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Geological evidence for post-40 m.y. B.P. large-scale northwestward displacement of part of southeastern Alaska

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ABSTRACT
The Leech River complex on southern Vancouver Island and schistose rocks on southern Baranof Island have very similar geologic histories. Both were derived from probable Upper Jurassic-Cretaceous terrigenous elastic rocks and minor associated volcanogenic rocks and chert. Each underwent (1) at least two penetrative deformations locally involving folding, disruption, and transposition of thinly layered sequences, and (2) synkinematic, low-pressure, Buchan-type metamorphism. Progressive metamorphic zones ranging from greenschist to amphibolite facies are related to granitic intrusive bodies. Deformation, metamorphism, and intrusion culminated about 40 to 42 m.y. ago. Apparently, these units, now separated by more than 1100 km, were once contiguous and lay at least as far south as the latitude of southern Vancouver Island. Shortly after 40 m.y. B.P., the allochthonous Leech River complex was emplaced at the southern edge of Vancouver Island, and the schists of Baranof Island and perhaps the entire Chugach terrane began their long northwestward journey along a system of dextral transcurrent faults.

INTRODUCTION
Recent paleomagnetic data (for example, Hillhouse, 1977; Beck, 1980) strongly suggest that some tectonic elements, or lithotectonic terranes, along the Pacific margin of North America have been displaced on the order of 1000 km or more from wherever they originated. In a sense, the geophysicists have been several steps ahead of field-oriented geologists, who in most cases have been unable either to find the southern sources of these exotic terranes or to document how and when they drifted and finally were accreted. I offer here some tentative geologic evidence for large-scale displacements along the margin. I suggest that two distinctive rock units—one the “linedated and schistose Sitka Graywacke” on Baranof Island in the Alexander Archipelago of southeastern Alaska, and the other the Leech River complex, on southern Vancouver Island in British Columbia (Fig. 1), now separated by 1152 km—were contiguous until at least about 40 m.y. ago; after that, Baranof somehow split off and moved northward along right-lateral transcurrent faults to its present position.

LEECH RIVER COMPLEX ON SOUTHEASTERN VANCOUVER ISLAND
The Leech River complex (Muller, 1977a, 1977b, 1980) is separated from Paleozoic and Mesozoic rocks of the Insular Belt of Wrangellia to the north by the San Juan fault (Fig. 2), and from lower Eocene Metchosin Volcanics to the south by the Leech River fault. The complex consists of terrigenous pelites and sandstones, with subordinate interbedded volcanic rocks and chert. Part of the complex underwent greenschist- to amphibolite-grade metamorphism. Preliminary Rb-Sr isotopic data (R. L. Armstrong, 1981, personal commun.) on metasedimentary rocks suggest a Late Jurassic to Cretaceous time of deposition.

In the area about 45 km northwest of Victoria, studied in detail by Fairchild (1979) and Fairchild and Cowan (1982), the Leech River complex records two regional deformational events (D1 and D2) and a synkinematic, regional, progressive metamorphism that reached amphibolite grade. Both deformations involved heterogeneous bulk shortening, which induced macroscopic folding and related mesoscopic lineations, parasitic folds, and axial-planar foliations. Pelitic rocks were converted to graphitic phyllites and biotitic schists. Thin sandstone layers were twice disrupted, and fragments were reoriented and transposed into the new foliation. Microscopic textures show that greenschist (chlorite zone) to amphibolite facies metamorphism began during D1 and extended into D2. The low-pressure metamorphism was of the somewhat unusual Buchan type, because the biotite zone is succeeded abruptly by almandine-bearing schists in which both andalusite and staurolite developed concurrently and synkinematically. The most intensely deformed, highest grade biotite-andalusite-staurolite schists are intruded by symmetamorphic, locally gneissic sills of granodiorite and felsic, tourmaline-bearing pegmatite. Several K-Ar determinations on hornblende and biotite from both igneous and metamorphic rocks range from 36.7 ± 2.6 to 41.2 ± 2.2 m.y. (Wanless and others, 1978). In short, the spatial and temporal coincidence of intense deformation, amphibolite facies metamorphism, and intrusive activity suggest that all were related genetically to a regional heating event in the early Tertiary, at about 40 m.y. B.P.

Neither the broadly correlative Jurassic-Cretaceous rocks in the San Juan Islands and North Cascades of northwestern Washington nor rocks on Vancouver Island north of the San Juan fault were affected by comparable early Tertiary
metamorphic and deformational events. Consequently, Fairchild and Cowan (1982) favored the hypothesis that the Leech River complex is allochthonous relative to the bulk of Vancouver Island. The complex was apparently derived from the west and emplaced against the southern edge of Wrangellia by 50 km of strike slip along the San Juan fault. There is no direct evidence for the sense of slip along the fault other than its steep to vertical dip and straight trace, which are both features compatible with large, transient displacements. The complex must have been juxtaposed with totally distinct rocks to the north and east after deformation and metamorphism had concluded at about 40 m.y. ago. Thus, on the basis of the geology sketched here, Fairchild and Cowan (1982) hypothesized that the Leech River complex is but a fragment of a now-vanished larger terrane, with the same unusual and distinctive history, that lay somewhere to the west or south of Vancouver Island in Eocene time.

METAMORPHIC ROCKS ON SOUTHEASTERN BARANOF ISLAND

Rocks that I believe correlate with the Leech River complex crop out on Baranof Island (Fig. 3) in a unit that Loney and others (1975) mapped as "lineated and schistose Sitka Graywacke." Most of the information in this section is summarized from their paper. The unit of interest consists of thick- to thin-bedded schistose graywacke interlayered with phylitic metapelites. It also contains subordinate layers and lenses of metavolcanic rocks and metaclast. Although not common rock types, both of these are more abundant in this unit than in most of the less deformed and metamorphosed rocks to the north that both Loney and others (1975) and Decker (1980) mapped as "Sitka Graywacke." The nomenclature and definition of rocks on Baranof and Chichagof Islands are in a state of flux (compare Loney and others, 1975, Pl. I, with Decker, 1980), but it is probable that the metamorphic unit was derived in part from the assemblage of poorly dated Upper Jurassic-Lower Cretaceous tennigenous graywacke and mudstone, volcanic flows and tuff, and radiolarian chert (Kelp Bay Group of Loney and others, 1975) that is widely exposed on Baranof and Chichagof Islands. These late Mesozoic-age rocks were intruded by several early Tertiary plutons, and they locally have been statically converted into hornfels in contact aureoles. On southeast Baranof Island, the progressive metamorphism related to Eocene intrusive bodies was dynamic rather than static. Lineations, folds, and foliations in metagraywackes and metapelites record two coaxial penetrative deformations, during which sandstone layers were disrupted and transposed. The second deformation occurred during low- to medium-pressure metamorphism, resulting in mappable metamorphic mineral zones that locally form broad, irregular aureoles around the Eocene plutons. One of the zones is characterized by staurolite and andalusite coexisting with biotite, almandine, quartz, and plagioclase. Loney and others (1975) commented on the unusual nature of this assemblage and classified the progressive metamorphism as Buchan type. To explain the observation that the largest region of intensely deformed rocks does not coincide with the innermost aureoles of exposed plutons, they inferred (Loney and others, 1975, p. 79) that "the greater degree of synkinematic metamorphism of the lineated and schistose unit was produced by local hotspots due to the proximity of adjacent plutons during the deformation." K-Ar ages determined on biotite-bearing metamorphic rocks on southern Baranof Island are 45.7 ± 1.4 and 45.2 ± 0.7 m.y.; Loney and others (1975) felt that a third age of 34.7 m.y. is anomalously young.
Ages for associated plutons range from 46.9 to 42 m.y. Another Eocene pluton about 75 km to the north is associated with similar synkinematically metamorphosed rocks.

The upper Mesozoic rocks on Baranof Island, which were variably metamorphosed and locally intruded during the early Tertiary, are part of the 2,100-km-long Chugach terrane (Pfäffer and others, 1977). This lithotectonic element extends across southern Alaska and contains several early Tertiary plutons and apparently related greenschist- to amphibolite-grade metamorphic complexes (Hudson and others, 1979). The Chugach terrane, consisting in part of the “lineated and schistose” unit, disappears beneath the waters of Chatham Strait along the eastern shore of Baranof Island (Fig. 3). This north-trending topographic lineament marks the trace of the Chatham Strait fault, an extension of the more easterly oriented Chatham Strait transcurrent fault and part of the northern extension of the “lineated and schistose” unit of Wrangel Island.

POST-40 M.Y. B.P. LARGE-SCALE TECTONIC TRANSPORT

The Leech River complex closely resembles the schists on southern Baranof Island in many respects. Both units were derived from an upper Mesozoic (probably Upper Jurassic-Lower Cretaceous) protolith of terrigenous clastic rocks and minor associated tuffs, volcanic flows, and cherts. Both underwent two penetrative deformations, which converted them into foliated and lineated transposed phyllites and schists. Synkinematic, progressive, low-pressure Buchan-type metamorphism produced mineral assemblages containing staurolite and andalusite in addition to biotite and almandine. The high temperatures, which promoted both ductile flow and recrystallization, were probably related to closely associated granitic intrusive rocks. The most reliable K-Ar ages, dating metamorphism and intrusion, overlap and span the interval from about 47 to 39 m.y. B.P. in the Eocene.

In light of these similarities, I postulate that the Leech River complex was originally contiguous with the schists on Baranof Island, which are themselves part of the larger Chugach terrane comprising late Mesozoic age rocks intruded by early Tertiary plutons. The schists were located at least as far south as the southern tip of Vancouver Island until sometime after 40 m.y. B.P. The hypothetical reconstruction in Figure 4A is, like many paleogeographic
maps, highly generalized. It depicts a terrane consisting largely of Jurassic-Cretaceous sedimentary rocks that broadly marked a late Mesozoic convergent margin along the western edge of North America. Several workers (for example, Muller, 1977a; Jones and others, 1978) already have emphasized the tectonic kinship of parts of the Chugach terrane, Upper Jurassic-Lower Cretaceous rocks in the Pacific Northwest, and the Franciscan Complex in California. The Mesozoic history of this tectonic element is not an issue here, but by perhaps mid-Eocene time (45 m.y. B.P.), it lay somewhere southwest of the present coastline of Vancouver Island, where it was intruded by a suite of intermediate to felsic stocks, sills, and dikes. How far to the west it might have lain is unknown. It was probably part of the North American continental margin rather than separated from it by an early Tertiary convergent plate boundary, for which there is no geologic evidence. This element apparently broke up after about 40 m.y. B.P. The Leech River complex was emplaced along the transient San Juan fault, and the schists of Baranof Island together with the rocks from which they were derived were transported to the northwest initially along a branch of the Queen Charlotte-Fairweather fault system. The rocks on Baranof have been displaced more than 1,100 km (Figs. 4B, 4C) at a minimum rate of 2 to 3 cm/yr.

Both the timing of the breakup and its setting in a plate-tectonic context are problematic. Emplacement of the Leech River complex postdated its metamorphism and deformation, which are dated at 39 to 42 m.y. B.P. Upper Eocene-lower Oligocene (Refugian-Zemorrian) strata of the Carmanah Formation unconformably overlie the projected trace of the San Juan fault on the west coast of Vancouver Island (Muller 1977b; dates from B. Cameron, 1981, personal commun.). These ages seem to constrain breakup and emplacement to an interval of a few million years in the late Eocene. The Carmanah strata continue offshore into the Tofino basin (Tiffin and others, 1972). Snavely and others (1980) and Brandon and others (1981) implied that the Tofino basin formed in a forearc setting; perhaps it marks the initiation of the episode of plate convergence that is continuing today offshore of Oregon, Washington, and Vancouver Island. This regime may have been immediately preceded by right-lateral transcurrent faulting, rifting, and complicated small-plate tectonics to account for the displacements hypothesized here.

MAJOR FAULTS IN SOUTHEASTERN ALASKA
As several workers, including Loney and others (1967), Ovenshine and Brew (1972), and Plafker and others (1976), have pointed out, southeastern Alaska contains a plexus of faults with a complicated and imperfectly known tectonic history. The active Queen Charlotte-Fairweather fault (Fig. 3) is now accommodating most of the relative motion between the Pacific and North American plates. Some of the major faults within the Alexander Archipelago and adjacent mainland probably were once active parts of the same right-lateral, transcurrent system. Three structures that might have accommodated part of the northwestward displacement of the schists on southern Baranof Island are the Chatham Strait, Border Ranges, and Peril Strait faults (Fig. 3).

Only the Chatham Strait fault has a well-documented displacement history involving a maximum of about 200 km of post-Silurian, possibly Cenozoic, right-lateral slip (for example, Ovenshine and Brew, 1972). The total post-Cretaceous strike slip on the Peril Strait fault, which extends from the Fairweather fault to the Chatham Strait fault (Fig. 3), has been estimated as 11 km (Plafker and others, 1976) on the basis of the right-lateral separation of the Border Ranges fault. However, the topographically prominent present trace of the Peril Strait fault may have resulted from minor Tertiary reactivation along part of a longer structure with significant, but as yet undocumented, right-lateral slip. Loney and others (1975) pointed out that much of the present-day trace is marked by a zone of intense cataclasism and fault-related deformation wider than 1.5 km. Moreover, part of the Peril Strait fault serves as the contact separating the two vast lithotectonic elements, the Alexander and Chugach terranes. These features suggest that the present trace is partly coincident with an earlier fault with large displacement that perhaps once continued north as the Border Ranges fault. Decker and Plafker (1981) have relocated this fault on the mainland north of Chichagof Island, where it similarly separates the Alexander terrane on the east from the Chugach terrane in the Fairweather Range. On Chichagof Island and northern Baranof Island, the fault separating the Chugach terrane from rocks correlated with Wrangellia (Jones and others, 1978) has been interpreted as the separate “Archipelago” segment of the Border Ranges fault (Plafker and others, 1976; Berg and others, 1978). This fault was intruded by an undated, but probably Tertiary (Loney and others, 1975), tonalite stock, and it appears that a small piece of Wrangellia was already welded to the Chugach terrane when it was rifted from the Leech River complex.

In short, I suggest that a large part of the mid-Tertiary northward translation of the Chugach terrane and Wrangellia on Baranof and Chichagof Islands was accommodated along a major transcurrent fault coincident with parts of the Border Ranges and Peril Straits faults. The amount, sense, and timing of displacements on these faults are all poorly constrained by available evidence. Additional geologic and geochronological data are needed to test the large mid-Tertiary displacements hypothesized here.

IMPLICATIONS
The similar geologic histories of the Leech River complex and the schists on southern Baranof Island suggest that these now widely separated units were once contiguous at a latitude at least as far south as the southern tip of Vancouver Island. Much less likely, in view of these similarities, are alternative hypotheses such as (1) that a nearly identical sequence of deformational, metamorphic, and intrusive events affected Jurassic-Cretaceous sedimentary rocks in two small areas separated by more than 1,000 km at about 40 to 44 m.y. B.P., or (2) that a continuous, 1,000-km-long belt of Leech River-like metamorphic rocks once extended from southern Vancouver Island to Baranof Island, but a huge intervening section has disappeared.

If the model is indeed correct, then the early Tertiary paleogeography of the Pacific Northwest was radically different from what we had envisioned until now. For example, large tracts of Jurassic-Cretaceous eugeosynclinal rocks and possibly a part of Wrangellia used to lie west of the southern part of Vancouver Island, and perhaps they also occupied the region now underlain by the Eocene and younger rocks of the Olympic Peninsula and western Puget Lowlands. Another implication is that the entire Chugach terrane, now extending across southern Alaska, is allochthonous and has been displaced northward by at least 1,000 km since early Tertiary time. This conclusion follows from the work of the U.S. Geological Survey (Plafker and others, 1977; Plafker and Campbell, 1979) that has established the continuum of rocks on Chichagof Island with the Chugach terrane on the mainland. If the plate boundary along the continental
margin from Vancouver Island to the Fairweather Range has been largely conservative, characterized by transcurrent relative motions since about 40 m.y. B.P., then a large part of southeastern Alaska, including the Chugach terrane, may also have lain immediately west or even southwest of the present-day Pacific Northwest.

Other workers, using different types of data, have suggested that parts of southern Alaska have moved northward in the Cenozoic. Byrne (1979) based his conclusion on an analysis of northeast Pacific magnetic anomalies. Stone and Packer (1979) believed that paleomagnetic data from Jurassic, Cretaceous, and lower Tertiary rocks on the Alaska Peninsula indicate that it was at least as far south as lat 30°N in Late Cretaceous time and moved rapidly northward in the early Tertiary. Finally, paleomagnetic data recently obtained by Grommé and Hillhouse (1981) from the Chugach terrane itself support my hypothesis, which is based on independent geological evidence. Their data indicate that gabbro plutons in the Fairweather Range 30 km northwest of Chichagof Island have been displaced northward by 25° of latitude since they were intruded into the Chugach terrane about 41 m.y. ago.

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Reviewer's comment

The hot question now is not whether parts of southern Alaska have been displaced but how young is the movement. This article is critical in providing geological evidence for mid-Tertiary or younger displacement. It is clearly at the forefront of regional research in the northeast Pacific region. The manuscript has topical significance, moreover, in showing that such large displacements can take place in such young rocks.