Paleogeographic evolution of the United States Pacific Northwest during Paleogene time

PAUL L. HELLER
Department of Geology and Geophysics, University of Wyoming, Laramie, WY 82071, U.S.A.
ROWLAND W. TABOR
United States Geological Survey, 345 Middlefield Rd., Menlo Park, CA 94025, U.S.A.
AND
CHRISTOPHER A. SUCZEK
Department of Geology, Western Washington University, Bellingham, WA, 98225, U.S.A.

Received July 22, 1986
Revision accepted January 23, 1987

Paleogeographic reconstructions for Oregon and Washington during Paleogene time illustrate a major transition from a dominantly compressional (prior to middle Eocene time) to an extensional tectonic regime. This transition resulted in the development of three phases of Paleogene basin evolution in the United States Pacific Northwest. During the initial phase, basins formed along the continental margin during collision of oceanic islands. Sediments in these basins were derived from nearby orogenic highlands. The second phase of basin development began in middle Eocene time and consisted of rapid subsidence of individual basins that formed within a broad forearc region. Nonmarine basins that formed during this phase were caused by extension possibly associated with transcurrent faulting. Rapid sedimentation in both marine and nonmarine basins during this time consisted dominantly of sandstone derived from Cretaceous plutonic sources far to the east. The final stage of basin development was the modification of previous basin configurations by the growth of the Cascade volcanic arc, which was initiated in early Oligocene time. The rising Cascade Range diverted streams carrying eastern-derived material, thereby reducing overall sedimentation rates in the coastal basins and providing a local source of volcanic detritus.

Dans les états de l'Orégon et de Washington, les reconstitutions paléogéographiques durant le Paléogène illustrent une période de transition majeure d'un régime de compression tectonique dominante (antérieur à l'Eocène moyen) à un régime de distension tectonique. Trois phases de l'évolution du bassin paléogène dans le nord-ouest Pacifique des États-Unis sont dues à cette transition. Au cours de la phase initiale, des bassins se formèrent le long de la marge continentale lors de la collision des îles océaniques. Les sédiments dans ces bassins provenaient des hautes terres des monts avoisinants. La seconde phase de développement du bassin débuta à l'Éocène moyen, et elle correspond à une subsidence rapide des bassins individuels qui s'étaient formés au coeur d'une grande région d'arc frontal. Les bassins continentaux qui se développèrent durant cette phase doivent leur origine à une extension qui accompagnait probablement un décrochement. La sédimentation rapide dans les bassins marins et continentaux à cette époque était dominée par des grès dérivés des régions nourricières plutoniques crétacées situées plus à l'est. L'étape final du développement des bassins fut la modification des configurations des bassins déjà exitants provoquée par la croissance de l'arc volcanique des Cascades, lequel arc est apparu au début de l'Oligocène. Le soulèvement de la chaîne des Cascades a modifié la direction d'écoulement des cours d'eau qui transportaient des matériaux provenant de l'est, de ce fait réduisant les taux de sédimentation moyens dans les bassins côtiers et fournissant une source locale de détritus volcanique.

[Traduit par la revue]

Can. J. Earth Sci. **24**, 1652–1667 (1987)

Introduction

The past few years have brought renewed interest in the Tertiary sedimentary basins of the United States Pacific Northwest, both in terms of ongoing tectonic studies and, more immediately, for purposes of hydrocarbon exploration (Armentrout and Suek 1985). Despite the increased interest in the region, few comprehensive geologic compilations exist. The most recent synthesis of regional Tertiary tectonics was by Ewing in 1980. Since that time numerous articles have been published that have added to our knowledge of the Paleogene history of the Pacific Northwest. The purpose of this article is to summarize the paleogeographic history of Oregon and Washington during Paleogene time. We briefly review the igneous, sedimentary, and deformational histories of the area and then summarize this information on a series of paleogeographic maps. We also provide an extensive reference list as a starting point for future studies.

During Paleogene time the northwestern United States and adjacent British Columbia underwent a transition from a dominantly compressional to an extensional tectonic regime. Amalgamation and accretion of terranes in the San Juan Islands, North Cascade Range, Blue Mountains, and Klamath Mountains (Fig. 1) had culminated by middle to Late Cretaceous time (Davis *et al.* 1978; Hamilton 1978; Monger *et al.* 1982; Tabor *et al.*, in press). Regional compressional deformation, including both vestigial accretions in the coastal zone and unrelated thrust faulting in the foreland, ceased by about 50 Ma (see below). At about the same time, extension began in Oregon and Washington, and it was well underway throughout the western United States during Oligocene time (see below). The initiation of extension was characterized by the westward migration of magmatism, the beginning of tectonic rotation of crustal blocks, regional strike-slip faulting, and the formation of metamorphic core complexes. These and other major geologic events that occurred in the Pacific Northwest (Fig. 1) between about 60 and 30 Ma are summarized in the following sections.

Igneous activity

Volcanism in the Coast Ranges

The Paleogene stratigraphy of the Coast Ranges includes both accreted volcanic rocks of probable seamount origin and

Printed in Canada / Imprimé au Canada

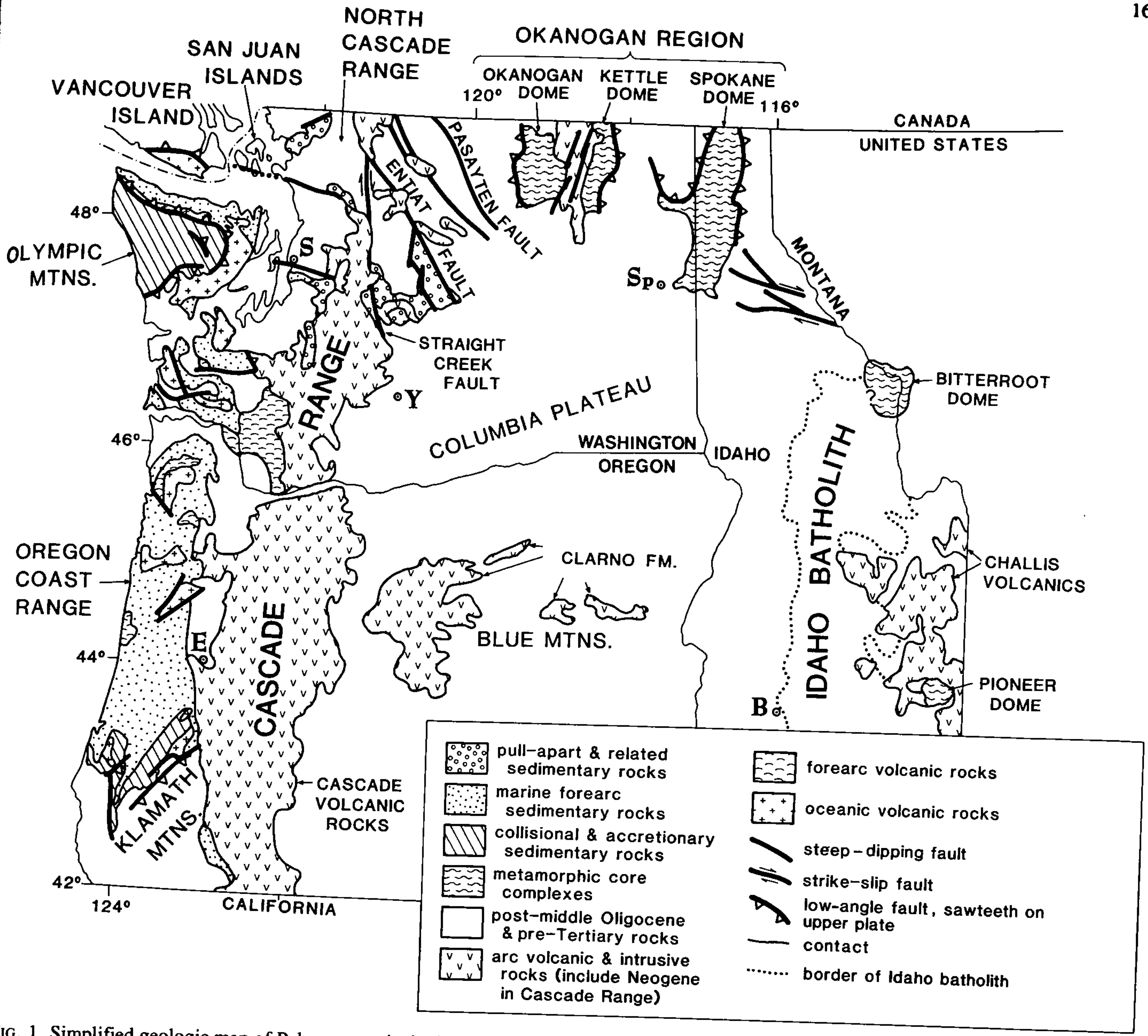


FIG. 1. Simplified geologic map of Paleogene units in the Pacific Northwest. Data from Barksdale (1975), Gard (1968), Heller and Dickinson (1985), Huntting *et al.* (1961), Hyndman (1980), Tabor and Cady (1978*a*), Tabor *et al.* (1968, 1980, 1982*a*, 1982*b*), United States Geological Survey (1964, 1966, 1969), Walker (1977), Wells (1979, 1981), Wells and Peck (1961), Wells *et al.* (1983), and J. C. Yount (written communication, 1984). B, Boise; E, Eugene; S, Seattle; Sp, Spokane; Y, Yakima.

post-accretion volcanic rocks. The former, from north to south (Fig. 2*a*), include the Metchosin Volcanics (Muller 1977), Crescent Formation (Cady 1975), Siletz River Volcanics (Snavely *et al.* 1968), and volcanic rocks of the Roseburg Formation of Baldwin (1974) now assigned to the Siletz River Volcanics of Molenaar (1985). These rocks are dominantly tholeiitic to alkalic basalts and may reach thicknesses of 15 km or more (Snavely *et al.* 1968; Cady 1975). Pillow basalt, in places interbedded with basaltic turbidite sandstone and siltstone and red pelagic limestone, is the most common deposit, although on Vancouver Island gabbros and sheeted dikes underlie the basalt (Massey 1986) and in places the upper part of the volcanic pile may consist of subaerial flows with columnar joints and scoria (Cady 1975; Snavely *et al.* 1968; Garrison 1973). Geochemical analyses of the pillow basalts show them to be low-K_2O tholeiites with a composition virtually identical to that of basalts formed at oceanic ridges (Snavely *et al.* 1968; Glassley 1974). In Oregon and on Vancouver Island, the upper part of the sequence is more alkalic and is subaerial, suggesting analogs with the Hawaiian Islands (Snavely *et al.* 1968; Muller 1977). A seamount origin for these volcanic rocks is inferred from their physical stratigraphy, geochemistry, and great thickness.

Duncan (1982) discerned a systematic variation in the age of the basalt on the basis of K–Ar and $^{40}Ar/^{39}Ar$ analyses. His data suggested that ages generally decrease from southern Oregon to the Columbia River and then increase to the north (Fig. 2*a*). Duncan argued that this age progression could occur if a hot spot that centered on a spreading ridge generated two seamount chains that were subsequently accreted to the continent. Wells *et al.* (1984), on the other hand, argued that reconstructed Kula–Farallon plate motions, relative to hot spots and the North American plate, preclude a simple scenario and that the hot-spot basalt eruptions were also related to the synchronous reorganization of the Kula–Farallon ridge or that the basalt was erupted in the wake of oblique continental rifting of North America.

Post-accretion volcanic units include alkalic flows, mafic sills, and dikes that erupted episodically from middle Eocene into Oligocene time. The basalt, diabase, and gabbro are interbedded with or injected into the sediments of the coastal basins. For example, the upper part of the Crescent Formation in southwestern Washington is interbedded with the arkosic sandstone of Megler, and the younger Goble Volcanics to the east are interbedded with sandstones of the Cowlitz Formation (Wells 1979, 1981). In Oregon, the Yachats Basalt (Snavely and MacLeod 1974) and the Tillamook Volcanics (Wells *et al.* 1983) consist primarily of subaerial flows overlying a base of pillow basalts that apparently erupted in a forearc-basin setting. The exact origin of these forearc volcanic rocks and subsequent intrusive activity is uncertain. Snavely and MacLeod (1974) and Snavely *et al.* (1980*b*) proposed that some of the volcanic rocks had erupted along a zone of tensional rifting. Wells *et al.* (1984) related this manifestation of regional extension to the obliquity and (or) decrease in rate of convergence between the Farallon and North American plates.

Arc magmatism

Several compilations of radiometric ages have documented the rapid sweep of arc-related magmatism across the northwestern United States between 70 and 35 Ma (Armstrong 1974, 1978; Snyder *et al.* 1976; Ewing 1980). The arc rocks include a wide variety of compositions from basalt to rhyolite and associated plutonic rock types, all of which are predominantly calc-alkalic in composition but are increasingly alkalic eastward towards the craton (Lipman *et al.* 1972; Armstrong 1978). At about 70 Ma, magmatism was centered in the region of the Idaho batholith, but it subsequently migrated eastward across Montana and then swept back to Idaho by 50 Ma. A northwest-trending belt of magmatic rocks formed during this later time interval, the Challis Volcanics, (Armstrong 1974, 1978). Subsequently the locus of igneous activity migrated westward into Oregon; volcanic rocks of the Clarno Formation in central Oregon were first erupted about 45 Ma (Oles and Enlows 1971; Enlows and Parker 1972; Armstrong 1978; Taylor 1981; Fiebelkorn *et al.* 1983), and the Little Butte Volcanics, the oldest dated rocks of the Cascade arc, erupted in the Oregon Cascade Range by about 38 Ma (Sutter 1978; Lux 1982). In northern Washington the westward shift of the arc apparently began a little earlier and perhaps migrated more quickly than in Oregon, with widespread magmatism occurring from the Okanogan region to the North Cascades at about 50 Ma (Fig. 2*b*) (Fox *et al.* 1977; Frizzell and Vance 1983; Tabor *et al.* 1984; Armstrong 1978). Arc magmatism has been restricted to the Cascade Range of Washington and Oregon for at least the past 35 Ma. Determining the rate and magnitude of arc migration in the Pacific Northwest is difficult because of the contemporaneous and subsequent extensional and rotational history of terranes throughout the region (Hamilton 1969; Armstrong 1974; Simpson and Cox 1977). These terrane movements have affected the distribution of volcanic rocks and, to some extent, increased the apparent rate and magnitude of Eocene arc migration. The apparently wider sweep of magmatism in Oregon than in Washington may be due mostly to a greater amount of subsequent extensional movement in Oregon.

Sedimentary basin evolution

Major sedimentary basins that developed during Paleogene time were concentrated along the coastal zone (Armentrout *et al.* 1983) (Fig. 3). Relatively few sedimentary deposits older than Eocene age are preserved in the Pacific Northwest. Paleodispersal patterns in the Eocene basins indicate flow was dominantly from the east and south (Fig. 3). When corrected for tectonic rotations (Beck 1980), most basins in western Oregon and southwest Washington show original dispersal from the east or southeast.

Paleogene sandstones throughout the region can be conveniently characterized by three petrofacies (e.g., Heller and Ryberg 1983). (1) *Lithic sandstones* are restricted to the northern Olympic Peninsula (Fig. 2*a*) (Aldwell and Lyre formations, Twin River Group, the sandstones of Scow Bay) and the lower part of the stratigraphic section in the southern Oregon Coast Range (Fig. 2*a*) (Roseburg, Lookingglass, and Flournoy formations). These sandstones contain a mixture of volcanic, metamorphic, and sedimentary lithic fragments that were derived from local orogenic uplands (e.g., Klamath Mountains and Vancouver Island). (2) *Arkosic sandstones* dominate most sections between 50 and 40 Ma, including the Tyee and Yamhill formations in Oregon and the sandstone at Megler, Puget Group, and the Chuckanut and Swauk formations in Washington. In contrast to the lithic sandstone, the arkose contains conspicuous white mica, potassium feldspar, and quartz grains, and volcanic fragments dominate the lithic components (Heller and Ryberg 1983; Chan 1985). In Oregon, source areas for most of these deposits were probably the plutonic uplands far to the east (Heller *et al.* 1985), such as the Idaho batho-

FIG. 2. Time–space tectono-stratigraphic cross sections: (A) roughly north–south section through the Oregon and Washington coastal ranges and (B) east–west section across northern Washington. Time scale from Palmer (1983). Data from Armentrout and Berta (1977); Armentrout *et al.* (1983); Armstrong (1978, 1982); Baldwin (1974); Barksdale (1975); Beck and Burr (1979); Duncan (1982); Engels *et al.* (1976); Frizzell and Vance (1983); Fulmer (1975); Gresens *et al.* (1981); Harms and Price (1983); Heller and Dickinson (1985); Johnson (1984*a*); McDougall (1980, 1981); McLean (1977); Pearson and Obradovich (1977); Rau (1981); Snavely *et al.* (1980*a*); Tabor and Cady (1978*a*); Tabor *et al.* (1984); Turner *et al.* (1983); Vine (1969); Wells (1979, 1981); and Worsley and Crecelius (1972). Ad, Aldwell Formation; As, Alsea Formation; Ba, Bateman Formation; Bk, Blakeley Formation; BP, Barlow Pass Volcanics of Vance (1957); Bs, Bastendorff Formation; Ck, Chuckanut Formation of Johnson (1984*a*); Cl, Coaledo Formation; Cr, Crescent Formation; Cs, Chumstick Formation; Cw, Cowlitz Formation in Oregon and in Washington; Ek, Elkton siltstone member (of Tyee Formation); Fl, Flournoy Formation; GV, Goble Volcanics; KD, Kettle dome; Ke, Keasey Formation; KM, Klondike Mountain Formation; LC, Lincoln Creek Formation; Lk, Lookingglass Formation; lM, McIntosh Formation (lower part); Ly, Lyre Formation; MS, sandstone at Megler; Na, Naches Formation; Ns, Nestucca Formation; OC, O'Brien Creek Formation; OD, Okanogan dome; Oh, Ohanapecosh Formation; PB, Pittsburg Bluff Formation; PC, Pipestone Canyon Formation; PG, Puget Group; Ro, Roseburg Formation; RR, Raging River Formation; Rs, Roslyn Formation; Sa, Sanpoil Volcanics; SB, sandstone of Scow Bay; SD, Spokane dome; SP, Silver Pass volcanic member (of Swauk Formation); SR, Siletz River Volcanics; Sw, Swauk Formation; TP, Tunnel Point Sandstone, TR, Twin River Group; TV, Tillamook Volcanics; Ty, Tyee Formation; uM, McIntosh Formation (upper part); Wn, Wenatchee Formation; YB, Yachats Basalt; Yh, Yamhill Formation.

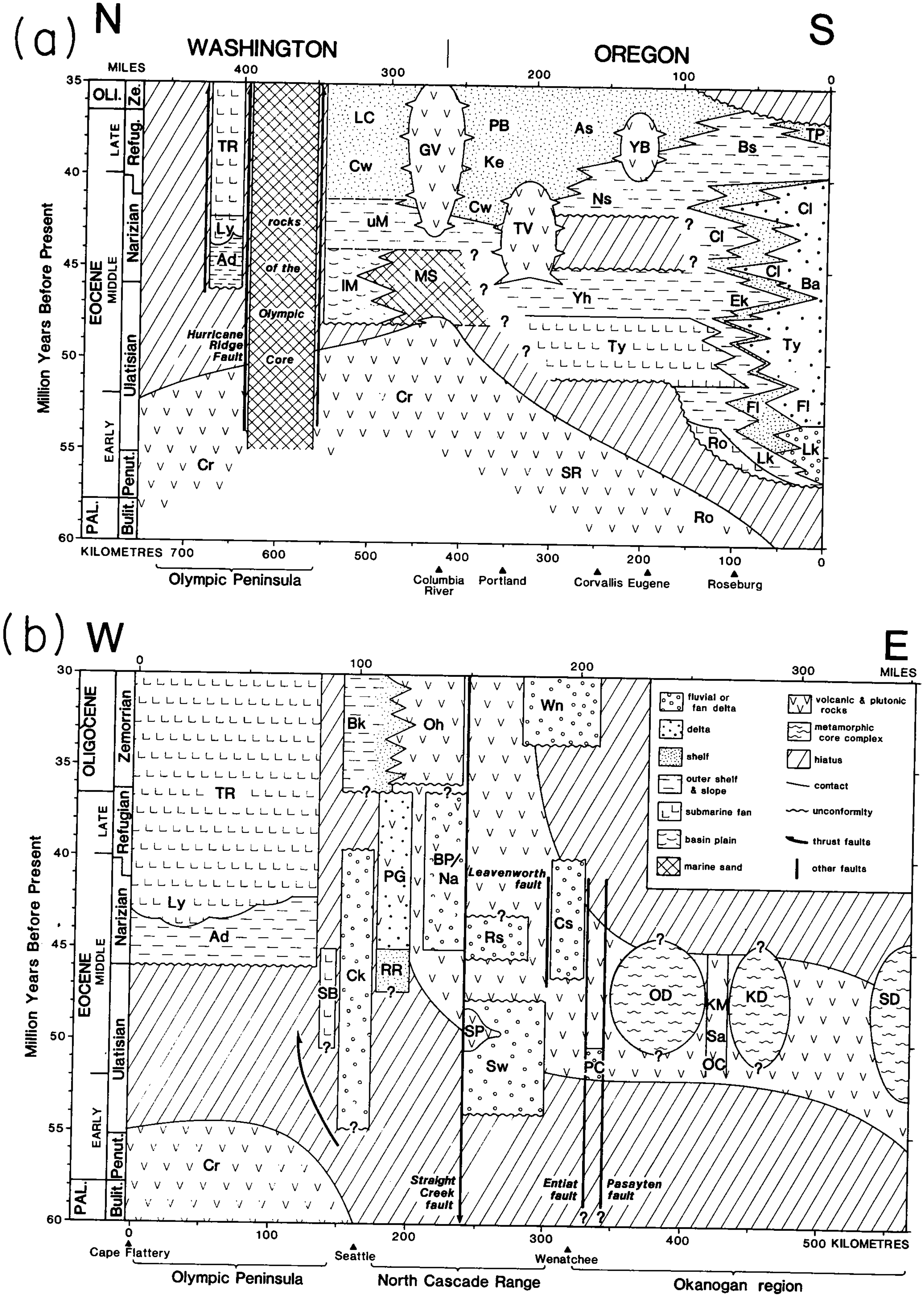
ism occur-
es at about
ınce 1983;
n has been
Oregon for
ignitude of
because of
and rota-
(Hamilton
These ter-
f volcanic
t rate and
ntly wider
n may be
xtensional

Paleogene
rmentrout
deposits
orthwest.
flow was
corrected
n western
dispersal

be con-
Heller and
he north-
e forma-
') and the
n Oregon
Flournoy
volcanic,
hat were
Mountains
ate most
nd Yam-
r, Puget
Washing-
ains con-
z grains,
s (Heller
areas for
lands far
o batho-

---

tal ranges
rmentrout
; Frizzell
cDougall
oor et al.
a Forma-
huckanut
n Oregon
ome; Ke,
ormation
rmation;
oup; Ro,
Spokane
ndstone,
rmation;



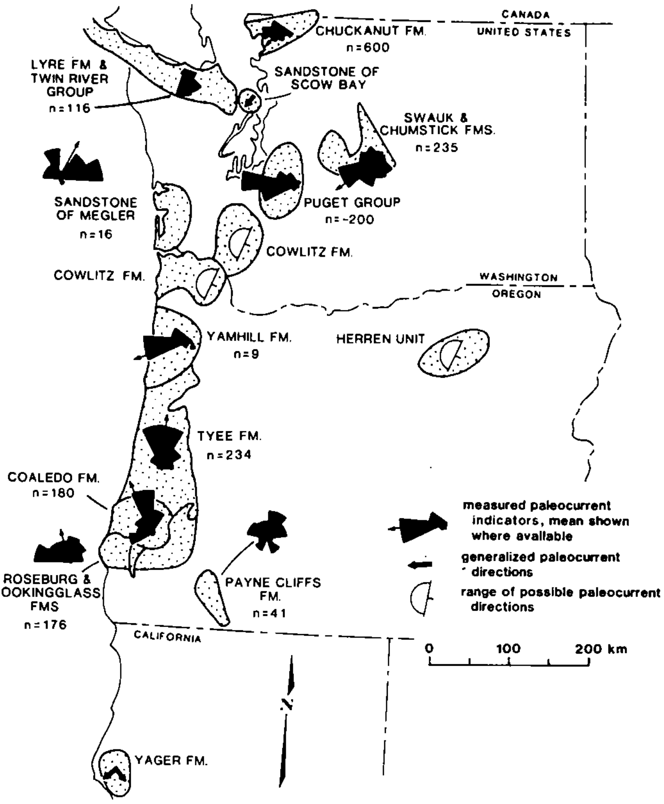


FIG. 3. Distribution of major Eocene sedimentary deposits in Oregon and Washington and their directional information. Measured and generalized paleocurrent directions determined from sedimentary structures. *N* is the number of measurements. Range of possible paleocurrent directions determined from sandstone compositional variations. Data sources—Chuckanut Formation: Johnson (1984*a*); Coaledo, Tyee, and Roseburg–Lookingglass formations: Heller and Ryberg (1983); Cowlitz Formation in Oregon: Timmons (1981), Niem and Van Atta (1973); Cowlitz Formation in Washington: Snavely *et al.* (1958), Heller (1983); Herren unit: Heller (1983); Lyre Formation and Twin River Group (part): Snavely *et al.* 1980*a*; sandstone of Megler: Heller (1983); Payne Cliffs Formation: McKnight (1984); Puget Group: Buckovic (1979); sandstone of Scow Bay: Melim (1984); Swauk and Chumstrick formations: Buza (1979); Yager Formation: Underwood (1983); Yamhill Formation: Heller (1983).

lith, which is known to have been rapidly uplifted and unroofed during this time (Ferguson 1975; Criss *et al.* 1982). In Washington, source areas are presumed to be the North Cascades and Okanogan uplands (Gresens *et al.* 1981; Johnson 1984*a*). (3) *Volcanolithic sandstones* and other tuffaceous sedimentary rocks dominate deposits younger than about 40 Ma (e.g., Nestucca, Coaledo, Blakeley, and Lincoln Creek formations) (Figs. 2*a*, 2*b*). Cascade volcanic-arc rocks appear to be the source for much of the volcanic detritus in these units (Snavely and Wagner 1963; Dott 1966; Galloway 1974; Heller and Ryberg 1983).

Deposition during Paleogene time primarily took place in collisional (synorogenic) basins, marine forearc basins, and nonmarine graben and (or) pull-apart basins. Collisional basin deposits are only found in the Coast Ranges and are related to seamount accretion or subsequent accretionary wedge development (Tabor and Cady 1978*b*; Heller and Ryberg 1983). Deformed submarine-fan deposits and discontinuous belts of mélange of the Roseburg Formation in the southern Oregon Coast Range are interpreted as representing trench sedimentation typical of convergent margins (Ryberg 1983). Depositionally overlying the Roseburg Formation are moderate- to coarse-grained, nonmarine to marine deposits of the Lookingglass and Flournoy formations of early Eocene age (Baldwin 1974; Molenaar 1985) (Fig. 2*a*). Overlapping all of these units are relatively mildly deformed sandy deltaic to submarine-ramp facies of the Tyee Formation (Snavely *et al.* 1964; Chan and Dott 1983; Heller and Dickinson 1985) that are interpreted as post-collisional forearc-basin deposits (Heller and Ryberg 1983). The transition is recorded by an upsection decrease in intensity of deformation, paleodepth of water, and abundance of locally derived lithic detritus.

Overlying the collisional-basin deposits in Oregon and southwest Washington are arkosic to volcanolithic sandstones deposited in marine forearc basins. These units include the Tyee Formation and younger deposits in the Oregon Coast Range and the McIntosh and Cowlitz formations and overlying units in the Columbia River area (Fig. 2*a*). The lower member of the Cowlitz Formation in northwestern Oregon now serves as the reservoir for gas in the Mist field. These basins are characterized by rapid sedimentation rates; rates for the Tyee Formation may have exceeded 650 m/Ma (Heller and Dickinson 1985). Deposition in these basins postdated collision of volcanic basement against North America (Heller and Ryberg 1983; Snavely 1984). Basin configuration probably followed previous topography that developed during collision.

Following collision of volcanic terranes in the Pacific Northwest, marine deposits continued to accumulate and deform along an active trench, building an accretionary prism of sedimentary rocks on the Olympic Peninsula and off the coast of Oregon (Snavely *et al.* 1980*a*). In the core of the Olympic Mountains the accretionary prism consists of packages of highly deformed and partially metamorphosed marine sandstones and siltstones that are separated by high-angle faults. In these rocks, the age, amount of deformation, degree of metamorphism, and number of intercalated tectonic lenses of basalt and gabbro generally decrease toward the west (Tabor and Cady 1978*a*). The clastic rocks are lithic to feldspathic sandstone from both basaltic and continental sources. These units are interpreted as turbidites that have been deformed into an accretionary wedge along an inner trench slope (Stewart 1970; Tabor and Cady 1978*a*, 1978*b*). The major high-angle faults between and within the sedimentary packages are interpreted as folded thrust faults that formed as successive increments of sediments underthrust the accumulating accretionary wedge along the subduction zone (Tabor and Cady 1978*b*). The source area and pre-accretionary displacement history of sedimentary rocks in the Olympic core are, as yet, unknown.

The Eocene sedimentary sequence along the periphery of the northern Olympic Peninsula (Fig. 2) is much less deformed than the Olympic core rocks. The source area for the Eocene sequence probably was nearby Vancouver Island to the north (Ansfield 1972; Snavely *et al.* 1980*a*). The northern Olympic rocks consist of a deepening-upward sequence of slope to submarine fan to basin plain facies that resulted from continued subsidence (Fig. 2*a*) (Ansfield 1972; Snavely *et al.* 1980*a*). Collision of the seamounts that were the origin of the Crescent Formation was probably complete prior to deposition of these units; however, minor deformation and continued subsidence within this basin suggest that some intraplate compression continued in this region until middle Miocene time. Sedimentation along the northern Olympic Peninsula, therefore, represents the northern extension of the less deformed forearc-basin sequence found farther south.

Continental sedimentary rocks of Eocene age are mostly limited to graben or wrench-type pull-apart basins in the North Cascade Range, the Puget trough (Johnson 1985), and the Okanogan region (Fig. 2*b*). Possible exceptions are thin sequences of fluvial or deltaic deposits of the Payne Cliffs Formation in the Klamath Mountains (Fig. 3) (McKnight 1984) and the Herren unit in the Blue Mountains (Fig. 3) (Pigg 1961; Elmendorf and Fisk 1978). In contrast, sedimentation in basins formed in graben or pull-apart settings is characterized by very thick, rapidly deposited alluvial sequences such as the Chuckanut Formation of Johnson (1984*a*), 6000 m thick and deposited at a rate of about 400 m/Ma (Johnson 1984*a*); the Swauk Formation, 6800 m thick (Tabor *et al.* 1984); and the Chumstick Formation, 5800 m thick (Gresens *et al.* 1981). Rapid deposition of deltaic facies of the Puget Group at about 250 m/Ma (Turner *et al.* 1983) suggests deposition in a similar pull-apart tectonic setting. Restricted deposition of the marine Blakeley Formation in the Puget Sound basin (McLean 1977) (Fig. 2*b*) during late Eocene and Oligocene time may also represent sedimentation in a pull-apart basin (J. C. Yount, oral communication, 1982).

Tectonic styles

Compressional tectonics

Collisional deformation of Paleogene age in the United States Pacific Northwest is limited to the Oregon Coast Range and Olympic Mountains. Rocks were intensely deformed in both areas by collision of oceanic seamounts at roughly 50 Ma and, in the Olympic Mountains, by subsequent accretionary tectonics. In the Oregon Coast Range, east-northeast-trending thrust faults juxtapose the Roseburg Formation with the Mesozoic terranes of the Klamath Mountains (Fig. 1) and cut the Tertiary volcanic basement and overlying sedimentary rocks of the Roseburg Formation (Baldwin 1974; Ryberg 1983).

Collision of the Crescent terrane of the Olympic Mountains took place about 50 Ma as evidenced by (1) inclusion of continental detritus within the deformed Crescent basalts of early and early middle Eocene age (ca. 55 Ma, Duncan 1982), indicating that these ocean islands were forming near the continental margin at this time (Cady 1975); and (2) olistostromal blocks derived from deformed Crescent Formation in late middle to late Eocene (45 Ma) sedimentary rocks that peripherally overlie the Crescent (Snavely, *in* Muller *et al.* 1983). Stacked reverse faults having westward tectonic transport and local pervasive deformation of Eocene through late middle Miocene sedimentary and volcanic rocks in the core of the Olympic Mountains (Fig. 1) were formed by the growth and deformation of an accretionary prism during plate convergence (Tabor and Cady 1978*a*, 1978*b*). The especially thick accumulation of accretionary-prism sediment in this region has also been ascribed to gravitational nappes descending from an area rapidly uplifted during triple-junction migration (Fox 1983). In addition, the continual northward migration of oceanic plates relative to North America may have transported Tertiary terranes along the edge of the continent until they encountered Vancouver Island and were trapped south of it. In this model, ongoing convergence continued to squeeze the Olympic rocks of the Crescent terrane against and under Vancouver Island (Yorath *et al.* 1985). Such intraplate shortening is recorded by folds, thrust, and reverse faults in rocks along the northern Olympic Peninsula and the Vancouver Island shelf (MacLeod *et al.* 1977; Muller *et al.* 1983; Yorath *et al.* 1985) and may be related to the possible emplacement of the Leech River Schist along the southern tip of Vancouver Island at about 40 Ma (Fairchild and Cowan 1982). Folding of the Olympic structure into its present broad horseshoe shape (Fig. 1) may have occurred during accretion (Tabor and Cady 1978*b*; Beck and Engebretson 1982) or during more recent extension in the Pacific Northwest.

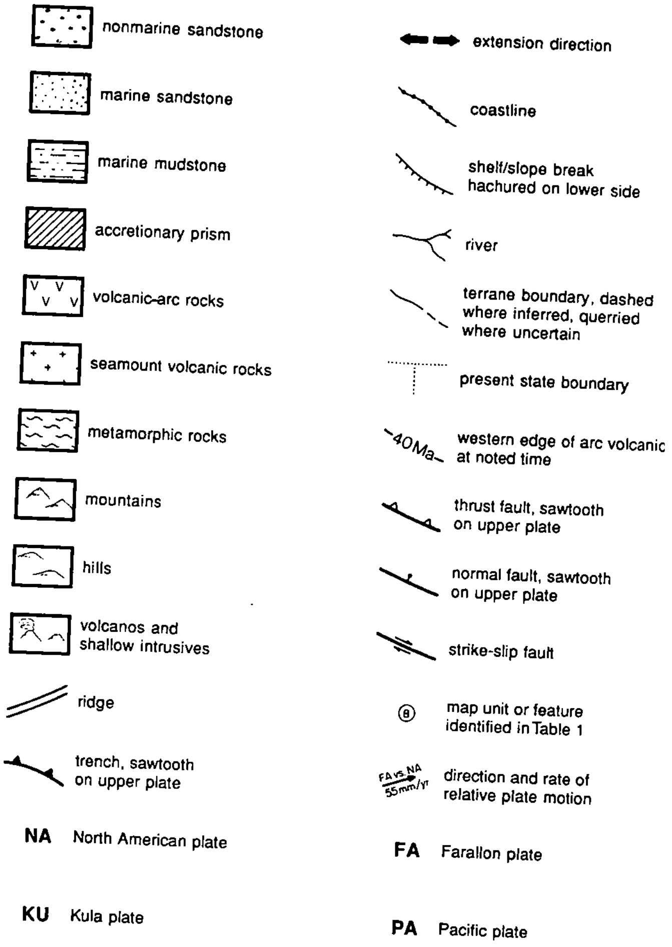


FIG. 4. Key for paleogeographic maps (Figs. 5, 6, 7).

Transcurrent faults

Large-scale strike-slip faults that probably were active during Paleogene time have been documented or inferred throughout western Washington and Oregon. The most notable of these features is the Straight Creek fault (Fig. 1), which runs along the North Cascade Range of Washington (Misch 1977; Vance and Miller 1981) into Canada where it joins the Fraser fault system (Davis *et al.* 1978; Ewing 1980; Price *et al.* 1985; Price and Carmichael 1986). Right-lateral movement along the Straight Creek fault was apparently active from late Cretaceous through early Eocene time, but Oligocene and early Miocene plutons that cut the fault are generally not disturbed (Vance and Miller 1981; Tabor *et al.* 1984; Vance 1985). The amount of early Tertiary displacement may be in excess of 100 km, inferred from the proposed offset of faults and major lithologic units (Price *et al.* 1985; Kleinspehn 1985). Movement along this fault may have formed pull-apart basins in which the Chuckanut Formation of Johnson (1984*a*)

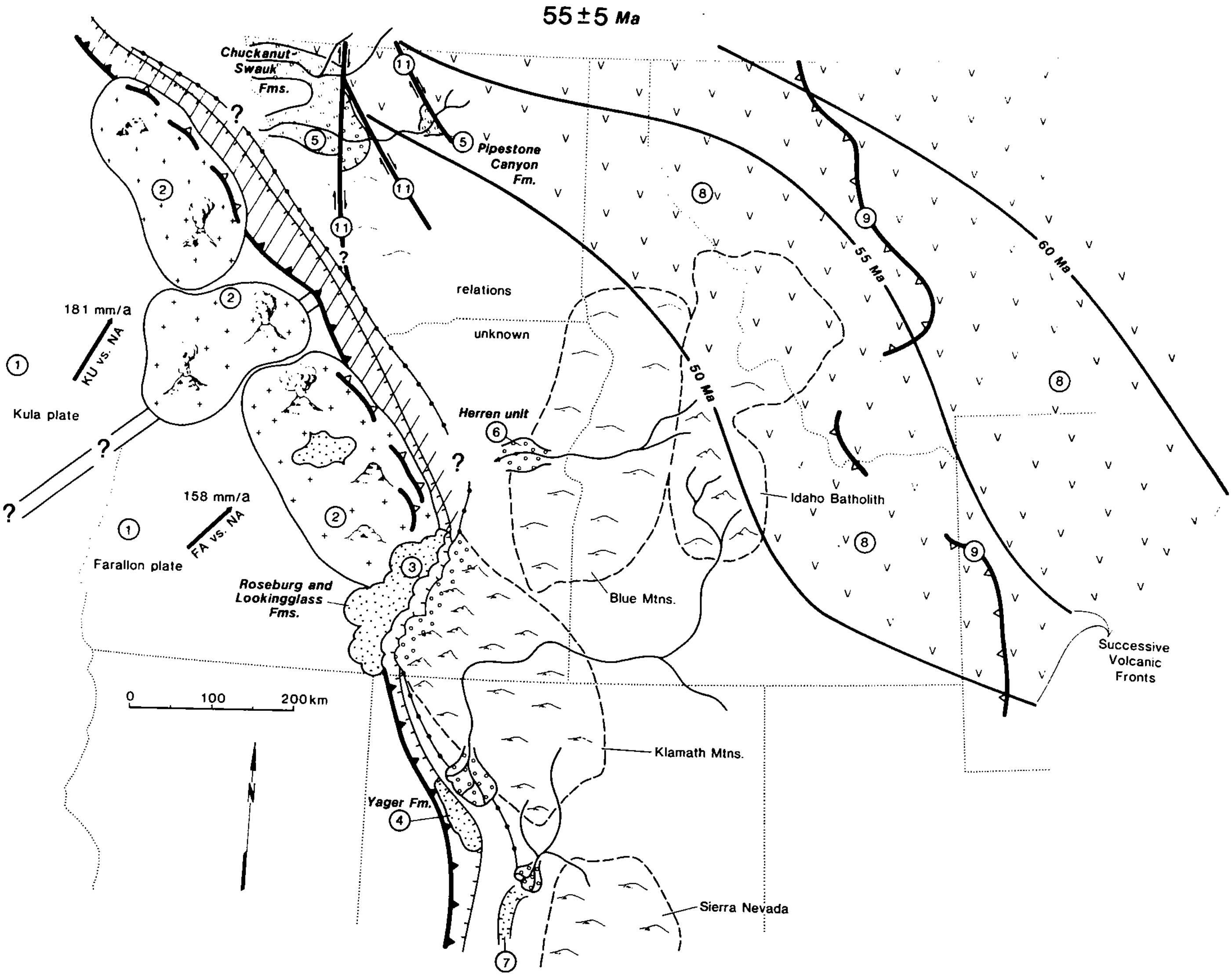


FIG. 5. Paleogeographic reconstruction of the Pacific Northwest at 55 ± 5 Ma. Geology is palinspastically restored; the state boundaries are present day. See Fig. 4 for key.

and the Swauk Formation were deposited, and they may subsequently have been displaced by it (Tabor *et al.* 1984; Johnson 1984*a*, 1984*b*, 1985). At the southern terminus, the Straight Creek fault is obscured by overlapping rock units, but it may curve eastward into the trend of the Olympic Wallowa lineament (Tabor and Frizzell 1979), may continue straight (Davis *et al.* 1978), may curve westward toward the mid-Tertiary continental margin (Heller 1983), or may end, with displacement transferred to faults to the west (Johnson 1984*b*).

Several northwest-trending faults that join or are cut by the Straight Creek – Fraser fault system also may have accommodated dextral shear during early and mid-Tertiary time. These structures include the Entiat fault (Laravie 1976) and the Ross Lake fault (Misch 1977; Kleinspehn 1985) along the east edge of the North Cascade Range in Washington (Fig. 1), a proposed but not exposed strike-slip fault that may underlie the Puget trough (Johnson 1984*b*), and a proposed structure beneath the continental shelf of Oregon (Snavely *et al.* 1980*b*, 1982).

The widespread distribution of these subparallel structures suggests that they may have accommodated nonrigid, intraplate deformation that developed in response to the oblique subduction of the Kula or Farallon plates beneath North America (Davis *et al.* 1978; Ewing 1980; Beck 1983). Reconstructed relative plate motions (Engebretson *et al.* 1985; Rea and Duncan 1986) indicate a large northward component of movement of the Pacific Basin plates with respect to the North American plate during Paleogene time. Similar intra-arc strike-slip faults form in response to oblique subduction in some modern convergent margins (Beck 1983).

Extensional tectonics

Just prior to 50 Ma, regional extension began in the area east of the Oregon and Washington Coast Ranges. Fault-bounded basins developed within the Cascade Range of Washington and included the Chuckanut Basin (Johnson 1984*a*), Chiwaukum graben (Gresens *et al.* 1981), and Swauk Basin (Tabor *et al.* 1984). Dike swarms were emplaced in the eastern Cascades about 50 Ma, including the Teanaway (Tabor *et al.* 1982*b*), the Golden Horn – Monument Peak (Tabor *et al.* 1968), and the Duncan Hill – Cooper Mountains – Railroad Creek (Cater and Wright 1967; Tabor *et al.* 1980) dike swarms, all of

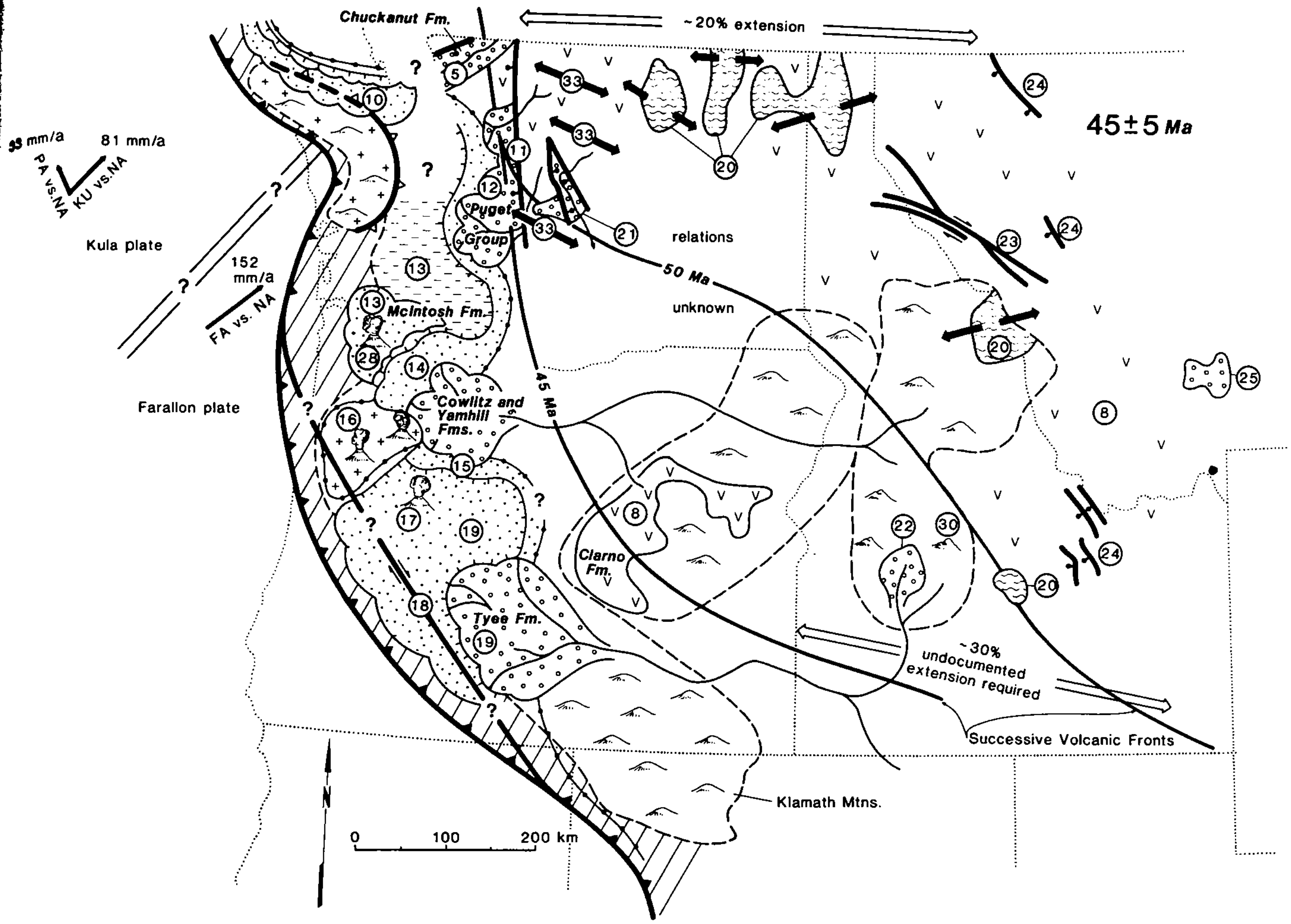


FIG. 6. Paleogeographic reconstruction of the Pacific Northwest at 45 ± 5 Ma. Geology is palinspastically restored; the state boundaries are present day.

which trend generally northeast, and the Corbaley Canyon dike swarm, which trends west-northwest (Gresens 1982). Strike-slip faults and low-angle faults with normal (i.e., younger over older) displacements developed during this time in eastern Washington, Idaho, and western Montana (Armstrong 1974; LeBrecque and Shaw 1973; Mapel and Shropshire 1973; Ruppel 1968, 1980; Rhodes and Cheney 1981; Rasmussen and Fields 1983; Harms and Price 1983; Bennett 1986). Perhaps the most striking features of extensional origin are the metamorphic core complexes that developed in northeastern Washington (Okanogan, Kettle, and Spokane domes) and Idaho (Bitterroot and Pioneer core complexes) (Coney 1979; Armstrong 1982). Although the origin and development of the core complexes are controversial, they appear to be part of the belt of metamorphic core complexes that runs along the length of the Cordilleran hinterland from British Columbia to Mexico and formed as a result of regional extension (Coney 1979; Armstrong 1982).

Although the timing of many of these extensional events is poorly constrained, the best evidence from dated sedimentary and volcanic sequences involved in these events and from the uplift ages on basement terranes suggests that extension begun by about 50 Ma was primarily a Paleogene event (Armstrong 1974, 1982; Tabor *et al.* 1980, 1984; Fox and Beck 1985; Price and Carmichael 1986; Templeman-Kluit and Parkinson 1986) and may continue today. In some way regional extension may be related to the transcurrent faulting previously described (Ewing 1980; Price and Carmichael 1986).

Tectonic rotation

One of the most striking and enigmatic aspects of the Cenozoic development of the Pacific Northwest is the large-scale tectonic rotation of terranes throughout the region that is indicated by paleomagnetism. Paleomagnetic study of igneous and sedimentary sequences has shown that the Oregon Coast Range and Washington Coast Ranges, the Cascade Range in Oregon and southern Washington, the Clarno Formation in central Oregon, volcanic rocks of Challis age in northeastern Washington, and Mesozoic terranes in the Klamath and Blue Mountains all have been rotated clockwise since their time of formation (Simpson and Cox 1977; Magill *et al.* 1981; Beck 1980; Hillhouse *et al.* 1982; Mankinen and Irwin 1982; Wells and Coe 1985; Wilson and Cox 1980). Many workers have noted that the rotation history of the Oregon Coast Range is different from that of the Washington Coast Ranges and have suggested that these ranges behaved as discrete blocks rather than as one large rigid block.

Three principle models have been proposed to explain the tectonic rotation of this region (Beck 1980). In one model rotation occurred as rigid oceanic fragments pivoted during colli-

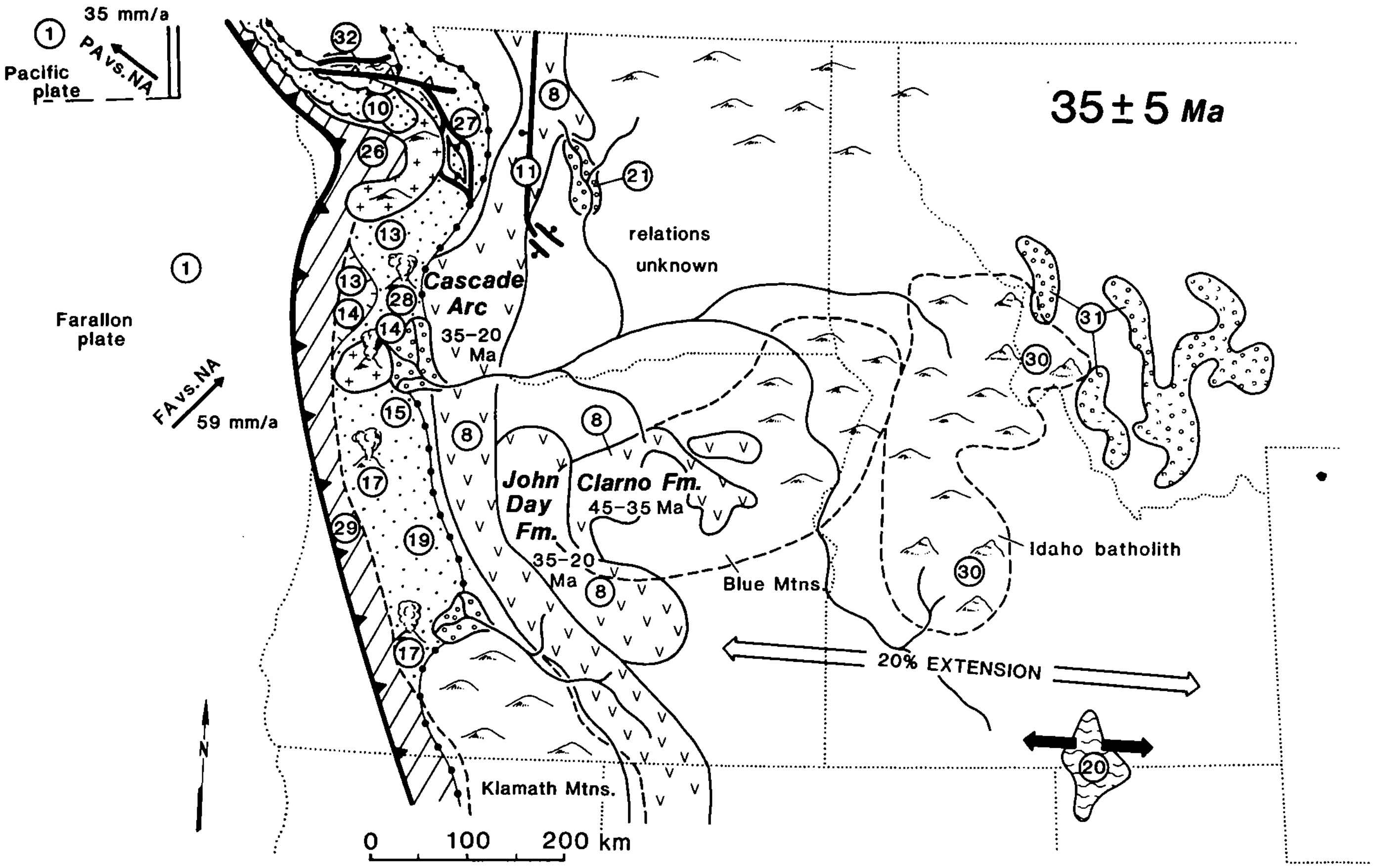


FIG. 7. Paleogeographic reconstruction of the Pacific Northwest at 35 ± 5 Ma. Geology is palinspastically restored; the state boundaries are present day. See Figure 4 for key.

sion with North America (Simpson and Cox 1977; Magill *et al.* 1981; Hillhouse *et al.* 1982). In the second model, rotation occurred during later extensional deformation in the Cordillera that began after the collisions were complete (Simpson and Cox 1977; Coney 1979; Magill *et al.* 1981; Heller and Ryberg 1983). In the third model rotations occurred as the continental margin responded on a variety of scales to a right-lateral shear couple, possibly driven by oblique subduction of oceanic plates to the west (Beck 1980; Wells *et al.* 1984). Each of these mechanisms probably contributed to various extents. Tertiary rotation south of the Olympic Mountains occurred after collisions were complete, however (Wells *et al.* 1984; Heller and Ryberg 1983), suggesting that the second model is the most important one in that area.

Paleogeographic reconstructions

From the data described previously we can interpret the paleogeographic development of the Pacific Northwest during Paleogene time (Figs. 4–7). In order to draw the reconstructions, we made certain assumptions concerning palinspastic restoration. First, we assumed that except for minor displacements along Tertiary faults, Mesozoic terranes reached their present positions relative to cratonal North America by Cenozoic time. Although some of these terranes were possibly emplaced as recently as Tertiary time (Monger and Irving 1980; Tabor *et al.*, in press), displacement histories are not yet well known.

We made a second assumption about the timing and magnitude of extension that affected the Cordillera during Cenozoic time. Reported west-southwest and west-northwest extension with the Great Basin (Zoback *et al.* 1981) would have the effect of moving outboard terranes westward relative to the craton. Extension began in Idaho, Oregon, Washington, and western Montana by about 40 Ma, as discussed previously by Bennett (1986). To the south, in the Great Basin, pre-Basin and Range extension began about 40 Ma and Basin and Range extension began post-17 Ma (Proffett 1977; Coney 1979; Solomon *et al.* 1979; Zoback *et al.* 1981; Gans and Miller 1983). Best-constrained estimates of the total amount of Cenozoic extension range from 30 to 100% in the central Great Basin (Proffett 1977) and from 65 to 100% in the southern Great Basin (Wernicke *et al.* 1982). For palinspastic restoration we arbitrarily assumed that 65% extension has occurred across the Great Basin and that about 20% extension, likely a minimum value, has occurred along the United States – Canada border (see Fox and Beck 1985). These values are consistent with the rotations of terranes in the Pacific Northwest (Gromme *et al.* 1986; Wells and Heller, in press). A different estimate of the magnitude of extension would affect the location, but not the timing, of events relative to the craton.

We do not know what lies beneath the basaltic shroud of the Columbia Plateau. Geophysical studies indicate the lithosphere is about 25 km thick (Smith 1978), which is considerably thinner than surrounding lithosphere. The thinness of the lithosphere implies that the region has been extended by a significant amount (Laubscher 1981). Gresens and Stewart (1981) indicated that the Eocene and Oligocene arkosic sedimentary sequences on the northern part of the plateau probably extend

TABLE 1. Sources of data for paleogeographic reconstructions

Map No.	Major units or features	References
1.	Relative plate vectors	Engebretson *et al.* (1985)
2.	Tillamook and Siletz River volcanics and Crescent Formation	Snavely *et al.* (1968), Tabor and Cady (1978*a*, 1978*b*), Duncan (1982)
3.	Roseburg and Lookingglass formations	Miles (1981), Heller and Ryberg (1983), Molenaar (1985)
4.	Yager Formation	Underwood (1983)
5.	Chuckanut and Swauk formations, Pipestone Canyon Formation of Barksdale (1948)	Barksdale (1948), Johnson (1984*a*), Tabor *et al.* (1984)
6.	Herren unit	Pigg (1961), Elmendorf and Fisk (1978)
7.	Princeton gorge (submarine canyon)	Dickinson *et al.* (1979)
8.	Challis Volcanics and Cascade volcanic rocks; Clarno Formation	Armstrong (1978), Engels *et al.* (1976), Daniel and Berg (1981), Fiebelkorn *et al.* (1983), Lux (1982), Frizzell and Vance (1983), Gromme *et al.* (1986)
9.	Eastern limit of the thrust belt	Armstrong and Oriel (1965), Harrison *et al.* (1974)
10.	Aldwell and Lyre formations, Twin River Group	Brown *et al.* (1956), Brown and Gower (1958), Drummond (1978), Snavely *et al.* (1980*a*, 1980*b*), Rau (1981)
11.	Straight Creek, Entait, and Pasaytan faults	Davis *et al.* (1978), Lawrence (1971), Vance and Miller (1981), Gresens (1982), Tabor *et al.* (1980, 1984)
12.	Puget Group, Naches Formation	Vine (1969), Buckovic (1979), Tabor *et al.* (1984)
13.	McIntosh, Lincoln Creek, and Cowlitz formations, etc.	Snavely *et al.* (1958), Rau (1966, 1981), Wells (1979, 1981)
14.	Cowlitz, Keasey, Pittsburg Bluff, Scappoose formations	Niem and Van Atta (1973), McDougall (1980, 1981)
15.	Tyee, Yamhill, Nestucca, Alsea, Yaquina, Eugene formations	Snavely *et al.* (1977, 1982), McDougall (1980), Rau (1981), Heller (1983)
16.	Tillamook Volcanics	Magill *et al.* (1981), Wells *et al.* (1983), Wells *et al.* (1984)
17.	Yachats Basalt and correlative rocks	Snavely and Wagner (1961), MacLeod and Snavely (1973), Fiebelkorn *et al.* (1983)
18.	Strike-slip fault	Snavely *et al.* (1980*a*, 1980*b*, 1981)
19.	Tyee, Elkton siltstone member (of Tyee Formation), Bateman, Coaledo, Spencer formations, and correlative rocks	Baldwin (1974), Armentrout (1980), Heller and Dickinson (1985), Chan (1985)
20.	Kettle, Okanogan, Priest River, Bitterroot, Pioneer, Albion metamorphic core complexes, Republic graben	Armstrong (1982), Fox *et al.* (1977), Chase *et al.* (1978), Cheney (1980), Hyndman (1980), Miller (1980), Rhodes and Cheney (1981), Harms and Price (1983)
21.	Chumstick, Roslyn, and Wenatchee formations	Buza (1979), Gresens *et al.* (1981), Tabor *et al.* (1982*b*, 1984)
22.	Fluvial sedimentary rocks	Kern (1959)
23.	Strike-slip faults	Harrison *et al.* (1972, 1974), Bennett (1986)
24.	Low-angle normal (?) faults	Ruppel (1968, 1980), LeBrecque and Shaw (1973), Mapel and Shropshire (1973), French (1979), Ruppel and Lopez (1981)
25.	Three Forks Basin	Robinson (1961, 1963)
26.	Subduction complex	Stewart (1970), Tabor and Cady (1978*a*, 1978*b*), Rau (1979)
27.	Blakeley Formation	McLean (1977)
28.	Goble Volcanics and upper part of Crescent Formation	Wells (1979, 1981), Wells and Coe (1985), Duncan (1982)
29.	Subduction complex	Snavely *et al.* (1980*b*, 1981), Snavely and Wagner (1982)
30.	Idaho batholith	Ferguson (1975), Criss *et al.* (1982)
31.	Renova and Passamari formations	Kuenzi and Fields (1971), Rasmussen and Fields (1983)
32.	Leech River and San Juan faults	Cowan (1982), Fairchild and Cowan (1982), Yorath *et al.* (1985)
33.	Dike swarms	Cater and Wright (1967), Tabor *et al.* (1968, 1980, 1982*b*), Gresens (1982)

some distance under the basalt and that similar rocks crop out to the south in Oregon (Pigg 1961; Elmendorf and Fisk 1978), suggesting the possible continuity of sedimentary rocks beneath the Columbia River basalt group. Gravity data suggest a considerable mixture of intermediate(?) volcanic rock under the basalt (Washington Public Power Supply System 1981), which we would expect in an extensional basin.

The paleogeographic maps are palinspastic, removing the movements due to faulting, extension, and tectonic rotation. However, for reference, the base maps show the state boundaries as they are today. An explanation of the symbols used in the paleogeographic maps is shown in Fig. 4. Principal formation names and sources used in the reconstructions can be found in Table 1.

55 ± 5 Ma (Fig. 5)

Between about 60 and 55 Ma, oceanic islands (seamounts) formed adjacent to the continental margin, perhaps on or near the Kula–Farallon ridge or adjacent transforms. These islands collided with the North American plate in Oregon and Washington about 50 Ma, causing the subduction zone to jump to the west. The leading edge of the Challis volcanic arc migrated westward commencing between 60 and 55 Ma, coincident with the end of thrusting in the foreland region (Armstrong and Oriel 1965; Dorr *et al.* 1977). Thus the migration of arc magmatism was apparently not caused by the westward jump of the subduction zone during seamount accretion, which took place about 50 Ma (Heller and Ryberg 1983). Furthermore, if these small accreted terranes were detached from their lithosphere during collision, then once these crustal fragments were accreted they would have only locally affected the shape of the subducted slab near the offshore trench (Karig *et al.* 1976) and would have had no major effect on the projection of the deeper part of the slab (Furlong *et al.* 1982), which controls the location of the arc magmatism.

Rivers flowing from the Idaho batholith during this time debouched near the southern Klamath Mountains (Yager Formation) (Underwood and Bachman 1986) and, possibly, in eastern Oregon (Herren unit). The Chuckanut–Swauk river system tapped local source areas in the North Cascades as well as areas to the northeast. Locally derived lithic sediments were deposited as the seamounts collided with the Klamath Mountains.

45 ± 5 Ma (Fig. 6)

From about 50 to 40 Ma was a time of major crustal extension in the United States Pacific Northwest and of abundant arkosic sedimentation along the former continental margin. Extension was associated with transcurrent faulting and is documented by the development of metamorphic-core complexes, low-angle faults with normal separation, grabens, dike swarms, and strike-slip faults. Although some strike-slip movement may have occurred along the Straight Creek fault (see above) and subsidiary faults at this time, dip-slip movement predominated.

Westward migration of the volcanic arc continued until about 40 Ma in the Pacific Northwest. Magma began erupting and intruding in the forearc basins during this time (which was roughly contemporaneous with the initiation of Cascade arc volcanism) and continued into Oligocene time. Abundant sediment in the forearc region was derived from local uplifts, from broad thermal doming associated with the westward sweep of arc magmatism, from uplift of the Idaho batholith, from relief produced by widespread faulting, from possible doming over metamorphic-core complexes, and from erosion of volcanos over a broad region.

35 ± 5 Ma (Fig. 7)

Extension was somewhat abated but continued from about 40 to 30 Ma in the Pacific Northwest, as documented by structural uplift in the Idaho batholith and by developing basins associated with faulting in western Montana (Rasmussen and Fields 1983). Extension also began in the region south of the Snake River plain by this time. Minor intraplate shortening of the previously emplaced Crescent terrane (including the Olympic Mountains) beneath Wrangellia along southern Vancouver Island (Yorath *et al.* 1985) may have occurred until about 40 Ma, coincident with cooling ages from the enigmatic Leech River Schist (Fairchild and Cowan 1982).

Clarno volcanism waned as the Cascade arc began to erupt about 35–40 Ma. Elevation of the Cascade Range may have blocked rivers flowing from the east. Sedimentation rates in the coastal basins were sharply reduced, although the ancestral Columbia River was able to maintain flow across the Cascade trend and deposited an extensive delta in the region of the present mouth of the Columbia River. The ancestral Snake River, which formerly debouched at the north end of the Klamath Mountains, was pirated or otherwise diverted and flowed into the ancestral Columbia River, setting up drainage patterns that persist to the present.

Summary and conclusions

The change from a dominantly convergent tectonic regime to an extensional and transcurrent regime occurred in Oregon and Washington near the beginning of middle Eocene time (about 50 Ma). As a result, there were three phases of basin development in the region. During the initial phase, sediments principally accumulated in coastal basins in a convergent margin setting. Trench and ocean-basin sediments were reworked into deformed accretionary prisms during the collision of oceanic islands (Fig. 5). These deposits were composed of lithic clastic sediments derived from local orogenic uplands.

A second phase of basin development, in part overlapping the first, consisted of rapid, coarse clastic sedimentation that took place over a broad forearc region (Fig. 6). Specific deposits and basins consisted of two types: (1) nonmarine sediments deposited in extensional (pull-apart?) basins genetically related to major strike-slip faults and (2) marine sediments deposited in rapidly subsiding basins along the continental margin. These desposits were composed mostly of arkosic sandstone derived from the uplifted Cretaceous plutonic belt to the east, including the Idaho batholith.

The final phase of Paleogene basin formation was characterized by a drastic reduction in both area and volume of sedimentation. Sedimentation occurred primarily in shallow-marine environments in the coastal basins. These sandstone and mudstone deposits were composed predominantly of volcanic–lithic grains and tuff beds derived from the developing Cascade volcanic arc just to the east (Fig. 7). Initiation and growth of volcanic edifices in the Cascade arc probably acted as an effective dam for most of the west-flowing river systems draining the Idaho batholith to the east. These river systems were integrated into the ancestral Columbia River, whose delta and submarine-fan systems in the northern Olympic Peninsula were the primary sites of rapid deposition along the coastal zone during this time.

Acknowledgments

We thank the many workers who have discussed regional relationships with us, but especially M. E. Beck, Jr., P. J. Coney, D. S. Cowan, W. R. Dickinson, D. C. Engebretson, K. E. Fox, Jr., V. A. Frizzell, Jr., P. D. Snavely, Jr., J. C. Yount, and R. E. Wells, not all of whom agree with our interpretations. Reviews by J. M. Armentrout, W. R. Dickinson, D. M. Miller, P. D. Snavely, Jr., J. A. Vance, and R. E. Wells are appreciated. This research was supported by National Science Foundation grants EAR 84-17117 (to PLH) and EAR 81-21957 (to CAS). Support was also graciously provided by the United States Geological Survey and to PLH by the Geological Society of America, Amoco Production Company, Arco Exploration Company, and the Laboratory of Geotectonics in the Department of Geosciences at the University of Arizona.

ANSFIELD, V. J. 1972. Eocene submarine cone–fan deposits and their significance, northern Olympic Peninsula, Washington. Geological Society of America, Abstracts with Programs, **4**: 435.

ARMENTROUT, J. M. 1980. Field trip log for the Cenozoic stratigraphy of Coos Bay and Cape Blanco, southwestern Oregon. *In* Geologic field trips in western Oregon and southwestern Washington. *Edited by* K. F. Oles, J. G. Johnson, A. R. Niem, and W. A. Niem. Oregon State Department of Geology and Mineral Industries, Bulletin 101, pp. 177–217.

ARMENTROUT, J. M., and BERTA, A. 1977. Eocene–Oligocene foraminiferal sequence from the northeast Olympic Peninsula, Washington. Journal of Foraminiferal Research, **7**: 216–233.

ARMENTROUT, J. M., and SUEK, D. H. 1985. Hydrocarbon exploration in western Oregon and Washington. American Association of Petroleum Geologists Bulletin, **69**: 627–643.

Armentrout, J. M., Hull, D. A., Beaulieu, J. D., and Rau, W. W. 1983. Correlation of Cenozoic stratigraphic units of western Oregon and Washington. Oregon Department of Geology and Mineral Resources, Oil and Gas Investigation 7.

Armstrong, F. C., and Oriel, S. S. 1965. Tectonic development of Idaho–Wyoming thrust belt. American Association of Petroleum Geologists Bulletin, **49**: 1847–1866.

Armstrong, R. L. 1974. Geochronometry of the Eocene volcanic–plutonic episode in Idaho. Northwest Geology, **3**: 1–15.

——— 1978. Cenozoic igneous history of the U.S. Cordillera from lat. 42° to 49°N. *In* Cenozoic tectonics and regional geophysics of the western Cordillera. *Edited by* R. B. Smith and G. P. Eaton. Geological Society of America, Memoir 152, pp. 265–282.

——— 1982. Cordilleran metamorphic core complexes—from Arizona to southern Canada. Annual Review of Earth and Planetary Sciences, **10**: 129–154.

Baldwin, E. M. 1974. Eocene stratigraphy of southwestern Oregon. Oregon State Department of Geology and Mineral Industries, Bulletin 83.

Barksdale, J. D. 1948. Stratigraphy in the Methow quadrangle, Washington. Northwest Science, **22**: 164–176.

——— 1975. Geology of the Methow Valley, Okanogan County, Washington. Washington Division of Geology and Earth Resources, Bulletin 68.

Beck, M. E., Jr. 1980. The paleomagnetic record of plate margin tectonic processes along the western edge of North America. Journal of Geophysical Research, **85B**: 7115–7131.

——— 1983. On the mechanism of tectonic transport in zones of oblique subduction. Tectonophysics, **93**: 1–11.

Beck, M. E., Jr., and Burr, C. D. 1979. Paleomagnetism and tectonic significance of the Goble Volcanic Series, southwestern Washington. Geology, **7**: 175–179.

Beck, M. E., Jr., and Engebretson, D. C. 1982. Paleomagnetism of small basalt exposures in the west Puget Sound area, Washington, and speculations on the accretionary origin of the Olympic Mountains. Journal of Geophysical Research, **87**: 3755–3760.

Bennett, E. H. 1986. Relationship of the trans-Challis fault system in central Idaho to Eocene and Basin and Range extensions. Geology, **14**: 481–484.

Brown, R. D., Jr., and Gower, H. D. 1958. Twin River Formation (redefinition), northern Olympic Peninsula, Washington. American Association of Petroleum Geologists Bulletin, **42**: 2492–2493.

Brown, R. D., Jr., Snavely, P. D., Jr., and Gower, H. D. 1956. Lyre Formation (redefinition), northern Olympic Peninsula, Washington. American Association of Petroleum Geologists Bulletin, **40**: 94–107.

Buckovic, W. A. 1979. The Eocene deltaic system of west-central Washington. *In* Cenozoic paleogeography of the western United States. *Edited by* J. M. Armentrout, M. R. Cole, and H. TerBest, Jr. Pacific Coast Paleogeography Symposium 3, Society of Economic Paleontologists and Mineralogists, Pacific Section, pp. 147–163.

Buza, J. W. 1979. Dispersal patterns and paleogeographic implications of lower and middle Tertiary fluviatile sandstones in the Chiwaukum graben, east-central Cascade Range, Washington. *In* Cenozoic paleogeography of the western United States. *Edited by* J. M. Armentrout, M. R. Cole, and H. TerBest, Jr. Pacific Coast Paleogeography Symposium 3, Society of Economic Paleontologists and Mineralogists, Pacific Section, pp. 63–73.

Cady, W. M. 1975. Tectonic setting of the Tertiary volcanic rocks of the Olympic Peninsula, Washington. Journal of Research of the U.S. Geological Survey, **3**: 573–582.

Cater, F. W., and Wright, T. L. 1967. Geologic map of the Lucerne quadrangle, Chelan County, Washington. United States Geological Survey, Geologic Quadrangle Map GQ-647.

Chan, M. A. 1985. Correlations of diagenesis with sedimentary facies in Eocene sandstone, western Oregon. Journal of Sedimentary Petrology, **55**: 322–333.

Chan, M. A., and Dott, R. H., Jr. 1983. Shelf and deep-sea sedimentation in Eocene forearc basin, western Oregon—fan or non-fan? American Association of Petroleum Geologists Bulletin, **67**: 2100–2116.

Chase, R. B., Bickford, M. E., and Tripp, S. E. 1978. Rb–Sr and U–Pb isotopic studies of the northeastern Idaho batholith and border zone. Geological Society of America Bulletin, **89**: 1325–1334.

Cheney, E. S. 1980. Kettle dome and related structures of northeastern Washington. *In* Cordilleran metamorphic core complexes. *Edited by* M. D. Crittenden, P. J. Coney, and G. H. Davis. Geological Society of America, Memoir 153, pp. 463–483.

Coney, P. J. 1979. Tertiary evolution of Cordilleran metamorphic core complexes. *In* Cenozoic paleogeography of the western United States. *Edited by* J. M. Armentrout, M. R. Cole, and H. TerBest, Jr. Pacific Coast Paleogeography Symposium 3, Society of Economic Paleontologists and Mineralogists, Pacific Section, pp. 15–28.

Cowan, D. S. 1982. Geologic evidence for post-40 m.y. B.P. largescale northwestward displacement of part of southeastern Alaska. Geology, **10**: 309–313.

Criss, R. E., Lanphere, M. A., and Taylor, H. P., Jr. 1982. Effects of regional uplift, deformation, and meteoric–hydrothermal metamorphism on K–Ar ages of biotites in the southern half of the Idaho batholith. Journal of Geophysical Research, **87**: 7029–7046.

Daniel, F., and Berg, R. B. 1981. Radiometric ages of rocks in Montana. Montana Bureau of Mines and Geology, Bulletin 114.

Davis, G. A., Monger, J. W. H., and Burchfiel, B. C. 1978. Mesozoic construction of the Cordilleran "collage", central British Columbia to central California. *In* Mesozoic paleogeography of the western United States. *Edited by* D. G. Howell and K. A. McDougall. Pacific Coast Paleogeography Symposium 2, Society of Economic Paleontologists and Mineralogists, Pacific Section, pp. 1–32.

Dickinson, W. R., Ingersoll, R. V., and Graham, S. A. 1979. Paleogene sediment dispersal and paleotectonics in northern California. Geological Society of America Bulletin, **90**, part II: 1458–1528.

Dorr, J. A., Jr., Spearing, D. R., and Steidtmann, J. R. 1977. Deformation and deposition between a foreland uplift and an impinging thrust belt, Hoback Basin, Wyoming. Geological Society of America, Special Paper 177.

Dott, R. H., Jr. 1966. Eocene deltaic sedimentation at Coos Bay, Oregon. Journal of Geology, **74**: 373–420.

Drummond, J. M. 1978. Evolution of Tertiary marine sedimentary basins in British Columbia. Bulletin of Canadian Petroleum Geology, **26**: 33–56.

Duncan, R. A. 1982. A captured island chain in the Coast Range of Oregon and Washington. Journal of Geophysical Research, **87B**: 10 827 – 10 837.

Elmendorf, J., and Fisk, L. H. 1978. The age of the "Pilot Rock Flora," Umatilla County, Oregon. Geological Society of America, Abstracts with Programs, **10**: 215.

Engebretson, D. C., Cox, A., and Gordon, R. G. 1985. Relative motions between oceanic plates of the Pacific basin. Geological Society of America, Special Paper 206.

Engels, J. C., Tabor, R. W., Miller, F. K., and Obradovich, J. D. 1976. Summary of K–Ar, Rb–Sr, U–Pb, and fission-track ages of rocks from Washington State prior to 1975 (exclusive of Columbia Plateau Basalts). United States Geological Survey, Miscellaneous Field Studies Map MF-710.

Enlows, H. E., and Parker, D. J. 1972. Geochronology of the Clarno igneous activity in the Mitchell quadrangle, Wheeler County, Oregon. Ore-Bin, **34**: 104–110.

Ewing, T. E. 1980. Paleogene tectonic evolution of the Pacific Northwest. Journal of Geology, **88**: 619–638.

Fairchild, L. H., and Cowan, D. S. 1982. Structure, petrology, and tectonic history of the Leech River complex northwest of Victoria, Vancouver Island. Canadian Journal of Sciences, **19**: 1817–1835.

FERGUSON, J. A. 1975. Tectonic implications of some geochronometric data from the northeastern border zone of the Idaho batholith. Northwest Geology, **4**: 53–58.

FIEBELKORN, R. B., WALKER, G. W., MACLEOD, N. S., MCKEE, E. H., and SMITH, J. G. 1983. Index to K–Ar age determinations for the state of Oregon. Isochron/West, **37**: 3–60.

FOX, K. F., JR. 1983. Melanges and their bearing on late Mesozoic and Tertiary subduction and interplate translation at the west edge of the North American Plate. United States Geological Survey, Professional Paper 1198.

FOX, K. F., JR., and BECK, M. E., JR. 1985. Paleomagnetic results for Eocene volcanic rocks from northeastern Washington and the Tertiary tectonics of the Pacific Northwest. Tectonics, **4**: 323–341.

FOX, K. F., JR., RINEHART, C. D., and ENGELS, J. C. 1977. Plutonism and orogeny in north-central Washington—timing and regional context. United States Geological Survey, Professional Paper 989.

FRENCH, A. B. 1979. Younger over older thrust faulting in the eastern Garnet Range, west central Montana. M.S. thesis, University of Arizona, Tucson, AZ.

FRIZZELL, V. A., JR., and VANCE, J. A. 1983. Cenozoic volcanism of the Cascades of Washington. Eos, **64**: 886.

FULMER, C. V. 1975. Stratigraphy and paleontology of the type Blakeley and Blakeley Harbor formations. *In* Conference on future energy horizons of the Pacific Coast, Paleogene symposium and selected technical papers. *Edited by* D. W. Weaver, G. R. Hornaday, and A. Tipton. American Association of Petroleum Geologists, Society of Economic Paleontologists and Mineralogists, and Society of Economic Geophysicists, Pacific Sections Annual Meeting, Proceedings, pp. 210–271.

FURLONG, K. P., CHAPMAN, D. S., and ALFELD, P. W. 1982. Thermal modeling of the geometry of subduction with implications for the tectonics of the overriding plate. Journal of Geophysical Research, **87B**: 1786–1802.

GALLOWAY, W. E. 1974. Depositional diagenetic alteration of sandstone in northeast Pacific arc-related basins: implications for graywacke genesis. Geological Society of America Bulletin, **85**: 379–390.

GANS, P. B., and MILLER, E. L. 1983. Style of mid-Tertiary extension in east-central Nevada. *In* Geologic excursions in the overthrust belt and metamorphic core complexes of the Intermountain region. *Edited by* K. D. Gurgal. Utah Geological and Mineralogical Survey, Special Studies 59, Guidebook, part 1, pp. 107–160.

GARD, L. M., JR. 1968. Bedrock geology of the Lake Tapps quadrangle, Pierce County, Washington. United States Geological Survey, Professional Paper 388-B.

GARRISON, R. E. 1973. Space–time relations of pelagic limestones and volcanic rocks, Olympic Peninsula, Washington. Geological Society of America Bulletin, **84**: 583–594.

GLASSLEY, W. 1974. Geochemistry and tectonics of the Crescent volcanic rocks, Olympic Peninsula, Washington. Geological Society of America Bulletin, **85**: 785–794.

GRESENS, R. L. 1982. Early Cenozoic geology of central Washington State: I. Summary of sedimentary, igneous, and tectonic events. Northwest Science, **56**: 218–229.

GRESENS, R. L., and STEWART, R. J. 1981. What lies beneath the Columbia Plateau? Oil and Gas Journal, **79**: 157–164.

GRESENS, R. L., NAESER, C. W., and WHETTEN, J. T. 1981. Stratigraphy and age of the Chumstick and Wenatchee formations: Tertiary fluvial and lacustrine rocks, Chiwaukum graben, Washington: summary. Geological Society of America Bulletin, **92**, part 1: 233–236.

GROMME, C. S., BECK, M. E., JR., WELLS, R. E., and ENGEBRETSON, D. C. 1986. Paleomagnetism of the Tertiary Clarno Formation of central Oregon and its significance for the tectonic history of the Pacific Northwest. Journal of Geophysical Research, **91**: 14 089 – 14 103.

HAMILTON, W. 1969. Mesozoic California and the underflow of Pacific mantle. Geological Society of America Bulletin, **80**: 2409–2430.

——— 1978. Mesozoic tectonics of the western United States. *In* Mesozoic paleogeography of the western United States. *Edited by* D. G. Howell and K. A. McDougall. Pacific Coast Paleogeography Symposium 2, Society of Economic Paleontologists and Mineralogists, Pacific Section, pp. 33–70.

HARMS, T. A., and PRICE, R. A. 1983. The Newport fault: Eocene crustal stretching, necking, and listric normal faulting in NE Washington and NW Idaho. Geological Society of America, Abstracts with Programs, **15**: 309.

HARRISON, J. E., KLEINKOPF, M. D., and OBRADOVICH, J. D. 1972. Tectonic events at the intersection between the Hope fault and the Purcell Trench, northern Idaho. United States Geological Survey, Professional Paper 719.

HARRISON, J. E., GRIGGS, A. B., and WELLS, J. D. 1974. Tectonic features of the Precambrian Belt basin and their influence on post-Belt structures. United States Geological Survey, Professional Paper 866.

HELLER, P. L. 1983. Sedimentary response to Eocene tectonic rotation in western Oregon. Ph.D. thesis, University of Arizona, Tucson, AZ.

HELLER, P. L., and DICKINSON, W. R. 1985. Submarine ramp facies model for delta-fed, sand-rich turbidite systems. American Association of Petroleum Geologists Bulletin, **69**: 960–976.

HELLER, P. L., and RYBERG, P. T. 1983. Sedimentary record of subduction to forearc transition in the rotated Eocene basin of western Oregon. Geology, **11**: 380–383.

HELLER, P. L., PETERMAN, Z. E., O'NEIL, J. R., and SHAFIQULLAH, M. 1985. Isotopic provenance of sandstones from the Eocene Tyee Formation, Oregon Coast Range. Geological Society of America Bulletin, **96**: 770–780.

HILLHOUSE, F. W., GROMME, C. S., and VALLIER, T. L. 1982. Paleomagnetism and Mesozoic tectonics of the Seven Devils volcanic arc in northeastern Oregon. Journal of Geophysical Research, **87B**: 3777–3794.

HUNTTING, M. T., BENNETT, W. A. G., LIVINGSTON, V. E., JR., and MOEN, W. 1961. Geologic map of Washington. Washington State Division of Mines and Geology, scale 1 : 500 000.

HYNDMAN, D. W. 1980. Bitterroot dome – Sapphire tectonic block, an example of a plutonic-core gneiss-dome complex with its detached suprastructure. *In* Cordilleran metamorphic core complexes. *Edited by* M. D. Crittenden, P. J. Coney, and G. H. Davis. Geological Society of America, Memoir 153, pp. 427–443.

JOHNSON, S. Y. 1984*a*. Stratigraphy, age, and paleogeography of the Eocene Chuckanut Formation, northwest Washington. Canadian Journal of Earth Sciences, **21**: 92–106.

——— 1984*b*. Evidence for a margin-truncating transcurrent fault (pre-late Eocene) in western Washington. Geology, **12**: 538–541.

——— 1985. Eocene strike-slip faulting and nonmarine basin formation in Washington. *In* Strike-slip deformation, basin formation and sedimentation. *Edited by* K. T. Biddle and N. Christie-Blick. Society of Economic Paleontologists and Mineralogists, Special Publication 37, pp. 283–302.

KARIG, D. E., CALDWELL, J. G., and PARMENTIER, E. M. 1976. Effects of accretion on the geometry of the descending lithosphere. Journal of Geophysical Research, **81**: 6281–6291.

KERN, B. F. 1959. Geology of the uranium deposits near Stanley, Custer County, Idaho. Idaho Bureau of Mines and Geology, Pamphlet 117.

KLEINSPEHN, K. L. 1985. Cretaceous sedimentation and tectonics, Tyaughton–Methow Basin, southwestern British Columbia. Canadian Journal of Earth Sciences, **22**: 154–174.

KUENZI, W. D., and FIELDS, R. W. 1971. Tertiary stratigraphy, structure, and geologic history, Jefferson Basin, Montana. Geological Society of America Bulletin, **82**: 3373–3393.

LARAVIE, J. A. 1976. Geological field studies along the eastern border of the Chiwaukum graben, central Washington. M.S. thesis, University of Washington, Seattle, WA.

LAUBSCHER, H. P. 1981. Models of the development of Yakima deformation. Washington Public Power Supply System, Nuclear Project Final Safety Analysis Report 2, 3, amendment 18, appendix 2.50.

LAWRENCE, R. D. 1971. The Chewack–Paysaten Fault, western Okanogom County, Washington State. Geological Society of America, Abstracts with Programs, **3**: 147.

LEBRECQUE, J. E., and SHAW, E. W. 1973. Restoration of Basin and Range faulting across the Howell Creek Window and Flathead Valley of southeastern British Columbia. Bulletin of Canadian Petroleum Geology, **21**: 117–122.

LIPMAN, P. W., PROSTKA, H. J., and CHRISTIANSEN, R. L. 1972. Cenozoic volcanism and plate tectonic evolution of the western United States. I. Early and middle Cenozoic. Philosophical Transactions of the Royal Society of London, Series A, **271**: 217–248.

LUX, D. R. 1982. K–Ar and ^{40}Ar–^{39}Ar ages of mid-Tertiary volcanic rocks from the western Cascade Range, Oregon. Isochron/West, **33**: 27–32.

MACLEOD, N. S., and SNAVELY, P. D., JR. 1973. Volcanic and intrusive rocks of the central part of the Oregon Coast Range. *In* Geologic field trips in northern Oregon and southern Washington. *Edited by* J. D. Beaulieu. Oregon State Department of Geology and Mineral Industries, Bulletin 77, pp. 47–74.

MACLEOD, N. S., TIFFIN, D. L., SNAVELY, P. D., JR., and CURRIE, R. G. 1977. Geologic interpretation of magnetic and gravity anomalies in the Strait of Juan de Fuca, U.S.–Canada. Canadian Journal of Earth Sciences, **14**: 223–238.

MAGILL, J. R., COX, A., and DUNCAN, R. 1981. Tillamook volcanic series: further evidence for tectonic rotation of the Oregon Coast Range. Journal of Geophysical Research, **86B**: 2953–2970.

MANKINEN, E. A., and IRWIN, W. P. 1982. Paleomagnetic study of some Cretaceous and Tertiary sedimentary rocks of the Klamath Mountains province, California. Geology, **10**: 82–87.

MAPEL, W. J., and SHROPSHIRE, K. L. 1973. Preliminary geologic map and section of the Hawley Mountain quadrangle, Custer, Butte, and Lemhi counties, Idaho. United States Geological Survey, Miscellaneous Field Studies Map MF-546, scale 1 : 62 500.

MASSEY, N. 1986. Metchosin Igneous Complex, southern Vancouver Island: ophiolite stratigraphy developed in an emergent island setting. Geology, **14**: 602–605.

MCDOUGALL, K. A. 1980. Paleoecological evaluation of late Eocene biostratigraphic zonations of the Pacific coast of North America. Society of Economic Paleontologists and Mineralogists, Paleontological Monograph 2.

——— 1981. Upper Eocene foraminiferal biostratigraphy and paleoecology of northwestern Oregon. *In* Pacific Northwest Cenozoic biostratigraphy. *Edited by* J. M. Armentrout. Geological Society of America, Special Paper 184, p. 150.

MCKNIGHT, B. K. 1984. Stratigraphy and sedimentology of the Payne Cliffs Formation, southwestern Oregon. *In* Geology of the upper Cretaceous Hornbrook Formation, Oregon and California. *Edited by* T. H. Nilsen. Society of Economic Paleontologists and Mineralogists, Pacific Section, pp. 187–194.

MCLEAN, H. 1977. Lithofacies of the Blakely Formation, Kitsap County, Washington: submarine fan complex? Journal of Sedimentary Petrology, **47**: 78–88.

MELIM, L. A. 1984. Sedimentary petrology and depositional environment of the sandstones of Scow Bay, Indian and Marrowstone islands, northwestern Washington. American Association of Petroleum Geologists Bulletin, **68**: 506.

MILES, G. A. 1981. Planktonic foraminifers of the lower Tertiary Roseburg, Lookingglass, and Flournoy formations (Umpqua Group), southwest Oregon. Geological Society of America, Special Paper 184, pp. 85–103.

MILLER, D. M. 1980. Structural geology of the northern Albion Mountains, south-central Idaho. *In* Cordilleran metamorphic core complexes. *Edited by* M. D. Crittenden, P. J. Coney, and G. H. Davis. Geological Society of America, Memoir 153, pp. 399–423.

MISCH, P. 1977. Dextral displacements at some major strike faults in the North Cascades. Geological Association of Canada, Abstracts with Programs, 37.

MOLENAAR, C. M. 1985. Depositional relations of Umpqua and Tyee formations (Eocene), southwestern Oregon. American Association of Petroleum Geologists Bulletin, **69**: 1217–1229.

MONGER, J. W. H., and IRVING, E. 1980. Northward displacement of north-central British Columbia. Nature (London), **285**: 289–294.

MONGER, J. W. H., PRICE, R. A., and TEMPELMAN-KLUIT, D. J. 1982. Tectonic accretion and the origin of the two major metamorphic and plutonic welts in the Canadian Cordillera. Geology, **10**: 70–75.

MULLER, J. E. 1977. Evolution of the Pacific margin, Vancouver Island, and adjacent regions. Canadian Journal of Earth Sciences, **14**: 2062–2085.

MULLER, J. E., SNAVELY, P. D., JR., and TABOR, R. W. 1983. The Tertiary Olympic terrane, southwest Vancouver Island and northwest Washington. Geological Association of Canada / Mineralogical Association of Canada / Canadian Geophysical Union, Joint Annual Meeting, Victoria, B.C., Field Trip Guidebook 2, trip 12.

NIEM, A. R., and VAN ATTA, R. O. 1973. Cenozoic stratigraphy of northwestern Oregon and adjacent southwestern Washington. *In* Geologic field trips in northern Oregon and southern Washington. *Edited by* J. D. Beaulieu. Oregon State Department of Geology and Mineral Industries, Bulletin 77, pp. 75–132.

OLES, K. F., and ENLOWS, H. E. 1971. Bedrock geology of the Mitchell quadrangle, Wheeler County, Oregon. Oregon Department of Geology and Mineral Industries, Bulletin 72.

PALMER, A. R. 1983. The decade of North American geology, 1983 geologic time scale. Geology, **11**: 503–504.

PEARSON, R. C., and OBRADOVICH, J. D. 1977. Eocene rocks in northeast Washington—radiometric ages and correlations. United States Geological Survey, Bulletin 1433.

PIGG, J. H., JR. 1961. The lower Tertiary sedimentary rocks in the Pilot Rock and Heppner area. M.S. thesis, University of Oregon, Eugene, OR.

PRICE, R. A., and CARMICHAEL, D. M. 1986. Geometric test for Late Cretaceous – Paleogene intracontinental transform faulting in the Canadian Cordillera. Geology, **14**: 468–471.

PRICE, R. A., MONGER, J. W. H., and RODDICK, J. A. 1985. Cordilleran cross-section; Calgary to Vancouver. *In* Field guide to geology and mineral deposits in the southern Canadian Cordillera. *Edited by* D. Templeman-Kluit. Geological Association of Canada, pp. 3-1 – 3-85.

PROFFETT, J. M., JR. 1977. Cenozoic geology of the Yerrington district, Nevada, and implications for the nature and origin of Basin and Range faulting. Geological Society of America Bulletin, **88**: 247–266.

RASMUSSEN, D. L., and FIELDS, R. W. 1983. Structural and depositional history, Jefferson and Madison basins, southwestern Montana. American Association of Petroleum Geologists Bulletin, **67**: 1352.

RAU, W. W. 1966. Stratigraphy and foraminifera of the Satsop River area, southern Olympic Peninsula, Washington. Washington Division of Mines and Geology, Bulletin 53.

——— 1979. Geologic map in the vicinity of the lower Bogachiel and Hoh river valleys, and the Washington Coast. Washington Division of Geology and Earth Resources, Geologic Map GM 24, 1 : 62 : 500.

——— 1981. Pacific Northwest Tertiary benthic foraminiferal biostratigraphic framework—an overview. *In* Pacific Northwest Cenozoic biostratigraphy. *Edited by* J. M. Armentrout. Geological Society of America, Special Paper 184, pp. 67–84.

REA, D. K., and DUNCAN, R. A. 1986. North Pacific plate convergence: a quantitative record of the past 140 m.y. Geology, **14**: 373–376.

RHODES, B. P., and CHENEY, E. S. 1981. Low-angle faulting and the origin of Kettle dome, a metamorphic core complex in northeastern

Washington. Geology, **9**: 366–369.

Robinson, G. D. 1961. Origin and development of the Three Forks Basin, Montana. Geological Society of America Bulletin, **72**: 1003–1013.

——— 1963. Geology of the Three Forks quadrangle, Montana. United States Geological Survey, Professional Paper 370.

Ruppel, E. T. 1968. Geologic map of the Leadore quadrangle, Lemhi County, Idaho. United States Geological Survey, Quadrangle Map GQ-733.

——— 1980. Geologic map of the Patterson quadrangle, Lemhi County, Idaho. United States Geological Survey, Quadrangle Map GQ-1529.

Ruppel, E. T., and Lopez, D. A. 1981. Geologic map of the Gilmore quadrangle, Lemhi and Custer counties, Idaho. United States Geological Survey, Quadrangle Map GQ-1543.

Ryberg, P. T. 1983. Early Eocene depositional system along the southern Oregon Coast Range – Klamath Mountains borderland. Geological Society of America, Abstracts with Programs, **15**: 283.

Simpson, R. W., and Cox, A. 1977. Paleomagnetic evidence of tectonic rotation of the Oregon Coast Range. Geology, **5**: 585–589.

Smith, R. B. 1978. Seismicity, crustal structure and intraplate tectonics of the interior of the western Cordillera. *In* Cenozoic tectonics and regional geophysics of the western Cordillera. *Edited by* R. B. Smith and G. P. Eaton. Geological Society of America, Memoir 152, pp. 111–144.

Snavely, P. D., Jr. 1984. Sixty million years of growth along the Oregon continental margin. *In* U.S. Geological Survey highlights in marine research. *Edited by* S. H. Clarke. United States Geological Survey, Circular 938, pp. 9–18.

Snavely, P. D., Jr., and MacLeod, N. S. 1974. Yachats Basalt—an upper Eocene differentiated volcanic sequence in the Oregon Coast Range. Journal of Research of the U.S. Geological Survey, **2**: 395–403.

Snavely, P. D., Jr., and Wagner, H. C. 1961. Differentiated gabbroic sills and associated alkalic rocks in the central part of the Oregon Coast Range, Oregon. United States Geological Survey, Professional Paper 424-D, pp. D-156 – D-161.

——— 1963. Tertiary geologic history of western Oregon and Washington. Washington State Division of Mines and Geology, Report of Investigations 22.

——— 1982. Geologic cross section across the continental margin of southwestern Washington. United States Geological Survey, Open-file Report 82-459.

Snavely, P. D., Jr., Brown, R. D., Jr., Roberts, A. E., and Rau, W. W. 1958. Geology and coal resources of the Centralia–Chehalis district, Washington. United States Geological Survey, Bulletin 1053.

Snavely, P. D., Jr., Wagner, H. C., and MacLeod, N. S. 1964. Rhythmic-bedded eugeosynclinal deposits of the Tyee Formation, Oregon Coast Range. Bulletin of the Kansas University Geological Survey, **169**: 461–480.

Snavely, P. D., Jr., MacLeod, N. S., and Wagner, H. C. 1968. Tholeiitic and alkalic basalts of the Eocene Siletz River Volcanics, Oregon Coast Range. American Journal of Science, **266**: 454–481.

Snavely, P. D., Jr., Pearl, J. E., and Lander, D. L. 1977. Interim report on petroleum resources potential and geologic hazards in the outer continental shelf—Oregon and Washington Tertiary province. United States Geological Survey, Open-file Report 77-282.

Snavely, P. D., Jr., Niem, A. R., MacLeod, N. S., Pearl, J. E., and Rau, W. W. 1980*a*. Makah Formation—a deep-marginal–basin sequence of Late Eocene and Oligocene age in the northwestern Olympic Peninsula, Washington. United States Geological Survey, Professional Paper 1162-B.

Snavely, P. D., Jr., Wagner, H. C., and Lander, D. L. 1980*b*. Geologic cross section of the central Oregon continental margin. Geological Society of America, Map and Chart Series MC-28J.

Snavely, P. D., Jr., Wagner, H. C., Rau, W. W., and Bukry, D. 1981. Geologic cross section of the southern Oregon Coast Range and adjacent continental shelf. United States Geological Survey, Open-file Report 81-957.

Snavely, P. D., Jr., Wagner, H. C., and Rau, W. W. 1982. Sections showing biostratigraphy and correlation of Tertiary rocks penetrated in wells drilled on the southern Oregon continental margin. United States Geological Survey, Miscellaneous Field Studies Map MF-1482.

Snyder, W. S., Dickinson, W. R., and Silberman, M. L. 1976. Tectonic implications of the space–time patterns of Cenozoic magmatism in the western United States. Earth and Planetary Science Letters, **32**: 91–106.

Solomon, B. J., McKee, E. H., and Andersen, D. W. 1979. Stratigraphy and depositional environments of Paleogene rocks near Elko, Nevada. *In* Cenozoic paleogeography of the western United States. *Edited by* J. M. Armentrout, M. R. Cole, and H. TerBest, Jr. Pacific Coast Paleogeography Symposium 3, Society of Economic Paleontologists and Mineralogists, Pacific Section, pp. 75–88.

Stewart, R. J. 1970. Petrology, metamorphism, and structural relations of graywackes in the western Olympic Peninsula, Washington. Ph.D. thesis, Stanford University, Stanford, CA.

Sutter, J. F. 1978. K/Ar ages of Cenozoic volcanic rocks from the Oregon Cascades west of 121°30′. Isochron/West, **21**: 15–21.

Tabor, R. W., and Cady, W. M. 1978*a*. Geologic map of the Olympic Peninsula, Washington. United States Geological Survey, Miscellaneous Investigations Map I-994, scale 1 : 125 000.

——— 1978*b*. The structure of the Olympic Mountains, Washington—analysis of a subduction zone. United States Geological Survey, Professional Paper 1033.

Tabor, R. W., and Frizzell, V. A., Jr. 1979. Tertiary movement along the southern segment of the Straight Creek fault and its relation to the Olympic–Wallowa lineament in the central Cascades, Washington. Geological Society of America, Abstracts with Programs, **11**: 131.

Tabor, R. W., Engels, J. C., and Staatz, M. H. 1968. Quartz diorite – quartz monzonite and granite plutons of the Pasayten River area, Washington—petrology, age, and emplacement. *In* Geological Survey research 1968. United States Geological Survey, Professional Paper 600-C, pp. C45–C52.

Tabor, R. W., Frizzell, V. A., Jr., Whetten, J. T., Swanson, D. A., Byerly, G. R., Booth, D. B., Hetherington, M. J., and Waitt, R. B., Jr. 1980. Preliminary geologic map of the Chelan 1:100,000 quadrangle, Washington. United States Geological Survey, Open-file Map 80-841.

Tabor, R. W., Frizzell, V. A., Jr., Booth, D. B., Whetten, J. T., and Waitt, R. B., Jr. 1982*a*. Preliminary geologic map of the Skykomish River 1:100,000 quadrangle, Washington. United States Geological Survey, Open-file Map 82-747.

Tabor, R. W., Waitt, R. B., Jr., Frizzell, V. A., Jr., Swanson, D. A., and Byerly, G. R. 1982*b*. Geologic map of the Wenatchee 1:100,000 quadrangle, Washington. United States Geological Survey, Miscellaneous Investigations Map I-1311.

Tabor, R. W., Frizzell, V. A., Jr., Vance, J. A., and Naeser, C. W. 1984. Ages and stratigraphy of lower and middle Tertiary sedimentary and volcanic rocks of the central Cascades, Washington: applications to the tectonic history of the Straight Creek fault. Geological Society of America Bulletin, **95**: 26–44.

Tabor, R. W., Zartman, R. E., and Frizzell, V. A., Jr. In press. Possible tectonostratigraphic terranes in the north Cascades crystalline core, Washington. *In* Selected papers—the geology of Washington. *Edited by* J. E. Schuster. Washington Division of Mines and Geology, Bulletin 77.

Taylor, E. M. 1981. A mafic dike system in the vicinity of Mitchell, Oregon, and its bearing on the timing of Clarno – John Day volcanism and early Oligocene deformation in central Oregon. Oregon Geology, **43**: 107–112.

Templeman-Kluit, D., and Parkinson, D. 1986. Extension across the Eocene Okanagan crustal shear in southern British Columbia. Geology, **14**: 318–321.

Timmons, D. M. 1981. Stratigraphy, lithofacies, and depositional environment of the Cowlitz Formation, T.4 and 5N., R.5W. northwest Oregon. M.S. thesis, Portland State University, Portland, OR.

Turner, D. L., Frizzell, V. A., Jr., Triplehorn, D. M., and Naeser, C. W. 1983. Radiometric dating of ash partings in coals of the Eocene Puget Group, Washington: implications for paleobotanical stages. Geology, **11**: 527–531.

Underwood, M. B. 1983. Depositional setting of the Paleogene Yager Formation, northern Coast Ranges of California. *In* Cenozoic marine sedimentation, Pacific Margin, U.S.A. *Edited by* D. K. Larue and R. J. Steel. Society of Economic Paleontologists and Mineralogists, Pacific Section, Publication 28, pp. 81–101.

Underwood, M. B., and Bachman, S. B. 1986. Sandstone petrofacies of the Yager complex and the Franciscan Coastal Belt, Paleogene of northern California. Geological Society of America Bulletin, **97**: 809–817.

United States Geological Survey. 1964. Mineral and water resources of Idaho. Idaho Bureau of Mines and Geology, Special Report 1.

——— 1966. Mineral and water resources of Washington. Washington Division of Mines and Geology, Report 9.

——— 1969. Mineral and water resources of Oregon. Oregon Department of Geology and Mineral Industries, Bulletin 64.

Vance, J. A. 1957. The geology of the Sauk River area in the northern Cascades of Washington. Ph.D. thesis, University of Washington, Seattle, WA.

——— 1985. Early Tertiary faulting in the North Cascades. Geological Society of America, Abstracts with Programs, **17**: 415.

Vance, J. A., and Miller, R. B. 1981. The movement history of the Straight Creek fault in Washington State. *In* The last 100 million years (mid-Cretaceous to Holocene) of geology and mineral deposits in the Canadian Cordillera. Geological Association of Canada, Cordilleran Section, Program and Abstracts, pp. 39–41.

Vine, J. D. 1969. Geology and coal resources of the Cumberland, Hobart, and Maple Valley quadrangles, King County, Washington. United States Geological Survey, Professional Paper 624.

Walker, G. 1977. Geologic map of Oregon east of the 121st meridian. United States Geological Survey, Miscellaneous Investigations Series Map I-902.

Washington Public Power Supply System. 1981. Compilation and interpretation of gravity in Washington, Oregon, Idaho and adjacent parts of British Columbia. Washington Public Power Supply System, Nuclear Project No. 2, Final Safety Analysis Report 3, amendment 18, appendix 2.5L.

Wells, F. G., and Peck, D. L. 1961. Geologic map of Oregon west of the 121st meridian. United States Geological Survey, Miscellaneous Geologic Investigations Map I-325.

Wells, R. E. 1979. The Cape Disappointment – Naselle River area, Pacific County, Washington. United States Geological Survey, Open-file Report 79-389.

——— 1981. Geologic map of the Eastern Willapa Hills, Cowlitz, Lewis, Pacific, and Wahkiakum counties, Washington. United States Geological Survey, Open-file Map 81-674.

Wells, R. E., and Coe, R. S. 1985. Paleomagnetism and geology of Eocene volcanic rocks of southwest Washington, implication for mechanisms of tectonic rotation. Journal of Geophysical Research, **90B**: 1925–1947.

Wells, R. E., and Heller, P. L. In press. The relative contribution of accretion, shear and extension to Cenozoic tectonic rotation in the Pacific Northwest. Geological Society of America Bulletin.

Wells, R. E., Niem, A. R., MacLeod, N. S., Snavely, P. D., Jr., and Niem, W. A. 1983. Preliminary geologic map of the west half of the Vancouver (Wash.–Ore.) 1° × 2° quadrangle, Oregon. United States Geological Survey, Open-file Report 83-591.

Wells, R. E., Engebretson, D. C., Snavely, P. D., Jr., and Coe, R. S. 1984. Cenozoic plate motions and the volcano–tectonic evolution of western Oregon and Washington. Tectonics, **3**: 275–294.

Wernicke, B., Spencer, J. E., Burchfiel, B. C., and Guth, P. L. 1982. Magnitude of crustal extension in the southern Great Basin. Geology, **10**: 499–502.

Wilson, D., and Cox, A. 1980. Paleomagnetic evidence for tectonic rotation of Jurassic plutons in Blue Mountains, eastern Oregon. Journal of Geophysical Research, **85B**: 3681–3689.

Worsley, T. R., and Crecelius, E. A. 1972. Paleogene calcareous nanofossils from the Olympic Peninsula, Washington. Geological Society of America Bulletin, **83**: 2859–2862.

Yorath, C. J., Green, A. G., Clowes, R. M., Sutherland Brown, A., Brandon, M. T., Kanasewich, E. R., Hyndman, R. D., and Spencer, C. 1985. Lithoprobe, southern Vancouver Island seismic reflection sees through Wrangellia to the Juan de Fuca plate. Geology, **13**: 759–762.

Zoback, M. L., Anderson, R. E., and Thompson, G. A. 1981. Cenozoic evolution of the state of stress and style of tectonism of the Basin and Range Province of the western United States. *In* Extensional tectonics associated with convergent plate boundaries. *Edited by* F. J. Vine *et al.* Philosophical Transactions of the Royal Society of London, **300**: 407–434.