Testing terrane transport: An inclusive approach to the Baja B.C. controversy

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ABSTRACT

The Baja British Columbia hypothesis holds that a large segment of the western edge of northern North America (Baja B.C.) was situated alongside California and northern Mexico in middle Cretaceous time, was displaced northward in the Late Cretaceous and Paleocene by north-oblique convergence of the Kula plate with North America, and arrived near its present location by the early Eocene. A consistent body of paleomagnetic data supports this hypothesis. However, doubt persists, and various crucial tests of a geologic nature have been proposed. One such test concerns the provenance of zircons in Cretaceous sedimentary basins of Baja B.C. In this paper we use both paleomagnetic data and zircon occurrences to reconfirm the Baja B.C. hypothesis. We first argue that the only truly crucial tests yet performed have been paleomagnetic, and that all such tests have been positive. Second, we show that detrital-zircon data from the Upper Cretaceous Nanaimo Group, although not a crucial test, provide valuable paleogeographic information. Available data demonstrate a change in detrital-zircon provenance in the Nanaimo Group that closely matches the position of these rocks predicted by the Baja B.C. hypothesis. Detrital zircons in the Nanaimo Group suggest a change from a southwestern North American source rich in Grenville and 1.4–1.5 Ga rocks to an increasing contribution from older parts of the craton such as the Wyoming province. Together, detrital zircons and paleomagnetic inclinations allow us to assemble a detailed schedule of northward tectonic transport of the Baja B.C. terranes.

INTRODUCTION

Geology includes diverse subdisciplines with which to address complex questions. Taken separately, results obtained from any of geology's subdisciplines may lead to erroneous or conflicting interpretations. The ongoing controversy regarding the Baja British Columbia (Baja B.C.) hypothesis is an illustration of conflicting interpretations arising from clashing geological subdisciplines.

The Baja B.C. hypothesis holds that the Insular superterrane and associated Coast Mountains orogen were ~3000 km south of their present locations during the middle to Late Cretaceous and were displaced northward along the margin of North America between 90 and 50 Ma (Beck, 1976; Irving, 1985; Umhoefer, 1987). Using geologic correlations, some workers have rejected this hypothesis, proposing displacement of <1000 km (Price and Charmichael, 1986; Mahoney et al., 1999). Cowan et al. (1997) proposed several crucial tests of this hypothesis based on geological correlation, sedimentology, and structural geology. Cowan et al. (1997) recognized that the Baja B.C. hypothesis is founded on paleomagnetic data and that further paleomagnetic studies also are crucial tests. The geologic tests outlined in Cowan et al. (1997) have been cited by some (e.g., Mahoney et al., 1999) as a separate and definitive test of Baja B.C. We advocate an inclusive approach utilizing paleomagnetic, plate motion, paleontological, and geologic evidence that together can provide a comprehensive evaluation of terrane translation.

SOME TESTS ARE MORE CRUCIAL THAN OTHERS

The key question for models of latitudinal terrane transport involves paleolatitude. Based on first principles, there are two means to determine a rock's original latitude. Paleomagnetism, following the geocentric axial-dipole hypothesis, provides specific estimates of paleolatitude. The other way to determine paleolatitude is to utilize latitudinally dependent climatic zones, especially indicators of equatorial or polar climates, expressed in various ways in the rock record. Paleogeographic reconstructions combining these two methods have been very successful (e.g., Irving, 1956).

Baja B.C. dates from publication of the original Mount Stuart paleomagnetic results (Beck and Noson, 1972). Because the hypothesis requires that any middle or Upper Cretaceous rocks in these terranes formed at latitudes appropriate to California and northern Mexico, to disprove Baja B.C. simply has required that a steep mean inclination in an appropriate rock unit be encountered. A steep inclination would indicate magnetization at about the unit's present relative latitude. Several score of investigators working in five different laboratories have published 14 such paleomagnetic crucial tests since 1973. No such steep inclination has ever been found.[1]

Mahoney et al. (1999) reported Archean zircons in several Baja B.C. rock units and interpreted this find as a failed crucial test. Such interpretations of zircon provenance are limited by the distribution of potential zircon sources (including sediment recycling and igneous inheritance) and transport path length. Such complications make interpretations of latitudinal dependence of detrital zircon ages highly empirical, and thus unlikely to yield a crucial test such as Cowan et al. (1997) proposed. We agree with Gehrels et al. (1995, p. 834), who pointed out that detrital zircon provenance studies are best used "in conjunction with biogeographic, paleomagnetic, lithostratigraphic, and geochemical arguments."

TESTING THE SUPPORTING EVIDENCE

A means of refuting the Baja B.C. hypothesis is to propose interpretations of paleomagnetic data that do not entail poleward transport. Possible alternatives include tilting plutons, inclination shallowing in sediments, and remagnetization of

[1]GSA Data Repository item 99100, Summary of the crucial paleomagnetic studies, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, editing@geosociety.org, or at www.geosociety.org/pubs/drpint.htm.

Data Repository item 99100 contains additional material related to this article.

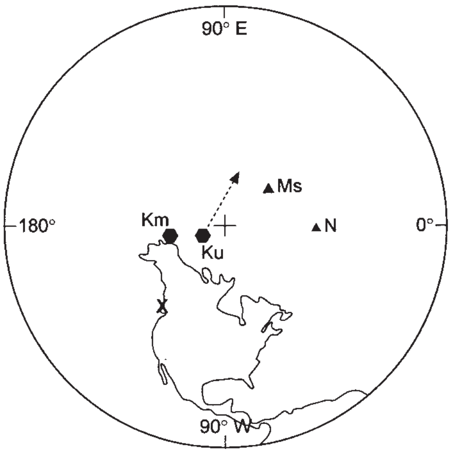

Figure 1. Paleomagnetic poles for Mount Stuart batholith (MS) and Nanaimo Group (N) are plotted as solid triangles. Octagons show middle Cretaceous (Km) (Van Fossen and Kent, 1992) and Upper Cretaceous (Ku) (Gunderson and Sheriff, 1991) poles for North American craton. Sampling locations for these studies are shown by X. Arrow shows trajectory of pole due to inclination shallowing alone.

volcanic rocks. Such alternatives are illustrated by two studies; the Mount Stuart batholith (Beck et al., 1981) and the Nanaimo Group sedimentary rocks (Ward et al., 1997). Observed paleomagnetic poles for these units are farther from the sampling sites than are the reference poles, as reflected in their shallow inclinations of remanent magnetization. The observed poles also are to the right of the reference poles, indicating clockwise rotations (Fig. 1).

The Baja B.C. hypothesis explains the mislocation of these poles by supposing that a block of crust including both sampling areas was displaced northward along the edge of North America. This interpretation accounts for their shallow inclinations and clockwise rotation (Beck, 1989).

Rejection of Baja B.C. requires that Mount Stuart has been tilted 35º downward toward the southwest. This possibility was mentioned by Beck et al. (1981), proposed by Butler et al. (1989), and investigated by Ague and Brandon (1996). Ague and Brandon (1996) concluded that the batholith has been tilted ~8º toward the southeast, resulting in no significant change in paleomagnetic inclination.

To explain the Nanaimo Group pole while rejecting Baja B.C. requires compaction enough to shallow the inclination by nearly 30°, plus clockwise rotation of 35°–40°. Inclination flattening is well known, although it is not found in all sedimentary rocks. In magnetite-bearing siltstones, 10°–15° of shallowing seems to be typical (Kodama, 1997).

Although clockwise rotation is common throughout the westernmost Cordillera (Beck, 1989), lower Tertiary rocks surrounding the Nanaimo basin have not been rotated significantly (Irving and Brandon, 1990; Beck and Engebretson, 1982; Beck et al., 1982). Thus, possible rotation must have occurred soon after the rocks formed.

Baja B.C. provides a simple explanation for both the Mount Stuart and Nanaimo poles. A “motor” exists to drive the process, in the form of known plate interactions. To explain the Mount Stuart and Nanaimo data (as well as the 12 other published Baja B.C. studies) without large displacement requires a chance conjunction of three unrelated processes: tilt, compaction, and vertical axis rotation. There are good reasons to doubt that either large-scale tilting or significant compaction has occurred. We conclude that Occam’s razor strongly favors the Baja B.C. concept.

TESTING POLEWARD MOTION OF BAJA B.C.

To evaluate possible poleward transport of Baja B.C., we must constrain the time and latitude at which poleward motion commenced, as well as the time and latitude at which it ended. The Eocene (50 Ma) Flores Volcanics (Irving and Brandon, 1990) indicate that Vancouver Island had its current relative position by 50 Ma, at a paleolatitude of 53ºN. Corrected for tilt by geobarometry (Ague and Brandon, 1996), the Mount Stuart paleomagnetic data of Beck et al. (1981) indicate that these rocks were located at 30ºN at 93–84 Ma. The Mount Stuart results were selected because these rocks are linked to terranes of the San Juan Islands (e.g., Brandon et al., 1988). (Using the pole from the Mount Tatlow syncline [Wynne et al., 1995] similarly places the Insular superterrane at 35ºN at 90 Ma.) The sedimentary rocks of the Upper Cretaceous Nanaimo Group link the San Juan–North Cascades thrust system to Vancouver Island. These sediments were deposited during the period of proposed poleward translation (Mustard, 1994), and overlie older terranes on the San Juan Islands and Vancouver Island.

Debiche et al. (1987) predicted displacement paths of terranes moving along western North America as a result of oblique convergence of the Farallon, Kula, and Pacific plates. According to their model the paleolatitude of Vancouver Island at 90 Ma and at 50 Ma both constrain the paleolatitude of the Nanaimo basin during transport (Fig. 2). Utilizing that model and the ideas of Cowan et al. (1997), we make several predictions for the Nanaimo Group. (1) The 50 Ma arrival time of Vancouver Island relative to North America, along with the rate of oblique motion between the Kula and North American plates, limits the amount of Baja B.C. displacement. Given these constraints, the basal sediments of the Nanaimo Group should not have been deposited much south of 35ºN. (2) A primary magnetization in the Nanaimo Group would record a “transport magnetostratigraphy” reflecting changes in magnetic field polarity corresponding to the age of the rocks and a pattern of increasingly steep inclinations with decreasing age. The inclinations should approximate the predicted paleolatitudes in Figure 2. (3) The sediments of the Nanaimo Group should also display a transport stratigraphy reflecting a change in the component of sediments derived from the craton during translation.

DISCUSSION OF THE NANAIMO GROUP

The paleomagnetic data of Ward et al. (1997) are the only published paleomagnetic results from the Nanaimo Group. Two formations were sampled, the lower to middle Campanian Pender Formation and the upper Campanian to lower Maastrichtian Spray Formation. Both formations have polarities consistent with the magnetic polarity time scale. The inclination of the Nanaimo sediments places the basin almost 30° south of their expected location on the North American margin. The mean inclination of the two units is essentially identical (42° vs. 41°), leading Ward et al. (1997) to conclude there was no detectable motion between deposition of the Pender and Spray Formations.

Comparison between observed and predicted paleolatitudes (Fig. 2) shows that the Ward et al. (1997) results place the Nanaimo Group too far south relative to North America to permit their

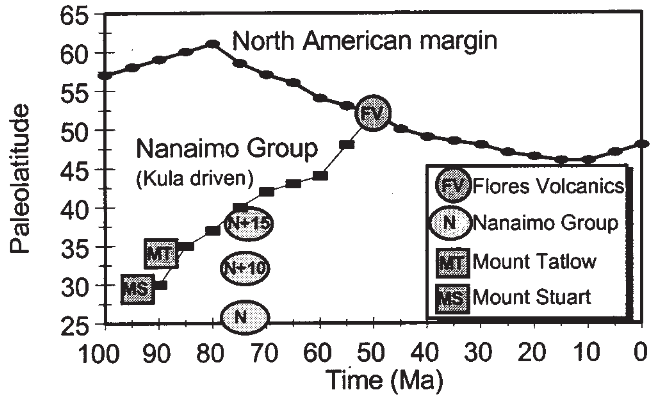

Figure 2. Paleolatitude of point on North American margin that is currently at 48°N (solid ovals) and Nanaimo Group (solid rectangles), according to plate model of Debiche et al. (1987). Model assumes 100% coupling of Baja B.C. to Kula plate from 85 to 50 Ma. Paleomagnetic results from Mount Stuart and Mount Tatlow constrain position of Nanaimo Group prior to translation, and results from Flores Volcanics constrain time and latitude at which relative poleward motion ceased. N+10 and N+15 are latitudes for Nanaimo Group corrected for 10° and 15° of inclination shallowing.

being in place at 50 Ma. Although Ward et al. (1997) concluded that inclination flattening is not likely, some flattening (10° of inclination for the Pender Formation and 15° for the Spray) would bring both the paleomagnetic data and the predicted location of the Nanaimo Group into close agreement (Fig. 2). The existing paleomagnetic data from the Nanaimo Group seems consistent with our predictions. Additional studies of Nanaimo Group paleomagnetism and potential inclination shallowing need to be made in order to perform more detailed tests.

Mahoney et al. (1999) presented U-Pb ages of detrital zircons from the Protection and DeCourcy Formations (with fewer [<20] results from the younger Geoffrey and Gabriola Formations). Mahoney et al. (1999) stated that there was no significant difference in the distribution of ages of detrital zircons, so the sediment source for the Nanaimo Group must have been constant. They also concluded that the source of the detrital zircons could not have been in the southwestern part of North America. Therefore, according to Mahoney et al. (1999), Baja B.C. has failed a crucial test.

From the detrital-zircon ages (Mahoney et al., 1999; Mustard et al., 1995) (Fig. 3) we observe the following. (1) In the Protection Formation, Grenville age zircons are most abundant relative to the younger units. (2) Zircons older than 2.0 Ga are rarest in the oldest units and are more common in the younger units. (3) The peak of the zircon age distribution (ignoring ages of <200 Ma) is 1.5–1.6 Ga in the Protection Formation and 1.6–1.7 Ga in the DeCourcy, Geoffrey, and Gabriola Formations. (4) In the Protection Formation, detrital zircons with ages between 1.3 and 1.5 Ga are very common. Zircons of this age are present but less common in the DeCourcy Formation and are absent in the Geoffrey and Gabriola Formations. Thus these data show a change in detrital zircon source with age in the Nanaimo Group. The key question then becomes how best to explain this change in terms of provenance.

Mahoney et al. (1999) cited the Belt Supergroup (Ross et al., 1992) as the probable source of Proterozoic zircons for the Nanaimo sediments, stating that there is no identified source of 1.5–1.6 Ga zircons in western North America. The Belt data presented by Ross et al. (1992) have abundant 1.4–1.8 Ga zircons and several Grenville age zircons. Although the range in zircon ages is similar to that reported from the Nanaimo Group, the distribution of ages is dissimilar (e.g., the Belt peak is 1.7 Ga). More important, there is no compelling explanation for the observed change in zircon ages shown in Figure 3 if the Belt Group rocks are the source of the Precambrian zircons and if the Nanaimo Group has remained stationary relative to North America during its deposition.

North American geology includes many potential sources for the zircons in the Nanaimo Group. By using the compilation of Hoffman

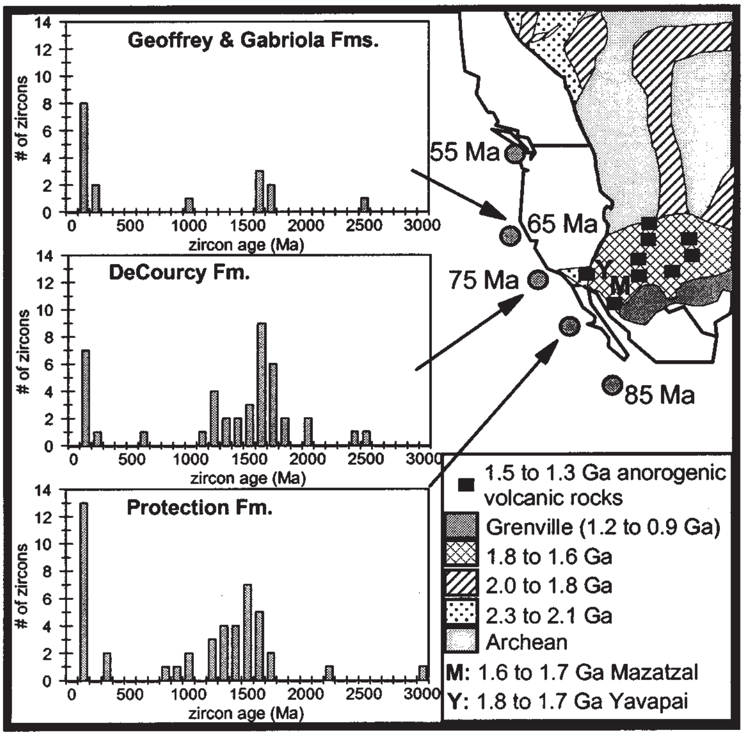

Figure 3. Histograms of U-Pb ages of detrital zircons from Mahoney et al. (1999) and Mustard et al. (1995), and basement ages of North America modified from Hoffman (1989). Gray circles denote positions of Nanaimo Group relative to margin of North America (taken from Fig. 2). Arrows denote locations of Nanaimo basin during deposition of units for which detrital zircon ages are available.

(1989), we propose the following explanation for the data shown in Figure 3. As suggested by Cowan et al. (1997), abundant Grenville age zircons are expected if the basal units of the Nanaimo Group were located as in Figure 3. The decline in abundance of Grenville age zircons in the upper units reflects movement of Baja B.C. north, away from Grenville crust in southwestern North America. In Arizona and New Mexico, the Mazatzal orogeny produced abundant 1.6–1.7 Ga metamorphic and igneous rocks. Farther to the northwest, the Yavapai orogeny produced igneous and metamorphic rocks of 1.7–1.8 Ga age. Throughout the southwestern part of North America, 1.3–1.5 Ga anorogenic volcanic rocks also occur. The Protection Formation has a 1.5–1.6 Ga peak in zircon ages, consistent with derivation from both the Mazatzal orogeny and the anorogenic volcanic rocks. The slightly older peak in zircon ages in the DeCourcy is consistent with a change to a source that includes more of the Yavapai orogeny, with continued contribution by the anorogenic volcanic rocks. Both formations have detrital-zircon ages consistent with a position near the southwestern margin of North America, and with progressive translation northward along this part of the margin. The younger formations (Geoffrey and Gabriola) are lacking in 1.3–1.5 Ga zircons, suggesting movement away from a source in the southwest. Age distributions similar to those of the Nanaimo Group are also found in Paleozoic sedimentary rocks from Sonora and Nevada, but not in southern British Columbia (Gehrels et al., 1995). We conclude that the existing detrital zircon data are consistent with a transport stratigraphy in the Nanaimo Group reflecting Late Cretaceous margin-parallel transport.

Late Proterozoic and Archean zircons are more common in the DeCourcy Formation, which, according to the Baja B.C. model, would have been within 1500 km of the Archean Wyoming province. Crust with Nd model ages of 2.1–2.3 Ga occurs in the American southwest (Mojavia of Bennett and DePaolo, 1987). Rocks with similar ages are found in Mojavia (i.e., 2.0–2.3 Ga Turtle Mountains Gneiss; Reed, 1993). Late Proterozoic to Archean inherited zircons occur in igneous rocks such as the Independence dikes (Chen and Moore, 1979). Taken separately, Archean zircons in the Nanaimo Group are not very diagnostic of provenance. Taken as a whole, and integrated with results from paleomagnetism and plate motion studies, the zircon data provide valuable evidence of the time table of tectonic transport of part of western North America and are in full accord with the Baja B.C. hypothesis.

CONCLUSIONS

Although many in the geological community now regard the Baja-B.C. problem as insoluble, this problem can be solved, given some willingness on the part of specialists across the geological spectrum to integrate their results with those of other subdisciplines. An open mind and the courage to embrace unexpected results are required. We are as blinkered by our specialty (paleomagnetism) as anyone else. To us the paleomagnetic evidence is solid, and attempts to explain it away with multiple, ad hoc hypotheses seem misguided. One impediment to acceptance of Baja B.C. sized northward transport may be the lack of a readily identified fault capable of accommodating the displacement. Hollister and Andronicos (1997) proposed a candidate, and other likely possibilities have been suggested (Cowan et al., 1997; Umhoefer, 1998; Tikoff and de Saint-Blanquat, 1998). We have shown that detrital zircon data from the Nanaimo Group, far from disproving Baja B.C., actually support it. Are there no truly crucial tests left? One way to disprove Baja B.C. is to find a "bomb-proof" steep paleomagnetic inclination in the right rocks. Perhaps a fossil flora or fauna known only from northern (or southern) climatic zones may also prove crucial. This possibility depends upon a firm understanding of Late Cretaceous to Eocene climate zones in the eastern Pacific. Other tests are possible. However, we suspect that only after data from all the relevant subdisciplines of geology are fully integrated into a coherent pattern will the bulk of the geological community be convinced.

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