and extension are not much in evidence until about 43 Ma. Pure shear (in map view) seems to have dominated much of the orogen: the characteristic style of deformation is basement involved folding and reverse faulting (England and Calon, 1991; Evans, 1994). Dextral motion on the Straight Creek fault of course appears to be almost entirely middle Eocene, but it is a discrete and rather unique structure and is not symptomatic of widespread right-lateral faulting. West- to northwest-striking faults appear to have had a significant left lateral component. This is compatible with pure shear and local tectonic escape, but it is also likely that this system acted as R' shears to accommodate distributed dextral shear and clockwise rotation (Figure 1).

Although the onset of contraction and uplift on Vancouver Island was at about the same time as in the Cascades, the culmination of deformation may have been a little later. A considerable part of the thinner Kula plate crust may have been subducted, with the northward translation accommodated by early motion on the Puget fault and/or Straight Creek fault, before the emergent ridge encountered the trench. A plausible interpretation of the LITHOPROBE transect of Clowes et al. (1987) across part of southern Vancouver Island is that the entire section between the Leech River fault and the top of the Juan de Fuca plate is Kula-Siletzia. This section is dominantly mafic and thins northward from about 25 km to 20 km thick. Shallow subduction of Kula-Siletzia crust could have caused the Cowichan belt deformation, while the later collision of the ridge crest would have allowed the full momentum of Farallon-Siletzia to come to bear on the crystalline buttress of British Columbia. Some models suggest that initially the Straight Creek fed into the Yalakom fault, a more northwest-striking fault that was part of the early Eocene transtensional system above the Kula Plate (Umhoefer and Schiarizza, 1996). Onset of motion on the crosscutting Fraser fault seems to be later; the timing is similar to the postulated ridge collision after 45 Ma.

Collision of Siletzia likely contributed to Pacific plate reorganization in the late middle Eocene. The already short Kula-Farallon spreading ridge lost its hotspot to North America early in the orogen, probably making it less viable. The abrupt drop-off in magmatism in the north Cascades after 46 Ma and initiation the Straight Creek-Fraser system may be symptomatic of this change, the timing of which is not well constrained from plate reconstructions (Stock and Molnar, 1988). More significantly, at about 43 Ma the Pacific plate, probably for reasons of its own, abruptly changed direction (causing the Emperor-Hawaii seamount bend). By 39 Ma the Farallon plate had slowed drastically (Engebretson et al., 1985). Collision and break-off of the portion of the downgoing slab inboard of Siletzia both may have had an effect. Cessation of strike slip on the Straight Creek-Fraser system accompanied this slowing. Also in the 43-39 Ma interval NE directed contraction diminished, throughgoing drainage from the east reestablished itself, and there was widespread magmatism in the nascent arc, forearc and backarc. In the central Cascades this is distinctly bimodal (rhyolite and basaltic andesite predominating). The few dikes I have seen (rhyolite) strike north, suggesting relaxation across the Straight Creek fault and a shift to more northerly maximum principle strain.

4.3. Late Eocene and subsequent events

From about 37-34 Ma the NNW-striking Entiat fault reactivated with dominantly right-lateral sense (Evans, 1994). This may have accommodated the opening of a graben along the north-south trend of the Columbia River (Reidel et al., 1989). Except for this short-lived event, major deformation seems to have been largely confined to the Columbia embayment and southward. An extensive system of folds in the embayment, including the Yakima fold belt but extending into the Puget-Willamette lowland (Graven, 1990; Wells and Coe, 1985), suggest broadly NW-directed contraction during much of the Oligocene and

Miocene, presumably driven by the collapse of the Basin and Range. The more or less fanning pattern is somewhat ambiguous: folds in much of the Columbia embayment parallel the Blue Mountains, but near the northern margin of the embayment they become east-west to WNW-ESE, echoing the trend of the crystalline buttress to the north. This pattern may be more indicative of basement trends than a real rotation of strain.

A number of Oligocene-Miocene composite batholiths and smaller bodies intrude the Straight Creek fault. These mostly lack strong fabrics and were passively emplaced, suggesting extension (or at least a lack of compression) across the trend of the fault. The Straight Creek system has clearly had a strong control on the location of the Cascade arc. The generally northward-directed contraction since the late Eocene, parallel to the Straight Creek, probably accounts better for the lack of post-Eocene dextral slip on the fault than do the “pinning” plutons. Compressive stress may in fact have been generally northwest-directed, which would be conducive to sinistral slip across the Straight Creek.

5. DISCUSSION

5.1. Relationship of the mid-Eocene event and the Laramide orogeny

The strong basement involved folding in the Pacific Northwest is similar to Laramide deformation further south and east, but its onset is somewhat later. Both the Laramide orogeny and the mid-Eocene event have been attributed to extremely high convergence rates between the Farallon and North American plates (Engebretson et al., 1985). It is possible that the apparently collisional features outlined above are simply due to the northward migration and increasing impingement of the Farallon plate on the region in the middle Eocene. Indeed rocks of the Klamath Mountains appear to have migrated north and deformed along with Siletzia, and the most logical extension of the Straight Creek fault is east of the Klamath Mountains, implying that displacement on the Straight Creek was driven by Farallon-North America convergence. In that sense the history proposed here is not much different than some alternate models, in that much of the middle Eocene event can be attributed to secondary translation of the new forearc northward against the crystalline buttress to the north. However the preponderance of evidence in favor of an external origin for Siletzia, and the strong coincidence between the time of accretion and the onset of orogeny imply that collision initiated or reactivated most of the middle Eocene structures in the region, however much they may have been modified by the continuing effects of rapid, oblique subduction.

Similarly, it has been suggested that strong plate convergence alone cannot explain the severity of Laramide deformation inboard, and that the orogeny was strongly modified by the impingement of oceanic plateaus and aseismic ridges (Livaccari et al., 1981). Plate reconstructions imply that the complements of the Hess Rise and other areas of thickened oceanic crust encountered the early Tertiary margin of North America (Henderson and Engebretson, 1984). Such features have a strong effect on tectonism and volcanism in the Andes, and the migrating pattern of uplift and magmatic gaps in the western United States may be analogous (Henderson and Engebretson, 1984). Other probable influences on the Laramide orogeny are the migration of slab windows (Breitsprecher and Thorkelson, 2001; Thorkelson and Taylor, 1989), which plausibly explain voluminous alkalic magmatism of the interior; and the overriding of hot spots (Murphy et al., 1998). Thus the mid-Eocene event in Washington may be a better analogue for the Laramide orogeny than the Laramide is for the mid-Eocene event.

5.2. Neotectonic significance of Eocene structures

Eocene suture

Beginning about the middle Miocene, oblique subduction and increasingly strong plate coupling have created a minor resurgence of the middle Eocene event. An example of this is the reactivation of the apparent middle Eocene suture on the steep western flank of the Cascades. Active seismicity defining this structure suggests that as Siletzia translates north it is both internally deforming and underthrusting below the old forearc (Figure 4). The Cascades in response are uplifting and form a west-verging anticlinorium. The 1996 M5.3 Duvall earthquake was symptomatic of this contractional component of forearc migration in northern Puget Sound. The east-west contraction of the west margin of the Cascades is probably in part due to gravitationally-induced stresses.

The suture in the southern Washington Cascades corresponds to a complex array of tight, mostly NNW-trending folds and poorly exposed faults. These structures are now associated with considerable seismicity. Focal mechanisms suggest mostly dextral slip on NNW-striking faults (Figure 10). Interpretation of the NNW-striking faults as en-echelon segments of a throughgoing, north-striking, strike-slip fault bounding Siletzia is awkward: instead of the extension expected between right-stepping segments, focal mechanisms suggest east-west reverse faulting (Stanley et. al, 1996). Aeromagnetic maps (Figure 3) and topographic alignments suggest the NNW-trending structures instead continue in both directions and are part of a regional set. The areas of densest microseismicity are close to volcanoes and are probably symptomatic of local crustal weakness due to high heat flow. The structures of the western Cascades are more simply interpreted in terms of distributed transpression: i.e. they are not linked in a simple matter. These structures are, however, apparently associated with a well known, throughgoing strike slip fault to the east, the Straight Creek fault.

Straight Creek fault system

Beginning at the OWL, the southward trace of the Straight Creek system is mostly covered by younger volcanic rocks. The Rimrock Lake inlier is an exception: it consists of strongly sheared Jurassic and Cretaceous rocks intruded by a variety of mostly Miocene plutons (Miller, 1989). Major faults in the Rimrock Lake inlier trend north. Two of these faults similarly separate slices of the two major pre-Tertiary terranes (Indian Creek gneiss and Russell Ranch unit) and may be strands of the Straight Creek. Alternately, the main fault may pass to one side of the inlier or the other. In any case the Rimrock Lake inlier can be considered part of the Straight Creek fault zone. Sobczyk (1994) concluded based on gravity modeling that the Straight Creek fault continued at southward at least to Mt. Adams.

Between the southern Washington Cascades and the Klamath Falls area, the Cascade Range is extremely straight, not parallel to the arcuate Cascadia subduction zone (Figure 11). The east side of the Oregon Cascades is on trend with the Rimrock Lake inlier and defined by steep north-striking faults (e.g., the Hood River fault; Figure 10). I suggest that this is the continuation of the Straight Creek fault zone. The modest deflection of the Fraser-Straight Creek fault into this trend in northern Washington is comparable to the small post Eocene clockwise rotation of the backarc suggested by the paleomagnetism of the Clarno Formation. In Oregon the more northerly-trending high Cascades structures deflect and cut the prevailing northwest-striking structural grain in the same way the exposed portion of the Straight Creek interferes with the OWL. This is particularly evident at the intersection of the Cascades and Brothers fault zone. There, WNW-striking strike-slip faults bend steadily northward and appear to merge and feed displacement into the oblique/normal Green Ridge fault. Similar intersections are quite characteristic of the east side of the Oregon Cascades and correspond with the major volcanoes (John Dilles, personal communication, 2001).

The proposed continuation of the Straight Creek parallels the inboard side of Siletzia. It is the natural boundary of the Oregon forearc block, which is actively rotating and translating northward (Miller et al., 2001; Wells et al., 1998). The obviously active faults that might accommodate this translation are the NNW-striking structures in the western Cascades of Washington (Figure 12). Some of these are older faults dragged into subparallelism with the Straight Creek (e.g., Darrington-Devils Mountain fault zone); others may have originated as synthetic faults, upturned thrusts or sheared axial surfaces in the middle Eocene. Complex folding of late Eocene and early Oligocene strata (Gard, 1968; Vine, 1969) suggests that this system has been extensively modified since the mid-Eocene. Northeast-trending folds, for example, may be Oligocene-Miocene and related to expansion of the Basin and Range. It is possible that forearc migration persisted throughout most of the Tertiary (Wells and Heller, 1988), and the structures of the southern Washington Cascades may reflect this. From a more regional perspective, however, the Oligocene and early Miocene tectonics of Washington were rather subdued.

The seismic zones of the western Cascades are bounded rather suspiciously by the Straight Creek trend, and there is sparse seismicity along the trace of the fault (Figure 12). Similarly, paleomagnetic evidence from the 12 Ma Pomona flow suggest a possible increase in distributed shear rotation approximately where the Straight Creek trend intersects the Columbia River (Sheriff, 1984; Wells and Heller, 1988). NNW-striking faults east of the Straight Creek trend are also locally active, but have much less seismicity and probably lower slip rates. The difference is apparently accommodated by oblique rifting of the High Cascades (Figure 12). Pliocene to recent dikes and rifts in the southernmost Washington Cascades, on the Straight Creek trend southeast of the western Rainier zone illustrate this (Leeman et al., 1990). The tremendously thick Plio-Pleistocene fill of the high Cascade graben system is a more pronounced example.

Although slip is likely somewhat distributed, the Straight Creek in its guise as the High Cascades graben system likely accommodates part of the translation of the Oregon forearc, which may be up to 6mm/yr relative to the backarc in Oregon (less if rigid block behavior is assumed). Geologic and GPS data suggests translation diminishes steadily northward in Washington (Miller et al., 2001). Strain transferred to the NNW-striking faults appears to be in turn transferred to reverse faults (e.g., Doty, Seattle, Sequim/Little River). The Straight Creek trend represents a significant break in seismicity as far north as the Canadian border. However the main strand of the fault itself is cut and statically metamorphosed by the Miocene Snoqualmie batholith (Ellis, 1959), which is little deformed. Furthermore the fault is not very obvious between the Rimrock Lake inlier and Snoqualmie Pass. In Washington, the area east of the Cascades has a strain pattern very similar to that of the forearc, so the small slip differential is readily accommodated. The room problem presented by transfer of northward displacement to the NNW structures is probably accommodated by antithetic faulting (NE sinistral) and north-south shortening of the fault slices themselves. The Straight Creek fault therefore probably acts as a mechanical discontinuity rather than a discrete fault in Washington.

6. SUMMARY AND CONCLUSIONS

Mid-Eocene orogeny in Washington was exactly coincident with accretion of Siletzia. Siletzia itself is an oceanic flood basalt that most likely formed a plateau centered on the Farallon plate west of what is now southern Oregon. Anomalously thick crust extended to the Kula-Farallon ridge axis and beyond, with the Metchosin volcanics of southern Vancouver Island apparently forming an island on the ridge crest (Massey, 1986; Muller, 1979). A persistent strait seems to have separated the two outcrop belts of the

Crescent basalts (Babcock et al., 1994). It funneled continent-derived debris between the emergent ridge and plateau.

An endogenous origin for Siletzia in a backarc or forearc setting is less easy to visualize but conceivably correct. Unlike many geologic controversies, little room for compromise exists between an external and endogenous origin for the early Eocene basalts of western Oregon and Washington. In the absence of conclusive evidence, circumstantial arguments, the great magnitude of its bounding faults, and the presence of good analogues strongly favor an external origin. Sedimentation patterns, dike orientations and absence of evidence for rifting seem to be weaknesses of the endogenous model that have not been thoroughly addressed. Whether or not Siletzia formed in place, there seems to be some consensus that it is "accreted": that is it became at least partly coupled to the Farallon plate and is significantly translated relative to its position at the start of the mid-Eocene.

Accretion of Siletzia was broadly 50-40 Ma and mostly 48-42. Initial strain was widely distributed but by 46 Ma appears to have become more concentrated on and near large faults. Northward translation in particular appears to have been largely confined to the Straight Creek fault. Away from it pure contraction dominated. A component of sinistral shear on west- to northwest-striking faults, however, is consistent with subordinate distributed right lateral shear. Strong confining stresses may favor this “venetian blind” style of rotation.

Collision may account for the rapid uplift of amphibolite facies rocks in the Cascade core and southern Vancouver Island. Final uplift of the Leech River complex on Vancouver Island was relatively late (c. 41-39 Ma) and may reflect the secondary collision of the spreading center and “Farallon Siletzia” with the crystalline buttress to the north.

Eocene strain in the western U.S. Cordillera is complex and spatially variable, but can plausibly be related to the contrasting effects of convergence of the Farallon and Kula plates and the slab windows between them (Breitsprecher and Thorkelson, 2001). The Paleogene record of the Cascadia region appears to be dominated by, progressively:

1. Kula subduction (transpressive arc);
2. slab-window and hot spot effects (extension and effusive volcanism);
3. plateau and ridge accretion (more or less collisional);
4. strong, Laramide style contraction and northward translation driven by the Farallon plate.

These events, and the demise of Kula-Farallon spreading, may have contributed to late middle Eocene plate reorganization in the Pacific. Slowing of the Farallon plate allowed a persistent shift to northwesterly-directed contraction in the Columbia embayment that may have persisted from late Eocene to mid-late Miocene time. This more than pinning plutons may account for the lack of post-Eocene dextral strike slip on the Straight Creek fault system. The fault system was, and remains, a major conduit for arc magmas.

Increasingly strong coupling between the Farallon remnants (Juan de Fuca system) continues to drive Siletzia north. Resisted by the crystalline buttress to the north, in Washington it is deforming by an interlinked system of folds, reverse faults, right lateral and subordinate left lateral faults related to the Straight Creek fault (Figure 1). Beginning most likely in the latest Miocene or early Pliocene it also began to underthrust below the Cascades, uplifting the Cascade anticlinorium.

The Straight Creek fault can be logically extended southward along the east side of the southern Washington and Oregon Cascades. It is the natural boundary of the Cascadia forearc block, and still appears to accommodate part of the northward translation of the block, albeit in a fashion that is complex, distributed, and variable along strike.

PART II

1. INTRODUCTION

The subsurface structure of the Columbia Basin is one of the least understood aspects of the entire North American Cordillera. This is unfortunate, for it conceals a major discontinuity in the Cordillera: the end of the long terrane belts of Canada (McGroder, 1991; Monger, 1984). This discontinuity appears to correspond to the northern edge of the Columbia embayment, a persistent, wedge shaped topographic low that is generally though to have formed as the Blue Mountains swung northward in front of the expanding Basin and Range (Wise, 1963).

The Columbia Basin, as the term is used here, is defined on the basis of physiography: it consists of the main outcrop area of the Columbia River Basalt Group (CRBG) east of the Cascade crest and north of the Blue Mountains. The CRBG ranges up to about 5 km in thickness; a comparable thickness of older Tertiary sedimentary and volcanic rocks in turn underlies the CRBG (Glover, 1985). Both the CRBG and the older Tertiary section are thickest within the Columbia embayment but extend well beyond its margins, notably into the Blue Mountains.

The structure of the Columbia Basin is dominated by the Yakima fold belt, a series of long, narrow, evenly spaced anticlines, generally bounded by thrust or reverse faults. For the most part the Yakima folds trend WSW, and can in some cases be traced into or across the Cascade Range (Beeson et al., 1989). To the east the Yakima folds bend abruptly into the Olympic-Wallowa line (OWL), a complex WNW-striking structural zone (Kienle et al., 1977). Northeast of, and extending into the zone of the OWL, Yakima folds trend nearly east-west (Figure 13).

In this study I correlate seismicity in the western Columbia Basin to structure. The results suggest an intriguing pattern of superimposed thick- and thin-skinned contraction. Specific correlations should be regarded as preliminary, because the hypocenters have not been relocated. The broader conclusions, however, are not strongly dependent on the accuracy of locations.

I also estimate the direction of active contraction across the Columbia Basin using three independent methods: lineations on young faults, earthquake focal mechanism solutions, and GPS measurements. The results are consistent with studies that suggested a regional shift in strain vectors in the latest Miocene (Barrash et al., 1983; Lawrence, 1979). Dynamic topography appears to modulate the regional strain field, causing radially-directed strain near the margins of the Columbia Basin.

Finally I speculate on the basement structure of the Columbia Basin and the history of the Columbia embayment, taking paleomagnetic data and plate reconstructions for the region at face value.

1.1. Sources of data and provisos

Hypocenters are from the Pacific Northwest Seismic Network (PNSN). All magnitudes cited are local magnitudes. The PNSN was established in 1969 and was essentially in its present form by 1977. Most of the instruments are within the Columbia embayment, where the catalog should be reasonably complete at about the M1.7 level (Ludwin et al., 1991). Not to squander the already sparse data I have not used any minimum cutoff for the Columbia Basin. Thus some of the clustering of earthquakes is dependent on the density of station coverage. In order to minimize spurious or misleading events, I eliminated all those classified as explosions, probable explosions and “surface” events.

Most hypocentral locations are precise to within 2km, but worse in areas of poor seismometer coverage. A transect across the Hanford nuclear reservation is crucial to the analysis; this area has quite good station coverage. Systematic accuracy of locations is a bigger issue. The velocity model for much of the region, while in rough agreement with seismic studies, is a simple “pancake style” one (Ludwin et al., 1991). It does not account for the possibility of lateral juxtaposition of rock units with strongly contrasting velocity, or the known lack of horizontality of some major breaks. Thus there are likely some artifacts and systematic mislocation of earthquakes: viewing a clear image through old, wavy glass is a good analogy. Nevertheless, in the spirit of exploration I have assumed that prominent alignments of hypocenters and sharp breaks between areas of contrasting seismicity are real, especially where the alignments include events with consistent focal mechanisms.

Focal mechanisms are determined automatically at the University of Washington for all events with p-wave first arrivals recorded by ten or more instruments. Some individual mechanisms have large uncertainties, but collectively they provide a consistent picture of the strain in the area. Although I use P- and T- axes in the usual way as proxies for maximum and minimum principle strain, respectively, it should be noted that P- and T- axes are geometrical abstractions without definite physical significance. The concept of the strain “ellipsoid” itself is not always a useful one, because it is based on assumptions of mechanical isotropy. The structure of Cascadia is complex and clearly non-isotropic. Also strain is probably somewhat depth-dependent (Hooper and Conrey, 1989).

GPS data is from the Pacific Northwest Geodetic Array (PANGA). Miller et al. (2001) discuss details of data processing and strain modeling. Ubiquitous Quaternary deformation not withstanding, strain rates east of the Cascades are very low: probably no more than 1mm/100km per year (Hemphill-Haley, 1999; Murray and Lisowski, 2000). Thus I use the GPS data only as an indication of the general direction of tectonic transport.

Fault fabrics provide a concrete check on the geophysical data. Most of the data are from young reverse or thrust faults (those involving Pliocene or younger deposits). Most are from in and around the OWL. This is a weakness, because the OWL might be expected to show some refraction of strain and therefore not be representative of the Columbia Basin as a whole. However the other sources of data suggest this effect is slight; regional strain axes in the southwest half of Washington appear to be fairly consistent.

1.2. Note on the cross sections

The cross sections show seismicity projected from 5km on either side. This may produce some blurring or spurious superposition of events. There is no vertical exaggeration of the earthquake plots but the overlying topography is exaggerated by a factor of five.

Topography of the Columbia Basin is largely a result of post-middle Miocene structural uplift. Late, laterally extensive Columbia River Basalt flows (e.g., the Priest Rapids flows at 14.5 Ma) were originally more or less horizontal and are still generally preserved atop the anticlinal ridges (Figure 14). Thus the topographic profile of Yakima fold is somewhat faithful to their structural geometry, with the exception of the frontal hinge zones, which are typically deeply eroded. Secondary folds and backthrusts are common, as are normal faults created by bending and gravitational collapse.

The modern Washington Cascade Range is essentially and anticlinorium that is largely post-middle Miocene in age (Beeson et al., 1989). During the middle Miocene its eastern flank was a gentle, little incised erosional surface (Mackin and Cary, 1965). Upland surfaces and uniform ridgetops (locally capped at elevations of over 2000m by Columbia River basalts) are the remnants of this surface. Thus the projected base of the basalts can also be used to estimate neotectonic uplift (Figure 15).

2. CORRELATIONS OF STRUCTURE AND SEISMICITY

2.1. General distribution of seismicity

Map views of seismicity in the Columbia Basin are not very enlightening: the epicenters suggest irregular patches with a vague and problematic association with surface structures (Figure 16). This, however, is partly an effect of the dominant structural grain; we are looking down on a system dominated by variably dipping reverse faults. Projected onto cross-sections, the hypocenters form much clearer alignments, and the dip of these alignments is mostly consistent with focal mechanisms within them. A majority of Yakima folds show some evidence of seismic strain, but the earthquakes do not always occur on the frontal faults. This is not surprising, as major faults are often completely aseismic between ruptures. The frontal faults appear to vary considerably in their dip and depth to decollement, as might be expected from the variety of fold shapes in the Columbia Basin. Earthquakes occur throughout the seismogenic crust, and some structures appear to cut entirely across it.

2.2. Eastern transect

Structures south of and within the OWL.

The Horse Heaven Hills and Rattlesnake Mountain are anticlines that verge north, with gentle, planar backlimbs and steep to overturned forelimbs (Figure 17). Sparse earthquakes appear to define listric, south dipping thrust faults. Listric thrust faults readily explain the fold geometry, and project to the mapped frontal faults. There appears to be a seismic gap along the frontal faults of both ridges extending between the near-surface and about 5km depth. The Columbia River basalts here are several kilometers thick (Glover, 1985); it seems likely that the faults are locked and accumulating strain at least within the basalts.

The Horse Heaven Hills anticline is somewhat broader than Rattlesnake Mountain. This appears to be due both to a somewhat greater depth to decollement and a lower average ramp dip (also, Rattlesnake Mountain is a short, complex fold typical of the OWL zone, and is somewhat oblique to the cross section). The decollement appears to be of great extent, rising gently to the north, and corresponding to an apparent zone of few earthquakes. This "shadow zone" is likely to be in part an artifact of the velocity model. However the probable decollement is at the depth predicted by structural studies of the Yakima folds (Laubscher, in Kienle et al., 1977). It is most likely controlled by the onset of ductility in quartz, although it may locally correspond to the unconformity at the base of the Tertiary section.

Structures of the northeastern fold belt.

The Saddle Mountains and Frenchman Hills verge north, and are bounded by south-dipping frontal reverse faults. Most of the active seismicity associated with these anticlines, however, appears to define steeply north-dipping planes, outside the zones of highest strain. The readiest explanation of this otherwise perplexing pattern is that the north-dipping alignments define the axial surfaces near the base of the backlimbs of the folds. If this is the case the numerous small earthquakes recorded just north of the Saddle Mountains are in fact related to folding of the Frenchman Hills. These events appear to cluster along steep, NE-striking cross faults, but focal mechanisms mostly are consistent with overall north-south contraction. This is to be expected in synclinal hinge zones, even if these hinges are very slight at the surface. The total moment of these earthquakes is consistent with a conservative estimate of active shortening (about 0.04 mm/yr) across the Saddle Mountains, estimated from structural relief (Reidel, 1984). As the seismicity seems mostly the result of minor bending strains it may not exactly correspond to strain accumulation on the frontal fault, however.

Most of the seismicity ends abruptly at 5-10km depth (shallower in the north), suggesting a gently south-dipping decollement. Sparse earthquakes and at least one focal mechanism suggest that the frontal fault of the Frenchman Hills is similar to that of the Horse Heaven Hills. The frontal thrust of the Saddle Mountains is even more vague, but can be divined from a dipping break in seismicity. This fault appears to have an average dip of about 40^{o}, becoming shallower at depth (based on the steep axial surfaces). This is consistent with geologic interpretations (Reidel et al., 1989). The particularly dramatic gravitational collapse structures in the frontal hinge zone of the Saddle Mountains are to be expected where a relatively steep reverse fault shallows abruptly at or near the surface. There are a few shallow normal-sense focal mechanisms in this zone. From the lack of small earthquakes the frontal fault it is probably entirely locked. Seismicity behind it is probably due to diffuse brecciation and minor faulting, which is much in evidence near the frontal hinge zone.

The broad uplift, very gently dipping backlimb, and frontal reverse fault of the Saddle Mountains are compatible with a mid-crustal decollement and more or less listric ramp to the surface, as seems to be the case in the Horse Heaven Hills. The obvious surface fold, however, is a tighter anticline with sharp hinges and abrupt changes in geometry along strike. This is the "Crest anticline" of Reidel (1984). Near the deep BN1-9 gas exploration well the Saddle Mountains appear to be the result of a fault bend or fault propagation fold superimposed on the higher, broader, deeper seated uplift. The sharp syncline and anticline behind the frontal fault may be caused by the abrupt junction of a gentle intra-basalt fault with the steeper ramp from the basement. To the east the fold becomes narrower and more symmetrical, suggesting more of a kink or lift-off geometry, again controlled by slip at the base of the basalt.

In many areas along their margin, the basalts are underlain with little discordance by clay-rich sedimentary rocks of the Wenatchee formation and equivalents (Tabor et al., 1982). There are some thin but laterally extensive sedimentary interbeds in the basalts, mostly fine grained. It would be surprising if these weak layers did not act at least locally as decollements. Shallower secondary folding and faulting may help accommodate possible deficits in horizontal shortening as the ramps from the deeper decollement steepen toward the surface. This would be especially important if the faults bend abruptly at the base of the basalts. Also, at greater depths other mechanisms of shortening may operate, for example pressure solution and small-scale faulting and folding, that are less of a factor near the surface. Thin-skinned folding superimposed on the deeper-seated pattern of shortening is a logical result. The characterization of the frontal faults as "listric" is only an approximation: there is some suggestion of abrupt bends in the faults. Shear-fault bend folding (Suppe and Connors, in press) and depth-dependent distributed shear (Chester et al., 1991) likely contribute the geometry of the Yakima folds, notably their generally very gently dipping backlimbs. Growth folding is also a likely complication.

The Frenchman Hills, Saddle Mountains, and the eastward projection of Umtanum Ridge (Gable Mountain) bend and die out eastward. Just south of the end of the Umtanum Ridge structure there is a NNW-striking, subvertical alignment of earthquakes. This alignment parallels tremendous dikes that are prominent on aeromagnetic maps (Figure 3), and which project to the eastern limit of the Saddle Mountains and Frenchman Hills (Finn and Stanley, 1997). Focal mechanisms in this zone are consistent with dextral motion. It appears that the faults along which the dikes intruded are now active as a tear faults bounding the Yakima Fold Belt. Where the zone of dikes crosses the OWL, NNW-striking dextral faults were active in the late Pleistocene to Holocene (Reidel et al., 1994). Seismicity as deep as 30km on such structures suggests that despite the evidence for mid-crustal detachment, the Yakima fold belt is fundamentally thick-skinned. Alignments of seismicity below 10 km have a similar spacing and consistent offset from ramps above the 5-10 km decollement. It seems possible that the deeper structures originally controlled the surface faults, but as the Tertiary section thickened, the decollement stepped upward and sheared off the deeper faults.

2.3. Western transect

Toppenish Ridge and the Satus Pass uplift.

Toppenish Ridge is a youthful, asymmetric, north verging anticline with a prominent Holocene fault scarp along part of its base (Campbell and Bentley, 1981; Repasky et al., 1998). The structure defines the north edge of the greater Satus Pass uplift, which also incorporates the Horse Heaven and Columbia Hills (Figure 18). Like the Wenatchee Mountains, the Satus Pass uplift is more or less symmetric and suggests an uplifted basement block on which the narrower folds are piggy-backed. Seismicity below Toppenish Ridge extends to 20-25 km and contrasts with the nearly complete lack of seismicity under the lower Yakima Valley to the north. The boundary between the seismic and aseismic blocks roughly defines a steep south-dipping plane (Figure 18). While there is not clear evidence of a decollement at c. 5-10km depth, the geometry of the Yakima folds is similar to that further east, and it seems likely that the narrower folds are partly decoupled from the larger, deeper-seated uplift. Where there is evidence of such decoupling, it appears to be at a slightly shallower level than in the east. This is most likely due to increased heat flow near the Cascades, but thinning of the Tertiary section away from the center of the Columbia Basin may also play a role.

Structures of the western fold belt, in and around the OWL.

In this area ENE-trending anticlines plunging off the eastern flank of the Cascades bend abruptly and become parallel or nearly parallel (en echelon) to the OWL, which trends ESE. The OWL on the east flank of the Cascades and western part of the Columbia plateau appears to be a wedge-shaped, compound uplift that refolds and dextrally distorts the Yakima fold belt. This uplift is complexly thrust to the north over the Roslyn-Kittitas syncline and to the south over the compound syncline along the trend of the Naches River (Figure 7). Both synclines approximately parallel the OWL and are similarly superimposed on more easterly-trending Yakima folds. They suggest moats symmetrically flanking the OWL (Figure 19)

On trend with the Naches syncline is a prominent, steeply south-dipping alignment of earthquakes with focal mechanisms suggesting a steep north-directed reverse fault. Many of the hypocenters lie under the little deformed lower Naches Valley, an area of subdued topography and little obvious structural relief. Much of the valley, however is covered by the mid-Pleistocene Tieton andesite or younger river gravels. The alignment of earthquakes continues under Cleman Mountain, but ends short of the surface and appears to be overthrust by the strongly south-verging Cleman structure (Figure 20). To the northwest the alignment of seismicity projects toward the Indian Flat fault, which cuts both Columbia River basalts and Fifes Peak volcanics (Paul Hammond, map in preparation). The Indian Flat fault or an en echelon structure likely controls the steep north-verging flank of the Edgar Rock dome, a large complex fold developed in a broad Fifes Peak volcano. The Edgar Rock dome appears to be an en echelon complement of Cleman Mountain, with similar structural relief but opposite vergence (Carkin, 1988).

The structures along the south side of the OWL outlined here and mapped in some detail by Hammond (in preparation) and Bentley et al. (unpublished mapping) were interpreted by Campbell (1989) as part of a throughgoing shear zone, the White River-Naches River fault zone. The White River fault zone has a different trend than the Naches River fault zone, appears to be restricted to the west side of the Straight Creek fault, and did not necessarily form as the continuation of the Naches Zone, although the two have no doubt interacted. The Naches River zone itself is not clearly a throughgoing fault in the uppermost crust, corresponding instead to impressive but very discontinuous faults and folds. However the apparent continuity of the seismicity along strike (Figure 20) suggests that it may be more throughgoing at depth. Campbell further suggested that the Naches River shear zone is dominantly dextral. This appears not to be the case at present, as focal mechanisms and fault fabrics imply only a modest component of strike slip on OWL-parallel structures. A former episode of strike slip is possible, however, and seems not unlikely given the complexly relaying, en echelon nature of folding and faulting along strike. Campbell's proposal that the Naches fault defines the OWL is an interesting one, and it may fundamentally be the master structure. Nevertheless in terms of both topography and structure the OWL is a poorly defined zone rather than an individual fault (Kienle et al., 1977). The OWL defined by Raisz (1945) and the OWL defined by Campbell (1989) correspond to the northern and southern boundaries of this zone, respectively. The lack of a pronounced uplift south of the Naches fault may be due to recent reactivation and/or very low strain rates on the putative Naches fault. That the siesmicity is concentrated adjacent to a portion of the OWL that has conspicuously escaped uplift suggests that it might mark a nascent structure.

An alignment similar to that associated with the Naches fault zone, but shorter and less well defined, projects to the surface near the northern margin of the OWL, defined by Manastash Ridge (Figure 20, profile 4). Seismicity also extends deep under the Boyleston Mountains, a series of en echelon north verging anticlines that extend under the thick fill of the Kittitas Valley (Owens, 1995; Waitt, 1979). The simplest interpretation of the seismicity is that moderately to steeply dipping reverse faults cut the entire seismogenic crust, and break the surface. However Jarchow (1991), based on a seismic refraction study, argued fairly convincingly that the faults associated with the Boyleston Mountains and the front of the OWL dipped shallowly (<30º) within the Columbia River basalts. Also the consistent narrowness and locally boxlike geometry of the Yakima folds within the OWL strongly suggests detachment at shallower levels (Figure 14). Umtanum Ridge is controlled by gently dipping thrust faults, and extension is not pronounced in its forelimbs, so that the faults probably do not steepen much with depth. The folds and faults associated with the OWL, like the Saddle Mountains, are probably hybrid structures. Pronounced buckling in the imbricate frontal fault system of Manastash Ridge (Bentley, 1977) is consistent with the intersection of a shallow thrust fault with a steeper basement-involved reverse fault.

2.4. Northwestern Columbia Basin and the Okanogan highlands

Numerous small earthquakes are centered in the area around Entiat (the so-called "Chelan swarm"), and sparser seismicity extends northeast along the edge of the North Cascades past Lake Chelan. There is an abrupt break to the southwest; beyond the Entiat fault the Chiwaukum basin is relatively quiet. Another cluster of epicenters lies between Moses Coulee and Grand Coulee.

The Chelan swarm is of considerable interest both because of the frequent small earthquakes, not uncommonly felt, and because the strong earthquake of 1872 (M7+) was likely centered somewhere in the general area. Focal mechanisms and the distribution of earthquakes recorded by the PNSN suggest contraction across two sets of structures at approximately right angles to each other. Most of the events appear to be the result of reverse motion on minor NNE-striking faults on either side of the Columbia River (Figure 21). A few such faults are mapped in the crystalline rocks north of Lake Chelan (Stoffel et al., 1991); they parallel late Eocene dikes. Sparse seismicity in the Okanogan also appears to be the result of reactivation of Eocene extensional structures, notably those in the immediate hanging wall of the Okanogan Valley detachment. A number of low folds and a few reverse faults in the Columbia River basalts also trend NE. The best developed of these run along lower Grand Coulee, directly on trend with the Republic Graben.

Another apparent structural control of the Chelan swarm is a zone of folds and faults parallel to the OWL. As with the OWL, the pattern of faults and folds suggests dextral and perhaps sinistral wrenching across the zone. Like the OWL it contains northwest-striking Eocene dikes, not just the usual northeast-striking ones. It is also a compound uplift: Badger Mountain has about 400 meters of structural relief (Grolier and Bingham, 1978). Thin outliers of basalt west of the Columbia River that rest unconformably on gneiss are also differentially uplifted. While the structure clearly is basement controlled and continues into the Cascades, it has no obvious effect on the Entiat fault and may be cut by it. However the Eagle Creek fault, southwest of the Entiat fault, trends northwest, and a number of parallel lineaments reemerge on the west side of the Chiwaukum basin, extending as far as the Straight Creek fault. These appear to be associated with very sparse seismicity.

The EEL (Ephrata-Entiat Mountains lineament) seems to be an appropriate name for this OWL-parallel lineament and structural zone. Leaving aside its problematic relationship with the Entiat fault and its projection beyond Ephrata under the Columbia River plateau (it can plausibly be traced past Clarkston to at least John Creek, a tributary of the Snake River, but has very limited topographic expression), the EEL appears to be part of the same regional NW-striking fault set as the OWL, and is the most northerly yet recognized (Figure 10).

2.5 Summary and discussion

Despite initial impressions, Yakima folds are never simple. Varied structural style and wavelength, along with patterns of seismicity suggest at least local decollement at a variety of structural levels:

- within and at the base of the basalts;
- at 5-10 km (controlled by quartz ductility and perhaps guided by the basement/Tertiary contact);
- below the brittle-ductile transition (controlled by feldspar ductility).

Coincidence between very shallow structures and steeper structures suggests that the steeper structures are more fundamental, although their surface expression may be subtle. The 5-10 km decollement appears to fundamentally control the geometry and spacing of Yakima folds, the Horse Heaven Hills being the clearest example. East-west striking structures in the northern Yakima fold belt have a different spacing and some suggestion of deeper basement control. These including the Frenchman Hills, Saddle Mountains and Umtanum Ridge as well as discontinuous structures on trend to the west, notably the central segment of Manastash Ridge and structures within Kittitas Valley.

The superposition of various structural styles is probably a by-product of changing rheology and deformation processes at depth. With increasing temperature and pressure, deformation is presumably more and more penetrative. At depth, small scale folding and faulting, pressure solution, collapse of pore spaces and metamorphism to denser phases can together accommodate substantial strain. The more rigid rocks at shallower levels would be compensate by more brittle mechanisms, i.e. increased fault displacement and buckling, accommodated by slip along decollement horizons.

3. STRAIN VECTORS AND STRAIN CHANGES

3.1 Columbia embayment

P-axes in the Columbia Basin suggest maximum contraction directed about N15E, with considerable local scatter from nearly northwest to nearly northeast (Figure 22). The scatter is presumably the result of some combination of fault block interactions, other variations in stress (e.g., those due to topographic gradients), and uncertainties in deriving the mechanisms. T-axes are mostly vertical, reflecting the dominance of crustal thickening rather than conjugate faulting as the means of contraction. In the southern Cascade Range the latter becomes more important.

Movement of GPS stations relative to North America is NNE (Figure 10). There is probably a small component of recoverable strain from the subduction zone directed ENE, which may explain why the GPS vectors are directed slightly more easterly than the focal mechanisms.

Fault orientations and slip vectors determined for faults near the OWL suggest a very similar maximum principle strain directed slightly east of north (Figure 23). Most of these faults cut Plio-Pleistocene strata. Striations from reverse faults in southwest Washington also suggest contraction directed about N15E (Wells, 1999), supporting the notion that the northeast- to east- trending folds of the Puget-Willamette lowland and the Yakima fold belt form a single interlinked system (Beeson et al., 1989).

The NNE-directed contraction active at present, and in the recent geologic past, is somewhat different than the NNW contraction implied by the mostly ENE-trending Yakima folds and NNW-striking Columbia River basalt dikes (Figure 3). The major implications of this are that typical ENE-trending Yakima fold structures should on average have a small left-lateral component, and that the Olympic Wallowa line is predominantly contractional, with a subordinate component of dextral strike slip.

Barrash et al. (1983) suggested the change between the NNW- and NNE- directed regimes of the Columbia Basin occurred about 10 million years ago, while Lawrence (1979) suggested the change occurred in the early Pliocene in the Blue Mountains, based on changes in the orientation of joint systems. The NNW orientation of even the youngest CRB dikes (10-6 Ma), the apparent lack of major relief on the OWL until after about 7 Ma (Walls et al., 1994), and the abrupt drop in the volume of volcanic detritus from the southern Washington Cascades at about 6 Ma all suggest a latest Miocene date for the transition.

Barrash et al. (1983) and Walls et al. (1994) suggested that the NNE contraction was at first very rapid but slowed abruptly by the middle Pliocene: basalt gravels of the Thorp Formation and equivalents appear to rest on a pediment that beveled deformed strata of the late Miocene Ellensburg formation. However in the absence of diagnostic tephras, it is difficult to distinguish the Thorp and equivalents from later Pleistocene gravels, so the pediments in most cases may be younger. Unequivocal Thorp and Ringold sediments are commonly strongly folded and/or faulted as, for example, on Rattlesnake Mountain (Reidel et al., 1989), the Saddle Mountains (Reidel, 1984) and Manastash Ridge (Miner, unpublished mapping). While the Ellensburg-Thorp unconformity is significant, it does not mark the end of deformation in the Columbia Basin.

3.2 Modulation of strain by dynamic topography

Contraction is not exclusively NNE directed in Washington, especially in the areas to the north underlain by more crystalline basement. P-axes in the northwest Cascades, northern Puget Sound and Vancouver Island tend to trend northwest. In the Chelan area *P*-axes are bimodally distributed, with contraction directed both approximately northeast and northwest (Figure 24). The northeast-trending structures of lower Grand Coulee, initially parallel to basement trends, curve eastward, paralleling the basalt margin (Figure 18). The Blue Mountains uplift is also somewhat concentric to the Columbia Basin, and there are several focal mechanisms with northwest-trending P- or nodal axes.

The northeast half of Washington, with its thicker, more buoyant crust, has long acted as a strong "backstop" against which southwestern Washington is deforming, mostly dissipating NNE-directed stress. The mixture of P-axes in the transition zone suggests that the maximum and intermediate compressional stresses are similar enough in magnitude that the resulting strain axes readily exchange in response to local effects. This in turn implies that horizontal compressive stress is roughly isotropic, and that contraction can potentially occur in any direction, depending on local conditions. High topographic gradients, as along the edge of the Columbia Basin, may generate the critical differential stress. The orientation of weak zones in the basement is also an important control. The strain "ellipsoid" in the Entiat area can be visualized by flattening an upright boiled egg somewhat more WNW-SSE than ENE-SSW. The opposite is generally the case to the south. In both cases uplifts and basins are rhombic, and it may be more useful to visualize strain in terms of a prism (e.g. cleavage rhomb) with the long (dilatational) axis subvertical.

The downgoing Juan de Fuca plate is strongly arched under the Olympic Mountains, northern Puget Sound and the Okanogan highlands (Bostock and VanDecar, 1995). P-axes seem to parallel the contours of the arch in Puget Sound (Ma et al., 1996). Above the crest of the arch in the North Cascades there are a few focal mechanisms suggesting NW-SE dilatation, apparently complementing the contractional mechanisms in the Entiat area, which lies above the southeast limb of the arch. While a slab arch subducting in a steady fashion need not have a strong surface effect, a change in the dip of the slab or tightening of the arch would constrict the overlying mantle, causing uplift and flow away from the arch. The Juan de Fuca plate system reorganized in the early Pliocene, when the Explorer and Gorda subplates began moving independently of the main Juan de Fuca plate (Riddihough, 1984). The resulting change in motion of the Juan de Fuca plate appears to have complicated the geometry of the slab arch (Bostock and VanDecar, 1995). The arch itself may have originated in the Miocene: 20-14 Ma plutons in the North Cascades appear to have increasingly pronounced NE trends, perhaps due to tension above the crest of the arch.

To the south, along a line extending from Willapa Bay through Snoqualmie Pass, the downgoing Juan de Fuca plate appears to be torn and to the south assumes a steeper dip (Michaelson and Weaver, 1986). This appears to correlate with the persistently low Columbia River corridor (the Columbia trans-arc lowland of Beeson et al., 1989). Other, perhaps interrelated controls on the anomalously low topography of this portion of the forearc, arc and backarc are the older age of subducting crust and the partly to dominantly mafic crust of the upper plate, especially Siletzia (Trehú et al., 1994; Wells et al., 1998).

Like the Olympic-Okanogan arch, the Klamath-Blue Mountain uplift appears to be young, and it may have a similar cause. Very rapid uplift of the Klamath Mountains may be related to subduction of the younger crust of the Gorda plate (McNutt, 1983), but even the far inboard end of the Blue Mountains has also risen at significant rates in the last few million years. Approximately half of the 2 km of uplift in the Hells Canyon area is Pliocene and younger (Bond, 1963). Similarly, the base of the Columbia River Basalts now lies at altitudes as high as 3 km in the Wallowa Mountains.

Uplift of the B.C. Coast Mountains commenced about 10 Ma, and accelerated in the Pliocene (Farley et al., 2001). The latter may correlate to the breakoff and probable underplating of the Explorer subplate (Riddihough, 1984). Total post-10 Ma uplift in the Mt. Waddington area is about 3 km (Matthews, 1991). The downplunge end of this uplift is represented by the modern Washington Cascade Range, which is uplifted about 2 km in the north and 1 km in the south. At the Columbia Gorge much of this uplift appears to be Pliocene and younger (Beeson et al., 1989). Presumably the Cascade uplift is also due to the subduction of progressively more bouyant oceanic crust. The high topography and high heat flow of the Cascades make them prone to gravitational spreading. In retrospect it is not surprising that the 1996 Duvall earthquake was directed west, in contrast to the northerly directed maximum principle strain in the Puget lowland.

Neotectonic uplift in the northwest appears to be widespread, perhaps extending to the Rocky Mountains. Horizontal crustal strains over much of the region are low, however, and do not necessarily correlate to the topography. Mantle response to changing plate margin conditions in the Pliocene may be one factor. Along this line two processes can be envisioned: failure or steepening of portions of the Juan de Fuca slab may have allowed mantle upwelling, or shallowing of subduction may have displaced mantle material eastward or away from slab culminations. In addition, the Yellowstone hotspot plays a strong role in topography and structure (Suppe et al., 1975). Whatever processes are responsible, rapid differential uplift is a widespread in the region, and its role in generating critical stresses and earthquakes is perhaps underappreciated.

3.3 Relationship of the Yakima fold belt to the Basin and Range province

Most Yakima folds trend west-southwest, parallel to the Olympic-Okanogan arch and Blue Mountains uplift. While the Blue Mountains are to some extent an anticlinal uplift, the Blue Mountain front can also be viewed as a monoclinal step separating the Northern Basin and Range, with its high topography and heat flow, from the Columbia Basin, a persistent, anomalous topographic low. Based on analogy with the northern flank of the Alps and the fold belt of the Jura, Laubscher (in Kienle et al, 1977) suggested that the Yakima fold belt formed due to a combination of north-directed gravitational collapse and right lateral wrenching of the Tertiary cover sequence. Indeed the Oregon Basin and Range and the Blue Mountains contain numerous down-to-the-north normal and oblique right-normal faults (Walker and MacLeod, 1991) that are the apparent complements of the contractional and oblique right-reverse structures of the Yakima foldbelt. The structural block bounded by the OWL, Brothers fault zone, Cascade crest and the western edge of the craton can be viewed as an extensional allochthon (with a contracting toe), that is also undergoing dextral shear.

Active strain measured with GPS suggests that gravitational collapse may still be feeding the Yakima fold belt. Sites in the Yakima fold belt are moving to the NNE, while sites in the northern Basin and Range, including Burns, are moving WNW. This implies some divergence as well as right lateral shear. Although the GPS velocities have been explained in terms of rigid block motion involving most of Oregon (McCaffrey et al., 2000), geologic and paleomagnetic evidence instead suggests distributed shear at a variety of scales (e.g., Sheriff, 1984). Major structures in the Blue Mountains such as the John Day fault appear to have a mid-late Miocene contractional history followed by a latest Miocene and younger (post-Rattlesnake tuff) extensional episode (Thayer and Brown, 1966). The Oregon Basin and Range appears be expanding northward at the expense of the Yakima foldbelt: the Blue Mountains were a depocenter as late as the middle Miocene. They appear to have undergone rather young uplift, and incipient gravitational collapse. This is part of a broader, complex, and evolving system of intraplate deformation (Hemphill-Haley, 1999), for which block models are at best an approximation.

3.4. Origin and nature of the Olympic-Wallowa line (OWL)

The OWL is the most prominent of a family of faults and associated structures in eastern Washington and Oregon. This system is fairly penetrative on a regional scale (Figure 10), but only a few of the fault zones have a pronounced structural expression. These faults appear to act as transforms accommodating differential motion within and in front of the northern Basin and Range (Lawrence, 1976). However their latter-day function does not necessarily explain their origin. A number of authors have speculated that the OWL has an older history. Any explanation of the origin of the OWL, however, must also account for other structures in the system, for example the Brothers fault zone (BFZ). This precludes the origin of the OWL as a pre-Tertiary terrane boundary (because the BFZ cuts at a high angle across such terranes). A related idea, that the OWL is a preexisting structure that subsequently acted as the continuation of the Straight Creek fault, appears untenable for a number of reasons (Cheney, 1999). There is good evidence that the Straight Creek continues southward; its apparent end at the OWL is simply due to overlap by late- to post-kinematic strata and perhaps a small left step. However the Straight Creek fault and OWL do appear to have interacted in the middle Eocene, and the EEL also may be defined by mid-Eocene structures. The OWL family does seem to have an older history.

The OWL family of structures closely corresponds to the westward excursion of Cordilleran structural and magmatic trends (Wise, 1963). Given the evidence that this pattern may have originated in the latest Cretaceous or earliest Tertiary, the OWL family may simply have originated during expansion of the proto-Basin and Range. However this hypothesized expansion seems may have been much different in style than the post-middle Eocene Basin and Range (Hodges and Walker, 1992). Furthermore the OWL and EEL have identical trends to their southern brethren, despite the fact that prior to the middle Eocene the continental margin was apparently quite irregular, and the north and south sides of the Columbia embayment were likely under the influence of separate oceanic plates.

The OWL does not in fact appear to extend as far as the Olympics; like other structures of the system it cannot be traced with much confidence past the Cascade crest. The western ends of these structures correspond to the eastern margin of Siletzia. Because Siletzia appears to have collided in the middle Eocene, might not the initiation of the OWL-type structures be related? Their orientation relative to the Straight Creek fault is quite similar to antithetic Reidel shears (R’) that accommodate the “venetian blind” style of rotation. Wells and Coe (1985) presented paleomagnetic evidence that suggested that this style accommodated rotation during accretion and translation of the Gray's River volcanics (Siletzia). Collision would seem to favor this style because it simultaneously accommodates shear and contraction. OWL-parallel sinistral/oblique structures appear to accommodate active rotation of the modern Cascadia forearc (Goldfinger et al., 1997). In the mid-Eocene the much stronger contraction may have caused a dextral shear couple between the Straight Creek fault and the craton. Collision plausibly accounts for the formation of a regionally coherent fault system cutting across a complex preexisting structural fabric. The OWL in the middle Eocene seems to have been dominantly contractional, but there is some suggestion of a left lateral component in fabrics of the Taneum Lake and Easton Ridge fault zones. The EEL may be a good place to further test the hypothesis, because it is developed in rocks with late Cretaceous to middle Eocene cooling dates.

4. WHAT LIES UNDER THE BASALTS?

4.1. Speculations based on the Baja BC hypothesis

Rodi (in Barrash et al., 1983) inferred from seismic data that underneath the basalts, a major break between “continental” (i.e. granitic) and “oceanic” (gabbroic) basement trended east-west and lay north of the OWL. This appears to correspond to an abrupt thickening of the Tertiary section (Figure 25), also along an east-west step (Glover, 1985; Reidel et al., 1989). A similar step occurs east of Snoqualmie Pass, where a series of major faults accommodates the transition from the North Cascades/Coast belt to lower-grade and less-intruded terranes correlative with those of the northwest Cascades, San Juan Islands, and southern Vancouver Island (Brown, 1987; Miller et al., 1993). When last seen on the east flank of the Cascades, these faults strike northwest-southeast, parallel to the OWL, but appear to be swinging into more east-west strikes away from the right lateral Straight Creek fault (as more clearly do their offset equivalents west of the Straight Creek fault). I speculate that east west-trend of folds within and north of the OWL are controlled by these faults, and that the north part of the Pasco Basin is likely underlain by terranes of the Northwest Cascades system (NWCS) and “Eastern melange belt” (EMB). In this scenario the rapid thickening of the Tertiary section across the Saddle Mountains area is the exact counterpart of the thickening of Tertiary rocks between the north and south Cascades. The apparent correspondence of the OWL with this transition in the Cascades is somewhat accidental.

The east-trending Yakima folds end abruptly at a series of high angle structures (occupied by Saddle Mountains basalt dikes) that are roughly on trend with the Pasayten fault (Finn and Stanley, 1997; Reidel et al., 1994). Although later thrust faulting presumably conceals the break, the Pasayten trend marks the boundary between the Insular and Intermontane superterranes, which are apparently displaced roughly 2000km relative to each other (Cowan et al., 1997; Wynne et al., 1995). NWCS and EMB rocks appear to have accreted by the mid-Cretaceous, prior to translation, so it is reasonable that they should be truncated (Figure 26). The probable terrane boundary intruded by the dikes (Reidel, 1994) appears to bend into and be cut by the KBML, which has been postulated to be part of the Baja BC boundary system (Riddihough et al., 1986).

The KBML may continue as the Hite fault, which bounds the Blue Mountains terranes and may offset the west-striking portion of the Salmon River suture (to the Cheney fracture zone?). The continuity of the KBML and Hite fault seems to support the notion that the Insular and Intermontane terranes moved together for a time. This late stage translation was distributed over a broad zone including areas often considered undisplaced craton. Both the Pasayten and Hite systems have previously been considered likely sutures between craton and outboard terranes (Reidel et al., 1994). However the Hite fault is outboard of the Blue Mountain accreted terranes, and so, therefore is the Palouse slope, which lies west of the Hite fault system and east of the Pasayten trend. The western portion of the Palouse slope is therefore probably peri-cratonic and considerably displaced. The Hite fault is also on trend with the eastern boundary of the Omineca Belt in the Purcell trench. The northern Rocky Mountain trench appears to have locally accommodated at least 1000km of slip (Gabrielse, 1985). This presumably was transferred via the Omineca-Okanogan belt to faults roughly along the KBML.

4.2. Eocene structural continuity

On somewhat firmer ground, Eocene structures can be plausibly traced by overlying drape folds in the Columbia River basalt. For example the Leavenworth, Eagle Creek and Entiat faults all appear to turn south, paralleling the trend of the Straight Creek fault (Tabor et al., 1982). The Hog Ranch uplift, which appears to correspond to the hanging wall of the Leavenworth fault, is the most pronounced example of this and has been much noted (Campbell, 1989; Reidel et al., 1994). The Hog Ranch axis is a broad upwarp and diffuse tear structure in the basalts. It accommodates the change in vergence from south to north on several folds with a generally right-lateral sense. The Entiat fault appears to be the master fault of the Chiwaukum Basin; it perhaps continues under Sentinel Gap. Late Eocene strike slip on the Entiat fault implies extension across the Sentinel Gap trend. Thus the deepest part of the Columbia Basin may correspond to a late Eocene graben or downwarp. This is probably not the dramatic rift envisioned by Catchings and Mooney (1988), but rather a more local basin generated by fault-fold interference (Reidel et al., 1994).

Structures on trend with the Republic graben can be traced into the Chelan and Wenatchee blocks, which are distinguished by somewhat different uplift histories. Much of the Chelan block did not cool below hornblende and biotite blocking temperatures until the middle Eocene, contemporaneous with strong contraction across the block-bounding Entiat fault. Some NW to NNW directed extensional fabrics (Haugerud et al., 1991; Miller and Patterson, 2000), however, are likely early Eocene. Prior to the middle Eocene, the Chelan block was continuous with and similar in structure to the Okanogan metamorphic complexes, but perhaps less extended. The Wenatchee block and areas south and west appear less extended still; ductile fabrics of Eocene age are not widespread. Nevertheless evidence for major normal faulting, in part low angle, appears to be widespread, especially within and at the base of the Swauk formation. Fission track dates suggest exhumation of the Mt. Stuart area in the early Eocene (Evans, 1994). The strong but less deep seated extension toward the early Eocene margin is consistent with extension being driven by divergence of the downgoing Kula and Farallon plates (Babcock et al., 1994; Breitsprecher and Thorkelson, 2001): the slab window and temperature of the lower crust would have increased eastward.

5. SUMMARY AND CONCLUSIONS

Seismicity reveals that active deformation of the Columbia Basin involves the entire seismogenic crust, but is accommodated somewhat differently at various crustal levels. This results in a basically thick-skinned regime that is regionally and locally overprinted by more thin-skinned deformation. Longer wavelength uplifts such as the Wenatchee Mountains and Satus Pass uplift are deep-seated, and locally appear to be bounded by moderately dipping reverse faults extending to at least 20 km, where they likely flatten into ductile shear zones in the lower crust. A shallower decollement at 5-10 km appears to be more or less regional in extent and controls the basic geometry of Yakima folds. Much of this upper crustal seismicity appears to define axial surfaces. The faults themselves appear to be broadly listric, steepening somewhat upward. The great variation in structural style along and between folds is attributable to fault-bend and kink-style, liftoff folds controlled by slip at the base and within the Columbia River basalts. Thin-skinned structures in the Tertiary rocks probably accommodate shortening that is taken up by more penetrative shortening at depth.

The direction of maximum principle contraction in the Columbia Basin is approximately N15E. This is generally the case for the southwestern half of the state, and significantly different from the NNW Miocene direction inferred from fold axes and orientation of dikes as young as 6 Ma. The implied clockwise rotation of strain axes in the latest Miocene or early Pliocene is consistent with earlier studies of young but not clearly active structures (Barrash et al., 1983; Lawrence, 1979). The onset of contraction across the OWL and extension in the Blue Mountains appear to date from this time. The two processes are presumably interlinked, and are the latest manifestation of the function of the Columbia Basin as a gravitational sink (Laubscher, in Kienle et al., 1977)

Long-wavelength uplift since the late Miocene is widespread and presumably due in part to the mantle response to changing plate motion. This relatively rapid uplift appears to be more or less independent of horizontal strain rates in the crust and is an underappreciated source of crustal stresses. The Coast Mountains/Cascades anticlinorium and the superposed Olympic-Okanogan upwarp are prominent examples of such uplifts, which began in the Miocene but accelerated in the Pliocene.

The two-stage history of the OWL since the Miocene demonstrates that some caution is necessary when speculating on its possible earlier history. It is clearly not a Cretaceous terrane boundary and it is not the continuation of the Straight Creek fault. It and the related EEL (Entiat-Ephrata line, a.k.a. Badger Mountain) do appear to have been active in the middle Eocene, however, at the same time as the Straight Creek. Based on analogy with active structures of the Cascadia forearc and widespread evidence for sinistral motions in the middle Eocene I speculate that the OWL family of structures may have originated as R' shears that accommodated some of the dextral shear between Siletzia and the craton in the middle Eocene. However an earlier late Cretaceous-early Eocene origin as transforms accommodating extension is possible (Hooper and Conrey, 1989). Seismicity appears to support the notion that the Naches fault is a throughgoing fault at depth, possibly the original master fault of the OWL (Campbell, 1989).

The sub-basalt structure of the Columbia Basin is no less complex than the geology exposed around its perimeter. However the paucity of geophysical data allows great conceptual freedom. Based on the Baja BC hypothesis and the assumption that the Pasayten fault-Ice Harbor trend, KBML, and Hite fault approximate major crustal boundaries, it is possible to construct a vaguely plausible terrane map of Washington. The southern margin of Baja BC emerges as a likely control of the east-west structures on the north side of the greater Pasco Basin, including its westward extension under the OWL. The step in basement properties and the thickness of Tertiary strata around the Saddle Mountains appears to continue under the Kittitas Valley (Jarchow, 1991) and is exposed in the Central Cascades, where it has generally, and probably mistakenly, been associated with the OWL. On firmer ground, detailed studies of Eocene deformation in the Cascades now allow a more realistic appraisal of the possible history of such structures as the Entiat fault. The present strain regime can to some extent be viewed as a minor resurgence of that of the middle Eocene event: most obviously, the rhombohedral uplifts and basins between the Straight Creek fault and the Sentinel Gap trend have been reactivated in a similar transpressive fashion.

Relocation of earthquakes using a more realistic velocity model and/or differential travel times is necessary to substantiate the very preliminary correlations presented here. Detailed, three-dimensional crustal tomography of the Columbia Basin appears to be a worthy goal (Glover, 1985; Jarchow, 1991), and might shed light on some of the most fundamental questions about the history of the Cordillera.

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