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PALEOGENE TECTONIC EVOLUTION OF THE PACIFIC NORTHWEST[1]

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ABSTRACT

Three consecutive tectonic regimes are recorded in the Paleogene of the North American Cordillera between 40° and 60° latitude. The Paleocene (65–53 Ma) regime produced crustal shortening along the eastern edge of the Cordillera, as well as a weak magmatic arc in British Columbia. The lower and middle Eocene regime (53–42 Ma) produced a robust volcanic arc superimposed on a network of strike-slip and normal faults and large north-northeast trending extensional metamorphic reset terranes. The Late Eocene and Oligocene regime (42–30 Ma) produced a north-south Cascade arc south of 50° latitude, and tectonic quiescence to the north and east. This sequence of events is consistent with the following tectonic model. In Paleocene time, continuous subduction took place from 40° to 60° latitude; low-angle subduction south of 49° created the Laramide magmatic gap. At about 53 Ma, amalgamation of the Pacific, Kula and northern Farallon plates created a Pacific-North America transform boundary north of 47° latitude. Transform motion was in part taken up on the Fraser-Tintina strike-slip system, cross-cutting the volcanism produced from the remnant of the subducted slab. At about 42 Ma, inland transform motion ceased, and all transform motion took place on the Queen Charlotte transform. South of 47°, subduction continued with a steady steepening of the subduction angle from north to south with time.

INTRODUCTION

In the Pacific Northwest (here defined as the North American Cordillera from 42° to about 60° north latitude), Paleogene rocks are widespread and lithologically and structurally varied. In particular, geochronologic work in the last two decades (such as Mathews 1964; McDowell 1971; Armstrong 1975) has outlined an intense, short-lived Eocene magmatic and tectonic event from 53 to 42 Ma ("Ma" used as defined in Berggren et al. 1978). This event is in large part separable from the regimes preceding and following. The varied and well-preserved rock record of the Paleogene should be amenable to paleotectonic interpretation, and be consistent with what is known of offshore plate motions during the early Tertiary.

This paper is an attempt to make such a reconstruction. It reviews and reinterprets what is known of Paleogene geology and tectonics in the area, and offers a synthesis of the Paleogene evolution of the Pacific Northwest.

EARLY TERTIARY ARC SYSTEMS

Paleocene (65–53 Ma). – A northwest-southeast trending belt of plutons yielding Paleocene dates exists in western British Columbia and Washington (figure 1*a*).

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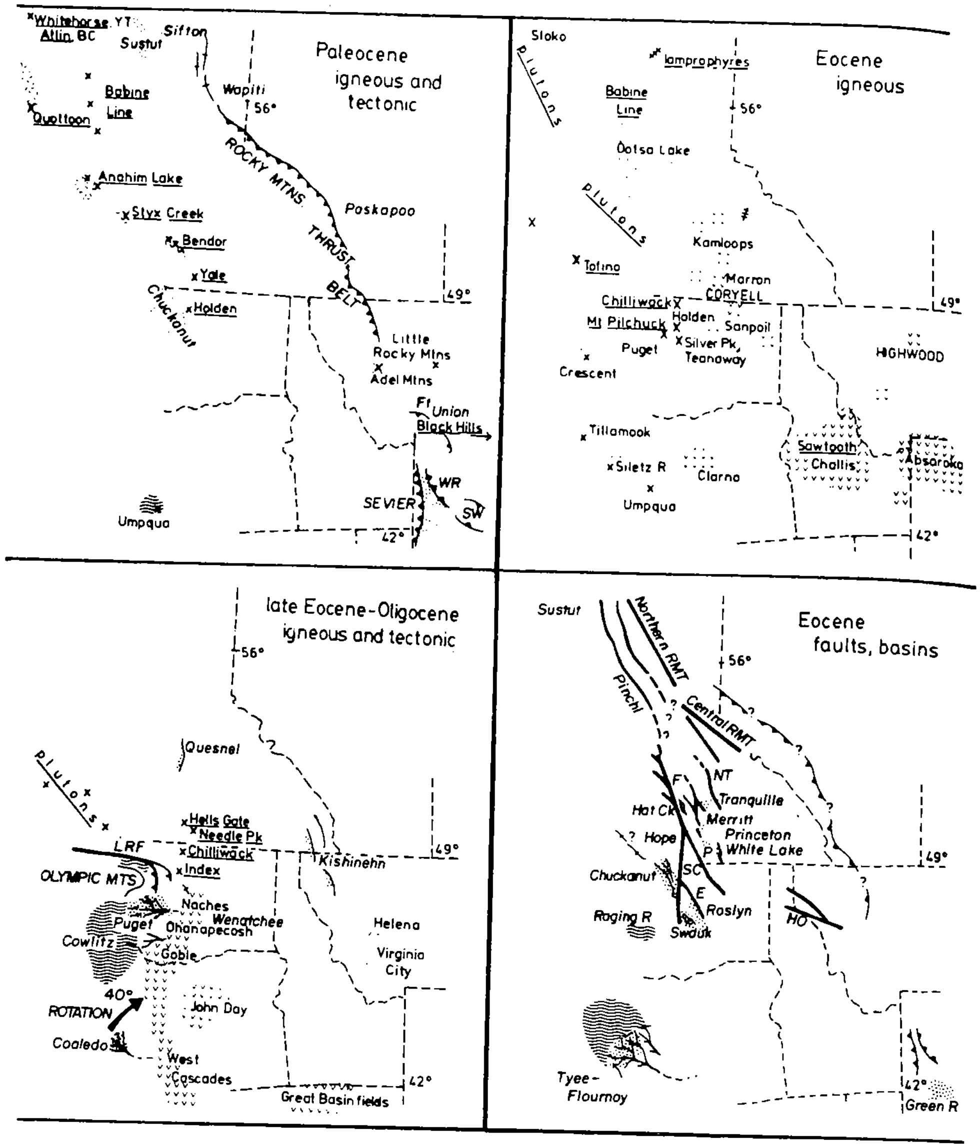

Fig. 1. – Igneous and tectonic elements of the Paleogene of the Pacific Northwest. Volcanic field names are in lower case, pluton names are in lower case and underlined, sedimentary basins are in lower case italics (waved rule = marine, stipple = non-marine). For sources see text. (A) Paleocene (65–53 Ma) igneous and tectonic elements. (B) Eocene (53–42 Ma) igneous elements. (C) Late Eocene and Oligocene (42–30 Ma) igneous and tectonic elements. (D) Eocene faults and sedimentary basins (fault names: HO = Hope-Osborn, E = Entiat, SC = Straight Creek, P = Pasayten, F = Fraser, NT = North Thompson, RMT = Rocky Mountain Trench). All maps are restored to pre-Basin and Range configuration, after Armstrong and Suppe (1973) and Armstrong et al. (1977).

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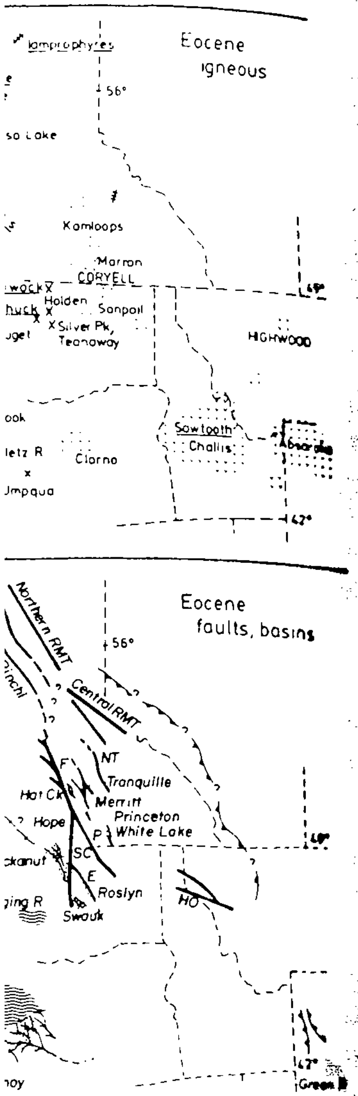

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Most of these plutons lie in the eastern half of the Coast Crystalline Complex of British Columbia. From north to south, reported Paleocene plutons are: several in the Atlin area, northwestern British Columbia (Bultman 1979) and the adjacent Whitehorse area of the Yukon (Morrison et al. 1979); the Quottoon pluton (Armstrong and Runkle 1979); small stocks in the north-south Babine intrusive belt of central British Columbia (Carter 1974); plutons in the Anahim Lake map-area (Church 1973; Carter 1974); the Styx Creek pluton (Woodsworth 1979); the Bendor plutons (Woodsworth 1977); the Yale intrusions (Richards and White 1970) and the Clark Mountain plutons in the Holden area of Washington (Cater and Crowder 1967). No Paleocene volcanics have been reported from this region. Paleocene volcanic ash is, however, known in the Sustut basin of north-central British Columbia (Eisbacher 1973).

Reported Paleocene magmatic activity is discontinuous and far inland south of latitude 48°. The Adel Mountains volcanics of western Montana give an age of 65 Ma (Chadwick 1972). Volcanics and plutons in the Little Rocky Mountains of central Montana erupted at 58 to 66 Ma (Hearn et al. 1978). Alkalic plutons of the Black Hills in South Dakota and Wyoming range from 59 to 49 Ma (McDowell 1971). Voluminous Paleocene magmatism in the western United States is restricted to the Colorado and Arizona-New Mexico segments (Snyder et al. 1976).

It is inferred that the belt of Paleocene dates in British Columbia and Washington marks the site of intermediate to silicic arc-related intrusion during the period 65 to 53 Ma. This arc extended from latitude 48° north beyond latitude 60°, and represented the continuation of late Cretaceous magmatism in the Coast Crystalline Complex. South of latitude 48°, magmatism was discontinuous and far inland; this region formed part of the "Laramide magmatic gap" noted by previous workers (Burchfiel and Davis 1972; Snyder et al. 1976; Armstrong 1979). The absence of volcanics along the Paleocene arc is presumably due to later uplift and erosion of the Coast Mountains.

There are comparatively few Paleocene dates from the Pacific Northwest as a whole (see Griffiths 1977 and Armstrong 1979). This was taken by Vance (1977) to support Paleocene transform faulting in the area. However, the dates that are reported, coupled with the low sample density in much of the Coast Crystalline Complex, suggest that some form of magmatic arc did exist at that time.

Eocene (53–42 Ma). – Extrusive and intrusive igneous rocks of Eocene age are reported from most portions of the Pacific Northwest. They form a narrow (about 70 km) belt north of 56° latitude along the Alaska-British Columbia boundary, a 250-km wide belt from 56° to about 48° latitude, and a broad (500–800 km) field from 48° to 42° latitude (figure 1*b*).

In northern British Columbia, most Eocene igneous rock is intrusive, located along the eastern margin of the Coast Crystalline Complex (Christopher 1973; Carter 1974; Smith 1977; Bultman 1979). Volcanics are preserved locally (Sloko volcanics; Souther 1977).

In central and southern British Columbia, intermediate to felsic volcanic rocks are more extensive. Large plutons are restricted to the eastern margin of the Coast Crystalline Complex (Woodsworth 1977; Tipper 1978) and the eastern Coryell province. In central British Columbia, Eocene volcanics of the Ootsa Lake Group are known (Church 1972; Eisbacher 1973; Souther 1977), associated with abundant small stocks of the Babine intrusions (Carter 1974). Near latitude 51°, intermediate volcanics of the Kamloops Group are dated as Eocene (Mathews 1964; Hills and Baadsgaard 1967; Ewing, in prep.). These rocks interfinger southward with alkaline and calc-alkaline volcanics of the Marron Formation (Mathews 1964; Church 1973, 1979); volcanics and sediments overlying the Marron are also Eocene (Church 1973, 1979). The alkaline rocks of this area are comagmatic with the Coryell intrusives of southernmost British Columbia (Little 1961; Church 1973; Ross 1974), of early Eocene age. East of the broad volcanic areas, lamprophyres of Eocene age have been reported (Wanless et al. 1972, 1973; Parrish 1979).

In the northwestern United States, Eocene volcanic and related intrusive rocks have been reported over a wide area (Armstrong 1979). Andesites and dacites of the Sanpoil volcanics interfinger northwards with the Marron volcanics; they yield early to middle Eocene dates, as do the younger Klondike Mountain and older O'Brien Creek Formations (Pearson and Obradovich 1977). Associated Eocene plutons have also been reported (Engels et al. 1976). In northwestern Washington, Eocene magmatism is recorded in the Holden area (Duncan Hill pluton, Old Gib volcanics; Cater and Crowder 1967), the Mount Pilchuk stock (Yeats and Engels 1971) and the Silver Peak volcanics (Gresens et al. 1977). Middle to late Eocene volcanics occur in the Puget Group of the Seattle area (Buckovic 1979). Early phases of the Chilliwack batholith may be as old as 49 Ma (Misch 1966; R. L. Armstrong, personal communication).

To the south, the andesitic Clarno volcanics of central Oregon have given ages from 42 to 48 Ma (Swanson and Robinson 1968; Enlows and Parker 1972; J. A. Vance, personal communication). In Idaho, the calc-alkaline Challis volcanics cover a wide area; associated plutons, such as the Sawtooth Batholith, have also been dated (Armstrong 1974, 1975; Siems and Jones 1977). The Absaroka volcanics to the east are correlative (Chadwick 1970, 1972; Smedes and Prostka 1972); minor activity in the Absaroka field continued to 36 Ma (Love et al. 1976). East and northeast of the Challis and Absaroka fields are alkaline volcanic and plutonic rocks of the Highwood province (Central Montana province of Larsen 1940; Lipman et al. 1972). Eocene plutons of potassic intermediate to felsic rock core many of the mountain complexes of central Montana (Marvin et al. 1973; Hearn et al. 1978; Snee and Sutter 1979). In the Black Hills alkaline plutonism continued into Eocene time (McDowell 1971). A small amount of alkaline magma formed the Rattlesnake Hills in central Wyoming (Pekarek et al. 1974).

Other Eocene plutonism is recorded from the west coast of Vancouver Island (Tofino pluton, 50 Ma; Carson 1972). South of 42°, Eocene volcanics are not reported except for isolated areas in Colorado and New Mexico (see Snyder et al. 1976).

It is inferred that a continuous volcanic and plutonic arc existed during Eocene time from latitude 42° north to northernmost British Columbia. This arc was narrowest in the north, where later uplift has removed most of the volcanic cover. In central and southern British Columbia, it was some 250 kilometers wide; southward it widened to 500–800 kilometres in Oregon, Idaho, Wyoming and Montana, then ceased altogether. This magmatic arc was of calc-alkaline character throughout, except for two alkaline provinces, the Coryell in southernmost British Columbia, and the Highwood in central Montana. This arc is the Challis volcanic episode of Armstrong (1979). In most areas, volcanic activity appears to have reached a maximum at 48–51 Ma, and died away more or less rapidly to about 42 Ma.

Late Eocene and Oligocene (42–30 Ma). – Dates from this time span form three groupings; a north-south belt from 50° latitude south beyond 42°, a northwest-southeast line close to the continental margin north of 49°, and scattered dates in the interior (figure 1*c*).

Plutons of Late Eocene and Oligocene age are reported from southernmost British Columbia and northern Washington; the Hells Gate pluton (42 Ma; Wanless et al. 1973), Needle Peak pluton (39 Ma; Monger 1970), part of the Chilliwack Batholith (38 Ma, Misch 1966), and the Index pluton (34 Ma; Yeats and Engels 1971). South of latitude 48°, volcanics of this age are widespread in Washington (Naches Formation, 39–41 Ma, Tabor and Frizzell 1979; Ohanapecosh Formation, younger than 38 Ma;

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J. A. Vance, personal communication; also Fiske et al. 1963; Goble volcanics, about 40 Ma; Beck and Burr 1979). Voluminous magmatic activity in Oregon and northern California began by 35 Ma (western Cascades, Hammond 1979, Smith 1979; John Day Formation, Swanson and Robinson 1968); little is recorded in the 8 m.y. preceding. Volcanism in the Great Basin (northern Nevada and adjacent areas) is about 40 Ma in age (Stewart and Carlson 1976; Snyder et al. 1976).

Scattered plutons are recorded along the continental margin north of 49°. Small quartz diorite plutons are scattered across Vancouver Island (Carson 1972), and a larger body is found in the central Queen Charlotte Islands (Wanless et al. 1969). In southeastern Alaska, small stocks host porphyry molybdenum deposits (Quartz Hill plutons, 30 Ma; Hudson et al. 1979).

In Montana and Wyoming, minor volcanism occurred during Late Eocene and Oligocene time. The Helena field (37 Ma) and the Virginia City field (33 Ma) erupted in Montana (Chadwick 1978). A date of 36 Ma is reported from the southeastern Absaroka field (Love et al. 1976).

It is inferred that the north-south alignment of ages south of 50° latitude marks the inception of the Cascade volcanic arc. This arc, well established by 35 Ma, is at a 30°–40° angle to the arc trend of the Eocene, although the two overlap and are indistinguishable in northern Washington (Vance 1979). This arc appears to have terminated northward at about 48°–50° latitude during Late Eocene and Oligocene time. North of this, magmatic activity took place only close to the continental margin and in low volume.

Summary. – Early Tertiary magmatism in the Pacific Northwest showed three distinct but short-lived phases. The first (65–53 Ma) was an igneous arc extending northwest from northwestern Washington, with discontinuous magmatism in Montana and South Dakota. The second (53–42 Ma) was marked by a robust magmatic arc trending northwest-southeast from latitude 60° to latitude 42°, dominantly calc-alkaline but containing two alkaline provinces. This arc began about 53 Ma, reached its maximum intensity at 48 to 50 Ma, and decayed to 42 Ma. The third (42–30 Ma) was marked by the inception of the north-south Cascade arc south of 50° latitude and low-intensity plutonism along the continental margin north of 49°.

EARLY TERTIARY FAULTING, FOLDING, AND BASIN DEVELOPMENT

Paleocene. – Evidence for Paleocene tectonic activity is largely confined to the eastern edge of the Cordillera (figure 1*a*). North of 46° latitude, thin-skinned deformation continued from Late Cretaceous through Paleocene time in the northern Rocky Mountains (Monger and Price 1979). Several thrusts cut Paleocene fluvial sediments of the Paskapoo Formation and the Wapiti Group (shown on Tipper 1978); the time of last movement on these thrusts is not known. At 56° latitude, the Sustut and Sifton nonmarine successor basins received sediments from late Cretaceous to middle Eocene time (Eisbacher 1973).

South of 46°, thin-skinned thrusting took place in the Sevier system, or Idaho-Wyoming thrust belt (Armstrong 1968; Dorr et al. 1977). The thick-skinned Laramide uplifts to the east were also active in the Paleocene. Movement on the Wind River thrust continued into early Eocene time (Dorr et al. 1977). Climatic deformation of the Sweetwater uplift occurred in latest early Eocene, ending about 50 Ma (Love 1970). Latest movement on the Laramide Elkhorn thrust in central Colorado has been bracketed between 49 and 56 Ma (Marvin et al. 1978).

West of the Rocky Mountains, Paleocene tectonism is obscure. The Chuckanut nonmarine sediments of northwestern Washington have been considered to be of Paleocene age (Weaver 1937; Miller and Misch 1963), but much of the great thickness of material may be early Eocene (51 Ma – Vance and Naeser 1977, Frizzell 1979). A small amount of Paleocene fluvial sediment is preserved in the Methow trough of north-central Washington (Pipestone Canyon Formation – Barksdale 1975). The presence of other Paleocene sedimentary basins or Paleocene tectonic features has not been demonstrated in the Pacific Northwest; some features, however, may be masked by later Eocene activity.

The observable tectonic record indicates that Paleocene crustal shortening took place along the entire eastern margin of the Pacific Northwest. Telescoping of the sedimentary succession took place in the Rocky Mountain and Sevier fold and thrust belts. Basement shortening took place in the Laramide basement-cored uplifts, and presumably in the hinterland of the thrust belts, although direct evidence is lacking. No other inferences about Paleocene tectonics can be drawn from present knowledge. In particular, there is no direct evidence for or against Paleocene strike-slip faulting in the Pacific Northwest, such as suggested by Vance (1977).

Eocene. – Significant tectonism and basin development occurred in lower and middle Eocene time in most parts of the Pacific Northwest (figure 1*d*). Evidence for the nature of this episode comes largely from three areas: southern British Columbia, the North Cascades of Washington, and southwestern Oregon.

In southern British Columbia, small fault-bounded sedimentary basins developed in lower Eocene time. The Tranquille basin received about 500 m of lacustrine and volcanogenic material (dated at 50 Ma; Mathews 1964; Ewing 1979*a*). Similar accumulations occurred to the north (Chu Chua Formation – Campbell and Tipper 1972) and to the west (McAbee sediments, 50 Ma – Hills and Baadsgaard 1967). Material probably of an equivalent age occurs at Merritt (Coldwater beds – Cockfield 1948) and Hat Creek (Church 1975). These occurrences will be discussed at greater length in a separate paper. Their geometry, structure and stratigraphy suggest that they formed within an interlocking strike-slip and dip-slip fault network marked by local grabens, and rapid changes in both thickness and facies. Other sedimentary basins occur to the south at Princeton (48 Ma – Hills and Baadsgaard 1967) and White Lake (47 Ma – Church 1973). They appear to be controlled by north-south trending subsidence structures similar to Hat Creek (Church 1975, 1979).

Other major tectonic features of southern British Columbia are the metamorphic reset terranes. These terranes, found in the entire Pacific Northwest, will be discussed in a separate section.

The northern Cascades of Washington experienced a complex series of tectonic events during early and middle Eocene time. A thick sequence of nonmarine sediments (Swauk and Chuckanut Formations) is in part of early Eocene age (Vance and Naeser 1977; Frizzell 1979). This sequence is deformed by tight concentric folds (Foster 1960; Miller and Misch 1963) which are crosscut and overlain by 47-Ma Teanaway basalt (Foster 1960; Tabor and Frizzell 1979). The fold axes are northwest-trending in the northwestern Cascades, become nearly north-south to the south, then swing nearly east-west in the Swauk outcrop area east of the Straight Creek Fault; in the latter area the Teanaway dike swarm cuts fold axes at right angles (Foster 1960). After the Teanaway volcanism, nonmarine sediments of the Roslyn Formation were deposited. These sediments correlate with the thick graben fill of the Chiwaukum graben, and the Puget Group deltaic sediments to the west (Buckovic 1979). Tuff in the graben fill yields zircon fission-track dates from 47 to 40 Ma (Vance and Naeser 1977; Frizzell 1979).

The Straight Creek Fault runs north-south through the North Cascades, and has been inferred to localize right-lateral displacement (Misch 1966; Monger and Price 1979). The timing of this movement has been disputed. Vance (1977) suggests that this movement was pre-Eocene, with Eocene dip-slip reactivation of the zone. Frizzell (1979), on the other hand, considers 160 km of motion to have occurred after Chuckanut-

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Swauk deposition – nearly as much as Misch (1977) proposed for total movement on the fault (about 180 km). Vertical Chuckanut-equivalent conglomerates are reported within the northern extension of the fault zone at Hope, British Columbia (Read 1960; McTaggart 1970).

Several inferences can be drawn regarding early Tertiary tectonics in the North Cascades. The Teanaway dike complex represents west-northwest/east-southeast extension, while the immediately preceding Swauk foldbelt represents north-south compression. These events are compatible with a single stress regime, with principal compression slightly east of north. Alternate compression and rifting indicate an exchange of the positions of intermediate and least principal stresses at about 47 Ma. This orientation of stresses is roughly consistent with right-lateral strike-slip movement on the Straight Creek Fault. The swinging of Chuckanut-Swauk fold axes into the line of the Straight Creek Fault suggests rotation of stresses and/or structures consistent with right-lateral movement on the fault. Similar sigmoidal patterns are seen in the older terrains in southern British Columbia (see Tipper 1978). Alternatively, the change in fold axes may represent buttressing against the Mount Stuart Batholith to the northeast (J. A. Vance personal communication).

In southwestern Oregon, a complex middle Eocene deltaic and turbiditic sequence (Tyee and Flournoy Formations) was built over deformed early Eocene Roseburg Formation distal turbidites and early Eocene Umpqua basalts (Baldwin 1974; Perttu and Benson 1980). Deformation of the Roseburg Formation indicates syndepositional folding and net northeast-southwest shear (Perttu and Benson 1980). This shearing dies out gradually upward into north-down dip-slip faulting, as noted along the Canyonville fault zone (Perttu 1976); the middle Eocene Flournoy Formation passes unbroken over this zone. Deltaic and marine deposition continued through middle Eocene time. In northwestern Oregon and western Washington basaltic seamounts grew to and above sea level during this time (Snavely et al. 1968). The Tyee delta was succeeded in late Eocene time by marine to deltaic strata of the Coaledo and Spencer Formations (Baldwin 1974). Post-Tyee rotation of over 70° clockwise has affected the Oregon Coast Range and the Klamath Mountains (Simpson and Cox 1977); about 40° of this occurred before the eruption of the Yachats basalts at 39 Ma (Simpson and Cox 1977).

A throughgoing system of strike-slip faults was probably active during Eocene time north of latitude 47°. Several features distinguish individual faults in this system. Their straight ground trace is often composed of many braided fault segments with a total width of one to four kilometres. The faults show variable dip-slip offsets of Eocene strata, frequently localizing Eocene pocket basins and eruptive centers. They are geometrically related to extensional structures such as grabens and metamorphic reset terranes (see below). They are continuous over tens to hundreds of kilometres, and show minor structures, pervasive shearing and subhorizontal slickensides which indicate strike-slip movement. The major throughgoing faults with inferred Eocene strike-slip motion are shown on figure 1*d*. From north to south, these include ten fault systems.

1. The Hope-Osborn fault system of northern Idaho is related to an offset of Eocene metamorphic reset terrane (Miller and Engels 1975) and is inferred to have Cretaceous to Eocene right-lateral displacement.

2. The north-south Straight Creek Fault has been discussed above. Although is cut locally by post – 40 Ma batholiths, it can be traced northwards into British Columbia (McTaggart 1970), where it merges with the Pasayten fault.

3. The Entiat fault is the northwest-southeast straight fault which forms the northeast boundary of the post – 45 Ma Chiwaukum graben. It can be traced northwestward into the Marblemount zone of

Misch (1966, 1980) and into the Straight Creek Fault (see the compilation of Haugerud 1980). Its straight trace and continuity suggest an earlier, possibly Eocene, strike-slip history before its known dip-slip motion.

4. The Pasayten fault trends northwest-southeast and forms the northeast boundary of the Cretaceous-Paleocene Methow trough (Barksdale 1975). The age of main motion is poorly understood, but dip-slip motion occurred during or after the Paleocene. It joins with the Straight Creek Fault north of Hope, British Columbia (Monger 1970).

5. The Fraser Fault Zone is a northwest-southeast trending braided fault zone which has been traced from the Hope area to Quesnel, British Columbia. Eocene sediments and volcanics have been trapped and folded in this zone west of Hat Creek (Duffell and McTaggart 1952).

6. A complex network of faults in southern British Columbia, mentioned above, localizes sedimentary basins and volcanic centers. This network is bounded on the northeast by the North Thompson fault zone (Campbell and Tipper 1972) and its extensions. These Eocene structures are largely concealed to the northwest, but may join with the Fraser Fault Zone or the northern Rocky Mountain Trench. The network terminates to the southeast at the Shuswap-Okanogan metamorphic reset terrane (described below).

7. The Bowron River Fault, is a northwest-southeast straight fault extending southeast from the northern Rocky Mountain Trench along the eastern boundary of the Eocene Bowron River coalfield.

8. The central Rocky Mountain Trench is a broad linear furrow running southeast from the northern Rocky Mountain Trench to the Canoe River area in east-central British Columbia. It has the same appearance as the northern Trench, although it is of different orientation. The Rocky Mountain Trench south of Canoe River is quite different in nature; strike-slip movement has not occurred there (Price 1977).

9. Several northwest-trending faults, including the Pinchi fault zone, lie parallel to and southwest of the northern Rocky Mountain Trench. Mesozoic motion on these zones has already been proposed (Gabrielse and Mansy 1978; Monger and Price 1979) but Eocene activity is permissible and consistent with other activity.

10. The northern Rocky Mountain Trench (Gabrielse and Dodds 1977) runs northwest from east-central British Columbia to approximately latitude 60°. It is related to the Tintina Trench on the north, on which 450 km of right-lateral displacement since 80 Ma has been inferred (Tempelman-Kluit et al. 1976). In British Columbia, the Trench localizes the Cretaceous-Eocene Sifton Basin, and bounds the Eocene – reset Wolverine metamorphic complex on the northeast (Parrish 1979).

It is impossible with the available data to firmly establish the timing and magnitude of movements along these faults. The total post-80 Ma displacement has been estimated in the Yukon and in northern Washington. The establishment of Eocene displacement comes from their relationship to pocket basins, as mentioned above, and to metamorphic reset terranes.

Late Eocene and Oligocene. – Tectonic elements of these ages are largely restricted to the Pacific coast south of latitude 49° (figure 1*c*). There, deltaic to marine sediments were deposited in Late Eocene and Oligocene time (Puget Group – Buckovic 1979; Cowlitz Formation – Armentrout et al. 1980; Coaledo Formation – Baldwin 1974). The Oregon Coast Range was rotated about 40° before 39 Ma, as mentioned above. Left-lateral movement on the Leech River Fault began after 40 Ma (Fairchild 1979) and may be related to the arching and eastward movement of the Olympic Mountains (Tabor and Cady 1978).

Elsewhere, a number of grabens and half-grabens are known. The Quesnel basin, containing about 150 metres of continental strata (W. H. Mathews and G. E. Rouse, in preparation) is localized along the Fraser Fault Zone, suggesting local dip-slip reactivation. West-down listric normal faults cut earlier thrusts in the Rocky Mountains

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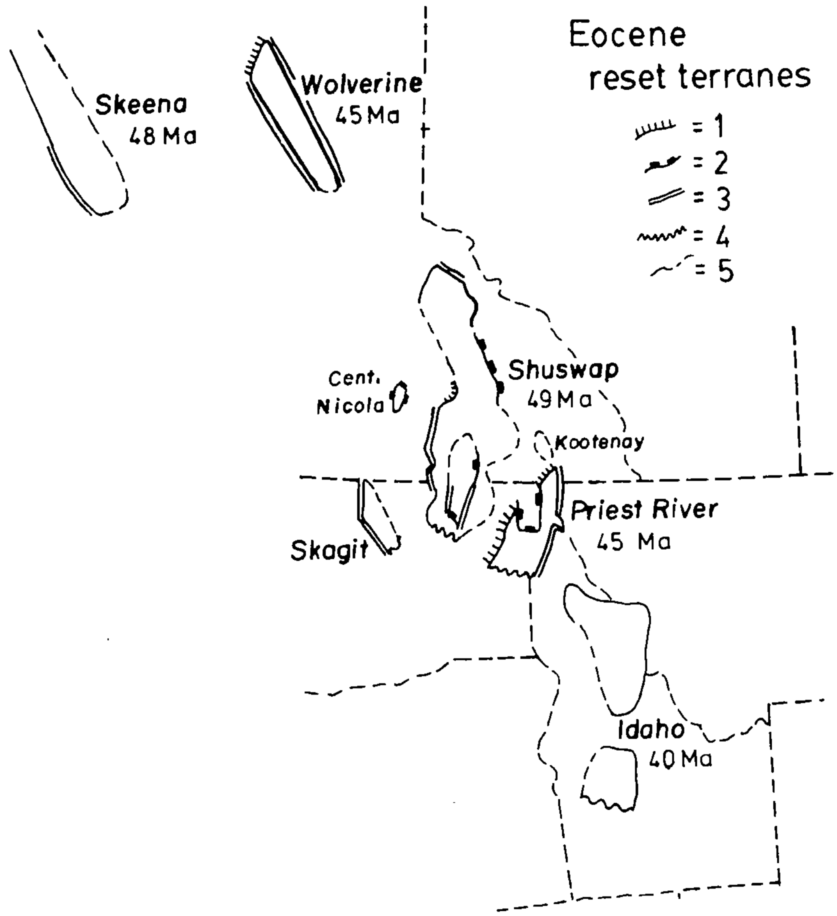

Fig. 2. – Eocene reset metamorphic terranes. Ages are the average minimum age of biotite K-Ar resetting. For sources see text. Boundaries: 1 = resetting front, 2 = denudation fault, 3 = throughgoing fault, 4 = unconformity, 5 = type not determined or inferred contact.

of southern British Columbia and Montana (Price and Mountjoy 1970), creating half-grabens which are filled in part by the Late Eocene and Oligocene Kishinehn Formation (Jones 1969). These faults may represent postorogenic extension associated with late subsidence of an Eocene-uplifted crystalline hinterland.

EARLY TERTIARY RESET TERRANES

Large areas of high-grade metamorphic rock in the Pacific Northwest yield isotopic dates of 40 to 55 Ma. These dates are generally discordant; biotite K-Ar yields Eocene dates while hornblende K-Ar and/or whole-rock Rb-Sr yield Mesozoic dates at the same location. Figure 2 shows those terranes in which K-Ar ages have been reset as defined by a survey of often insufficient radiometric data. Their boundaries are shown at the approximate 60-Ma "chrontour," or line of equal reset biotite K-Ar date. From south to north, these major terranes are: the Idaho reset terrane (Armstrong 1974, 1975); the Priest River terrane (Miller and Engels 1975; also called the Selkirk terrane by Coney 1979; the new name is after the Priest River metamorphics of Daly 1912, and is suggested to avoid confusion with the large Selkirk structural features in Canada); the Okanogan terrane in central Washington (Fox et al. 1977); the Skagit terrane (Misch 1966; Engels et al. 1976); the Shuswap terrane (Ross 1974; Medford 1975); the Kootenay Lake terrane (W. H. Mathews, personal communication); the Central Nicola terrane (Preto et al. 1979; R. L. Armstrong, personal communication); the Wolverine terrane (Parrish 1976, 1979) and the Skeena terrane (Hutchinson et al. 1979; Berg et al. 1978). The major terranes south of 54° are elongate slightly east of north, and step *en echelon* along a broad northwest-trending zone. The areas of resetting roughly correspond with areas of sillimanite-grade rocks, but this correspondence is not exact (for example, Parrish 1976).

The contacts of these reset terranes with adjoining nonreset rocks fall into four types. In the first, there is a continuous stratigraphy and structure across the boundary, with a *resetting front* marked by a rapid succession of chrontours; this is seen in the Wolverine terrane (Parrish 1976) and the Priest River terrane (Miller and Engels 1975). In the second, mylonitic flat faults or *denudation faults* separate reset metamorphics from nonreset sediments and volcanics. This is reported from the Priest River terrane (Newport fault – Miller 1971), the northern Shuswap complex (Read 1976) and northern Washington (Cheney 1979). In the third class, reset areas are bounded by *steeply-dipping faults*, some of which have inferred strike-slip motion; this is reported from the Okanagan fault system (Church 1975), the borders of the Republic graben (Muessig 1967) and the Skagit terrane (Misch 1966). In the fourth case, younger rocks overlie the reset terrane on an *unconformity*, as noted along the margins of the Columbia River Plateau and the Snake River Plain.

Nonreset Eocene and earlier rocks which are inferred to lie atop the reset terrane are known from the Midway-Greenwood area of British Columbia (Monger 1967) and the adjacent Republic area of Washington (Muessig 1967). Both areas show profound extension, evidenced by profuse normal faults of both high and low angle, and extensive rotation of fault blocks (E. Irving, P. Schwimmer personal communications). Along the western margin of the Shuswap terrane, slide breccia and fanglomerate within the middle Eocene strata indicate an uplifted source area to the east (Monger 1967; Church 1973).

It is inferred that these reset terranes are metamorphic core complexes, similar to those described by Coney (1979). The presence of denudation faults, sharp thermal gradients shown by resetting, and high-grade metamorphic rocks is similar to the core complexes of the Basin and Range country. The metamorphic reset terranes differ from the latter only in their age; all known core complexes south of the Snake River Plain are late Oligocene to Miocene in age (Coney 1979).

Several mechanisms have been proposed for producing these reset terranes. Purely hydrothermal mechanisms have been suggested (Little 1961; Medford 1975; Hyndman 1978) to be associated with intense Eocene magmatism. Criss and Taylor (1979) have outlined large hydrothermal systems in the Idaho terrane with oxygen isotopes. This mechanism may locally be important; but the amount of Eocene magmatism in many of these terranes, notably the northern Shuswap, northern Priest River and Wolverine terranes, is minor, and probably insufficient to generate the extensive resetting. Furthermore, this model does not easily explain the presence of denudation faults and related core complex deformation.

Other mechanisms involve the uplift of hot metamorphic infrastructure over a broad area. This might be achieved in a compressional environment by crystalline thrusts related to Rocky Mountain thrusting, but the latter is probably earlier than the observed resetting. The alternative is uplift in an extensional environment by

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ductile normal faulting as proposed by Davis and Coney (1979) for the Basin and Range core complexes. I favor this model for the genesis of the early Tertiary reset terranes, as it is consistent with the extension seen elsewhere in southern British Columbia (noted by Price 1979) and the lack of known Eocene compressional features in most areas of the Pacific Northwest.

The preferred model, then, for reset terrane evolution calls for large areas of rapid uplift of hot metamorphic rock and associated intrusive bodies, with tectonic and erosional denudation in an extensional regime, during early and middle Eocene time. If the Davis and Coney model is valid, we may expect that the long axis of the core represents the intermediate stress axis (the axis of elongation of the megaboudinage), and that the extension which generated the Pacific Northwest core complexes was directed west-northwest/east-southeast. The *en echelon* geometry strengthens this inference, as does the close relationship of the core complexes with major faults, which is explored below.

DISCUSSION AND SYNTHESIS

The Paleogene geology of the Pacific Northwest, as described above, consists of a succession of magmatic arcs, and a system of faults and folds associated with basins and metamorphic core complexes. Each of these categories yields clues to the nature and cause of Paleogene tectonic activity.

Paleogene magmatic trends. – The evidence for three distinct magmatic trends in the early Tertiary has been outlined above, together with inferences concerning their geometries. If we assume as a corollary of plate-tectonic theory that these three linear, generally calc-alkaline magmatic arcs mark a subjacent subducted slab of oceanic lithosphere, then a history of the geometry of that slab can be determined.

In the northwestern United States, scattered, mostly alkalic, Paleocene magmatism in the interior was succeeded by intense, widespread, calc-alkaline Challis episode (Armstrong 1979). This was followed by the development of the north-south Cascade arc and the Great Basin volcanic fields. It is reasonable to infer that Paleocene magmatism marks the presence of a very shallowly dipping slab which nearly excluded magmatic activity. The extensive Eocene arc suggests that the subducted slab still dipped at a low angle beneath the continent, but now permitted magmatic activity north of 42°. The Late Eocene and Oligocene arc, on the other hand, implies a moderately east-dipping subducted slab north of latitude 42°. These inferences are those of Snyder et al. (1976) and Cross and Pilger (1978), and are compatible with the early Tertiary magmatic history of the southwestern United States described by Coney and Reynolds (1977) and Keith (1978).

In British Columbia, a weak Paleocene plutonic arc gave way to a robust volcano-plutonic arc somewhat to the east in the early and middle Eocene. This volcanism ceased by the late Eocene, and no Oligocene magmatic arc can be defined, except for near-margin plutonism. This history suggests that a subducted slab was present beneath British Columbia through Paleocene and early to middle Eocene time. This interpretation is at variance with that of Vance (1977), who questions the existence of the Paleocene arc, proposing instead a transform margin during that time. Further geochronologic work in British Columbia is necessary to resolve this question. The subducted slab ceased to produce magmas by 45–42 Ma, and no Oligocene subducted slab can be inferred north of 50°. This was noted in a general fashion by Griffiths (1977).

Eocene tectonic elements. – Evidence has been presented in a previous section for a significant episode of strike-slip faulting with concurrent basin development, folding and local rift basalts. Also discussed above were the broad areas of Eocene metamorphic resetting which are inferred to represent metamorphic core complexes

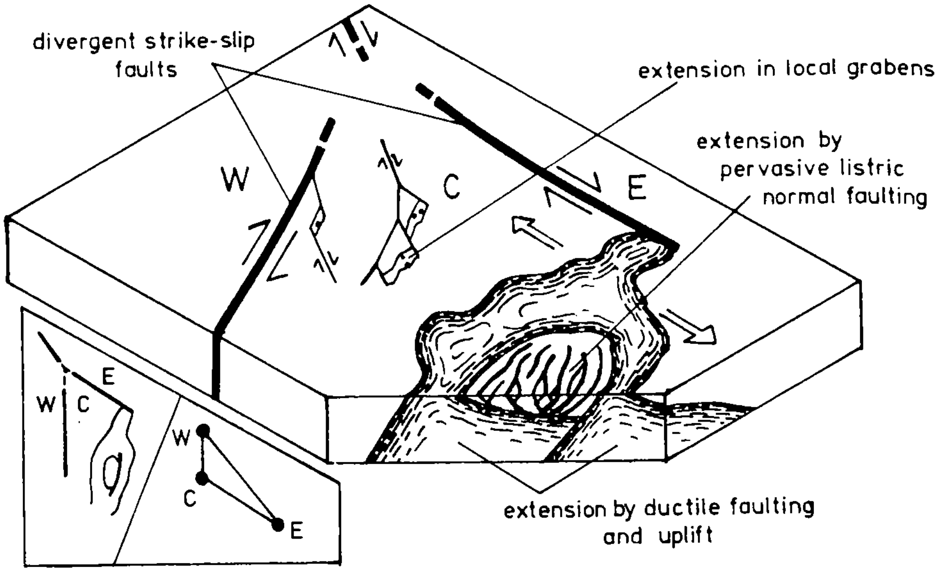


Fig. 3. – Conceptual block diagram showing the relationship between strike-slip faulting and formation of grabens and metamorphic core complexes. Insert at lower left shows a plan view (L) and a schematic displacement vector diagram (R).

formed by west-northwest/east-southeast extension across a ductile metamorphic infrastructure.

One model for relating a strike-slip fault system with metamorphic core complexes is presented on figure 3. In this model, two primary dextral strike-slip faults of divergent orientation exist, with the fault on the west being the southward-continuing feature. Displacement on the other fault (between blocks C and E) must then be taken up through extension roughly perpendicular to its trend. This is accommodated through listric normal faulting and graben development in the brittle superstructure, and ductile spreading, growth faulting, and associated uplift in the mobile infrastructure. Secondary strike-slip faults produce associated extension in minor grabens and metamorphic core complexes.

Integration in this manner of the inferred strike-slip fault system and the metamorphic core complexes in the Pacific Northwest leads to the network shown on figure 4*a*. Thus the northern boundary of the Shuswap reset terrane is the central Rocky Mountain Trench, and its southern boundary inferred to be the Pasayten fault. The Hope-Osborn fault system of northern Idaho likewise forms the northern boundary of the Idaho reset terrane. Movement on the Pasayten fault implies a large, concealed extensional area beneath the Columbia Plateau, separating the northern Cascades from northeastern Oregon and western Idaho. The need for the latter has been mentioned by Davis et al. (1978) in another context.

By ignoring secondary faults and reset terranes, we can simplify this tectonic model to a five-block scheme. Assuming that most of the motion on the bounding faults was strike-slip and that block rotation was small (which is supported by the straightness of the major faults), a displacement vector diagram can be constructed (figure 4*b*) by using the fault azimuths as slip vectors between blocks. This diagram contains an internal check (the azimuth of the Fraser Fault Zone) and is probably true to a first approximation. Further,

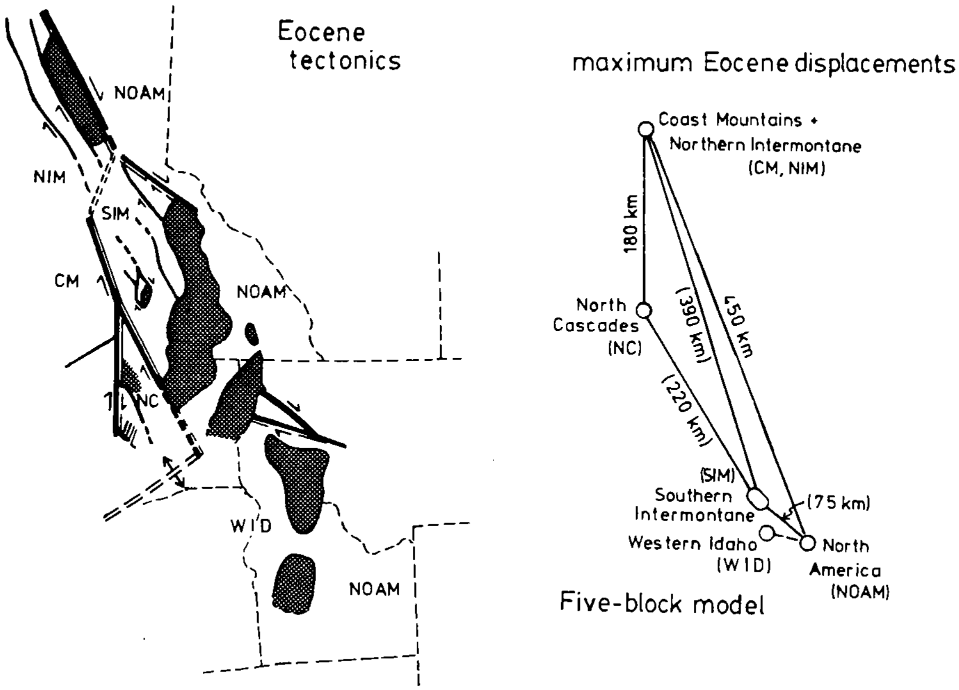


Fig. 4. – *a*: Eocene faults and metamorphic reset terranes in the Pacific Northwest. Double lines are the boundaries of the blocks used in the five-block model; block names as in 4*b*. *b*: Maximum Eocene (or middle Cretaceous to Eocene) lateral displacements calculated from a five-block model. For discussion see text.

if we assume that all of these faults and extensional zones were active concurrently, and that the estimates of motion on the Tintina Trench (450 km) and the Straight Creek Fault (180 km) since the middle Cretaceous are valid, the amounts of displacement across each of the other boundaries may be calculated; they are shown on figure 4*b*. Note that this model predicts about 75 km of net crustal extension across the Shuswap terrane from middle Cretaceous to late Eocene time; that is, about 35% to 50% crustal extension.

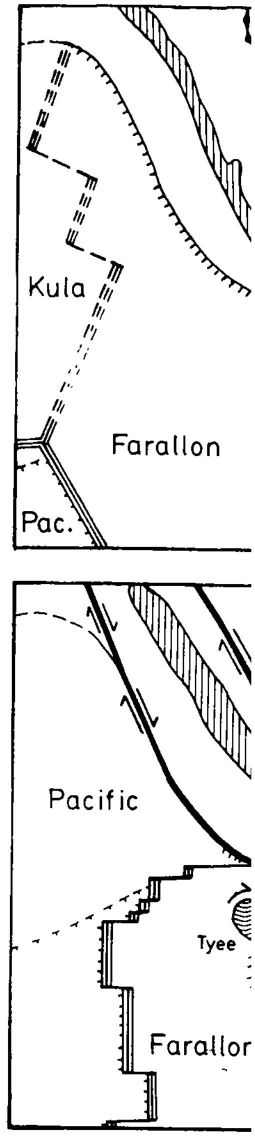
As mentioned before, it is by no means proven that this magnitude of displacement occurred during the Eocene. The lack of known Paleocene basin development in the Southern Intermontane block suggests, however, that the minor strike-slip faults in this area were not then active. This might be taken to extend to the major faults and core complexes as well. Furthermore, some displacement on this system must be Eocene, to account for the broad core complexes, the extensive basin development and listric normal faulting of that age. This minimum displacement is difficult to determine; it must be estimated from the minimum amount of extension across the Shuswap needed to produce resetting and listric normal faulting. I conjecture that 10%–20% might be a reasonable minimum, with 50% permissible during the Eocene. According to this conjecture, a minimum of 20% and a maximum of 100% of the total strike-slip and extensional activity shown in figure 4*b* marks Eocene tectonism.

Synthesis. – During the Paleocene a subducted slab extended continuously from northern British Columbia to Mexico. In the United States, this slab dipped shallowly beneath the continent, producing a broad area of little or no magmatic activity and pronounced Laramide foreland deformation (Cross and Pilger 1978). The crust was dramatically shortened along the entire landward edge of the Cordillera during this time. In the lower and middle Eocene, a subducted slab still existed in all areas. North of 42°, a large flareup of magma generation occurred, marking the partial collapse of the shallowly dipping slab in the Idaho-Montana area (Snyder et al. 1976; Armstrong 1979). This magmatism was superimposed on a throughgoing system of dextral strike-slip faults, metamorphic core complexes and volcano-sedimentary basins which suggests net right-lateral displacement of 100–500 km. In the Late Eocene and Oligocene there was no subducted slab north of 50°; to the south, the subducted slab continued its steepening and collapse (Coney and Reynolds 1977; Keith 1978; Dickinson 1979), forming the north-south Cascade arc and the Great Basin volcanic fields. An offshore transform margin is inferred north of 50° based on the lack of both arc magmatism and onland deformation. The newly-accreted Coast Range oceanic terrane rotated some 40° clockwise before 39 Ma (Simpson and Cox 1977; J. Magill personal communication).

There are three mechanisms for generating large strike-slip systems such as that of the Pacific Northwest: the faulting could represent a transcurrent system related to collision of a continental block, as the Central Asia faults are related to the collision of India (Molnar and Tapponier 1975); or, it could represent a subduction-related transcurrent fault system resulting from oblique subduction, as in the western Pacific (Fitch 1972); or, it could represent an onland transform margin similar to the San Andreas fault system of California. The first mechanism does not appear to apply to the Pacific Northwest during the early Tertiary, despite an earlier accretionary history (Monger and Price 1979). The second and third mechanisms produce the two models which are illustrated in figure 5.

Both models have similar conditions at 60 Ma (Paleocene, figure 5*a*) and 38 Ma (latest Eocene, figure 5*d*). The overall geometry and timing of spreading ridges and ridge reorientation or extinction in the Pacific is taken from Byrne (1979). The two models differ in explaining the events between about 55 Ma and 42 Ma. The first model (subduction-related transcurrent faulting) results from the assumption that the Eocene arc was a product of an active Eocene subduction zone. The crosscutting of the arc and the strike-slip regime must then indicate transcurrent faulting due to oblique subduction (figure 5*b*). Indirect plate-motion evidence may support the existence of oblique subduction, as I have argued previously (Ewing 1979*b*). This model, however, suffers from two drawbacks; the lack of an adequate initiating mechanism for a fault system not confined to the arc, and the need to allow about five million years lag-time between changes in plate geometry and changes in arc patterns (as noted by Snyder et al. 1976).

The second model (transform faulting) considers the Eocene arc in British Columbia to be derived from a headless subducted slab which remained from a previously active subduction zone (figure 5*c*). At 55–57 Ma the Pacific plates underwent a drastic reorganization, resulting in the amalgamation of the Pacific, Kula and (this model proposes) the northern end of the Farallon plates. Thus the subduction zone off British Columbia ceased to be active at that time, and a largely transform Pacific-North America boundary was established north of about latitude 48°. Much of this transform motion was taken up on the strike-slip and extensional network which this paper infers; other motion offshore accounts for the 350 km of Eocene displacement observed on the Denali Fault Zone of Alaska (Lanphere 1978). At 45–42 Ma transform motion ceased inland, and was entirely taken up offshore on the



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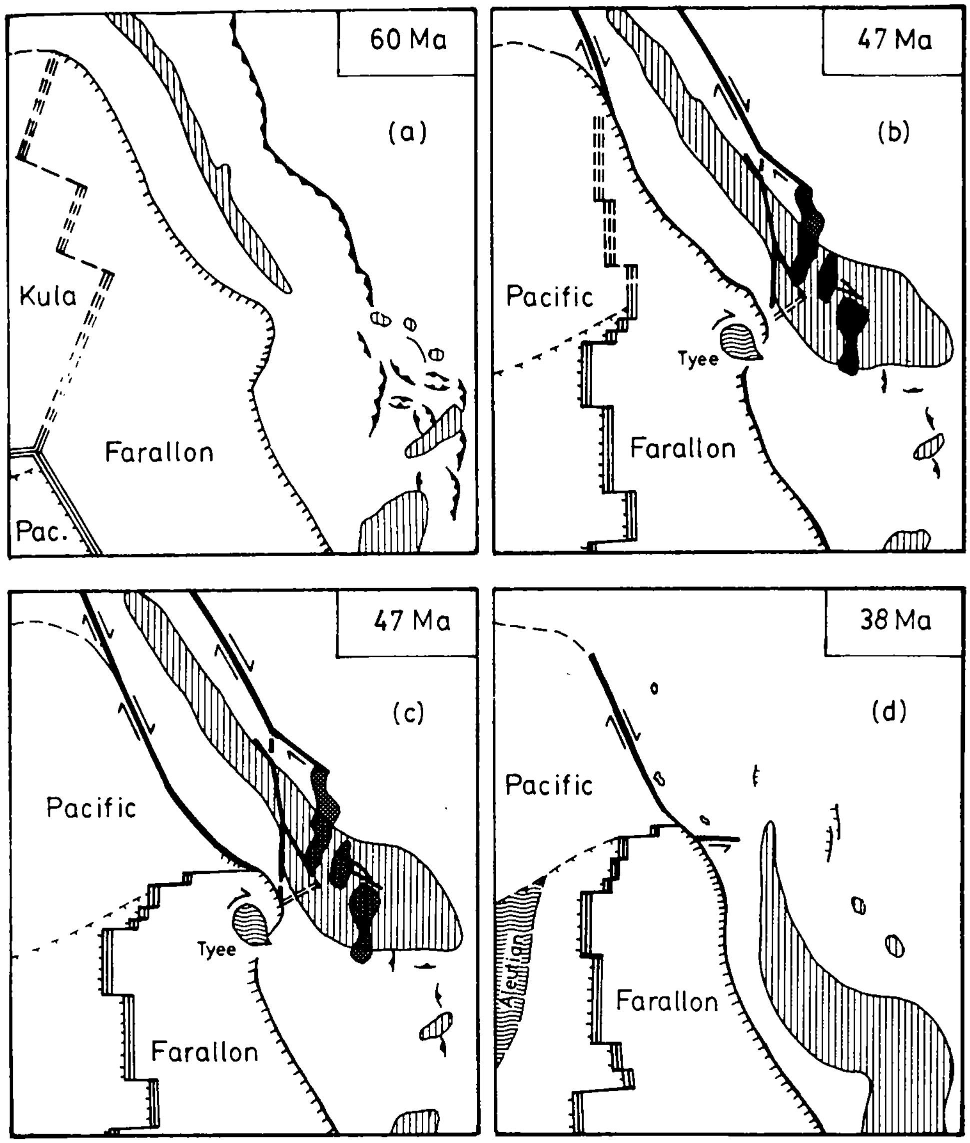

Fig. 5. – An interpretation of early Tertiary plate tectonics in the Pacific Northwest. Vertical ruled areas are magmatic arcs, shaded areas are metamorphic core complexes, wavy lined areas are turbidite fans. Small barbs outline the extent of presently preserved magnetic lineations on the Pacific plate. Oceanic plate boundaries after Byrne (1979). A) Paleocene. B) Eocene, model I. C) Eocene, model II. D) Late Eocene and Oligocene.

Queen Charlotte transform system. This is the preferred model, as it allows a geologically reasonable lag-time between plate geometry changes and arc transitions, and accounts for the broad outlines of the tectonics of the Pacific Northwest using only one major plate reorganization. Future work will test these models, and hopefully bring us closer to an understanding of the geologic history of the Paleogene of the Pacific Northwest.

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SEASONAL SEDIMENTA

F. M. BRO
Departmer

The sequence of sediments bet
Coalfield is described with part
consists of regularly-bedded lan
escape shafts. The escape shafts
units accumulated within the li
failure of recruitment of new s
sandstone accumulated during w

INTRODUCTI(

This study is concerned
succession between the I
Coal and the Bullion (or U
in the Upper Carbonifero
(Westphalian A) of the Lan
The area has been mapped
1:10560 (6 inches to 1 mi
tute of Geological Science
Geological Survey) and the g
in the memoirs by Earp et
et al. (1938), Tonks et al. (
al. (1927). Further contr
stratigraphy relevant to this
made by Eagar (1951, 19
and Magraw (1957). Surfa
the succession under study a
rarely complete. The enti
exposed, however, at Ra
Landgate Quarry, and in a s
Inchfield Moor (see fig. 1)
normally varies between 1
thins to zero where the tw
form the Union Coal in the n
of the coalfield (see fig. 1).
was formerly visible in vario
and until recently could be
ground at Old Meadows C
nately this mine is now disu

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sity, Bristol BS8 1HR.

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