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Alternative Hypotheses for the Mid-Cretaceous Paleogeography of the Western Cordillera

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ABSTRACT

Two conflicting hypotheses specifying the paleogeographic disposition of the Insular and Intermontane superterranes at ca. 95 Ma are based on different evidence. One group of models, resting entirely on geologic evidence such as magmatic or stratigraphic links among terranes, places the two superterranes exclusively to the north of the Franciscan-Sierran subduction-arc system during late Mesozoic time. An alternative hypothesis, fully accommodating four sets of paleomagnetic data from Cretaceous rocks in the northwest Cordillera, restores most of the Intermontane superterrane ~1200 km south and the entire Insular superterrane (including Wrangellia) ~2900 km south of their expected (that is, current) latitudinal positions with respect to North America. In this model, the Insular superterrane and the orogenic belt that formed along its eastern edge during mid-Cretaceous collision lay south of the Franciscan-Sierran system in California at ca. 95 Ma; the entire crustal element was subsequently displaced northward by coast-parallel dextral slip between 80 and 60 Ma.

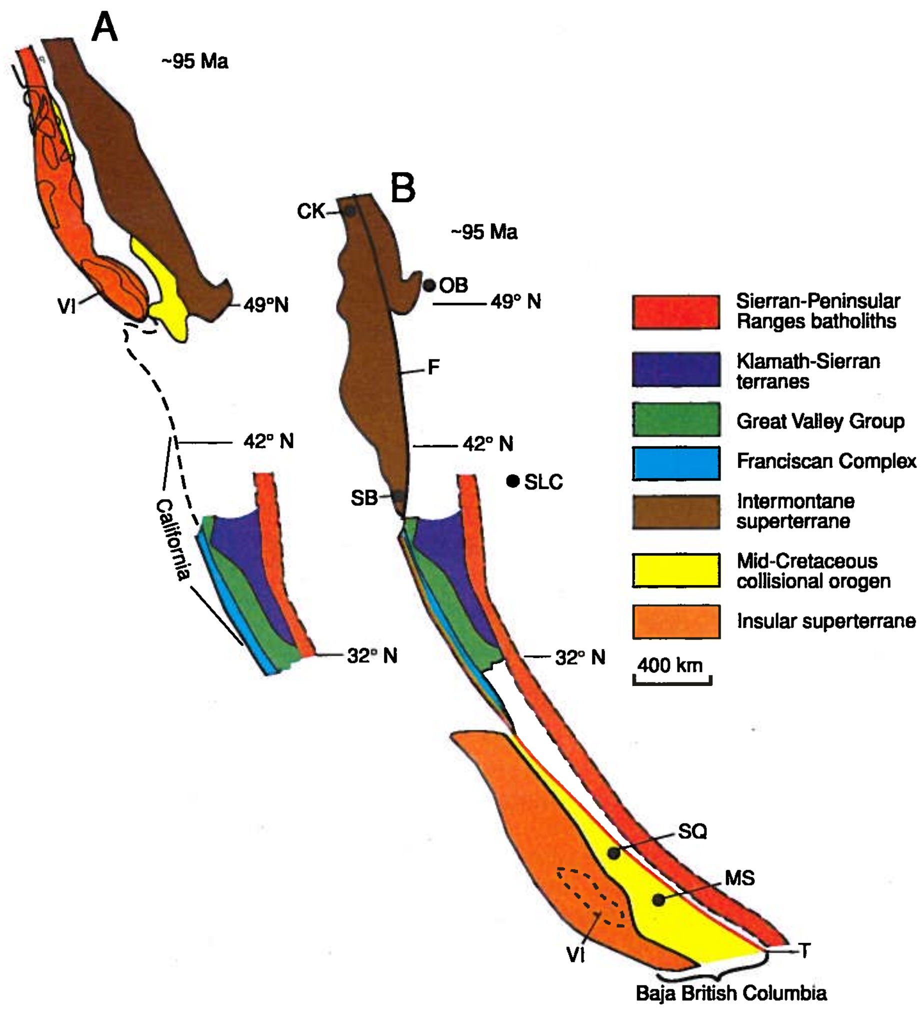

Figure 1. Greatly simplified maps illustrating alternative models for mid-Cretaceous paleogeography based on geologic arguments (A) or paleomagnetic data (B). The palinspastic base used in both incorporates two restorations: about 275 km of Cenozoic east-west extension in the Basin and Range province; and about 400 km of dextral slip on intrabatholithic transcurrent faults, restoring the Klamath-Sierran terranes, Great Valley Group, and Franciscan complex south of their present positions. Current location of Salt Lake City (SLC) and Vancouver Island (VI). Latitude 49°N is U.S.–Canada boundary; 32°N approximates U.S.–Mexico boundary. (A) After the collision ca. 90–100 Ma of Insular superterrane with the margin of North America, which already included the Intermontane superterrane, both superterranes lay north of the Franciscan-Sierran subduction zone–magmatic arc in California. (B) Insular superterrane collides south of the Franciscan-Sierran system in California. Heavy line marked "T" is the approximate position of the transcurrent (transform) fault along which Baja British Columbia was displaced northward after 90 Ma. F denotes a hypothetical fault now within the Intermontane superterrane along which its western two-thirds was translated northward after 70 Ma. CK, SB, SQ, MS, and OB locate the paleomagnetic data discussed in text. MS currently is ca. 180 km farther south of SQ due to Tertiary dextral strike-slip on the intervening Fraser–Straight Creek fault (partly shown as F in Fig. 2).

INTRODUCTION

One of the key objectives of tectonic analysis is to establish what I call here the *paleogeography* of a particular region through geologic time: the former configuration and geographic position of major crustal elements, regional structures, and plate boundaries. Typically, tectonic geologists use a diverse array of structural, sedimentologic, and isotopic evidence to support or corroborate a favored paleogeographic hypothesis. Paleomagnetic data that record the paleolatitude of a rock unit at certain times can also provide invaluable information about the positions and displacements of a tectonic element. It goes without saying that paleogeographic maps based on these data should be recognizably similar to maps based on geologic evidence alone. Models for the early Late Cretaceous (ca. 95 Ma) paleogeography of the western Cordillera of North America conflict with this truism (Fig. 1), and Cordilleran geologists are far from a consensus regarding which model is "correct."

NORTHWEST CORDILLERA

The whole debate over mid-Cretaceous paleogeography is summed up by the following two questions: Where were the Insular and Intermontane superterranes situated ca. 90–100 Ma? Did one or both lie exclusively north of the Franciscan-Sierran subduction system (subduction zone, fore-arc basin, and magmatic arc), which marked the continental margin in what is now California? Notwithstanding this particular controversy, it is important to emphasize that there *is* a consensus, affirmed at the May 1992 Penrose Conference on "Tectonic Evolution of the Coast Mountains Orogen" (reported in *GSA Today,* October 1992), on many aspects of the geology of the northwest Cordillera. Most notably, points of agreement include the identities of the two superterranes and the coincidence of the eastern boundary of the Insular superterrane with a zone of mid-Cretaceous and locally early Tertiary deformation extending at least 1300 km from northwestern Washington through the Coast Mountains of British Columbia into southeastern Alaska (Rubin et al., 1990). The Insular and Intermontane superterranes, as depicted in Figure 2, are each composed of a few dominantly late Paleozoic and Triassic terranes, which are themselves defined by stratigraphic sequences or complexes that extend for thousands of square kilometers. These terranes had been assembled into the larger superterranes by late Middle Jurassic time (see Monger et al., 1991, for stratigraphic details). One of the components of the Insular superterrane is the Wrangellia terrane. Some readers may be surprised that the paleogeographic disposition of Wrangellia—which has assumed legendary status as the prototype of Cordilleran tectonostratigraphic terranes—is still in contention.

Because the boundary zone along the eastern edge of the Insular superterrane figures prominently in the paleogeographic debate, I briefly review its nature and history below. In Figures 1 and 2 the zone is depicted as the "mid-Cretaceous collisional orogen." I believe most workers would agree on the following broad outline. Along the entire known length of the boundary, stratigraphic and plutonic units belonging to the Insular superterrane extend onto the mainland to an eastern limit marked by a zone of predominantly east-dipping, west-vergent imbricate thrust faults. U-Pb isotopic data from granitoid plutons (e.g., Rubin and Saleeby, 1992; Journeay and Friedman, 1993), and stratigraphic evidence (e.g. Brandon, et al., 1988) indicate that thrusting and high-pressure metamorphism occurred in the boundary zone between ca. 90 and 100 Ma.

The character and width of this zone of mid-Cretaceous deformation differ along strike. Between latitudes 54°N and 58°N (the "northern sector"), the imbricate zone is a maximum of 50 km wide (Fig. 2). It includes slices derived principally from Insular superterrane and the depositionally overlying Upper Jurassic and Lower Cretaceous Gravina sequence along its easternmost edge. North of 55°N some of the thrust sheets in the imbricate zone lithologically resemble the Intermontane superterrane, according to Rubin and Saleeby (1992), and others resemble the Yukon-Tanana terrane, widely exposed north and east of the Intermontane superterrane (Gehrels et al., 1992; Rubin and Saleeby, 1992). Between 54°N and 55°N, the upper plate of the imbricate zone consists of high-grade and locally migmatitic metamorphic rocks, but their "terrane affinity" is unknown (Crawford et al., 1987). North of 54°N, the Intermontane superterrane sensu stricto, which is widely exposed in central British Columbia (Fig. 2), evidently lies exclusively east of the thrust system. The two are separated by a continuous belt of Late Cretaceous and Paleogene plutons of the Coast plutonic complex (e.g., Wheeler and McFeely, 1991). The western margin of the plutonic complex was deformed about 60 Ma in the 600-km-long, steep, northwest-striking Coast shear zone shown in Figure 2 (e.g., McClelland et al., 1992a).

At about 52°N, the zone of mid-Cretaceous deformation along the eastern edge of the Insular superterrane emerges from the Coast plutonic complex and expands southward to a maximum width of ~225 km at 48°30'N. For the sake of simplicity, I refer here to the entire zone in this southern sector as the "Cascade–Southern Coast Belt orogen" (Fig. 2). The orogen is much wider than its along-strike counterpart in the northern sector. More important, it contains a greater variety of rock units. The western third of the orogen is an imbricate stack of nappes that structurally overlies the Insular

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superterrane. The nappes (San Juan–Cascade system south of 49°N) consist of supracrustal rock units ranging in age from early Paleozoic and possibly Precambrian to late Early Cretaceous (e.g., Brown, 1987; Brandon et al., 1988). Journeay and Friedman (1993) hypothesized that a minority of these units were derived from the eastern margin of the Insular superterrane. The majority, however, have no known Insular counterparts, so their tectonic provenance or homeland must have lain elsewhere.

The eastern two-thirds of the Cascade–Southern Coast Belt orogen, constituting the upper plate to the nappes (e.g., McGroder, 1991; Journeay and Friedman, 1993), includes a core of high-grade metamorphic rocks and orthogneiss flanked on the east by lower-grade rocks of the "Eastern Coast Belt" (Fig. 2). The latter includes several upper Paleozoic and lower Mesozoic units that originated in volcanic arcs or ocean basins, together with one or more sequences of Upper Jurassic and Lower Cretaceous clastic sedimentary rocks that were deposited partly in the Methow-Tyaughton basin. All the units are intricately juxtaposed along thrust and strike-slip faults of chiefly Late Cretaceous and early Tertiary age. Some workers (e.g., Rusmore et al., 1988) have speculated, on the basis of lithologic similarities, that pre-Upper Jurassic terranes in the Eastern Coast Belt and Intermontane superterrane were contiguous as early as Middle Jurassic time. Currently, however, the Intermontane superterrane sensu stricto is separated from possibly correlative units in the Eastern Coast Belt by the Pasayten, Yalakom, and Fraser fault systems (Fig. 2), all of which record Late Cretaceous or early Tertiary strike slip of at least several tens of kilometers (e.g., Monger, 1985; Hurlow, 1993).

Many lines of evidence demonstrate that all the elements of the Cascade–Southern Coast Belt orogen were contiguous and linked to one another and to the Insular superterrane by early Late Cretaceous time, ca. 90 Ma. In the Eastern Coast Belt, Albian and Cenomanian strata overlap diverse Jurassic and older basement terranes (Garver, 1992). Postkinematic plutons as old as 86–90 Ma intruded the Eastern Coast Belt and contiguous metamorphic rocks in the upper plate (e.g., Miller et al., 1993); U/Pb isotopic data from pre-, syn-, and postkinematic plutons in and adjacent to the imbricate zone indicate that most thrusting occurred between 97 and 91 Ma (Journeay and Friedman, 1993). The Turonian and younger Nanaimo Group, resting unconformably on the Insular superterrane, contains detritus derived from nappes in the imbricate zone (Brandon et al., 1988).

In summary, it is generally agreed that a zone >1300 km-long of mid-Cretaceous deformation and metamorphism in the northwest Cordillera coincides with the eastern edge of the Insular superterrane. Crustal shortening of tens (northern sector) to hundreds (southern sector) of kilometers was largely accommodated in a west-vergent imbricate thrust system. Deformation resulted from the Insular superterrane being driven against what was almost certainly the North American continental margin in an event variously referred to as "accretion," "collision," or "intra-arc contraction." Stratigraphic and plutonic links require that, by 90 Ma, the Insular superterrane and the flanking mid-Cretaceous orogenic belt were contiguous. The entire mid-Cretaceous orogen is sometimes referred to as the "boundary between the Insular and Intermontane superterranes," even though the latter, as strictly defined, is separated from the orogen by intervening Late Cretaceous and early Tertiary plutons and faults.

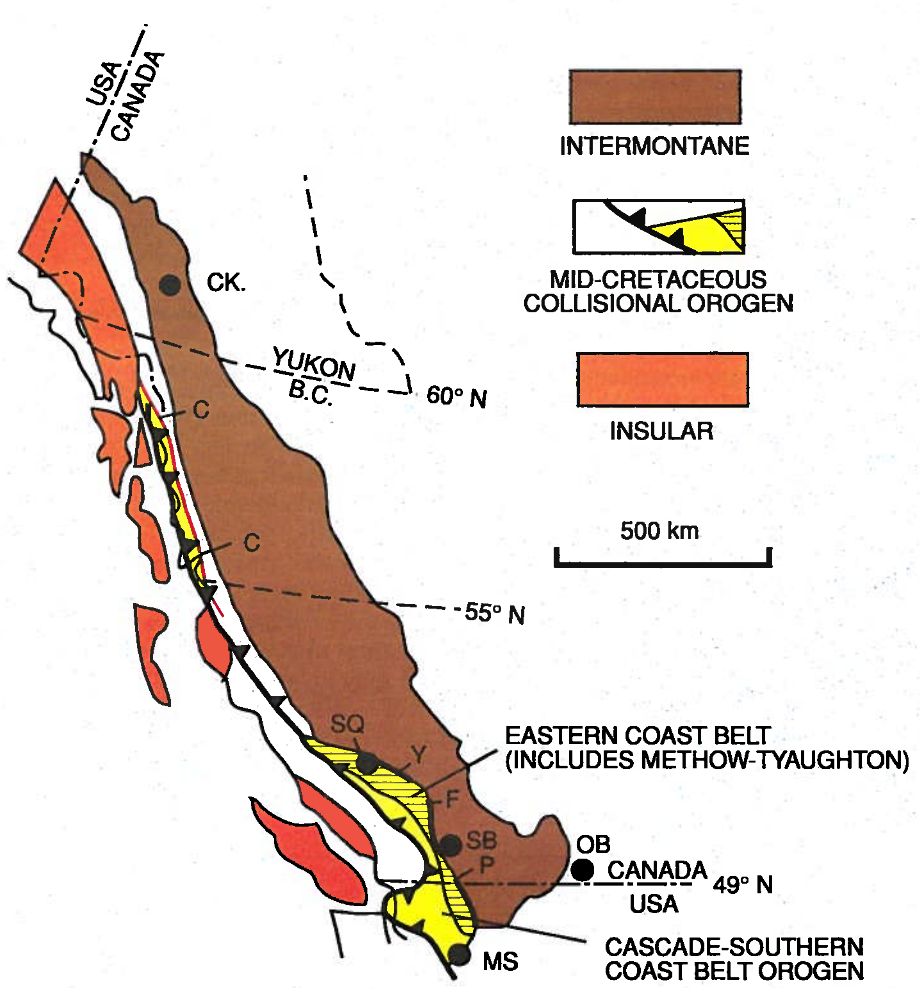

Figure 2. Map of present-day northwest Cordillera depicting the Insular superterrane and the Intermontane superterrane, and the mid-Cretaceous orogen along the eastern boundary of the Insular superterrane. The eastern Coast Belt within the orogen is denoted by horizontal lined pattern. The eastern boundary of the Cascade–Southern Coast Belt orogen is locally the high-angle Yalakom (Y), Fraser (F), and Pasayten (P) faults. North of lat 54°N, C denotes the early Tertiary Coast shear zone. CK, SQ, SB, MS, and OB are paleomagnetic localities discussed in text.

HYPOTHESIS 1: INSULAR SUPERTERRANE NORTH OF CALIFORNIA

Although the points in the preceding paragraph are widely accepted, there is as yet no consensus on the pre–Late Cretaceous disposition of the Insular superterrane. Where was it before it "collided," and where along the western margin of North America did the collision take place? On the basis of geologic evidence alone, several hypotheses have been proposed. Most workers (e.g., van der Heyden, 1992; McClelland et al., 1992b) specify that (1) the Insular and Intermontane superterranes had been juxtaposed with one another by Middle Jurassic time, and (2) they lay in approximately their present position with respect to California—that is, to the north of the Late Jurassic and younger Franciscan-Sierran system. The Jurassic boundary between the superterranes subsequently became the locus of intra-arc rifting or transform faulting, followed by intra-arc shortening to give rise to the mid-Cretaceous "collisional" orogen.

These models rest on interpretations holding that Upper Jurassic and Lower Cretaceous strata in the Gravina sequence (northern sector) and Eastern Coast Belt (southern sector) accumulated in the intra-arc basins that formed along the preexisting boundary between the superterranes. Additional evidence thought to indicate the proximity of the superterranes to one another and to the North American plate during late Mesozoic time includes (1) magmatic links—arcs built across terrane boundaries, and (2) provenance links—detrital zircons or populations of grains tying sediments to sources in one of the superterranes or in North America (e.g., McClelland et al., 1993; Garver, 1992).

In spite of minor variations among these models, they all yield a paleogeography in which the late Mesozoic (ca. 150–90 Ma) disposition of the Insular and Intermontane superterranes was essentially the same as today's: both lay north of the Franciscan-Sierran system (Fig. 1A). According to hypothesis 1, the Cascade–Southern Coast Belt orogen and imbricate thrusts along strike to the northwest formed as the Insular superterrane impinged against the currently contiguous Intermontane superterrane to the east.

PALEOMAGNETIC DATA FROM CRETACEOUS ROCKS

The paleogeography in hypothesis 1 is based on geologic evidence. Paleogeography can also be inferred using paleomagnetic data. Paleomagnetic directions in rocks can yield paleolatitudes, provided certain assumptions are satisfied. The usual procedure (reviewed in Beck, 1989) is to compare the measured paleomagnetic directions with the directions expected had the rocks in question been in their present latitudinal position with respect to cratonic North America. Equivalently, paleopoles calculated from the measured data can be compared with cratonic reference paleopoles.

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Since the 1970s, many paleomagnetic studies have been conducted on rocks from the northwest Cordillera (summarized by Beck, 1989; Irving and Wynne, 1990). Nearly all of the investigations dealing with mid-Cretaceous magnetizations have reported paleomagnetic inclinations shallower than those expected for cratonic North America. This type of discordance could be due to either (1) postmagnetization, northward latitudinal displacement relative to the craton, (2) tilting about a horizontal axis, or (3) a combination of displacement and tilt. Selecting the correct explanation requires knowing the direction and amount of postmagnetization tilting. For plutons, this feat is seldom achieved because unambiguous criteria for the paleohorizontal in plutons or country rock are commonly lacking.

Most paleomagnetic data relevant to the mid-Cretaceous paleogeography of the northwest Cordillera come from plutons ca. 90–100 Ma. These discordant data have been interpreted differently by two groups, both of which fully acknowledge the "paleohorizontal problem." One school of thought, represented by Beck et al. (1981), and Irving et al. (1985), assumes that the batholiths yielding the data have not been appreciably tilted and so favors the interpretation that post–middle Cretaceous northward displacements account for the discordance. Irving (1985) introduced the concept of Baja British Columbia to describe the crustal element that lay at least 2000 km farther south in mid-Cretaceous time and that subsequently moved northward. Irving et al. (1985), Umhoefer (1987), Umhoefer et al. (1989), and Oldow et al. (1989) viewed Baja British Columbia as consisting of the Insular superterrane and most of the Intermontane superterrane and placed it 2000–3000 km south, at the latitude of northwestern Mexico, at ca. 100 Ma. The other school, led by Butler et al. (1989), challenges the whole concept of Baja British Columbia and favors the alternative hypothesis that discordant paleomagnetic directions in plutons are due to regional, in situ tilt of the Coast plutonic complex.

Controversies like this one are understandably fed by perceived weaknesses in the paleomagnetic studies; for example, absent or ambiguous evidence for the paleohorizontal; poor controls on ages of magnetization; and failures of the fold test. It can be argued, however, that there are four data sets that overcome these weaknesses and allow highly reliable interpretations of discordance supporting post–middle Cretaceous translation rather than tilting. (1) Locality CK in Figures 1B and 2. Marquis and Globerman (1988) presented data from the 70 Ma layered volcanic rocks of the Carmacks Group, resting unconformably on the northern Intermontane terrane (Fig. 2). They calculated a northward displacement of 1490 ±940 km (13.4° ±8.5°). Butler (1990), using a different average of site-mean virtual geomagnetic poles, re-calculated a displacement of 1190 ±1140 km (10.7° ±10.3°). (2) Locality SB in Figures 1B and 2. Irving et al. (1993) expanded the earlier study of Irving and Thorkelson (1990) on the well-bedded volcanic and volcaniclastic Spences Bridge Group. The section is late Early Cretaceous age (104 Ma) and lies unconformably on several units of the southern Intermontane superterrane. Irving et al. (1993) reported a "best estimate of ... displacement from the south since mid-Cretaceous time of 1200 km." (3) Locality SQ in Figures 1B and 2. Maxson et al. (1993) calculated a paleolatitudinal northward displacement of ~2900 ±1000 km (26°) for the upper Lower to lower Upper Cretaceous Silverquick sedimentary unit and overlying Powell Creek volcanics, which are, at least in part, 94 Ma. The section is part of the Eastern Coast Belt and lies at the eastern edge of the mid-Cretaceous orogen. (4) Locality MS in Figures 1B and 2. Ague and Brandon (1992) used hornblende barometry to determine a paleohorizontal datum for the ca. 93 Ma age of emplacement and magnetization of the southwestern lobe of the Mount Stuart batholith. The pluton intruded the western nappes and metamorphic core of the Cascade–Southern Coast Belt orogen. Their analysis indicates a post–middle Cretaceous northward displacement of 2900 ±700 km, an amount fully in accord with the earlier results (~3100 km) of Beck et al. (1981) for Mount Stuart, and with displacements calculated for other plutons in the Coast plutonic complex by Irving et al. (1985).

HYPOTHESIS 2: INSULAR SUPERTERRANE SOUTH OF CALIFORNIA

The mid-Cretaceous paleogeography hypothesized in Figure 1A is based exclusively on geological evidence and interpretations; it ignores or rejects paleomagnetic data. Alternatively, we can hypothesize a ca. 95 Ma paleogeography based exclusively on the four paleomagnetic data sets listed above. The premises underlying Figure 1B are as follows: (1) The paleomagnetic directions have been corrected for postmagnetization tilting and, in the case of bedded volcanic rocks, do not contain systematic errors derived from regionally consistent paleoslopes. Consequently, the discordant inclinations are due entirely to paleolatitudinal displacements. (2) The mean value of each calculated displacement is used to restore a crustal element to its mid-Cretaceous position. Following the analysis of Marquis et al. (1990, Fig. 1) and Irving and Thorkelson (1990, Figs. 18 and 19), the mean is statistically the most probable displacement; displacements less than or greater than the mean but still within the 95% error limits are less probable. (3) Discordant declinations reported in some of the studies listed above are assumed to be due to local rotations about vertical axes, rather than to the wholesale clockwise rotation of an entire superterrane. (4) Mid-Cretaceous plutons that intruded the margin of cratonic North America east of the Intermontane superterrane, and for which tilts are known from bathozonal studies, yield concordant paleodirections (OB in Fig. 1B; Irving and Archibald, 1990) indicative of no net latitudinal displacement.

Two restorations, accommodating the four data sets, were used to

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construct Figure 1B. In one, the western two-thirds of the Intermontane superterrane is restored southward 1200 km, as required by the comparable displacements calculated for the Carmacks (CK) and Spences Bridge (SB) data sets. The more conservative estimate is used for Carmacks. Because geologic evidence (Brown et al., 1986) indicates that the eastern part of the Intermontane superterrane was attached to now adjacent North America by Middle Jurassic time, the latitude of the eastern third of the superterrane at 95 Ma is fixed in Figure 1B by the OB data set. In the other restoration, the displacement of ~2900 km calculated for both the Mount Stuart batholith (MS) and the Silverquick– Powell Creek section (SQ) is applied to the entire 1500-km-long crustal element, lying between 49°N and 58°N, that resulted from the collision of the Insular superterrane 90–100 Ma. As discussed above, it is widely accepted on geological grounds that this element included the Insular superterrane and the Cascade–Southern Coast Belt orogen (location of both MS and SQ). The restored position of the element is entirely south of present lat 32°N, the U.S.-Mexico border.

The restoration in Figure 1B has several implications, some of which I note here. Baja British Columbia is redefined in this paper to consist of the Insular superterrane and the contiguous mid-Cretaceous orogen flanking it to the east; in contrast to earlier hypotheses (e.g., Irving et al., 1985; Umhoefer, 1987), it does not include the Intermontane superterrane sensu stricto. The Insular superterrane collided in latest Early to earliest Late Cretaceous time with the North American margin where it extended south from the convergent plate boundary represented in California by the Franciscan subduction complex and Sierran magmatic arc. I hypothesize here that the collision occurred along the southern continuation of the Franciscan subduction zone. The mid-Cretaceous collisional orogen was fashioned from a heterogeneous fore-arc sliver situated continentward of the subduction zone. In what became the Cascade–Southern Coast Belt orogen in southeastern Baja British Columbia (Fig. 1B), the Early Cretaceous fore-arc basin is represented locally by the Methow-Tyaughton succession. The arc itself was probably the Peninsular Ranges batholith, which paleomagnetic data indicate originally lay at these paleolatitudes (e.g., Lund and Bottjer, 1991; Ague and Brandon, 1992).

As newly defined here, Baja British Columbia moved northward along a transform-fault system, parallel to the coast of California but west of the Franciscan Complex, between ca. 80 and ca. 60 Ma (modeled by Umhoefer, 1987, and Umhoefer et al., 1989). A logical inference is that during this interval, the Franciscan ceased growing as an accretionary wedge fed by sediments scraped off of descending oceanic crust; convergence between Pacific plates and North America was accommodated instead along the western margin of the Insular superterrane. Baja British Columbia and the Intermontane superterrane were juxtaposed north of California along dextral transcurrent faults in the northern part of the transform system during this interval; the likeliest candidates are the Pasayten fault, a "proto-Yalakom" fault parallel to but northeast of the present Tertiary trace of the Yalakom fault, and the Coast shear zone. The amalgamated superterranes were displaced northward ~1200 km with respect to cratonic North America, along an as-yet-unspecified fault system in the eastern Intermontane superterrane (F in Fig. 1B) originally hypothesized by Umhoefer (1987). All northward displacements were largely completed by 50–55 Ma (e.g., Irving and Brandon, 1990; Irving and Wynne, 1990).

COMMENTS

My purpose here, given the space available, is simply to present and compare two maps that each depict hypothetical mid-Cretaceous paleogeography. One map is based exclusively on paleomagnetic data and the other on geological arguments. It is obvious that at least one of these hypotheses is invalid; perhaps both are. It may turn out that the assumptions underlying the paleomagnetically derived displacements are flawed. However, the reliability of the assumptions and geological evidence invoked to support the "stabilist" hypothesis portrayed in Figure 1A should also be debated. I contend that this geological evidence at present does not support hypothesis 1 to the exclusion of hypothesis 2; rather, the evidence is compatible with more than one paleogeographic interpretation. In addition to continuing to compile lines of evidence thought to corroborate one hypothesis or the other, geologists should attempt to resolve the controversy by devising specific tests designed to rule out the predictions of hypothesis 2.

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