[AMERICAN JOURNAL OF SCIENCE, VOL. 297, FEBRUARY, 1997, P. 117–173]

American Journal of Science

FEBRUARY 1997

GEOLOGIC TESTS OF HYPOTHESES FOR LARGE COASTWISE DISPLACEMENTS—A CRITIQUE ILLUSTRATED BY THE BAJA BRITISH COLUMBIA CONTROVERSY

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ABSTRACT. We present two mutually contradictory hypotheses for the mid- and Late Cretaceous paleogeography of the western margin of North America. In Hypothesis A, representative of a family of models based on geologic evidence, the Insular and Intermontane superterranes and the intervening mid-Cretaceous Coast Mountains orogen were situated in their present positions relative to cratonic North America, 90 my ago. In the alternative Hypothesis B, based on paleomagnetic data, the Insular superterrane and the Coast Mountains orogen along its eastern edge were situated 3000 km south of their present positions, 90 my ago. This crustal element, Baja British Columbia, then moved northward between 90 and 70 Ma along the hypothetical, coast-parallel, Baja B.C. fault system. At 70 Ma, Baja British Columbia was juxtaposed with the western part of the Intermontane superterrane, which lay 1100 km south of its present position. Between 70 and 50 Ma, the composite block moved northward an additional 1100 km along the hypothetical Intra-Quesnellia fault, located within the Intermontane superterrane.

A goal of the hypothetico-deductive scientific method is the elimination of false hypotheses using empirical tests. A review of the logical arguments governing this method shows that if two contradictory hypotheses are judged to have non-negligible prior probabilities—if both have a significant likelihood of being true—then a crucial test can potentially lead to the refutation of one hypothesis and provide empirical support for the alternative. A crucial test is possible when an observational prediction of one model is prohibited by an alternative model. To evaluate whether hypothesis A or B can be ruled out by geologic evidence, we propose four crucial tests independent of paleomagnetic tests. To test the Baja British Columbia hypothesis, potentially useful geologic evidence includes: (1) the provenance of detritus in mid-Cretaceous strata in the Methow and Tyaughton basins; (2) the provenance of detritus in pre-Late Campanian strata in the Nanaimo Group; (3) offset geologic features in Baja British Columbia matching counterparts in southwestern California and northwestern Mexico; and

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(4) Late Cretaceous or older geologic features limiting offset across the transcurrent Baja B.C. fault to <1000 km.

INTRODUCTION

> *[The investigator] is not restricted to the employment of one hypothesis at a time. There is indeed an advantage in entertaining several at once, for then it is possible to discover their mutual antagonisms and inconsistencies, and to devise crucial tests—tests which will necessarily debar some of the hypotheses from further consideration. . . .*
>
> *In the testing of hypotheses lies the prime difference between the investigator and the theorist. The one seeks diligently for the facts which may overthrow his tentative theory, the other closes his eyes to these and searches only for those which will sustain it.*
>
> G. K. Gilbert (1886)

One of the goals of tectonic analysis is the invention and evaluation of hypotheses specifying the paleogeographic positions and configurations of major crustal elements, plate boundaries, and regional structures. In several instances, hypotheses or models—these terms are used interchangeably here—for the late Mesozoic and early Cenozoic paleogeography of the western margin of North America that are based on paleomagnetic data differ significantly from models based on geologic evidence. For example, some workers interpret paleomagnetic inclinations shallower than those expected for cratonic North America to indicate that certain units or terranes in figure 1 (Insular and Intermontane superterranes; Salinian block; Peninsular Ranges batholith) were displaced 1000 km or more northward along the margin of North America after Early Cretaceous time (Irving and Wynne, 1990; Champion, Howell, and Gromme, 1984; Lund and Bottjer, 1991; Beck, 1991; Ague and Brandon, 1992, 1996; Irving and others, 1995; Wynne and others, 1995). Other workers argue that, in each case, the geologic and paleomagnetic evidence is consistent with total post-middle Cretaceous displacements of at most a few hundred kilometers (Butler and others, 1989; Price and Carmichael, 1986; Butler, Dickinson, and Gehrels, 1991; Gastil, 1991).

We argue that scientific controversies like these should be subjected to systematic tests, designed to assess whether a particular hypothesis is true or false. A *geologic test,* as we use the term here, evaluates whether certain consequences deduced from a paleogeographic model are confirmed (supported) by or disconfirmed (contradicted) by geologic evidence. For example, the expected provenance of sediments deposited on a certain terrane that had not been displaced more than a few hundred kilometers relative to adjacent, stable North America might be utterly different from the provenance of sediments on a more far-travelled terrane. In principle, these contrary consequences can be tested with geologic evidence. Paleogeographic models can also be tested independently using entirely different kinds of evidence, such as paleomagnetic data or the geographic distribution of fossils.

In our opinion, there are as yet no standardized and widely accepted geologic tests for paleogeographic models invoking latitudinal displacements in excess of ~ 1000 km on coast-parallel, transcurrent faults. The purpose of this paper is to propose and advocate a method of evaluation based on *crucial geologic tests.* Such tests involve deducing mutually

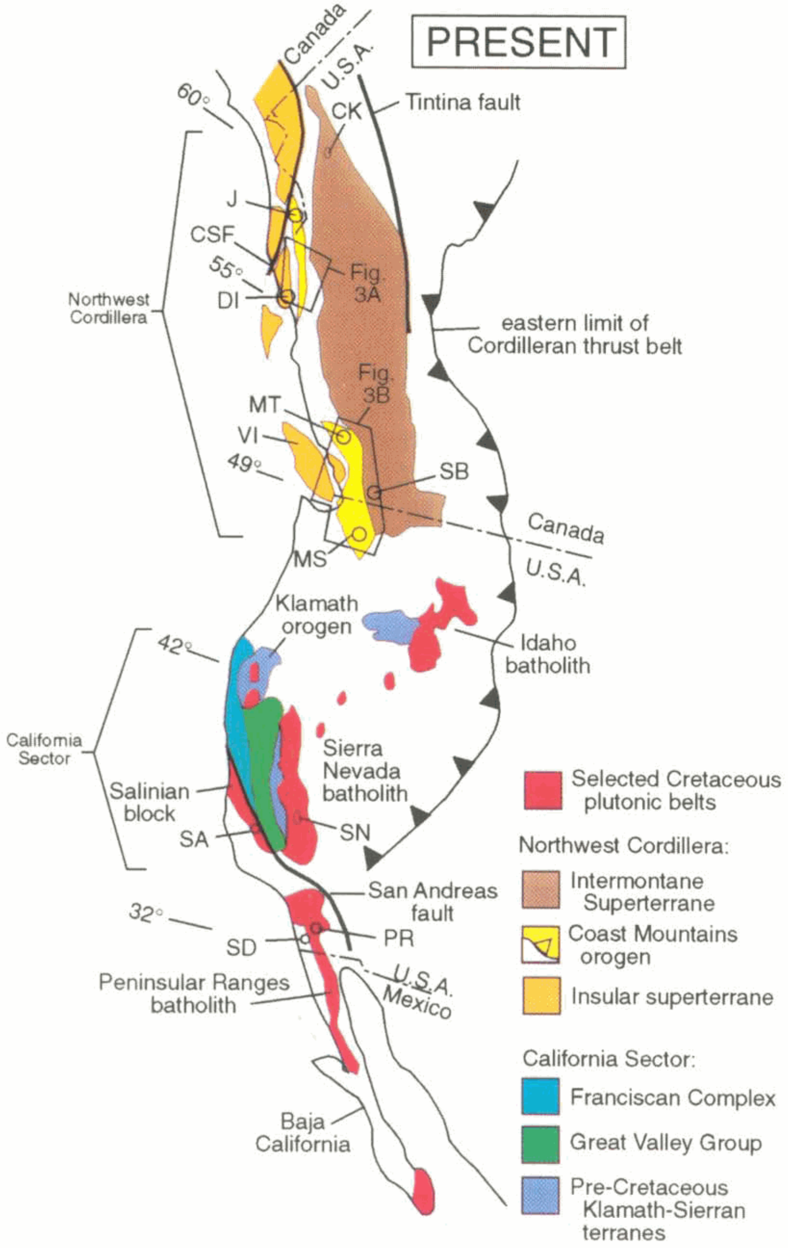


Fig. 1. Present geographic disposition of major crustal elements and other features discussed in the text. The Idaho batholith and the eastern limit of the late Mesozoic to early Cenozoic Cordilleran thrust belt in this figure and in figure 2A, B, and figure 4 are reference "points" that have remained at their expected latitudes relative to the North American craton since mid-Cretaceous time. In addition to the elements shown in color, the following also appear in this figure and in figure 2A and B: (1) Geographic features: J = Juneau, southeastern Alaska; SD = San Diego, California; VI = Vancouver Island, British Columbia. (2) Generalized sites for paleomagnetic data sets (see table 1): CK = Carmacks; DI = Duke Island; MS = Mt. Stuart, MT = Mt. Tatlow; PR = Peninsular Ranges; SA = Salinian Block; SB = Spences Bridge; SN = Sierra Nevada. CSF = Chatham Strait fault.

contradictory predictions from alternative paleogeographic hypotheses and evaluating which of these predictions are confirmed or disconfirmed by existing or newly acquired geologic evidence. To illustrate our arguments, we use one of the current controversies regarding the mid-Cretaceous (~90 Ma) paleogeography of the western margin of North America. One model holds that a crustal element extending from northwestern Washington through western British Columbia and into southeastern Alaska has lain in roughly its present position relative to California and continental North America since mid-Cretaceous time. The alternative model places this element, conceptualized as Baja British Columbia, several thousand kilometers south of its present position ~85 to 100 my ago. We believe that neither model has yet been tested geologically, largely because most geologists have already concluded that the Baja British Columbia hypothesis, which at present is based entirely on paleomagnetic data, has a negligible probability of being true. Cowan (1994) provided a brief review of the alternative models, and Kerr (1995) summarized different views of the controversy.

The paper is divided into five parts. The first two sections summarize the general paleogeographic controversy and introduce the geologic background of the problem. Part three develops two specific alternative models. Part four reviews the logic underlying the testing of scientific hypotheses. Part five discusses the predictions of each model and proposes several geologically feasible crucial tests. Although we believe that the method advocated here could be applied equally well to paleomagnetic and paleontologic evidence, we have deliberately restricted our critique to tests based on geologic evidence alone.

THE PALEOGEOGRAPHIC CONTROVERSY

The basic questions concerning the mid-Cretaceous paleogeography are simple. What did the western margin of North America from northwestern Mexico to southeastern Alaska look like about 90 my ago? With regard to the particular controversy dealt with in this paper, where were the Insular and Intermontane superterranes, which now constitute much of the northwest Cordillera, situated with respect to the Franciscan Complex and Sierra Nevada batholith in California (fig. 1)? Over the past 20 yrs or so, two different and fundamentally incompatible perceptions of mid-Cretaceous paleogeography have taken form. The specific models we present in figure 2 and outline in more detail below are representative of these differing views.

In one view (fig. 2A), the Insular and Intermontane superterranes both lay north of California, such that their total post-mid-Cretaceous northward displacement with respect to California and the remainder of western North America is <1000 km. This group, termed here the "northern option," encompasses a number of published models (Dickinson, 1976; Davis, Monger, and Burchfiel, 1978; Monger, Price, and Tempelman-Kluit, 1982; Saleeby and Gehrels, 1988; Wernicke and

Klepacki, 1988; Burchfiel, Cowan, and Davis, 1992; McClelland, Gehrels, and Saleeby, 1992; van der Heyden, 1992; and Monger and others, 1994). Although each model differs somewhat from the others in how it portrays the pre-mid-Cretaceous positions and displacements of the superterranes, all in the northern option are based on geologic evidence. Moreover, all are inconsistent with interpretations of discordant mid-Cretaceous magnetizations favoring large translations rather than tilting.

The other view (fig. 2B), which we call the "southern option," postulates that the part of the Insular superterrane now residing between latitudes 49° and 58°N (fig. 1) used to lie at least 2400 km south of its present position, relative to stable North America, about 90 to 100 my ago. In some southern-option models, part or all of the Intermontane superterrane (fig. 1) is also restored southward by some 1000 km or more. All models in the southern option (Irving and others, 1985; Umhoefer, 1987; Oldow and others, 1989; Irving and Wynne, 1990; Ague and Brandon, 1992, 1996; Cowan, 1994; Wynne and others, 1995; Bogue, Gromme, and Hillhouse, 1995) are consistent with the interpretation, originally proposed by Beck (1976), that shallower-than-expected magnetizations in mid-Cretaceous rocks in the northwest Cordillera reflect latitudinal translations rather than post-magnetization tilting. These models, including the one in figure 2B, imply that parts of the northwest Cordillera were displaced northward in excess of 1000 km and perhaps as much as 3000 km, between about 90 and 50 Ma. Irving (1985) named the displaced crustal block "Baja British Columbia" to acknowledge ". . . that the region formerly had a . . . more southerly position, and that the motions which brought it into its present position [were] predominantly in a coastwise sense, like [those] of Baja California today, but no specific mechanism of transport is implied" (Irving and Wynne, 1990, p. 490).

It is clear from the foregoing discussion that models in the northern option are incompatible with those in the southern option (fig. 2). For example, both models portrayed in figure 2 cannot be true, although both could be false. Our purpose in this paper is not to review or criticize the empirical basis for either option; Kerr (1995) has already discussed how the Baja British Columbia controversy originated and why it survives. Instead, our objective is to show how the dichotomy might be resolved using logically sound, crucial geologic tests.

GEOLOGIC BACKGROUND

The major difference between the two options is the paleogeographic position of the Insular and Intermontane superterranes relative to the Franciscan Complex and Sierra Nevada batholith in California. We first review the geology of these regionally extensive features and then describe pertinent rock units and structures as they are presently disposed in two corridors across the northwest Cordillera.

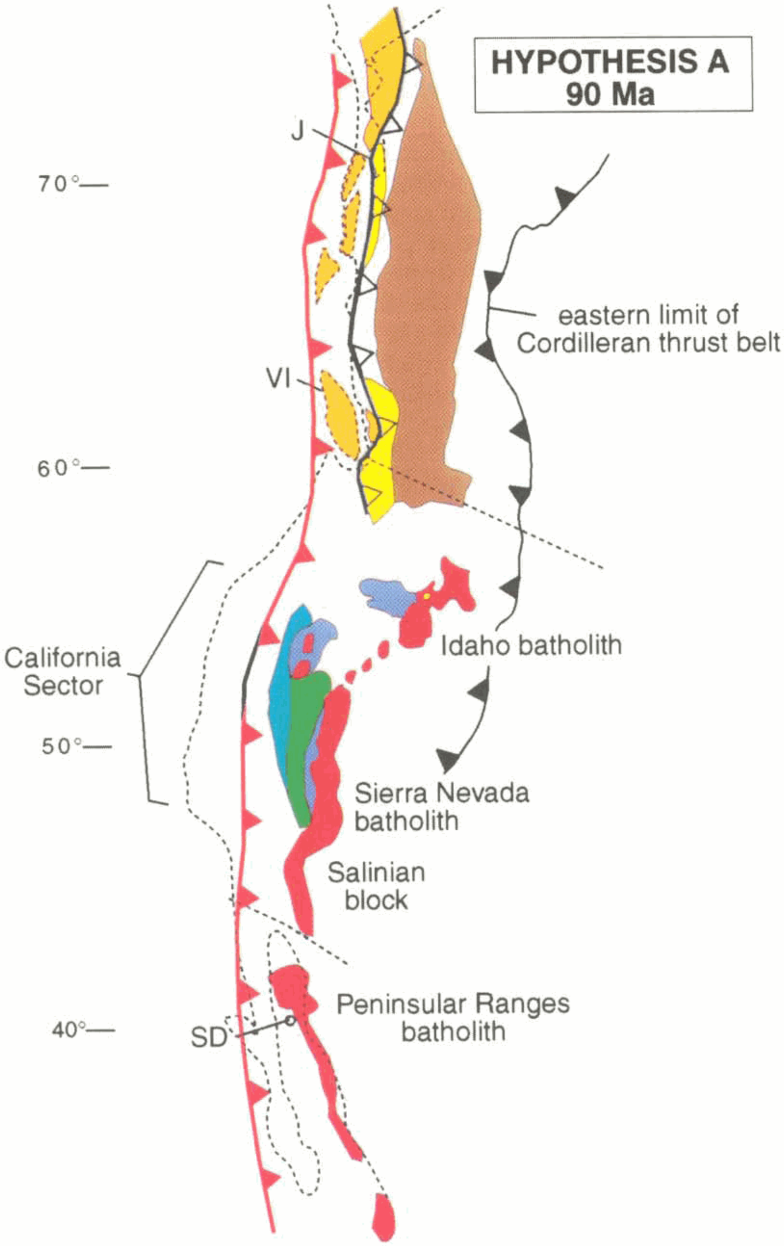


Fig. 2. Alternative hypotheses for early Late Cretaceous (90 Ma) paleogeography of the western margin of North America. Latitudes are relative to the mid-Cretaceous (124-88 Ma) reference pole for cratonic North America from Van Fossen and Kent (1992). The present-day coastline and international boundaries are adapted from figure 1 and depicted with a dashed line. The location and orientation of the coastline relative to the paleolatitudinal grid are determined by the paleolatitude and paleodeclination of selected coastal localities assuming that they were fixed to cratonal North America. Both 2A and B of this figure incorporate the removal of 275 km of east-west Cenozoic extension in the California sector east of the Sierra Nevada batholith. (A) The Insular and Intermontane superterranes and the Coast Mountains orogen along their common boundary are shown in their expected (that is, present) latitudinal positions relative to cratonic North America at 90 Ma. The red barbed line represents a single, west-facing, "Franciscan" convergent plate boundary extending the length of the continental margin. The position of the Peninsular Ranges batholith results from removing about 300 km of dextral slip on the San Andreas fault (fig. 1). The position of the Salinian block is determined by removing about 500 km of dextral slip on the San Andreas and earlier faults. Both these restorations are consistent with commonly cited geologic evidence (Dickinson, 1983; Butler, Dickinson, and Gehrels, 1991).

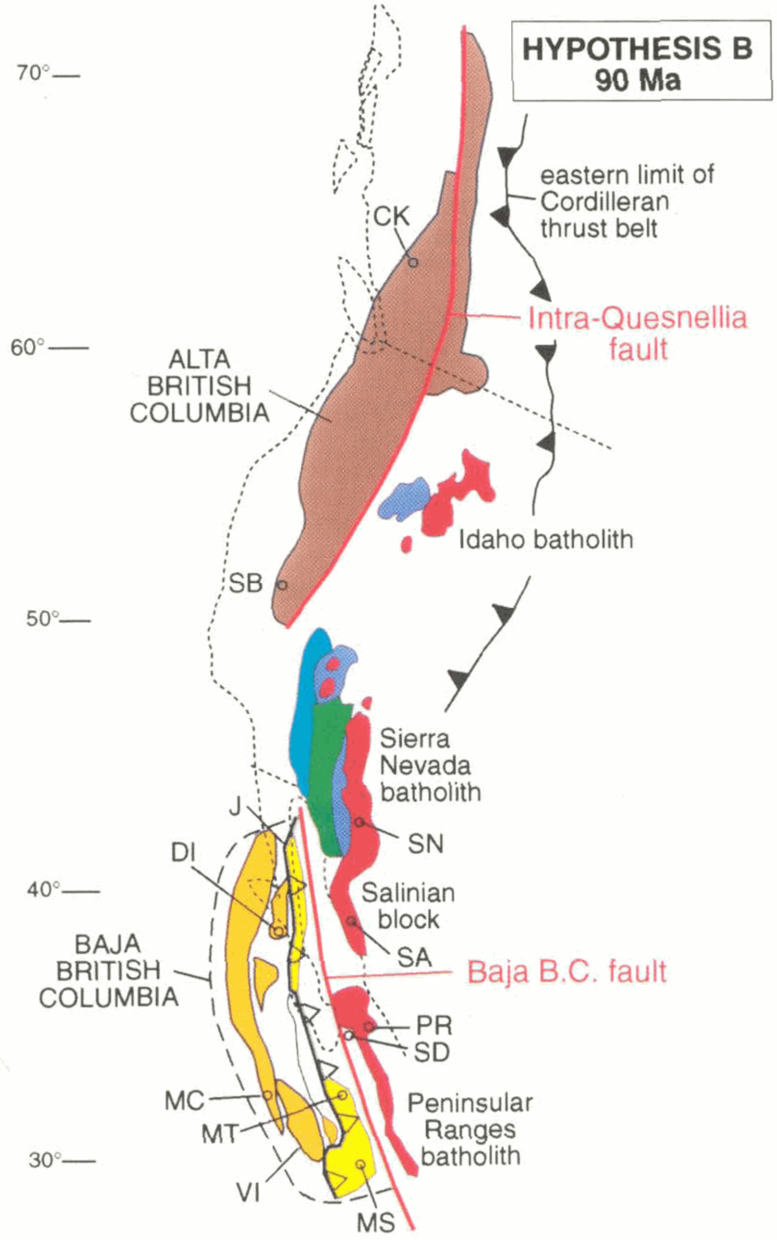


Fig. 2(B) Depicts the Baja British Columbia hypothesis as presented in this paper. Compare the positions of J, SD, and VI with those in figure 1. The geographic positions of Baja British Columbia, Alta British Columbia, the Sierra Nevada batholith and related Mesozoic elements to the west, the Salinian block, and the Peninsular Ranges batholith are all consistent with the paleomagnetic results in table 1 and reflect the mean values of the northward displacements calculated from corrected observed inclinations. None of these crustal elements has been rotated to account for anomalous declinations. The northward displacements were accommodated on the Baja B.C. and Intra-Quesnellia faults, shown in red. Baja British Columbia includes a western sliver of the Insular superterrane, the Baja Alaska of Stone, Panuska, and Packer (1982), that presently lies northwest of the Chatham Strait fault (compare the disposition of the superterrane in fig. 1). Its paleolatitude at 90 Ma is based on the MC data set in table 1. In (B), the MS and MT paleomagnetic localities are closer together than in figure 1 because 160 km of Cenozoic dextral slip on the Fraser-Straight Creek fault has been removed.

Mid-Cretaceous Geology of California

In the California sector, east of the San Andreas fault between about 34° and 43°N latitude, the Sierra Nevada batholith, Great Valley Group, and Franciscan Complex (fig. 1) represent the magmatic arc, fore-arc basin, and subduction complex developed along part of the western continental margin in response to late Mesozoic consumption of Pacific plates beneath North America. Geologic and paleomagnetic evidence (Frei, 1986) shows that at 90 Ma, the Franciscan-Sierran convergent margin lay within several hundred kilometers of its present latitude relative to cratonic North America. The following brief geologic sketch is based on the review of Cowan and Bruhn (1992).

Most of the Sierra Nevada batholith consists of granodioritic plutons emplaced into the continental margin from 110 to 80 Ma. These plutons represent the roots of an eastward-younging magmatic arc, from which the coeval volcanic cover was almost completely eroded. The well-stratified Upper Jurassic and Cretaceous Great Valley Group west of the batholith consists largely of volcanic and plutonic detritus eroded from the batholith. During Late Jurassic and Cretaceous time, until the Sierran arc was extinguished at 80 Ma, these Great Valley strata accumulated in a fore-arc basin. The basement of the western part of the basin is the Middle Jurassic Coast Range ophiolite. Immediately to the west, the lithologically diverse Franciscan Complex contains volcaniclastic, lithic, and arkosic sandstone and subordinate radiolarian chert and basaltic greenstone. Although these rocks range in age from Early Jurassic to early Tertiary, most are Late Jurassic and Early Cretaceous. Franciscan metamorphic rocks, including blueschists, that recrystallized at high pressures and low temperatures from about 140 to 90 Ma, are an important record of Early- to mid-Cretaceous subduction along the continental margin in California.

Northwest Cordillera

This sector of the western Cordillera, between about 48° and 58°N latitude, extends from northwestern Washington, through western British Columbia, into southeastern Alaska and southwestern Yukon Territory (fig. 1). Three major tectonic elements figure prominently in the debate over mid-Cretaceous paleogeography: the Insular and Intermontane superterranes, and the mid-Cretaceous contractional orogen and batholithic belt localized along the eastern margin of the Insular superterrane. For recent summaries of the geology of the superterranes, see Monger and others (1991), and of the mid-Cretaceous orogen, see Rubin and others (1990), Cowan and Brandon (1994), and Monger and Journeay (1994).

The Intermontane superterrane comprises several stratigraphically distinctive terranes, largely of late Paleozoic, Triassic, and Early to Middle Jurassic age, that are each exposed over thousands of square kilometers. The eastern part of the superterrane was emplaced onto the western margin of North America in Early to Middle Jurassic time

(Brown and others, 1986). The Insular superterrane in this sector consists of the Wrangellia and Alexander terranes, which are each defined by regionally extensive and distinctive Paleozoic or lower Mesozoic stratigraphic sequences. Both terranes are locally overlain by arc-related sedimentary and volcanic rocks of the Upper Jurassic and Lower Cretaceous Gravina sequence. The Insular superterrane presently continues northwestward, across the Cenozoic Chatham Strait fault, into southern Alaska, but the early Tertiary position of this part of the superterrane is still unresolved (compare Stone, Panuska, and Packer, 1982, and Irving and others, 1996, with Plafker, Moore, and Winkler, 1994).

The boundary between Insular and Intermontane superterranes is not a sharp line but rather a zone up to 200 km wide, extending for 1500 km through the entire northwest Cordillera (Monger and others, 1982; Rubin and others, 1990; Cowan, 1994). Although the character and width of the zone vary somewhat along strike, its unifying features are: (1) mid-Cretaceous west-vergent thrusting, attendant high-pressure metamorphism, and sedimentation, most of which occurred between 100 and 90 Ma, and (2) ~96 to 88 Ma calc-alkaline plutonism, which largely was contemporaneous with contractional deformation and related tectonic burial. The zone includes a number of lithologically diverse, fault-bounded terranes consisting of Jurassic and older rocks; some of these were overlapped by Albian and Cenomanian sediments that accumulated in syn-deformational basins (McGroder, 1989; Garver, 1992). Although several terms based on local geographic names in the northwest Cordillera have been used for this zone, we propose here that it be called the *Coast Mountains orogen,* because it is exposed mainly in the Coast Mountains of western British Columbia and southeastern Alaska. The southern end of the orogen extends about 200 km into the North Cascade Range of Washington.

We believe that there is a consensus regarding the following points (Cowan, 1994, p. 184): (1) The west-vergent imbricate thrust system in the Coast Mountains orogen delimits the eastern exposed edge of the Insular superterrane. (2) Crustal shortening of tens to hundreds of kilometers in the orogen resulted from the Insular superterrane being driven against and beneath a continental margin during a short-lived mid-Cretaceous orogenic event variously described as "collision," "accretion," or "intra-arc contraction." (3) Stratigraphic and plutonic links indicate that, by about 90 Ma, the Insular superterrane and the Coast Mountains orogen were fused into a single tectonic element. Therefore, the displacement history inferred for either, on the basis of geologic or paleomagnetic evidence, necessarily applies to the other as well.

There is not yet, however, a consensus regarding the following question, which lies at the heart of the Baja British Columbia controversy: Where was the Insular superterrane situated relative to cratonic North America when the Coast Mountains orogen developed along its eastern edge about 90 my ago? Models in the northern option (for

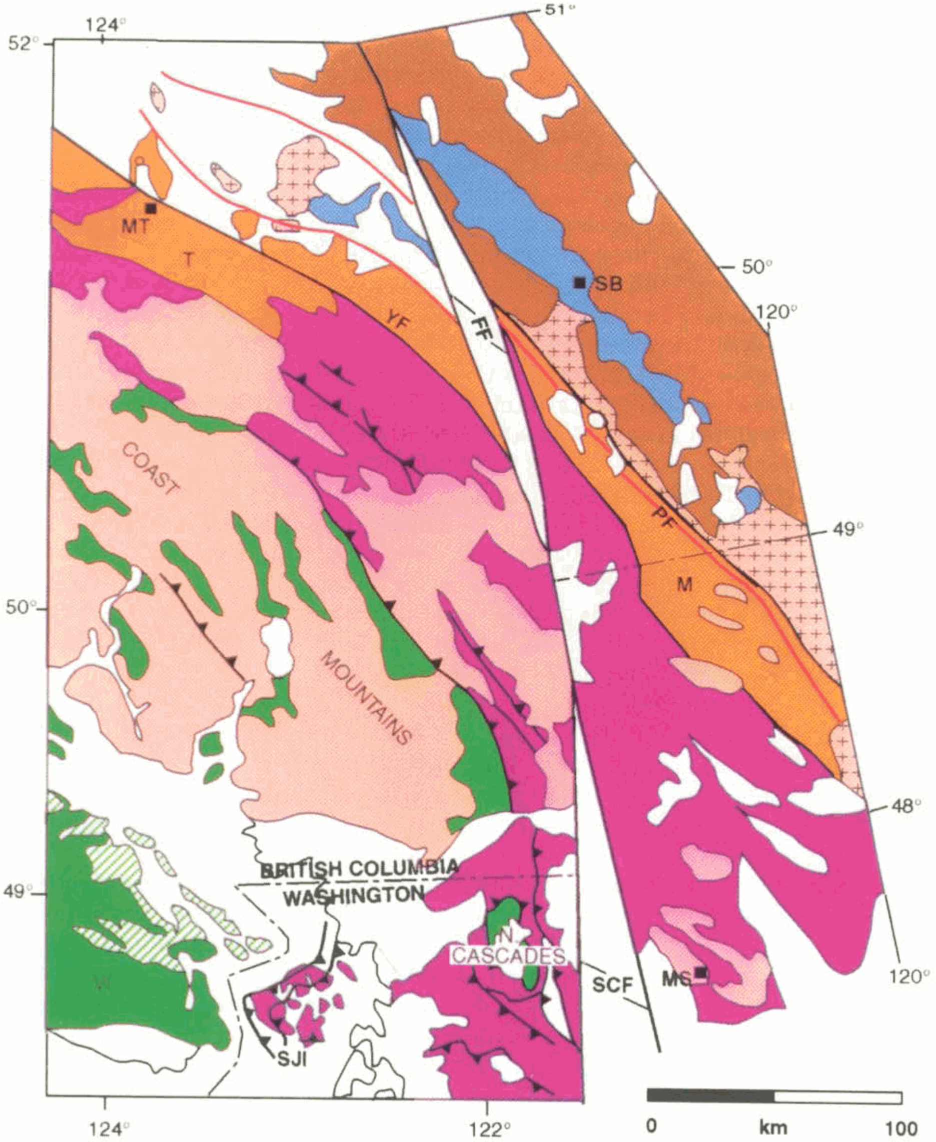
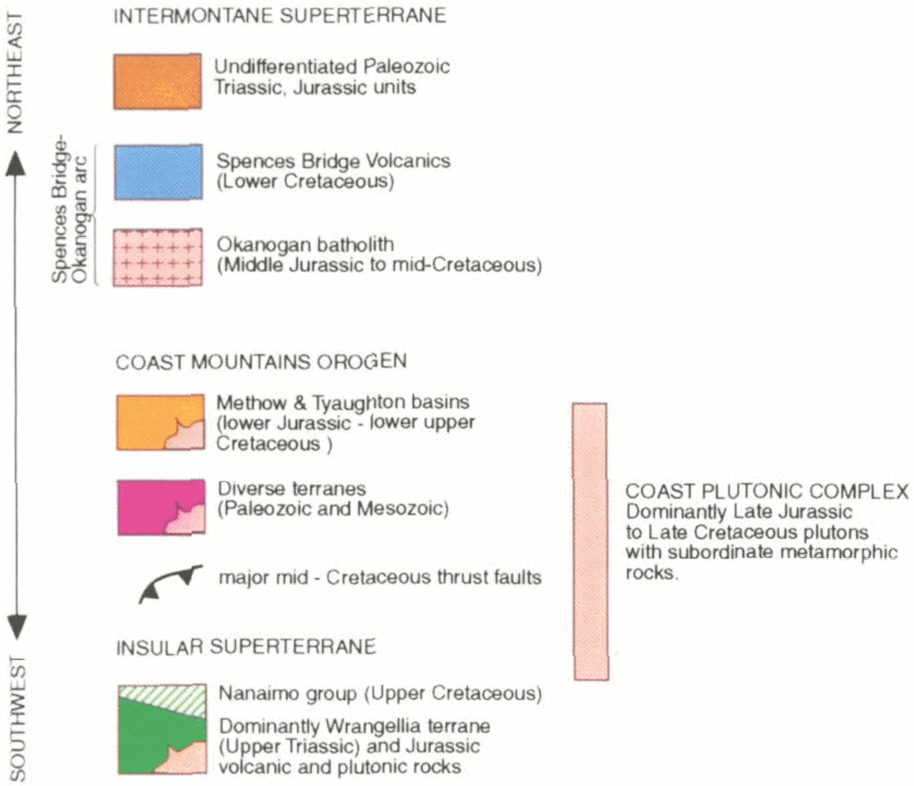


Fig. 3. Geology of two corridors across the Northwest Cordillera. Geologic units and features relevant to the alternative paleogeographic models are emphasized. Red lines delimit the areas within which the hypothetical Baja B.C. fault must lie, according to the geologic and paleomagnetic controls discussed in the text (prediction 7). (A) Geology in northwestern Washington and southwestern British Columbia between about 48° 15″ N and 52°N. Blank areas represent Tertiary and Quaternary units and the straits of Georgia and Juan de Fuca. Paleomagnetic study areas: MS = Mt. Stuart; MT = Mt. Tatlow; SB =



Spences Bridge. Heavy lines are major faults with known or inferred Late Cretaceous or early Tertiary strike-slip: FF = Fraser fault; PF = Pasayten fault; SCF = Straight Creek fault; YF = Yalakom fault. About 110 km of early Tertiary dextral offset on the Fraser fault, north of its junction with the Yalakom fault, has been restored; an additional ~50 km of dextral slip on the Straight Creek fault, which was diverted onto the Yalakom and other faults, has not been restored (Umhoefer and Miller, 1996). The gaps along the Fraser-Straight Creek fault result from restoration of the rocks east of the fault *en bloc*, without compensatory internal distortions. Geology compiled chiefly from Wheeler and McFeely (1991); local amendments are based on Mahoney and others (1992), Cowan and Brandon (1994), Monger and Journeay (1994), and Umhoefer and Miller (1996). Other geographic features: M = Methow region of Washington; T = Tyaughton region of British Columbia; SJI = San Juan Islands.

example, fig. 2A) place it north of the Franciscan-Sierran convergent plate boundary in California and envision the orogen as having formed more or less *in situ* during the collision of the Insular and Intermontane superterranes. Models in the southern option, and in particular the hypothesis depicted in figure 2B, hold that the Insular superterrane was situated south of California when it collided with the North American margin to form the Coast Mountains orogen.

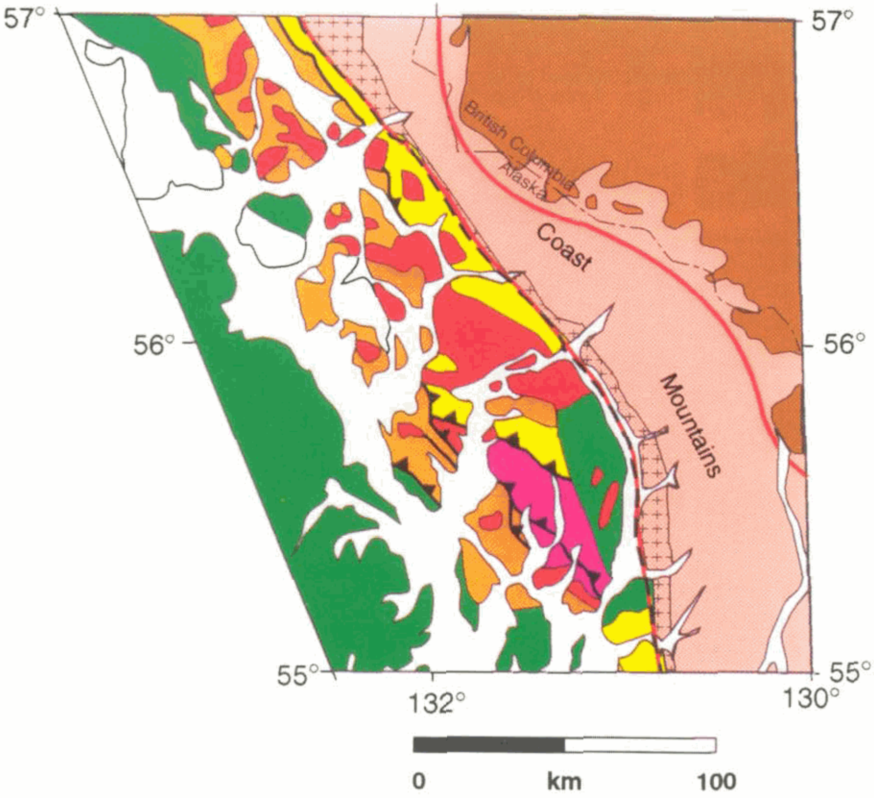
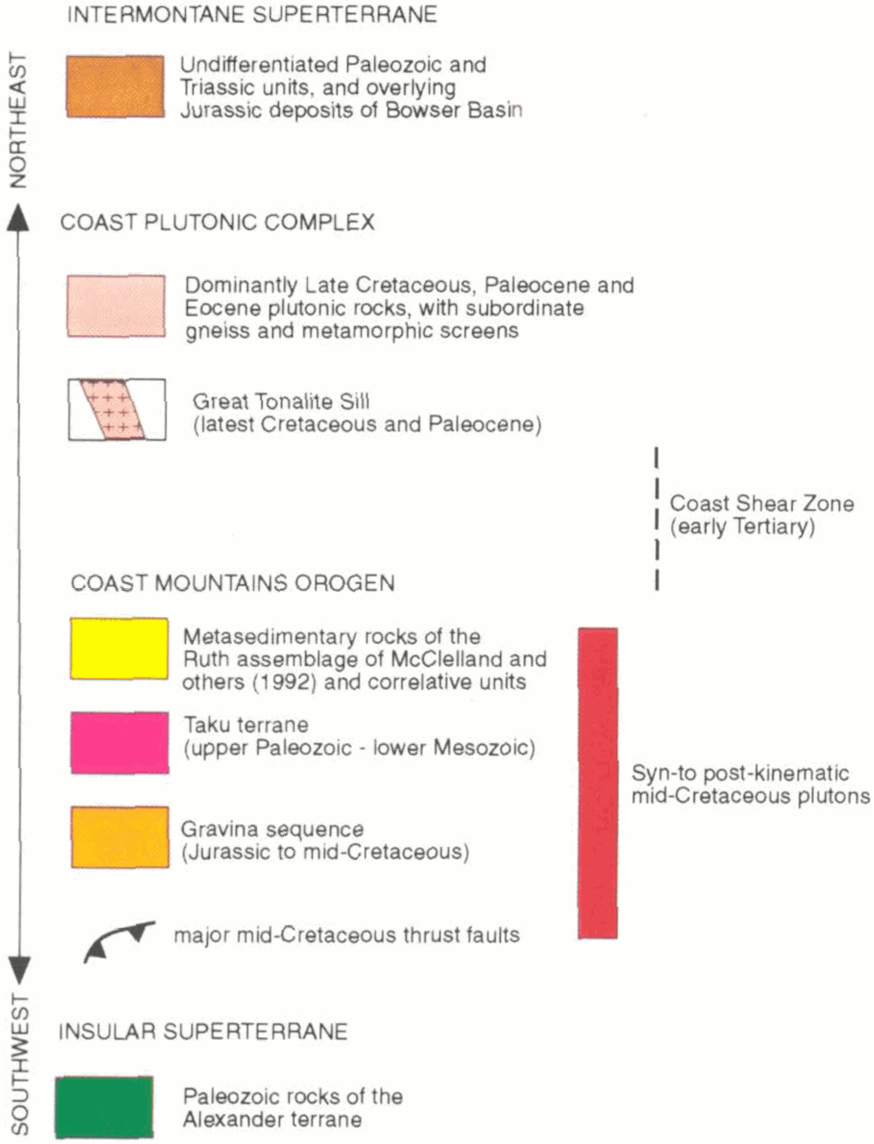


Fig. 3(B) Geology in southeastern Alaska and northwestern British Columbia between 55° and 57°N. Blank areas represent Tertiary and Quaternary units and the marine waters of Clarence Strait and contiguous fjords. The location of the Coast Shear Zone is generalized. Compiled chiefly from Wheeler and McFeely (1991), with local modifications based on McClelland and others (1992b), Gehrels and Berg (1992), Rubin and Saleeby (1992), and Brew and others (1993).

The geology relevant to the predicted consequences of the alternative models in figure 2 is summarized in the next two sections. Geologic features are presented as they are presently disposed from east to west in two corridors, extending from the Intermontane superterrane onto the Insular superterrane, between latitudes 48° and 52°N (fig. 3A), and 55° and 58°N (fig. 3B). The only palinspastic restoration incorporated in figure 3 is 110 km of early Tertiary dextral strike-slip on the Fraser fault (Umhoefer and Miller, 1996).

Corridor between 48° and 52°N.—The southern part of the Intermontane superterrane, which underlies much of central British Columbia (fig. 1), is exposed in the eastern part of the corridor (fig. 3A). The western edge of the superterrane is overlain locally by 104 Ma volcanic rocks of



the Spences Bridge Group (Thorkelson and Rouse, 1989), which have yielded one of the paleomagnetic data sets used to calculate paleolatitude (SB in figs. 1 and 3A; Irving and others, 1995). The Spences Bridge volcanics and a slightly older belt of plutonic rocks immediately to the southwest (110 Ma part of the Eagle Plutonic Complex: Greig, 1992; 110–114 Ma Okanogan Range batholith, Hurlow and Nelson, 1993) are interpreted collectively as part of a late Early Cretaceous, west-facing magmatic arc that resulted from subduction to the west (Thorkelson and Smith, 1989).

The high-angle Pasayten fault (Hurlow, 1994) and Fraser fault (Monger, 1989) separate the Intermontane superterrane from the Coast Mountains orogen. Roughly the eastern third of the orogen in the corridor from 48° to 52°N consists of unmetamorphosed, dominantly Triassic, Jurassic, and Lower Cretaceous units of the Eastern Coast Belt, flanked to the southwest by high-grade metamorphic rocks derived in part from these protoliths (Miller and others, 1994; Monger and Journeay, 1994). Pre-Upper Jurassic rocks in the Eastern Coast Belt are assigned to several terranes (Bridge River, Cadwallader, Methow, Shulaps; see Rusmore, Potter, and Umhoefer, 1988; Monger and Journeay, 1994; and Garver and Scott, 1995, for details).

Well-bedded sections of Middle Jurassic through lower Upper Cretaceous sedimentary and volcanic strata are part of the Methow and Tyaughton basins, named after the geographic regions where the strata are widely exposed in Washington and British Columbia, respectively. By Albian time, the two basins were contiguous (Garver, 1992), but their earlier histories and tectonic settings might have differed. The clastic sediments in Albian to Cenomanian strata are important because they may preserve a record of provenance and hence, mid-Cretaceous paleogeography. Garver (1992) and Garver and Brandon (1994) summarized earlier petrologic studies and presented new data concerning the provenance of detrital grains. A lower Albian volcanic petrofacies and a middle to upper Albian and possibly Cenomanian arkosic petrofacies contain abundant first-cycle detritus inferred to have been derived from contemporaneous magmatic arcs flanking the basin to the west and east, respectively. These sections are unconformably overlain by interbedded Cenomanian volcanic rocks and sedimentary rocks containing abundant clasts of chert and white mica. One of the paleomagnetic data sets used to calculate the paleolatitude of the Coast Mountains orogen was obtained from these rocks in the Tyaughton basin (MT in fig. 3A; Wynne and others, 1995).

Strata of the Methow-Tyaughton basins, together with closely associated pre-Late Jurassic terranes, pass southwestward into the northwest-trending metamorphic core of the North Cascades of Washington and Coast Mountains of British Columbia. The Mt. Stuart batholith, which is one of the abundant granitoid plutons emplaced into the core between about 90 to 93 Ma, has provided another paleomagnetic data set (MS in fig. 3A; Beck, Burmester, and Schoonover, 1981; Ague and Brandon, 1992, 1996) used to construct one of the alternative paleogeographic models presented below.

West of, and structurally beneath, the metamorphic core are imbricate thrust faults and nappes constituting the westernmost part of the Coast Mountains orogen. In some earlier references, these are called the San Juan-Cascades system (south of 49°N) and, along strike to the north, the Coast Belt thrust system. The nappes collectively include a variety of dominantly sedimentary and volcanic rock units that range in age from early Paleozoic to late Early Cretaceous (see Misch, 1966; Brown, 1987; Brandon, Cowan, and Vance, 1988; Journeay and Friedman, 1993; and Cowan and Brandon, 1994, for descriptions.) The rock units in these thrust-and-nappe systems are properly viewed as fragments of formerly more extensive lithotectonic elements, which were juxtaposed and imbricated between about 85 and 100 Ma. Several questions about these rock units are unresolved, including the pre-thrusting geographic positions of the elements—the *homelands*—from which they were derived. Cowan (1980), Brown and Blake (1987), Brandon, Cowan, and Vance (1988), and Garver (1988) among others noted that some units strongly resemble certain units in the California sector. Especially notable are the similarities between the Easton (or Shuksan in some literature) Metamorphic Suite in the North Cascades and the Pickett Peak terrane in the Franciscan Complex; between the Decatur terrane in the San Juan Islands and the lower Great Valley Group and its basement, the Coast Range ophiolite; between the Deadman Bay terrane in the San Juan Islands, and the North Fork and eastern Hayfork terranes in the Klamath Mountains; and between the moderate P/T greenschist and amphibolite of the Garrison and Vedder schists in the San Juan Islands and North Cascades, and the blueschists in the Klamath Mountains.

The thrust-and-nappe system lies structurally above the Insular superterrane, locally represented on Vancouver Island by the Wrangellia terrane, which in turn is overlain unconformably by the Turonian through Maastrichtian Nanaimo Group. Santonian strata, deposited about 84 Ma, contain clasts derived from certain nappes (Brandon, Cowan, and Vance, 1988). Arkosic petrofacies, containing abundant plagioclase inferred to have been derived from pre-late Cretaceous plutons of the Coast Plutonic Complex on mainland British Columbia, dominate the Campanian and younger part of the Nanaimo Group (Pacht, 1984; Mustard, 1994).

Based on diverse lines of geologic evidence, most workers agree that the components of the Coast Mountains orogen (Eastern Coast Belt, metamorphic core, and western thrust systems) were contiguous with one another and with the Insular superterrane by Turonian or Coniacian time (~85 to 90 Ma). The evidence includes: sedimentological links between clastic detritus and provenance (Brandon, Cowan, and Vance, 1988; Garver, 1992); the widespread presence of ~88- to 96-Ma granitoid plutonic rocks in the orogen and the eastern part of the Insular superterrane (Journeay and Friedman, 1993; Miller and others, 1993); and the similar ages of contraction (principally thrusting) in the western thrust systems and in the Eastern Coast Belt (Brandon, Cowan, and Vance, 1988; McGroder, 1991).

Corridor between 55° and 57°N.—From east to west, this corridor contains three major lithotectonic elements (fig. 3B), each of which extends at least several hundred kilometers farther to the northwest and southeast. As in the southern corridor, the easternmost element is the Intermontane superterrane, here comprising Devonian to Lower Jurassic sedimentary and volcanic rocks of the Stikine terrane (Anderson, 1993) and overlying Middle Jurassic to Cretaceous clastic strata of the Bowser Lake Group. The western limit for rocks confidently assignable to the Intermontane superterrane is defined by intrusive contacts with mainly early Tertiary plutons of the Coast Plutonic Complex (Wheeler and McFeely, 1991). This plutonic complex forms the core of the Coast Mountains and consists predominantly of Cretaceous to Eocene granitoid plutonic rocks and orthogneiss and subordinate metamorphic screens and pendants.

West of the Coast Plutonic Complex is the third element, consisting of the Insular superterrane and the Coast Mountains orogen marking the eastern boundary of the superterrane (Rubin and Saleeby, 1992; McClelland and others, 1992a and b; and Gehrels and others, 1992). Between latitudes 55° and 57°N, the Insular superterrane consists entirely of pre-Ordovician, Paleozoic, and Triassic rocks of the Alexander terrane. Along its eastern edge, the Alexander terrane is overlain by clastic and volcanogenic strata of the Gravina sequence, which range in age from Middle Jurassic to perhaps early Late Cretaceous (Berg, Jones, and Richter, 1972). The Gravina sequence is interpreted by the workers cited above and by Cohen and Lundberg (1993) as having accumulated in and adjacent to a volcanic arc constructed in part on the Alexander terrane.

In this corridor, the Coast Mountains orogen is a narrow (<50 km wide) zone of west-vergent imbricate thrust faults, syn-tectonic plutons, and moderate- to high-pressure metamorphic rocks. Isotopic data from calc-alkaline plutons in the thrust system (McClelland and others, 1992b; Rubin and Saleeby, 1992), together with stratigraphic arguments, indicate that imbrication, shortening, and attendant tectonic burial and metamorphism occurred mainly during the interval from about 90 to 100 Ma. Nappes in the thrust system consist of: the Gravina sequence; upper Paleozoic and Triassic strata of the Taku terrane (s.s., as redefined by McClelland and others, 1992a); an assemblage of metamorphic rocks distinguished by quartz-rich metaclastic strata, as well as marble, metapelite, and felsic and mafic metavolcanic rocks (the Ruth assemblage of McClelland and others, 1992a); and ortho- and paragneiss that Saleeby (1994) interpreted as metamorphosed Alexander terrane. The workers cited above agreed that the Ruth assemblage is not equivalent to either the Taku terrane or any component of the Insular superterrane. Instead, they suggested that it has North American affinities and is part of the Yukon-Tanana terrane, widely exposed north of the corridor (Mortensen, 1992). The Ruth assemblage is part of a narrow panel (generally <20 km wide) of comparable rocks extending for at least 600 km from southeastern Alaska (latitude 58°N) to British Columbia (53°N).

Also present in the corridor are two other remarkably linear and continuous features, localized along the eastern boundary of the mid-Cretaceous thrust system: the Great Tonalite Sill (Brew, 1988; Ingram and Hutton, 1994) and the Coast shear zone (Crawford and Crawford, 1991; McClelland and others, 1992b). The narrow sill, which is generally steeply dipping or vertical, less than 25 km wide, and at least 800 km long (Ingram and Hutton, 1994), actually consists of multiple sheet-like plutons, ranging in age from about 72 to 58 Ma (Gehrels and others, 1991; McClelland and others, 1992b; Brew and Ford, 1994). The length of the Coast shear zone is less well known, but the zone is evidently co-extensive with the entire western margin of the sill (Stowell and Hooper, 1990). On the basis of shear-sense indicators in the sill and in country rocks immediately to the southwest, McClelland and others (1992b) and Ingram and Hutton (1994) interpreted the Coast shear zone to be a steeply dipping, ductile-shear zone, which accommodated several kilometers of principally east-side-up dip-slip and which localized the emplacement of the composite sill. Shear-zone deformation and emplacement of the sill were largely coeval (that is, ~72 to 58 Ma), although some dip-slip apparently postdated solidification of the youngest plutons.

ALTERNATIVE PALEOGEOGRAPHIC MODELS FOR THE WESTERN CORDILLERA AT ~90 MA

In this section, we describe the main features of the alternative models, Hypothesis A and Hypothesis B, illustrated in figure 2A and B. Because it would be possible, in principle, to invent a myriad of models for the late Mesozoic paleogeography of the western Cordillera, each differing in the disposition of a certain terrane or in the configuration of a major structure, it is important to state why we generated these specific hypotheses. First, each model yields several predictions or consequences that can be compared with newly obtained or already published geologic evidence. Second, the models are mutually contradictory: if one is true, the other cannot be true. In particular, one or more of the consequences deduced from one hypothesis is incompatible with the consequences derived from the other. Third, the models postulate radically different magnitudes of post-mid-Cretaceous, coast-parallel dextral displacement of the Insular superterrane: 0 to 1000 km in hypothesis A, and 3000 km in hypothesis B. Finally, each hypothesis is consistent with certain evidence, but neither hypothesis has yet been refuted by commonly accepted geologic evidence.

The palinspastic map base used for both A and B of figure 2 incorporates two restorations. (1) The removal of 275 km of Cenozoic east-west horizontal extension (averaging figures in Hamilton, 1987, and Wernicke, 1992) in the Basin and Range province between 32° and 42°N. Consequently, the Franciscan-Sierran system and the Klamath orogen occupy more easterly positions than they do in figure 1. (2) The removal of 300 km of Cenozoic dextral slip on the northwest-striking San Andreas fault system and an additional 200 km of slip on earlier proto-San Andreas faults. As a consequence, the Peninsular Ranges batholith and Salinian block lie ~500 km southeast of their present positions with respect to the Sierra Nevada batholith (Dickinson, 1983).

Hypothesis A: Both Superterranes Situated North of California at 90 Ma

As we pointed out above, all models grouped in the northern option postulate that by 90 Ma, the Insular and Intermontane superterranes were not only north of the California sector but also joined together, in their present positions relative to one another, along the mid-Cretaceous Coast Mountains orogen extending from northwestern Washington, through the Coast Mountains, into southeastern Alaska. Most of these models also postulate that the superterranes had been juxtaposed by early Late Jurassic time (about 150–160 Ma), but there is not yet a consensus regarding the sense and amount of post-Late Jurassic displacements within the superterranes or along their common boundary. Therefore, in order to make hypothesis A not only representative of the group but also subject to a minimum number of assumptions, the model depicts (fig. 2A) an early Late Cretaceous paleogeography featuring the Insular and Intermontane superterranes in their present positions relative to each other and to cratonic North America. Along its entire 1500-km strike, the Coast Mountains orogen was contiguous with and directly west of the western edge of the Intermontane superterrane.

Hypothesis A incorporates the following assumptions, defined here as premises that are considered *a priori* to be true: (1) The Franciscan subduction complex, Great Valley fore-arc basin, and Sierran magmatic arc in the California sector (east of the San Andreas fault) at 90 Ma were situated at their present, expected, latitudinal position relative to cratonic North America. The Franciscan Complex in this sector represents the locus of a west-facing subduction zone, along which oceanic crust was consumed beneath North America in Early Cretaceous time. In figure 2A, the southern end of the Insular superterrane lay north of the California segment of the Early Cretaceous Franciscan margin. After the Coast Mountains orogen developed about 100 to 90 Ma, subduction continued along a single, west-facing convergent plate boundary, extending from the Franciscan in California northward along the western edge of the Insular superterrane. The voluminous Late Cretaceous and early Tertiary plutons in the Coast Mountains resulted from this subduction. (2) The Insular superterrane continued northwestward for at least 1000 km, across the future trace of the Chatham Strait fault, into (present-day) southern Alaska (fig. 1). (3) Shallower-than-expected mid-Cretaceous magnetization directions from the Insular and Intermontane superterranes and the Coast Mountains orogen result from erroneously estimated paleohorizontal datums, tilting, or compaction flattening and not from post-magnetization northward displacments of 1000 to 3000 km.

Hypothesis B: Insular Superterrane and Coast Mountains Orogen Situated South of California at 90 Ma

Hypothesis B (fig. 2B) is representative of models in the southern option. As such, it is drawn to be consistent with the mid-Cretaceous paleolatitudes calculated from four sets of paleomagnetic data from the northwest Cordillera (table 1): MS (Beck, Burmester, and Schoonover,

TABLE 1

Selected high-quality Cretaceous paleomagnetic results for terranes of western North America

Locality	Magnetization age (Ma)	Paleolatitude		Northward offset (km)
		Expected	Observed	
Baja British Columbia				
MS: Mount Stuart batholith, western Washington State	93–82	58.4 ± 3.0	30.2 ± 4.0	3100 ± 600
MT: Mount Tatlow, Tyaughton basin, southern British Columbia	98–74	62.7 ± 3.0	35.9 ± 3.5	2960 ± 450
DI: Duke Island ultramafic complex, southeastern Alaska	110	68.0 ± 3.0	41.3 ± 12.0	2970 ± 1360
Alta British Columbia				
SB: Spences Bridge volcanics, southern British Columbia	104	61.1 ± 3.0	50.8 ± 5.0	1140 ± 640
CK: Carmacks volcanics, northern British Columbia	70	69.2 ± 3.4	55.4 ± 6.1	1530 ± 770
Baja Alaska				
MC: MacColl Ridge Formation, southern Alaska	74–65	76.4 ± 3.0	31.7 ± 6.7	4960 ± 810
Batholiths in California and northwestern Mexico				
SN: Sierra Nevada batholith, central California	100–90	48.7 ± 3.0	42.9 ± 5.0	650 ± 640
SA: Salinian block, central California	83	46.9 ± 3.0	34.9 ± 4.8	1330 ± 630
PR: Peninsular Ranges batholith, southern California	120–100	43.9 ± 3.0	34.8 ± 3.3	1010 ± 490

Note: Calculations based on North American reference poles for 124 to 88 Ma (71.2°N, 194.1°E, $A_{95} = 3.7°$; Van Fossen and Kent, 1992) and 80 to 63 Ma (79.2°N, 189.9°E, $A_{95} = 4.2°$; Irving and others, 1995). All uncertainties are cited at the 95 percent confidence level.

References: MS: Beck, Burmester, and Schoonover (1981), Ague and Brandon (1996); MT: Wynne and others (1995); DI: Bogue, Gromme, and Hillhouse (1995)—they determined their preferred result of $\sim$3000 km offset using the mean of site poles after correction for anisotropy (AIRM-lo data in their table 5) (S. Bogue and S. Gromme, written communication, 1996); SB: Irving and others (1995); CK: Marquis and Globerman (1988); MC: Panuska (1985); SN: Frei, Magill, and Cox (1984), Frei (1986); SA: Whidden and others (in press); PR: Teissere and Beck (1973), Hagstrum and others (1985), Ague and Brandon (1992).

1981; Ague and Brandon, 1992, 1996) from the 93 Ma Mt. Stuart batholith; MT (Wynne and others, 1995) from Albian-Cenomanian Silverquick conglomerate and overlying volcanic rocks; DI, from the 110 Ma layered igneous rocks in the Duke Island ultramafic complex (Bogue, Gromme, and Hillhouse, 1995); and SB (Irving and others, 1995) from 104 Ma Spences Bridge volcanics. The SB data set is from strata deposited on the Intermontane superterrane. Data sets MS and MT are in the Coast Mountains orogen, which we assume was contiguous with the Insular superterrane by 95 Ma. Data set DI is from the Insular superterrane. We refer to this composite tectonic element, comprising the Insular superterrane and Coast Mountains orogen, as the *newly defined* **Baja British Columbia** (compare, for example, how the element was defined by Irving, 1985; Umhoefer, 1987; and Irving and Wynne, 1990).

Hypothesis B assumes that the paleomagnetic inclinations have been properly corrected for post-magnetization tilting. Table 1 summarizes paleomagnetically determined estimates of northward offset relative to cratonal North America. The uncertainties are cited at the 95 percent confidence level and provide an indication of the precision of the estimates. Following Irving and Wynne (1990), we emphasize that the mean is, by definition, the most likely estimate of the true northward displacement. Other estimates are possible, but they become increasingly unlikely as they move away from the mean. For example, estimated displacements at the extremes of the 95 percent confidence interval have a very low probability, 1 in 20, of occurring by chance alone. Consequently, we use the mean as the most likely displacement for our reconstruction in figure 2B: Baja British Columbia is placed 3000 km to the south (results from MS and MT, and DI after correction for anisotropy), and the western two-thirds of the Intermontane superterrane is placed 1100 km to the south (result from SB). Following a suggestion of Ted Irving (see Ague and Brandon, 1996), we call the latter displaced element **Alta British Columbia.** Tilt-corrected magnetizations from the 70 Ma volcanics of the Carmacks Group on the northern Intermontane superterrane yield a northward displacement of 1530 ± 770 km (Marquis and Globerman, 1988) which is greater than the displacement calculated for locality SB. In contrast, geologic (Brown and others, 1986) and paleomagnetic (Irving and Archibald, 1990) evidence indicates that the eastern edge of the Intermontane superterrane was in its present position relative to adjacent North America at 90 Ma. According to Irving and others (1995, p. 6069), these differences may be due to "strike-slip" attenuation and elongation of the Intermontane Belt during its northward travel" (Gabrielse, 1985).

In figure 2B, the batholithic belts in the Sierra Nevada and Peninsular Ranges are also restored using paleomagnetic data from mid-Cretaceous plutons and sedimentary strata (see table 1). The Sierra Nevada batholith and the attached Franciscan, Great Valley, and Klamath-Sierran basement elements to the west are restored 6° (650 km). This restoration, added to the ~500 km of slip on the San Andreas system, places the Salinian block ~1000 km south of its present position—a result compatible with the paleomagnetic results of Lund and others (1991) and Whidden and others (in press; see table 1). We restore the Peninsular Ranges batholith and its wall rocks (the Yuma terrane and part of the Serí terrane of Sedlock, Ortega-Gutiérrez, and Speed, 1993) 10° (1100 km), on the basis of certain interpretations of paleomagnetic data (Hagstrum and others, 1985; Lund and Bottjer, 1991; and Ague and Brandon, 1992). Butler, Dickinson, and Gehrels (1991) and Gastil (1991) alternatively used geologic arguments to favor a total post-mid-Cretaceous northward displacement of the Peninsular Ranges block of about

300 to 350 km. The net result of the two restorations used in this paper is a single, continuous batholithic belt positioned along the North American margin for at least 2700 km. We assume that this belt was a west-facing magmatic arc and that, prior to accretion of the Insular superterrane 90 to 100 my ago, the Franciscan subduction zone continued southward along the margin of western Mexico parallel to the arc.

Although paleomagnetic data fix the paleolatitude of Baja British Columbia, they do not fix its paleolongitude. Therefore, in hypothesis B we make the additional assumptions that, at 90 Ma: (1) Baja British Columbia was situated adjacent to the North American margin (that is, it was not an intra-oceanic element), and (2) it lay immediately west of the continental magmatic arc of the Salinian block and the Peninsular Ranges (fig. 2B). These assumptions imply that the Insular superterrane collided with the margin of North America *south* of California, and that subduction along the southern extension of the Franciscan zone ceased by 90 Ma. We ascribe the extinction of magmatism in the Peninsular Ranges batholith about 90 Ma (Todd, Kimbrough, and Herzig, 1994), and the mid-Cretaceous deformation and metamorphism in the Coast Mountains orogen to this collision. Hypothesis B contains no further assumptions about either the paleolatitudinal and paleolongitudinal positions or the displacement history of the Insular superterrane *before* its mid-Cretaceous juxtaposition with the North American continental margin.

A corollary of the 90 Ma paleogeography in figure 2B is that both Baja British Columbia and Alta British Columbia were displaced northward, on the order of 3000 and 1000 km respectively, between 90 and 50 Ma. These displacements were driven by the oblique convergence of the oceanic Farallon or Kula plates relative to North America. Given the original dispositions of Baja and Alta British Columbia as postulated in hypothesis B, the displacements must have been accomplished by coast-parallel translations on a system of dextral strike-slip faults. The hypothetical **Baja B.C. fault** separated Baja British Columbia from tectonic elements to the east, including the magmatic arc in the Peninsular Ranges and Salinian block, the Franciscan subduction complex, and finally the Intermontane superterrane of Canada (fig. 4). Judging from its length and its position near the continental margin, the Baja B.C. fault was almost certainly a continental transform fault. Also postulated is a second and more easterly fault system called the **Intra-Quesnellia fault** (Irving and others, 1995; see also Irving and others, 1985; and Umhoefer, 1987), which lay mostly within the Intermontane superterrane.

The post-mid-Cretaceous displacement history of Baja British Columbia and the Intermontane superterrane is determined as follows. Both tectonic elements were at their expected paleolatitudinal positions relative to cratonic North America by Eocene time, about 50 Ma (Fox and Beck, 1985; Irving and Brandon, 1990). The magnetizations at locality MT were acquired between 94 and 83 Ma (Wynne and others, 1995, p. 6082), and those at locality MS at ~90 to 85 Ma (Ague and Brandon, 1996). We conclude that Baja British Columbia began moving northward

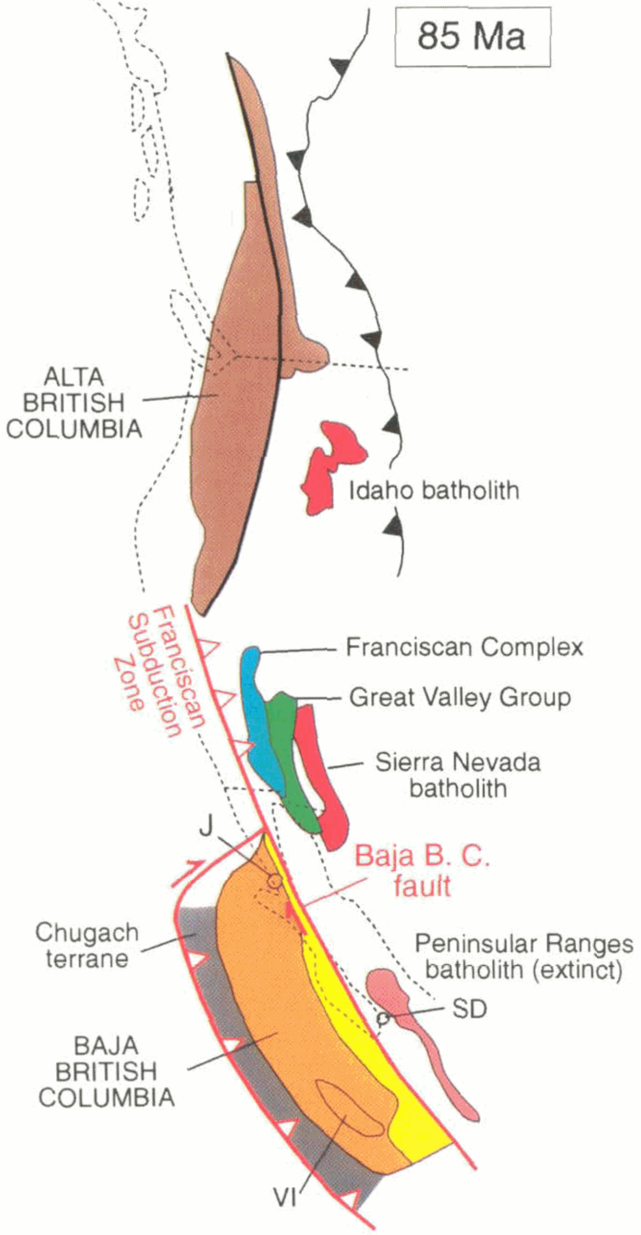


Fig. 4. Hypothetical four-stage displacement history for Baja British Columbia and Alta British Columbia. The present geographic positions of the Idaho batholith, the eastern limit of the Cordilleran thrust belt, Vancouver Island, and the international boundaries of the United States are as they appear in figure 1. Colors used for crustal elements are the same as those in figures 1 and 2, except extinct batholiths are shown in light red. Red lines with barbs are inferred active convergent plate boundaries (subduction zones); solid red lines are hypothetical active transform boundaries, including continental transform faults. (A) 85 Ma. Northward coastwise displacement of Baja British Columbia began no earlier than this time. This figure is basically the same as figure 2B, but certain elements in the latter have been deleted. The subduction zone west of Baja British Columbia was active before and at 85 Ma and gave rise to the magmatic arc in the Coast Mountains and to the subduction complex in the Chugach terrane. Baja British Columbia is inferred to have been accreted to North America along the southern extension of the Franciscan subduction zone, which progressively changed into the Baja B.C. transcurrent (transform) fault, possibly as a triple junction at the northern end of Baja British Columbia migrated northward. Arc magmatism east of the transform was extinguished.

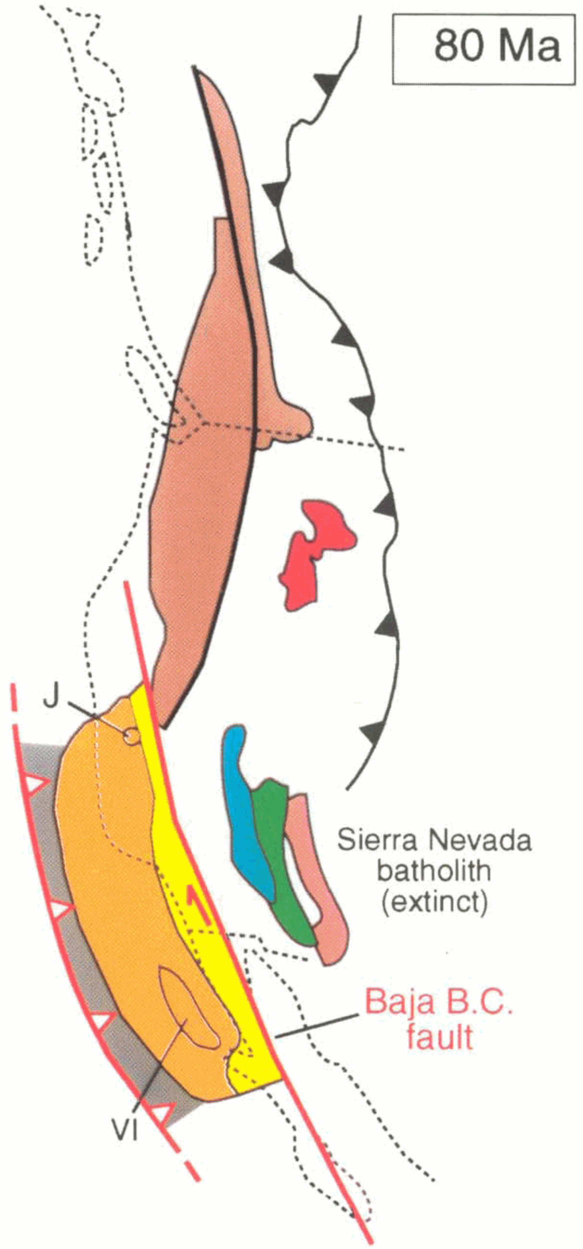


Fig. 4(B) 80 Ma. Baja British Columbia lay immediately west of the extinct Franciscan-Sierran system in present-day California.

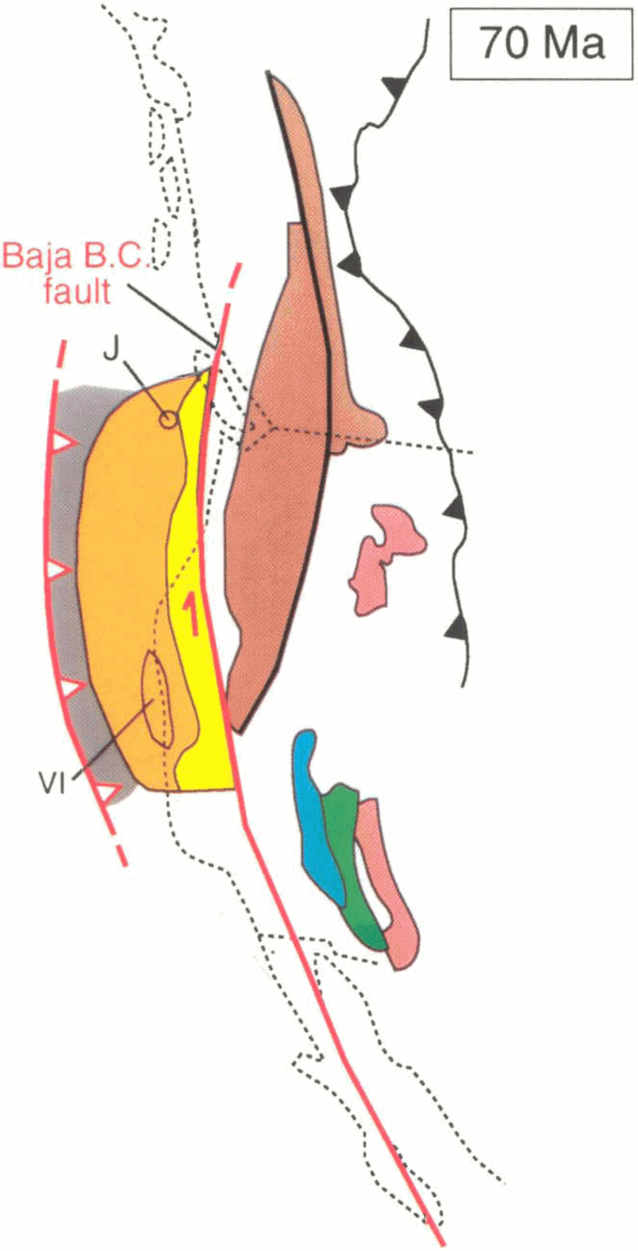


Fig. 4(C) 70 Ma. Baja British Columbia lay mostly north of California and had arrived in its present position relative to Alta British Columbia (the western two-thirds of the Intermontane superterrane). Plutonism in the Coast Mountains and accretion in the Chugach terrane record continued subduction beneath Baja British Columbia.

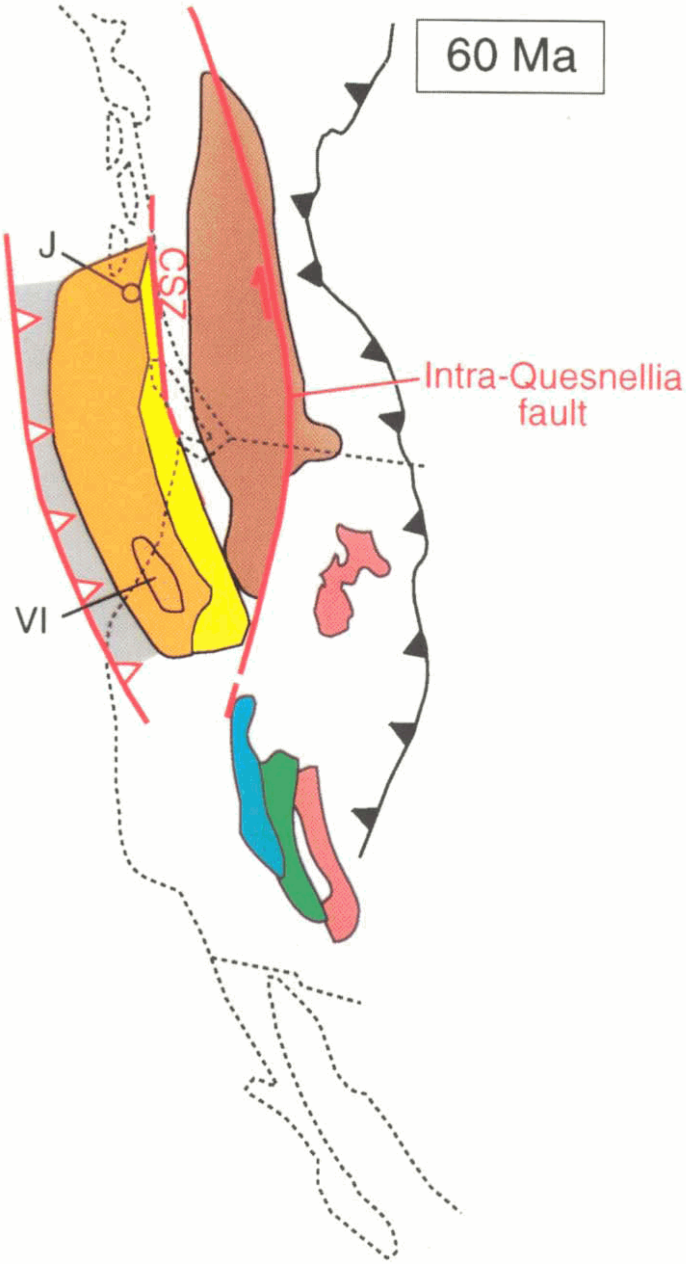


Fig. 4(D) 60 Ma. The composite crustal element consisting of Baja and Alta British Columbia begins to move northward along the Intra-Quesnellia fault. The Coast Shear Zone (CSZ), which is roughly coextensive with the now-extinct Baja B.C. fault, experiences active dip-slip at this time.

no earlier than 85 Ma. On the basis of the 70 Ma age of magnetization in the Carmacks Group (Marquis and Globerman, 1988), we conclude also that the western part of the Intermontane superterrane began moving northward no earlier than 70 Ma. A non-unique displacement history consistent with this evidence is hypothesized (fig. 4). Baja British Columbia moved 2000 km northward from 85 to 70 Ma at 13 cm/yr and was juxtaposed with the western Intermontane superterrane along the northern segment of the Baja B.C. fault. The composite tectonic element moved an additional 1000 km northward between 70 and 50 Ma at 5 cm/yr by dextral slip along the Intra-Quesnellia fault. These rates of displacement are compatible with the northward speeds of the Farallon and Kula plates during these intervals (Engebretson, Cox, and Gordon, 1985).

TESTING HYPOTHESES: LOGIC AND METHODOLOGY

> *In general, we look for a new law by the following process. First, we guess it. Then we compute the consequences of the guess to see what would be implied if this law that we guessed is right. Then we compare the result of the computation to nature, with experiment or experience, compare it directly with observation, to see if it works. If it disagrees with experiment, it is wrong . . . There is always the possibility of proving any definite theory wrong; but notice that you can never prove it right.*
>
> R. Feynman (1965, p. 156-157)

Now that we have presented and described two alternative paleogeographic models, how can the likelihood that one or the other is true be evaluated? Given *any* two contradictory hypotheses, what is the empirical basis for preferring one to the other? This section deals with two general topics relevant to these questions: how the principles of elementary logic govern the testing of hypotheses, and how early assessments of the probability that a hypothesis is true may influence the way in which it is evaluated. The former topic is reviewed in some detail, not only because the principles are rarely stated in the geological literature, but also because they bear directly on the specific tests we propose for resolving the Baja British Columbia controversy. All the authors are geologists who make no particular claim to expertise in the philosophy of science or in the discipline of elementary logic, so our analysis and critique are heavily influenced by Salmon (1963) and Hempel (1966), both of whom present comprehensive and readable introductions to these topics.

Scientific inquiry proceeds according to the *scientific method.* There are probably several acceptable definitions of this term, but the one we present here follows the quote above from Feynman (1965) and approximates what is generally called (for example, Medawar, 1969) the *hypothetico-deductive* method: (1) The invention of a hypothesis (model, law), which accounts for certain observed features and phenomena; (2) the deduction of the consequences of the hypothesis—predictions that must be true if the hypothesis is true; and (3) the acquisition of new observational evidence and the evaluation of whether it confirms (that is, supports) or disconfirms (that is, contradicts) the observational predictions.

Much research in tectonics centers on step (1) and results in the presentation of a new or modified model, which is shown to be consistent with various kinds of observational evidence. However, even a model explaining certain evidence is a guess that, by definition, is not known *a priori* to be true, so steps (2) and (3), ordinarily thought of as *testing* a hypothesis, are required to assess whether a model is indeed true or false.

Testing a Single Hypothesis Using Deductive Arguments

We begin by considering the relationships between a single hypothesis and the predictions and observations used to test it. These relationships are made clear if the steps constituting the scientific method are written as statements in deductive logical arguments. An argument (Salmon, 1963) consists of premises and a related conclusion. In a valid *deductive argument,* if the premises are true, then the conclusion must be true. The validity of a deductive argument depends on the relationship between the premises and the conclusion, not on whether each statement is in fact true or false.

Once a hypothesis is formulated, valid deductive arguments can be written in the following form (Salmon, 1963, p. 78):

Hypothesis.
> > > Observational prediction. (1)

In this paper, the symbol > > > indicates the conclusion of the argument. This argument simply states that if the hypothesis is true, the predicted observations—that is, the deduced consequences—must also be true. One criterion for how well a statement serves as a hypothesis is whether it makes specific predictions. If a hypothesis has vague or highly generalized consequences, its scientific value is diminished. To be testable, a hypothesis must be predictive.

Next, the predictions are compared with empirical evidence, which, in the case of paleogeographic models A and B, would include field observations, geochemical data, and the like. If the evidence shows that the observational prediction is true, this favorable comparison represents a *confirmatory instance* of the hypothesis, using the terminology of Salmon (1963). If the evidence shows that the prediction is not true, the test has uncovered a *disconfirmatory instance.* The failure to observe a predicted consequence does not constitute a disconfirmatory instance, because the evidence simply may not be preserved or resolvable in the geologic record.

The role of disconfirmatory and confirmatory instances in ascertaining the truth of a hypothesis is illustrated by arguments of the following form, involving conditional "if. . . then" statements in which a hypothesis appears as an inductive generalization. In the first statement of each argument, the *if* phrase is the antecedent, and the *then* phrase is the consequent:

If hypothesis H is true, then the observational
prediction must be true.
As shown by the evidence, the prediction is not true.
> > > The hypothesis is not true. (2)

If hypothesis H is true, then the observational
prediction must be true.
As shown by the evidence, the prediction is true.
> > > The hypothesis is true. (3)

Schema (2), incorporating a disconfirmatory instance, is a valid deductive argument representing the general form called *denying the consequent.* On the basis of the new evidence, the hypothesis can be said to have been disconfirmed, ruled out, refuted, or falsified. Arguments in the form of (3), however, are not deductively valid; they are examples of the fallacy of *affirming the consequent.* Even if the premises as stated are true, finding confirmatory evidence predicted by a hypothesis does not offer conclusive proof that the hypothesis is indeed true. The reason is that the deduced prediction may also be an observational prediction of one or more alternative hypotheses, including some that have not yet been invented. Unless this possibility has been eliminated, deductive logic shows that new confirmatory evidence cannot provide even partial support for a hypothesis being tested, nor can it increase the probability that the hypothesis is true.

Auxiliary hypotheses and multiple confirmatory instances.—Arguments like those in (2) and (3) are incomplete, because they do not include auxiliary hypotheses, which are the assumptions underlying a hypothesis accepted *a priori* to be true. Most tectonic and certainly most paleogeographic models are "open systems" (Oreskes, Shrader-Frechette, and Belitz, 1994) because they incorporate auxiliary hypotheses, but in the literature the latter are not always stated along with the hypothesis to be tested. The importance of *a priori* assumptions is clear from the following modification of (2):

If both hypothesis H and auxiliary hypothesis A are true,
then the observational prediction P is also true.
As shown by the evidence, P is not true.
> > > Therefore, H and A are not both true. (4)

In other words, a disconfirmatory instance may call into question the truth of one or more of the underlying assumptions and so lead to a modification and improvement of a generally correct model, rather than require a wholesale rejection of the main hypothesis. In the case of paleogeographic hypotheses A and B presented above, several *a priori* assumptions are stated explicitly. The truth of each should be reassessed if any of the tests advocated below result in a disconfirmatory instance of either model.

Ordinarily, more than one observational prediction can be deduced from a fertile hypothesis. Comments in the literature such as, "According to this tectonic model, we would expect to see the following features . . ." are similar to the premises in a modified version of (3) Hempel, 1966, p. 8):

If hypothesis H is true, then so are observational
predictions $P_1, P_2 \ldots P_n$.
As shown by the evidence, $P_1, P_2 \ldots P_n$ are all true.
> > > Hypothesis H is true. (5)

Schema 5 represents what we believe to be the logical argument that implicitly governs the way that most tectonic models are initially presented and then tested. For example, once a hypothesis has been invented, workers subsequently look for additional observational evidence that they claim is explained by the model. Arguments of this form, however, are fallacious, because they are examples of affirming the consequent. Even if several predictions are found, on the basis of multiple confirmatory instances, to be true, this result does not prove that the hypothesis is true. Clearly, prediction is an important quality of a good hypothesis, but the ability of a hypothesis to generate predictions provides no measure of its truth.

Testing Multiple Hypotheses

Deductive logic shows that observational evidence can refute a hypothesis but can never be used to prove conclusively that a hypothesis is true. Probably for this reason, a certain school of scientific philosophy (Popper, 1969; Medawar, 1979) favors tests involving refutation over those involving confirmation. Nevertheless, arguments in the form of (3) and (5) are used all the time by geoscientists in the belief that any evidence that is consistent with or explained by a particular model offers *partial* support, confirmation, or corroboration for the model. Moreover, the investigators may believe that the strength of this support depends mainly on the number of confirmatory instances that are achieved.

Are there circumstances where these beliefs can be justified using logical arguments? Salmon (1963, p. 85-86) proposed that if all competitive models but one are eliminated under certain conditions, then confirmatory evidence can indeed offer strong support for the surviving hypothesis. He specified the conditions in the following argument, which we have slightly modified:

> The hypothesis has a significant prior probability.
>
> If the hypothesis is true, then the observational prediction is true.
>
> Evidence shows that the observational prediction is true.
>
> No other hypothesis is strongly confirmed by the truth of this observational prediction; that is, other hypotheses for which the same observational prediction is a confirming instance have negligible prior probabilities.

> > > The hypothesis is true. (6)

Although obviously based on and similar to the deductive argument in (3) above, (6) is an inductive argument: the conclusion is a generalization that could be false even though the premises are true, but each confirmatory instance strengthens our confidence that the hypothesis is indeed true.

Salmon (1963, p. 84) defines *prior probability* as ". . . the probability, without regard for its confirmatory instances, that [a hypothesis] is true." We view prior probability as the scientific community's collective judgment at any particular time about whether a hypothesis is likely to be true and is therefore worthy of testing. These judgments are based on several considerations (Salmon, 1963, p. 84–85). Perhaps the most familiar example is the common tendency to place a higher burden of proof on those new hypotheses that challenge a long-standing, popular hypothesis. A widely accepted paradigm will generally be given the benefit of the doubt, while the novel challengers are accorded low prior probabilities. Another consideration is whether a hypothesis violates any of the general laws of the physical sciences. For example, the expanding-earth hypothesis is given a negligible prior probability because it would require the universal gravitational constant G to change with time.

As further examples of the influence of prior probability, we cite the following: (1) The hypothesis of continental drift as formulated by Wegener assumed a low prior probability, at least among North American geologists, partly because *ad hoc* hypotheses were invented solely to explain and neutralize certain observations that favored continental drift. For example, land bridges were accepted as an explanation for the geographic distribution of certain fossil fauna and flora in the Southern Hemisphere (Oreskes, 1991). (2) The meteorite-impact model for Meteor Crater in Arizona (Hoyt, 1987) was assigned a low prior probability around the turn of the century partly because of the widely held antagonism toward extraterrestrial explanations for terrestrial phenomena. (3) Bretz's hypothesis that landforms in the Channeled Scabland of Washington resulted from catastrophic floods was accorded a negligible prior probability partly because of what turned out to be erroneous beliefs about the mechanics of sediment transport and partly due to the lack of known terrestrial analogues. Having scientific authorities speak out against a new hypothesis, as they did against the meteorite-impact and catastrophic-flood models, can also influence assessments of prior probability.

Whatever their source or basis, judgments about prior probability are important because they can result in the early elimination of all contending hypotheses save one. Each new instance of confirmatory evidence then offers partial support for the surviving model, and, over time, confidence in the truth of the model may grow. However, the battlefield of ideas in the geosciences is littered with the corpses of widely favored hypotheses that were shot down by models thought to have negligible prior probabilities. Experience shows that hypotheses eventually judged to be false can, in their heyday, be amply supported by confirmatory observational evidence.

In order to avoid the premature and mistaken elimination of a true hypothesis, and doubtless for other reasons, geoscientists subscribe to the doctrine of *multiple working hypotheses*, which encourages the simultaneous evaluation of two or more alternative models. The doctrine implicitly recognizes that the alternative hypotheses all have appreciable prior probabilities. In tectonics, we think that it is typically applied in the following way. Two or three "working" hypotheses are presented as possible interpretations of, say, a tectonic feature or series of tectonic events. Then, the lines of evidence consistent with each model are listed; scores are tallied; and the interpretation that explains the most evidence is favored.

In our opinion, evaluations of this sort are not tests at all, because they do not involve the deduction of predicted consequences. Moreover, even the acquisition of additional confirmatory evidence cannot increase the probability that one of the hypotheses is true, because the multiple hypotheses all have significant prior probabilities. If, however, one or more of the working hypotheses can be eliminated from the competition using disconfirmatory evidence, then, by analogy with eliminations based on negligible prior probabilities, the surviving model or models gains some measure of empirical support.

Crucial Tests

As Gilbert (1886) implied over a century ago, *crucial tests* provide a logically sound basis for evaluating multiple hypotheses. A crucial test involves the deliberate search for observational evidence that can eliminate one of two alternative hypotheses. Contrary models will yield one or more mutually exclusive observational predictions. For example, hypothesis H_1 makes observational prediction P_1, and hypothesis H_2, P_2; P_1 and P_2 are incompatible and thus H_1 and H_2 cannot both be sustained by the same evidence. Stated differently, hypothesis H_1 prohibits P_2, and hypothesis H_2 prohibits P_1. If a prohibited observational prediction is found to be true, then the evidence refutes one of the hypotheses, as illustrated by the following deductive argument (a variant of schema 2):

If hypothesis H_1 is true,
then observational prediction P_2 cannot be true.
As shown by the evidence, P_2 is true.
> > > H_1 is not true. (7)

In practical terms, a crucial test defined by (7) above specifies the evidence that will refute a model or call into serious question one or more of its underlying assumptions. The elimination of one of two alternative hypotheses provides the surviving hypothesis with some measure of partial support. A model consistent with observational evidence may be strongly supported if it survives repeated attempts to refute it.

Summary

The goal of the doctrine of multiple working hypotheses should be to select the hypothesis with the maximum likelihood of being true. In some cases, all hypotheses but one can be eliminated by assigning them negligible prior probabilities, but the truth of the surviving hypothesis can never be conclusively proven by supporting evidence. To resolve controversies engendered by multiple hypotheses that all have significant prior probabilities, we advocate using crucial tests as the empirical basis for favoring one alternative model over another. In contrast, simply "tallying scores" and pointing out which hypothesis is supported by the most confirmatory evidence cannot serve as a logic-based method for preferring one hypothesis to any other. *Crucial tests involve making predictions and searching for evidence that a consensus would agree is prohibited by either hypothesis.* A crucial observation can eliminate one of the alternatives and provide some measure of empirical support for the surviving model.

TESTING HYPOTHESES A AND B: GEOLOGIC CONSEQUENCES PREDICTED BY EACH MODEL

In our opinion, many geologists familiar with the Baja British Columbia controversy give a low prior probability to hypothesis B. In contrast, we can find no reason to subject either hypothesis A or B to a higher burden of proof. Therefore, we consider that both hypotheses have an appreciable prior probability, because neither has been ruled out by widely accepted and well-established geologic evidence, and neither is "utterly implausible and unreasonable," to use Salmon's phrase (1963, p. 85). Our goal in this paper is to propose crucial geologic tests that may lead to a resolution of the dichotomy presented by hypotheses A and B. These tests, which exemplify the methodology discussed in the preceding section, may be applicable to the general problem of evaluating contradictory models that postulate either relatively minor ($\ll 1000$ km) or major ($\gg 1000$ km) coastwise displacements of tectonic elements along a continental margin.

Table 2 presents what we consider to be reasonable and straightforward predictions of hypothesis A and hypothesis B. These can be logically deduced from the paleogeographic reconstructions in figure 2 and from the assumptions underlying them. As might be expected for tectonic models addressing the possibility of thousands of kilometers of coast-parallel displacements, the predictions involve three main issues: (1) The amount and timing of slip on dextral transcurrent faults; (2) the provenance of sediments deposited on Baja British Columbia from ~90 to 50 Ma, just prior to and during its hypothetical northward journey; and (3) the geologic record of plate-tectonic motions, such as consumption of oceanic lithosphere at subduction zones and coastwise translations on transform faults. In this section, we discuss the predictions with respect to the following criteria: (1) Is each predicted consequence unique to a specific hypothesis? In other words, can it serve as a basis for a crucial test? (2) Is it likely that the required observational evidence can be obtained in a form that satisfies the prediction of the hypothesis? (3) What is the likelihood that the new evidence will be generally accepted as confirming or disconfirming a prediction?

Prediction 1: The Origin of Diverse Rock Units in the Coast Mountains Orogen

The Coast Mountains orogen, described above in the section entitled "Geologic Background," is composed of diverse rock units and terranes, most of which are fault-bounded fragments and nappes derived from larger homelands. Hypotheses A and B predict that these components were assembled to form the orogen, 90 to 100 my ago, at vastly different locations along the continental margin. According to hypothesis A, the components lay north of California at 100 Ma, in the hanging wall of the northward continuation of the Franciscan subduction zone (fig. 2A). According to hypothesis B, they must have lain south of California at the time the Insular superterrane collided with the southern extension of the Franciscan subduction zone at about 100 Ma (fig. 2B). A crucial test of these contradictory predictions would require geologic evidence confirming either a northerly or southerly paleolatitudinal position of the components in mid-Cretaceous time.

A basic assumption underlying such a test concerns the identity and location of the homeland of each tectonic fragment or nappe. Were these homelands part of the western Cordillera, and if so, where were they situated? Were the fragments instead derived from exotic homelands and assembled by chance? We briefly explore some possibilities using three components of the Coast Mountains orogen in the corridor between 48° and 52°N (fig. 3A): the Easton (Shuksan) Metamorphic Suite, the Decatur terrane, and the Deadman Bay terrane, each of which presently constitutes a nappe. Many workers (Brown, 1987; Monger and others, 1994) have interpreted the Shuksan as a fragment of a Late Jurassic-Early Cretaceous subduction complex. Brown and Blake (1987), emphasizing strong petrologic and isotopic similarities among blue-

TABLE 2

Predictions of paleogeographic hypotheses A and B (see fig. 2)

HYPOTHESIS A Both Superterranes North of California at 90 Ma	*HYPOTHESIS B* Insular Superterrane ~3000 km South, and Intermontane Superterrane ~1100 km South, of Expected Positions at 90 Ma
Tectonic setting of major rock units and crustal elements, ~110 to 95 Ma:	
A1. Assembly of rock units and terranes to form the Coast Mountains orogen 100 to 90 my ago occurred north of California.	B1. Assembly of rock units and terranes to form the Coast Mountains orogen 100 to 90 my ago occurred south of California.
A2. ~110 to 100 Ma magmatic arc on Insular superterrane, and coeval arc on western Intermontane superterrane formed above a single slab descending eastward at a subduction zone beneath the continental margin. These arcs collectively constitute the northward extension of the Sierran arc from the California sector.	B2. ~110 to 100 Ma arc on Insular superterrane and coeval Intermontane arc formed independently above two different descending slabs.
A3. Mid-Cretaceous (Albian-Cenomanian) Methow-Tyaughton sequence was deposited in an intra-arc setting, between the related Insular and Intermontane arcs. The provenance of east-derived arkosic and volcanogenic detritus in the Albian Methow-Tyaughton basin was the Intermontane arc (Okanogan Range batholith, Spences Bridge volcanics). The provenance of sediments possibly included pre-Cretaceous components of the Intermontane superterrane and Precambrian continental crust of North America to the east.	B3. Mid-Cretaceous Methow-Tyaughton sequence was deposited in a fore-arc setting, west of and adjacent to the northern Peninsular Range batholith. The provenance of east-derived, arkosic and volcanogenic detritus in Methow-Tyaughton basin was the northern Peninsular Ranges batholith and related volcanogenic rocks. The provenance of sediments possibly included other elements in the Yuma and Serí (Peninsular Ranges) terranes and pre-Cretaceous rocks in the southwestern United States.
Post-90 Ma history (after thrusting in Coast Mountains orogen along eastern edge of Insular superterrane):	
A4. The model itself does not predict the nature of the plate boundary west of the Franciscan system between ~90 and 60 Ma. Other hypotheses hold that subduction continued along the Franciscan trench in the California sector, but the slab descended at a shallower angle ("flat-slab subduction" of Dickinson and Snyder, 1979).	B4. Between ~90 and 60 Ma, Baja British Columbia moved northward along the coast, oceanward of the Franciscan Complex, along a major transform fault (Baja B.C. fault in fig. 4). Subduction and offscraping along the Franciscan trench ceased during all or part of this interval (that is, no Franciscan-related "flat slab").
A5. Subduction (oblique convergence) at the trench along the western edge of Insular superterrane continued from 90 to 60 Ma, giving rise both to Late Cretaceous and early Tertiary arc plutons in the North Cascades and Coast Mountains, and to the accretionary wedge in the Chugach terrane.	B5. Subduction at the trench on the western edge of Insular superterrane continued from 90 to 60 Ma, giving rise both to Late Cretaceous and early Tertiary arc plutons in the North Cascades and Coast Mountains, and to the Chugach accretionary wedge.

TABLE 2

(continued)

HYPOTHESIS A Both Superterranes North of California at 90 Ma	*HYPOTHESIS B* Insular Superterrane ~3000 km South, and Intermontane Superterrane ~1100 km South, of Expected Positions at 90 Ma
A6. Upper Cretaceous Nanaimo Group and Queen Charlotte Group, deposited from ~85 to 65 Ma on the Insular superterrane, accumulated in their present positions relative to the North American craton. Provenance of the east-derived sediments potentially included geologic elements east of Coast Mountains orogen, such as Intermontane superterrane, Idaho batholith, crystalline basement >2.1 Ga in age, and Proterozoic to lower Paleozoic miogeoclinal strata.	B6. Basins on Baja British Columbia moved northward 2000 km between 90 and 70 Ma. Provenance of detritus derived from outside the Coast Mountains orogen changed during this interval, from southwestern United States and northern Mexico (Precambrian basement <1.7 Ga), to Intermontane superterrane, Idaho batholith, and North American basement >2.1 Ga in age. The Nanaimo Group may retain a transport stratigraphy reflecting this change in provenance.
A7. Transcurrent faults between the Insular and Intermontane superterranes have accommodated a net dextral slip ≪1000 km between 90 and 70 Ma.	B7. The Insular and Intermontane superterranes were juxtaposed along the Baja B.C. fault, a major transcurrent fault system representing the northward continuation of the transform separating Baja British Columbia from North America at ~90 Ma (figs. 2B and 4). This fault accommodated at least 1900 km of dextral slip between ~90 and 70 Ma. On land, it is represented by or is near the Pasayten fault (fig. 3A), lies between the Yalakom and Fraser faults (fig. 3A), and coincides with or lies east of the Coast shear zone (fig. 3B).
A8. Any north-northwest-striking dextral transcurrent faults within the Intermontane superterrane have an aggregate post-100 Ma slip of ≪1000 km.	B8. The western two-thirds of the Intermontane superterrane was displaced northward relative to the eastern third along the Intra-Quesnellia fault, with post-100 Ma dextral slip of ~1000 km.

schists, proposed that the Shuksan is a tectonic slice derived from the Franciscan Complex. Brandon, Cowan, and Vance (1988) noted that the Middle Jurassic igneous rocks in the Decatur terrane resemble coeval arc-related ophiolitic complexes in California, and Garver (1988) interpreted the Decatur terrane as a fragment of the Great Valley Group and underlying Coast Range ophiolite. Brandon, Cowan, and Vance (1988) also pointed out that the upper Paleozoic and lower Mesozoic Deadman Bay terrane lithologically resembles coeval chert-basalt assemblages that are widespread in the Klamath-Sierran basement (fig. 1) in California.

In light of the arguments presented by the workers cited above and by others, we assume that the homelands for the Shuksan, Decatur, and

Deadman Bay terranes were Cordilleran, not exotic. We further assume, as these workers did, that the terranes are fragments of much larger tectonostratigraphic elements preserved in the California sector of the western Cordillera. Given these two assumptions, a future crucial test of prediction 1 would require geologic evidence that not only confirms that the terranes were derived from homelands at either the north or south end of California at 100 Ma, but that also rules out their derivation from the alternative site. In practice, this type of test would involve comparing the geologic characteristics of the terranes with those of potential homelands. Published interpretations based on such comparisons happen to conflict with one another: Brown and Blake (1987) proposed that the Shuksan is a fragment displaced northward from Franciscan rocks near latitude 42°N, while Garver (1988) favored a more southerly derivation of the Decatur terrane. Nevertheless, we believe that prediction 1 merits further consideration, but convincing tests await new information on how distinctive stratigraphic, petrologic, and isotopic characteristics are geographically distributed in potential homelands throughout the western Cordillera.

Prediction 2: Disposition of Magmatic Arcs

These consequences (table 2), deduced from hypotheses A and B, collectively illustrate the inability of the tectonic community to reach a consensus based on geologic evidence. Prediction 2 (one mid-Cretaceous magmatic arc in 2A versus two arcs in 2B) has already been debated in the literature. Armstrong (1988), van der Heyden (1992), and Armstrong and Ward (1993) among others cited geochemical and isotopic arguments consistent with their favored interpretation that 115 to 95 my old plutonic and volcanic rocks in the corridor between 48° and 52°N (fig. 3A) constituted a single, wide (> 500 km) arc. Thorkelson and Smith (1989), on the other hand, believed their stratigraphic and chemical evidence supported two discrete arcs consistent with prediction 2B, an interpretation also favored by Godwin (1975) and Souther (1991). We conclude that because each prediction (2A and 2B) apparently is supported by existing evidence, there is currently no logical basis for favoring one prediction over the other. Moreover, there is little likelihood that the hypothetical mid-Cretaceous contiguity of the Sierran and Insular-Intermontane arcs predicted by hypothesis A (see also Dickinson, 1976; Armstrong and Ward, 1993) can ever be either confirmed or refuted, because much of the region presently separating the exposed plutonic roots between latitudes 42° and 48°N is covered with Cenozoic deposits.

Prediction 3: Provenance of the Sediments in the Methow-Tyaughton Basins

First-cycle volcanic and plutonic detritus.—Here is an outstanding opportunity to test hypotheses A and B by attempting to rule out one or the other. This example illustrates the advantage conferred by predictions that can be restated as prohibitions: they afford a chance to eliminate a model from contention. One of the predicted consequences of each hypothesis, involving the provenance of east-derived, first-cycle arkosic and volcanogenic detritus in the Methow and Tyaughton basins, is specific and distinct, not vague (Garver and Brandon, 1994). From hypothesis A we infer that, during Albian and Cenomanian time (about 113-91 Ma), the detritus was supplied by a proximal, partly coeval magmatic arc, represented by the presently adjacent Okanogan Range batholith and Spences Bridge volcanics (see corridor map in fig. 3A). Alternatively, hypothesis B predicts a provenance in the Peninsular Ranges batholith and related volcanogenic rocks of southern California and northwestern Mexico, which lay east of the Methow and Tyaughton basins during this interval. Evidence unequivocally demonstrating an Okanogan-Spences Bridge provenance would be consistent with hypothesis A, but, more important, such evidence is *prohibited* by and therefore refutes hypothesis B. Similarly, a Peninsular-Ranges provenance is prohibited by and therefore rules out hypothesis A. Garver and Brandon (1994) concluded that this strategy might profitably be applied to the Baja British Columbia problem, but that further evidence needs to be obtained.

Examples of generic features of magmatic arcs that are useful in studies of provenance include: the age of plutonic and volcanic rocks; their major- and trace-element chemistry; their cooling history, reflecting the history of uplift and erosional or tectonic exhumation; isotopic characteristics, such as patterns defined by $^{16}O/^{18}O$, or initial $^{87}Sr/^{86}Sr$; U-Pb systematics of zircon and monazite, which may record inheritance from Precambrian basement, or Pb-loss after initial crystallization; the mineralogy of certain distinctive rock types; and the nature of the country rocks upon which the arc was built. It is beyond the scope of this paper to review all the characteristics of the Okanogan and Peninsular Ranges arcs that conceivably could be reflected in the Albian and Cenomanian sediments of the Methow and Tyaughton basins. We can identify, however, the criterion that new evidence must satisfy to refute convincingly either hypothesis: the evidence must be based on characteristics, such as the age of magmatism or isotopic systematics, that are widely acknowledged to be different in the preserved remnants of the two magmatic arcs. Thus, the characteristic features of each arc must be known in enough detail so as to avoid the possibility that specified evidence in the sedimentary record could be interpreted as consistent with both hypotheses A and B.

From the information already at hand, we believe that the first of the characteristics listed above, age, is unlikely to provide discriminating evidence regarding provenance. For example, the U-Pb isotopic ages of Cenomanian and older igneous rocks in each arc are known to be similar (compare Hurlow and Nelson, 1992 and Greig and others, 1992, with Todd, Kimbrough, and Herzig, 1994). Therefore, the age of a clast from Albian-Cenomanian strata in the Methow-Tyaughton basin is consistent with derivation from either source terrain and so cannot by itself preclude either hypothesis. In fact, just such a confirmatory instance has already been published. O'Brien, Gehrels, and Monger (1992) reported a concordant U-Pb age (zircon) of 156 ± 1 Ma for a clast of foliated tonalite in the Albian Jackass Mountain Group. They stated (p. 213) that this "... U-Pb age ... was expected. Lithological comparisons and current direction measurements have long suggested that the Eagle [Okanogan] plutonic complex is the source for abundant foliated plutonic clasts ... in the Jackass Mountain conglomerate." However, Late Jurassic foliated biotite tonalite is also present in the Peninsular Ranges batholith (Todd, Kimbrough, and Herzig, 1994; Thomson and Girty, 1994), which represents an alternative source for the tonalite clast.

Nevertheless, the potential for disconfirmation stands. We advocate a more thorough and systematic comparison of the other characteristics of the two magmatic arcs. Empirical evidence concerning chemistry, uplift and cooling history, isotope systematics, and even basic petrology is much more abundant for the Peninsular Ranges batholith and its related volcanic cover (Santiago Peak volcanics) and country rocks than for the Okanogan batholith, Eagle Complex, and Spences Bridge volcanics. New information from the latter arc may be required before diagnostic differences become apparent.

Detritus from outside the magmatic arc.—Prediction 3 also allows for the derivation of not only first-cycle clasts from an adjacent magmatic arc but also detritus from the wall rocks of plutons and from sources farther east (fig. 5). According to hypothesis A these sources could include the Intermontane superterrane and adjacent Precambrian rocks of the North American craton to the east. In hypothesis B, a potential provenance is the Serí and Yuma terranes (Sedlock, Ortega-Gutiérrez, and Speed, 1993), and Precambrian basement in the southwestern United States and northern Mexico. In either case, the possible source regions include Jurassic, Triassic, Paleozoic, and Precambrian rock units. An obvious difference in these composite sources is the age of the oldest crystalline basement (fig. 5): early Proterozoic and Archean (>2.05 Ga) east of the Intermontane superterrane and north of 49°N, and <1.7 Ga in the southwestern United States and northwestern Mexico (Gehrels and Dickinson, 1995, fig. 1). Hypothesis B would prohibit the presence of detrital zircons or clasts >2.05 Ga and especially >2.6 Ga in age in Albian-Cenomanian Methow-Tyaughton strata, unless: (1) the old zircons had been supplied by margin-parallel transport from >2.5 Ga basement (for example, Wyoming Province) situated 1500 km or more to the north of Baja British Columbia, or (2) old detrital zircons had been reworked from pre-Cretaceous rocks in the southwestern United States-northwestern Mexico source area (Gehrels and Dickinson, 1995). Conversely, hypothesis A would prohibit zircons or clasts between 1.7 and 1.4 Ga, and especially 1.0 to 1.3 Ga (Grenville Province) in age, in Methow-Tyaughton sediments. In addition to U-Pb ages of single zircons, the bulk Nd-isotopic composition of Methow-Tyaughton sedimentary rocks may provide evidence bearing on the age of the crust in their provenance (Barfod and Nelson, 1994).

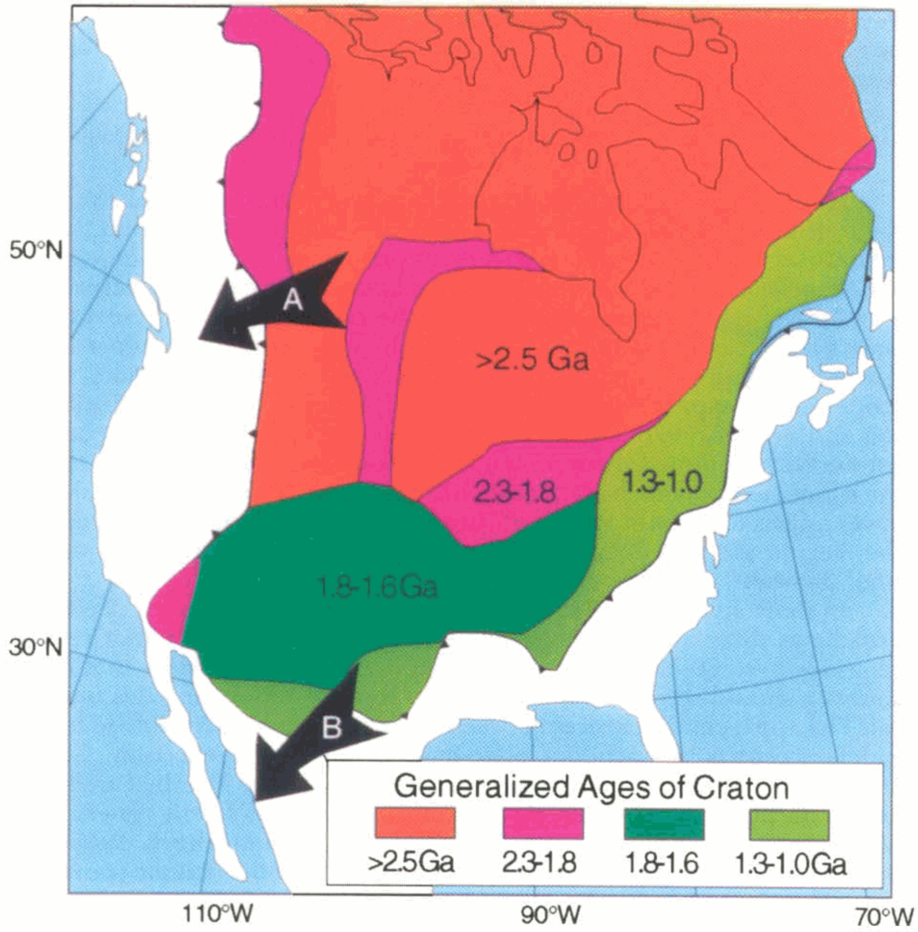


Fig. 5. Map generalized from Hoffman (1989) depicting the location of Precambrian basement terranes of North America that could have shed detritus into Albian and Cenomanian sediments accumulating in the Methow and Tyaughton basins, and into the Late Cretaceous Nanaimo basin. The arrow labeled (A) generalizes sediment-transport paths consistent with hypothesis A; the arrow labeled (B), paths consistent with hypothesis B and the inferred displacement history in figure 4.

Summary.—Hypotheses A and B make mutually exclusive predictions regarding the provenance of first-cycle volcanic, metamorphic, and plutonic detritus derived from the east. If detritus from either the Peninsular Ranges arc or the Okanogan-Spences Bridge arc is shown to be present in Albian-Cenomanian Methow-Tyaughton strata, one of the models or its assumptions can be ruled out. A condition of this test is that the detritus is both present and distinctive. If one were to study the Albian section and failed to find evidence of a feature characteristic of the

Peninsular Ranges arc, one could not conclude that hypothesis B had been refuted, nor could one conclude that hypothesis A had been supported or confirmed.

Prediction 4: Tectonic Setting of Late Cretaceous Franciscan Complex in California

Hypotheses A and B make seemingly incompatible predictions about the tectonics of western California between ~90 and 60 Ma (table 2). If hypothesis B is true, then the convergent plate boundary represented by the Franciscan subduction system changed during most of this interval to a transform boundary to accommodate the northward displacement of Baja British Columbia (fig. 4). Although hypothesis A (fig. 2) does not specify the nature of the Late Cretaceous Franciscan plate boundary, the model can be expanded to encompass a popular interpretation (Dickinson and Snyder, 1978; Dumitru, 1988; Wakabayashi, 1992): Franciscan subduction continued during Late Cretaceous and Paleogene time, but the subducted oceanic plate (Farallon?) descended at progressively shallower angles to account for the abrupt 80 Ma cessation of magmatism in the Sierran arc and for its subsequent progressive migration eastward (the "flat-slab" model).

In short, hypothesis A predicts that the Franciscan Complex (viewed broadly as the plate boundary) should contain a record of Late Cretaceous (~80 to 60 Ma) subduction, while hypothesis B predicts that the complex should record dominantly dextral strike-slip during this interval. The apparent differences between these predictions are blurred by a widely accepted independent plate-motion model (Engebretson, Cox, and Gordon, 1985), which specifies that, beginning ~90 Ma, the Farallon and Kula plates were obliquely converging with the North American plate. A reasonable consequence of such relative motion (Beck, 1986) is the partitioning of the margin-parallel component of the oblique convergence into dextral strike-slip on steep transcurrent faults in the hangingwall above the subduction zone, including accretionary complexes such as the Franciscan.

Many workers recognize that the difficulties in dating Franciscan stratigraphic units, mélanges, and structures mean that their evolution will continue to be poorly resolved in many instances. Moreover, McLaughlin and others (1988) and Jayko and Blake (1993) have inferred hundreds of kilometers of Late Cretaceous, pre-Middle Eocene dextral slip in the Franciscan Complex on the basis of distinctive rock units offset along high-angle faults. This evidence is compatible with either dextral-oblique slip across a Franciscan subduction zone or dextral slip along a transform separating the Franciscan from a northward-moving Baja British Columbia to the west (Umhoefer, 1987). Upper Cretaceous rocks in the Central Belt of the Franciscan might have been accreted between 80 and 60 Ma as a result of subduction (Blake, Howell, and Jayko, 1984), but there is no evidence precluding their emplacement after 60 Ma, when Baja British Columbia would have lain north of the California sector according to hypothesis B. Published isotopic ages (reviewed in Wakabayashi, 1992) indicate that exposed high-pressure rocks were metamorphosed between 165 and 80 Ma. Direct evidence of subduction, such as 80 to 60 Ma high pressure-low temperature metamorphic mineral assemblages in Franciscan rocks, remains lacking.

The foregoing examples show why we believe that the probability of actually carrying out a crucial test of hypotheses A and B based on *geologic* studies of the Franciscan Complex is small: the existing geologic evidence seems to be consistent with both models and therefore disconfirms neither. Perhaps Late Cretaceous geologic features preserved elsewhere in the western United States can be used to devise a crucial test. Several phenomena have already been cited as compatible with the continuous-subduction or flat-slab model, including (1) the post-80 Ma migration of magmatism eastward from its locus in the Sierran batholithic belt (Cross and Pilger, 1978; Dickinson and Snyder, 1978) in response to an acceleration in plate convergence and a putative decrease in the angle of slab descent, and (2) the maintenance of sub-normal ($\leq 15°C/km$) geothermal gradients in the Late Cretaceous Great Valley fore-arc basin, facilitated by the presence of a continuously descending plate of relatively cool oceanic lithosphere (Dumitru, 1988). If hypothesis B is indeed correct, then the conventional model of continuous Late Cretaceous Franciscan subduction (or its auxiliary hypotheses) needs revision. During much of the interval from ~80 to ~60 Ma, Baja British Columbia lay west of the Franciscan and effectively precluded subduction of additional oceanic lithosphere along the former Franciscan subduction zone. Subduction of lithosphere probably *did* continue beneath Baja British Columbia during its northward displacement, resulting in the intrusion of 80 to 60 Ma plutons from northwestern Washington, through the Coast Mountains into southeastern Alaska (see prediction 5 below). Possibly, the phenomena mentioned above—eastward migration of the late Mesozoic arc and maintenance of low geothermal gradients—are compatible with the eastward descent of an outboard oceanic plate beneath Baja British Columbia or with the sinking of the vestigial "Franciscan" plate.

Prediction 5: Tectonic Setting of Post-90 Ma Magmatic Arc and Subduction Complex in the Northwest Cordillera

Isotopic (U-Pb) studies on granitoid rocks in the central core of the Coast Mountains orogen (fig. 3A) show that many plutons were emplaced during the interval from 90 to 45 Ma (Miller, Bowring, and Hoppe, 1989; Friedman and Armstrong, 1995). These plutons, which post-date the largely pre-90 Ma, mid-Cretaceous shortening in the orogen, are commonly interpreted as part of a west-facing, calc-alkaline magmatic arc, constructed in response to Late Cretaceous and Paleogene subduction beneath the western edge of the Insular superterrane. Plutons of similar age continue northwestward through the Coast Mountains of British Columbia, into and beyond the corridor depicted in figure 3B.

The only difference between the predicted consequences of hypotheses A and B is that in the former case, the arc developed north of California in a fixed position relative to North America, whereas in the latter case, the arc developed on Baja British Columbia as it moved northward past California. As far as we know, the characteristics (for example, geochemistry, petrology) of the arc would be similar in both cases, so that additional geological evidence would not constitute a crucial test but rather be compatible with either hypothesis.

Another consequence of plate-consumption beneath the Insular superterrane was the accretion of a Late Cretaceous subduction complex along its western margin. Part of the Chugach terrane, presently exposed in southern Alaska (Plafker, Moore, and Winkler, 1994), is interpreted to represent an accretionary wedge formed in this manner. According to hypothesis A the Chugach terrane would have been accreted well north of California, whereas hypothesis B predicts that accretion occurred during the northward journey of Baja British Columbia past California (fig. 4). The geologic characteristics of the terrane are compatible with either history.

Prediction 6: Transport Stratigraphy in the Nanaimo Group

Hypotheses A and B make different observational predictions about the provenance of Late Cretaceous sediments deposited on the Insular superterrane. Stratified sequences of this age include the Nanaimo Group on southeastern Vancouver Island and adjacent islands (Mustard, 1994) and the upper part of the Queen Charlotte Group in the Queen Charlotte Islands (Haggart, 1991). Work to date has shown that most of the detritus above the basal beds of the Nanaimo Group (the more thoroughly studied sequence) was derived from the Coast Mountains, North Cascades, and San Juan Islands flanking the basin to the southeast. These sources are compatible with either model. However, if any detritus was supplied to the Nanaimo basin from east of the Coast Mountains, hypothesis A predicts that its provenance during the entire Late Cretaceous epoch lay north of the California sector where it might have included (fig. 1) the Intermontane superterrane, the Idaho batholith, Precambrian crystalline basement >2.1 Ga in age (fig. 5), and Proterozoic to lower Paleozoic strata of the Cordilleran miogeocline.

On the other hand, hypothesis B predicts that progressively younger sediments derived from the east changed in character in accord with the northward transit of Baja British Columbia along the continental margin. In early Late Cretaceous time (Turonian through Santonian), sources could have included Precambrian basement <1.7 Ga in age in the southwestern United States and northwestern Mexico, but by late Campanian time (about 75 Ma), the southern end of Baja British Columbia, including the Nanaimo basin, was situated north of California (fig. 4). East-derived sediments of late Campanian and Maastrichtian age in the Nanaimo Group would therefore include the same components predicted by hypothesis A. Hypothesis B therefore implies that the Nanaimo

Group may preserve a *transport stratigraphy* (Geist, Vallier, and Scholl, 1994), reflecting a progressively changing provenance. A crucial test of hypotheses A and B would involve establishing the provenance of east-derived detritus, especially using studies on the ages and chemistry of zircon, in the pre-Campanian Nanaimo Group. Detritus from the southwestern United States or northwestern Mexico is prohibited by hypothesis A; its presence would strongly support hypothesis B. Detritus from Archean continental basement (for example, zircons >2.5 Ga in age) is, on the other hand, prohibited by hypothesis B. Important auxiliary hypotheses for this test would postulate syndepositional transport paths and the degree of sedimentary recycling, especially for Precambrian detrital minerals. The studies of Ross and Parrish (1991) and Gehrels and Dickinson (1995) provided this type of information for Precambrian zircons.

Mustard, Parrish, and McNicoll (1995) presented U-Pb analyses of detrital zircons from early Campanian, early late Campanian, and Maastrichtian strata in the Nanaimo Group. They concluded that the zircons in Campanian strata were provided by the Coast Mountains and San Juan Islands, but that some zircons in Maastrichtian strata were derived from the Idaho batholith. These results are non-diagnostic and consistent with either hypothesis A or B, but they do demonstrate the feasibility of this type of test.

Prediction 7: Strike-slip Faults Between the Insular and Intermontane Superterranes

Hypothesis B, as presented in figures 2B and 4, requires a transcurrent fault or fault system with *at least* 1500 km of net dextral slip between Baja British Columbia (Insular superterrane plus Coast Mountains orogen) and the Intermontane superterrane. Although the total post-90 Ma displacement of Baja British Columbia relative to the Intermontane superterrane is 1900 km (the difference between their paleolatitudes at 90 Ma), the current length of the boundary between the two elements is 1500 km. According to the displacement history in figure 4, dextral slip on the Baja B.C. fault system was largely completed by 70 Ma, after which Baja British Columbia and the western Intermontane superterrane (Alta British Columbia) moved northward *en bloc* an additional 1100 km. In contrast, hypothesis A implies that the post-90 Ma net dextral slip on transcurrent faults between the Insular and Intermontane superterranes is at most a few hundred kilometers and definitely less than 1000 km.

Hypotheses A and B make fundamentally different predictions about the magnitude of 90 to 70 Ma dextral slip on transcurrent faults in the northwest Cordillera. These predictions would serve as the basis for future crucial geologic tests, if hypothesis B were judged to have an appreciable prior probability. In our opinion, however, many geologists have awarded hypothesis B a *low* prior probability, partly because they doubt that such a fault actually exists (Kerr, 1995). It is true that no one has yet identified the continuous, Late Cretaceous fault predicted by the model. On the other hand, we argue that no one has yet published geologic evidence strong enough to rule out the existence of the predicted Baja B.C. fault. In the following sections, we first identify what we believe to be the most likely location of the Baja B.C. fault, and then consider possible crucial tests based on the magnitude and history of offset on this hypothetical fault.

Probable location of the Baja B.C. fault.—A major problem associated with the Baja British Columbia controversy is that much if not all of the proposed eastern boundary of Baja British Columbia has been overprinted or obliterated by younger deformation and plutonism. Even so, it is useful to examine existing geologic and paleomagnetic evidence to delimit the area in which the proposed Baja B.C. fault must lie, as predicted by hypothesis B. Figure 3 shows these zones, ranging in width from a few kilometers to over a hundred, superimposed on the geologic maps of each corridor. Monger and Price (1996) and Irving and others (1996) present conclusions similar to ours for the region shown in figure 3A.

In the southern corridor, east of the future trace of the Fraser-Straight Creek fault, the predicted fault must either coincide with the Pasayten fault or lie in an incompletely mapped, narrow, 5 to 10 km-wide zone immediately west of the Pasayten fault (compare Cowan, 1994, p. 186). The MT paleomagnetic data set requires that the Methow strata west of the Pasayten fault belong to Baja British Columbia. This statement assumes the auxiliary hypothesis that the Methow and Tyaughton sediments accumulated in a contiguous Albian-Cenomanian basin (Garver, 1992). The rocks immediately east of the Pasayten fault, including the Spences Bridge volcanics (SB data set in fig. 2B), were intruded into or erupted onto the Intermontane superterrane. In a recent, comprehensive study of the Pasayten fault in Washington, Hurlow (1993, p. 1255) concluded that ". . . the Late Cretaceous to Early Eocene history of the Pasayten fault zone is not known. . ." and left open the possibility that slip of the requisite magnitude occurred in the zone depicted in figure 3A.

Farther north, adjacent to the trace of the Fraser fault, the probable locus of the Baja B.C. fault is wider (fig. 3A). The fault must lie north and east of the Tyaughton strata and the Yalakom fault and south and west of any part of the Intermontane superterrane that was contiguous with the Spences Bridge region in late Early Cretaceous time. Much of the area is presently covered with Tertiary and Quaternary units, but dated Lower Cretaceous volcanics correlated with the Spences Bridge Group (Mahoney and others, 1992; Hickson, 1992) define the northeastern boundary of the zone. The Yalakom fault itself is not a candidate, because it transects the Methow-Tyaughton basin (Garver, 1992) and appears to have accommodated only about 115 km of chiefly early Tertiary dextral slip (Umhoefer and Kleinsphen, 1995).

In the northern corridor (fig. 3B), the Baja B.C. fault must lie east of the Coast Mountains orogen and the 90 Ma and younger post-orogenic plutons that cross-cut the orogen. In addition, the fault must lie west of the Stikine terrane and any rock units that were conterminous with the

Stikine terrane at 90 Ma. Within these boundaries (fig. 3B), most of the zone, ranging in width from ~50 to ~125 km, is occupied by latest Cretaceous to Eocene plutonic rocks (dominantly 72-48 Ma; Gehrels and others, 1991) which largely postdate the hypothesized 90 to 70 Ma motion on the Baja B.C. fault. The Baja B.C. fault might have been the structure that localized emplacement of the slightly younger Great Tonalite Sill. Cowan (1994) suggested that the Coast shear zone, which developed along the western edge of the Great Tonalite Sill, may be a candidate for the Baja B.C. fault. This possibility is rejected here because the Coast shear zone is known to be younger than 72 Ma.

The location of the Baja B.C. fault in the vast, incompletely mapped western Coast Mountains south of the corridor in figure 3B is uncertain. We speculate that the fault roughly coincides with the southward extension of the Great Tonalite Sill and with probably correlative bodies like the Quottoon pluton (Gareau, 1991). If so, the length of this segment of the Baja B.C. fault in southeastern Alaska and northwestern British Columbia would be at least 800 km, even though most or all of the fault trace has been obliterated by younger plutons.

Crucial tests based on the amount of offset.—Now that we have delimited the area in which the postulated Baja B.C. fault would have lain, we can formulate a crucial geologic test to determine which of the mutually incompatible predictions of hypothesis A and hypothesis B is true and which is false. The different predictions are evident if we write the following statements:

If hypothesis A is true, then there is no fault system that
accommodated > 1000 km of dextral slip between 90 and 70 Ma; (8)
If hypothesis B is true, then there is a fault system that
accommodated > 1500 km of dextral slip between 90 and 70 Ma. (9)

These arguments show that if one could obtain observational evidence confirming the prediction in (9), then hypothesis A would be rejected. If, on the other hand, one obtained evidence supporting the prediction in (8), hypothesis B would be rejected. Of course, the new evidence might also be consistent with other unstated models, but more important, either hypothesis A or B *must* fail.

The required methodology is the same as that used to establish or limit the slip on any transcurrent fault: (1) match geologic features (ideally piercing points), such as distinctive rock units and dated macroscale structures, that have been offset along the fault; or (2) demonstrate relationships, such as overlapping sedimentary or volcanic rocks, or cross-cutting plutons or dikes, that preclude slip after a certain time. For structures like the Baja B.C. fault, which strike roughly parallel to the same geologic units or terranes for hundreds of kilometers, there is a low probability of being able to find and match offset geologic features. Moreover, the present ~1500 km length of the postulated Baja B.C. fault in the northwest Cordillera is less than the maximum hypothesized net dextral slip of Baja British Columbia relative to the Intermontane superterrane (~ 1900 km). Therefore, one would need to look in southwestern California or northwestern Mexico to find geologic features that might match with the present eastern edge of Baja British Columbia (fig. 2B). A convincing match of mid-Cretaceous (90 Ma) or older rock units and structures in the Salinian block or Peninsular Ranges of Alta and Baja California with offset equivalents in Baja British Columbia would be a confirmatory instance of hypothesis B. As noted by Page (1982), it is conceivable that parts of the missing fore-arcs, formerly belonging to the Salinian block and Peninsular Ranges batholith, are present in the Coast Mountains orogen.

Alternatively, hypothesis B would be ruled out and hypothesis A supported if geologic evidence were acquired limiting 90 to 70 Ma dextral slip across the putative Baja B.C. fault to <1000 km. Two tentative examples of such evidence have been mentioned in the literature. Mahoney and others (1992) and Monger and Price (1996) suggested that the Albian to Cenomanian non-marine strata locally preserved on the western Intermontane superterrane in the neighborhood of paleomagnetic site SB were deposited contiguously with correlative strata in the Methow-Tyaughton basins, which have yielded the MT paleomagnetic data set. If true, these strata constitute an overlap sequence limiting post-90 Ma net strike slip along any structures in the zone shown in figure 3A to a few tens of kilometers. As yet, however, this stratigraphic correlation is based solely on general lithologic characteristics, and further work on the sedimentology, petrology, and age of the isolated sections on the Intermontane superterrane is needed to evaluate the possibility of overlap.

The other example was suggested by McClelland and others (1992a, p. 120), who believe that, before the emplacement of the voluminous latest Cretaceous and younger plutons in the Coast Mountains of southeastern Alaska and northwestern British Columbia, the Ruth assemblage (fig. 3B) extended contiguously from the mid-Cretaceous thrust system on the western flank of the Coast Plutonic Complex eastward to the Stikine and Yukon-Tanana terranes. If this suggestion is true, then post-90 Ma dextral strike slip on all faults in the zone separating the Insular and Intermontane superterranes in figure 3B cannot exceed a few hundred kilometers. In this example, we feel that stronger evidence is needed to rule out the possibility that the isolated pendants of Ruth assemblage in the Coast Mountains were independently derived from lithologically similar units south of the California sector.

The kinds of evidence cited by Mahoney and others (1992), Monger and Price (1996), and McClelland and others (1992a) may eventually be acknowledged as important disconfirmatory instances of the Baja British Columbia hypothesis. We believe, however, that the evidence *as it has been presented so far* is not strong enough either to disconfirm hypothesis B or to support hypothesis A, because the correlations are currently based on superficial similarities. Nonetheless, detailed field, petrologic, and analytical studies are pending or underway. Judgments about "strength," "reliability," or "degree of support" in this context are, of course, completely subjective. One measure of the quality of the *published* evidence used in this crucial test will be whether a majority of workers ultimately accepts the new evidence as a refutation of hypothesis B.

Role of kinematic analysis.—Finally, we comment on whether meso- or microscale structural features—kinematic indicators or criteria—can provide a crucial test of hypotheses A and B. If these structures could be precisely dated, then they would constitute evidence for the sense-of-shear in fault or shear zones active between 90 and 70 Ma. A diligent study of rocks older than the latest Cretaceous and Paleogene plutonic rocks (older than 70 Ma) in the zones shown in figure 3 could have the following results: (1) indicators recording dextral strike-slip are present (very local to widespread; uncommon to abundant); or (2) dextral indicators of this age are completely absent. The evidence in (1) is compatible with either statement (8) or (9) above. Hypothesis A does not preclude the existence of early late Cretaceous dextral transcurrent faults, just those with displacements > 1500 km. Moreover, because the motions of the Farallon and Kula plates relative to North America were obliquely convergent during this period (Engebretson, Cox, and Gordon, 1985), dextral strike-slip motion conceivably could have been partitioned onto any favorably oriented, margin-parallel, steeply dipping fault.

What about result (2)? For example, Monger and Price (1996) implied that the lack of evidence for post-90Ma dextral slip on the Pasayten fault indicates that the total displacement on this fault is far smaller than the 1900 km predicted by paleomagnetic data, whereas Wynne and others (1996) held that the "missing" evidence does not rule out the hypothetical large displacements. We agree that the lack of dextral indicators in itself is not a disconfirmatory instance of statement (9). That is, it cannot be concluded that the consequent of statement (9) is false unless other *ad hoc* but reasonable explanations for the absence of indicators can be ruled out. For example, appropriate structures simply were not developed (not all ductile and brittle shear zones contain them); were not preserved (younger deformation has obliterated them); or cannot be precisely dated. We conclude that investigations of fabrics and small-scale structures have little relevance to the primary issue, namely the *amount* of dextral strike-slip.

Prediction 8: Strike-slip Faults in the Intermontane Superterrane

The different consequences for prediction 8 (table 2), regarding the magnitude of Late Cretaceous to Recent dextral slip on transcurrent faults within the Intermontane superterrane, are analogous to predictions A7 and B7. As in the case of the hypothetical Baja B.C. fault, a candidate for the putative Intra-Quesnellia fault (Irving and others, 1995) has not been identified on the ground south of latitude 54°N. Several workers (Price and Carmichael, 1986; Monger, 1993) have noted that 500 to 1000 km of post-mid-Cretaceous dextral slip on steeply dipping faults north of 54°N can be inferred from geological evidence. South of 54°N, however, only 100 to 200 km of dextral slip can be documented, principally on the Fraser-Straight Creek system, which lies mostly west of the Intermontane superterrane, and definitely west of paleomagnetic study site SB (fig. 3B). On the other hand, there is no published evidence known to us that rules out ~ 1000 km of dextral slip somewhere to the east within the southern Intermontane superterrane between 100 and 55 Ma. The postulated structure or structures might have been obliterated by widespread Eocene extension in this area (Umhoefer, 1987).

Although prediction A8 does not directly involve Baja British Columbia as defined here, a crucial test could result in the refutation of hypothesis B as we present it in figure 2B. The test would require the acquisition of new geological evidence from the southern half of the Intermontane superterrane, prohibiting total dextral slip of several hundred to 1000 km on north-northwest-striking faults.

Summary

Of the eight predictions in table 2, only predictions 3, 6, and 7 provide the basis for crucial geologic tests that have a high probability of refuting either hypothesis A or B. Potentially useful geologic evidence that must be acquired for these tests includes: (1) the provenance of east-derived detritus in Albian and Cenomanian strata in the Methow-Tyaughton section; (2) the provenance of east-derived detritus in pre-late Campanian strata of the Nanaimo Group; (3) Mid-Cretaceous and older rock units and structures in Baja British Columbia that match formerly contiguous geologic features in southwestern California and northwestern Mexico but have no counterparts in the western Intermontane superterrane; and (4) Late Cretaceous or older geologic features that limit dextral offset across the hypothetical traces of the Baja B.C. and Intra-Quesnellia faults to < 1000 km. In the case of (1) and (2), further geologic work is needed to characterize the distinctive geologic differences between the two widely separated regions hypothesized to have provided detritus to the Methow, Tyaughton, and Nanaimo basins. Also necessary are explicit auxiliary hypotheses that address the transport history of detritus shed from Precambrian source terranes.

Predictions A5 and B5 are very similar to one another and therefore do not constitute part of a crucial test. Although predictions A1, A2, and A4 differ from B1, B2, and B4, there is a strong probability, given our current assumptions or investigative approaches and techniques, that newly obtained geological evidence will be interpreted as compatible with either hypothesis A or B, and therefore cannot be used in crucial tests to differentiate between them.

DISCUSSION

For us, the Baja British Columbia controversy is more than just an invigorating debate about the late Mesozoic paleogeography of western North America. We view the dichotomy as an opportunity to revisit the logic governing how tectonic models are generated and tested. We conclude that controversies like this one can never be resolved by limiting research to studies that look only for evidence that is consistent with a favored hypothesis. Crucial tests, on the other hand, direct research toward investigations that can potentially rule out one of a pair of contradictory hypotheses or at least reveal that an assumption is false. The success of a hypothesis in explaining available evidence is not as important as is its success in surviving a crucial test when pitted against a contradictory hypothesis.

Although we focus in this paper on geologic tests for discriminating between hypotheses A and B, it is important to remember that two other independent kinds of tests, paleomagnetic and paleontologic, can be brought to bear on the dichotomy. There is a small literature on the paleobiogeographic evidence concerning Baja British Columbia (for example, Haggart and Carter, 1994). Paleomagnetic studies, however, are well advanced, especially given that the southern option represented by hypothesis B is based entirely on paleomagnetic data.

In paleomagnetic studies, there are two stages of hypothesis testing. The first is directed at identifying and dating a characteristic remanance. The tests involved in this stage are well known (Beck, 1989; Butler, 1992) and provide an independent procedure for rejecting aberrant results. The second stage of testing is directed toward tectonic interpretation. Is the new estimate of paleolatitude consistent with previous results? Hypothesis A predicts that the estimated paleolatitude is not significantly different from that predicted for an *in situ* position relative to cratonal North America. Hypothesis B predicts that new paleomagnetic data will yield estimates of northward displacement that are consistent with previous high-quality results, such as those from localities DI, MS, and MT (fig. 2). Crucial paleomagnetic tests of hypotheses A and B are based on quantitative evidence and are therefore very specific: Any reliable study that yields the same paleolatitudes as previous studies have yielded refutes Hypothesis A and simultaneously offers strong additional support for hypothesis B.

The "ultimate test" of the Baja British Columbia controversy will have been consummated when geologists, paleomagneticists, and paleontologists all agree that either the northern option or the southern option has been refuted by the sum of the observational evidence.

SUMMARY AND CONCLUSIONS

1. Two families of models for the mid-Cretaceous paleogeography of the western margin of North America differ primarily in where part of the northwest Cordillera is placed latitudinally relative to continental

North America. We propose two specific, contradictory, and predictive hypotheses, each representative of one of the families. In one model, the Insular superterrane lay north of California at 90 Ma. In the other, based entirely on a growing body of paleomagnetic data, the Insular superterrane and adjacent Coast Mountains orogen constitute Baja British Columbia. This crustal element lay 3000 km south of its present relative position at 90 Ma and, between 90 and 70 Ma, moved northward along a major dextral transcurrent fault, parallel to the western coast of North America.

2. Following the hypothetico-deductive method, a tectonic model is tested by first predicting its consequences and then acquiring new geologic evidence and evaluating whether predictions are confirmed or contradicted by the evidence. According to the logic underlying this method, even multiple instances of confirmatory evidence can never conclusively prove the truth of a hypothesis, nor do they provide partial support as long as the evidence is consistent with alternative models that are equally likely to be true. A pair of mutually contradictory hypotheses, such as the Baja British Columbia model and its alternative, offer the opportunity to design crucial tests, which will support one model while refuting and eliminating the other.

3. Comparing the predicted consequences of the Baja British Columbia model with those of its alternative, we find that only a few can be used for crucial tests. To evaluate the probability that part of the northwest Cordillera has been displaced thousands of kilometers along the North American margin, perhaps the most useful geologic evidence concerns the provenance of detritus in mid- and Late-Cretaceous strata, and the amount of Late Cretaceous net dextral offset on strike-slip faults. Other types of evidence, concerning, for example, the sense-of-slip on faults, and the Late Cretaceous plate-tectonic setting of magmatic arcs and the Franciscan Complex, would likely be viewed as compatible with both paleogeographic models and therefore would not constitute a crucial test.

4. A successful crucial test requires obtaining evidence showing that either one of two mutually contradictory predictions is true. However, the failure to observe a deduced consequence does not mean that it is false, nor does such a failure mean that the contradictory prediction is true. For example, the Baja British Columbia hypothesis as presented here predicts a transform fault, the Baja B.C. fault, with >1500 km of Late Cretaceous dextral slip. The failure so far to locate this fault is invoked by geologists as an argument against the Baja British Columbia model, yet the lack of evidence can be accounted for by other reasonable and plausible explanations. For example, the fault might have been obliterated by younger plutons, reactivated as a dip-slip fault, or removed by crustal extension. We conclude that a crucial test requires obtaining and publishing geological evidence that is complete and detailed enough to rule out Late Cretaceous slip of 1000 km or more across the hypothetical fault, whether or not remnants of the Baja B.C. fault still exist.

ACKNOWLEDGMENTS

Discussions over several years with Jay Ague, Ted Irving, Jim Monger, Margi Rusmore, and Paul Umhoefer helped fashion some of the material in this paper. We thank Scott Bogue and Sherman Gromme for elaborating on their paleomagnetic data from Duke Island and George Viele and Sandra Wyld for reviewing an earlier draft. Brandon acknowledges support from NSF grant EAR-9106652. Cowan thanks Ted Irving and Naomi Oreskes for their guidance on the philosophy of science, but they are absolved of any responsibility for how the topic is treated here.

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