Structural correction of paleomagnetic vectors dispersed about two fold axes and application to the Duke Island (Alaska) ultramafic complex

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[1] A new analysis of paleomagnetic data from the mid-Cretaceous (~110 Ma) ultramafic complex at Duke Island (southeast Alaska) supports large poleward transport of the Insular superterrane relative to North America consistent with the Baja British Columbia hypothesis. Previous paleomagnetic work has shown that the characteristic remanence of the ultramafic complex predates kilometer-scale deformation of the very well developed cumulate layering but that the layering was not horizontal everywhere before the folding. It is possible, however, to estimate paleohorizontal for the Duke Island ultramafic complex because the postremanence deformation of the intrusion occurred about two well-defined and spatially separate fold axes. In such a case the tectonically rotated paleomagnetic directions should be distributed along small circles centered on each of the two fold axes. The ancient field direction will lie on both small circles and therefore will be identifiable as one of their two intersection points. Interpreted this way, the tectonically rotated remanence of the Duke Island ultramafic complex defines a mid-Cretaceous (i.e., ancient) field direction that is within 2° of the paleomagnetic direction found by assuming the cumulate layering was initially horizontal (despite the paleomagnetic evidence to the contrary) and performing the standard structure correction. The inferred mid-Cretaceous paleolatitude of Duke Island is 21.2° (2350 km) anomalous with respect to cratonic North America. This result is concordant with southerly paleolatitudes determined by many other workers from bedded rocks of terranes farther inboard in the Insular and Intermontane superterranes. *INDEX TERMS:* 1525 Geomagnetism and Paleomagnetism: Paleomagnetism applied to tectonics (regional, global); 1594 Geomagnetism and Paleomagnetism: Instruments and techniques; 8157 Tectonophysics: Plate motions—past (3040); 8110 Tectonophysics: Continental tectonics—general (0905); 9350 Information Related to Geographic Region: North America; *KEYWORDS:* paleomagnetism, Duke Island, Baja BC

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1. Introduction

[2] As originally defined by *Irving* [1985], the "Baja British Columbia" ("Baja BC") hypothesis interprets the anomalously shallow and clockwise-rotated paleomagnetic remanence directions from middle and Late Cretaceous plutonic rock units of the western Canadian Cordillera as evidence of large-scale (i.e., thousands of kilometers) poleward transport relative to cratonic North America between 90 and 50 Ma. The hypothesis remains controversial for several reasons. To begin with, there are a variety of geological observations consistent with an alternative scenario in which the mid-Cretaceous units have moved only 1000 km or less relatively poleward. For example, there are plausible geological correlations between lithologic units on western terranes and similar ones to the east that are demonstrably in situ [e.g., *Monger and Price*, 1996]. No fault or fault system with documented offset equal to the full amount of transport has been identified. Moreover, there is paleomagnetic evidence from two plutons in one area (the Coast Mountains east of Prince Rupert) that has been interpreted as evidence of northeast-side-up tilting [*Butler et al.*, 2002, 2001c]. According to *Butler et al.* [1989], widespread undetected tilting in this direction could provide an alternative explanation for the discordant paleomagnetism of the five unlayered mid-Cretaceous plutons with shallow, clockwise-deflected remanence that originally motivated the Baja BC hypothesis [e.g., *Beck et al.*, 1981; *Irving et al.*, 1985].

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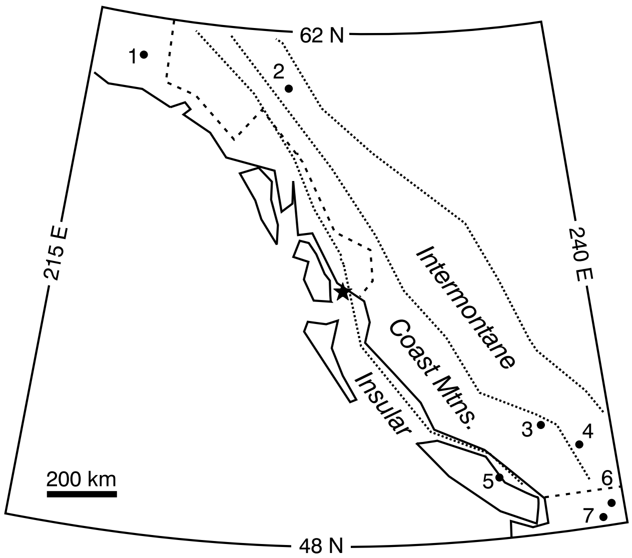

Figure 1. Sketch map showing study area and other relevant paleomagnetic localities. Dashed lines are United States–Canada border. Dotted lines are approximate boundaries of the three lithotectonic belts (Insular superterrane, Coast Mountains Orogen, and Intermontane superterrane) discussed in text. Paleomagnetic localities are as follows: star, Duke Island (this study); 1, MacColl Ridge [*Stamatakos et al.*, 2001]; 2, Carmacks Group [*Wynne et al.*, 1998, and references therein]; 3, Mount Tatlow [*Enkin et al.*, 2003, and references therein]; 4, Spences Bridge Group [*Haskin et al.*, 2003, and references therein]; 5, Nanaimo Group [*Enkin et al.*, 2001; *Kim and Kodama*, 2004]; 6, Methow block [*Enkin et al.*, 2002, and references therein]; 7, Mount Stuart [*Housen et al.*, 2003, and references therein].

[3] Because of the problems listed above, debate concerning Baja BC has shifted to more recent paleomagnetic studies in rock units that are layered or have other indicators of paleohorizontal [*Bogue et al.*, 1995; *Enkin et al.*, 2001, 2002; *Haskin et al.*, 2003; *Stamatakos et al.*, 2001; *Wynne et al.*, 1995]. These studies have the favorable attribute that postmagnetization tilting can be directly measured and compensated geometrically, thus circumventing the key uncertainty that plagues interpretation of paleomagnetism in unlayered plutonic rocks. *Butler et al.* [2001a, 1989] have argued that uncertainties (e.g., the possibility of unrecognized remagnetization or poor control on paleohorizontal) in some of these studies are so serious that the mid-Cretaceous paleolatitude of the units cannot be reliably inferred. To better assess the reliability of one of the key studies, *Butler et al.* [2001b] extended the previous work of *Bogue et al.* [1995] on the Cretaceous layered ultramafic intrusive complex on Duke Island in southeast Alaska (Figure 1). This restudy, which will be described in more detail in section 3, produced paleomagnetic evidence that was interpreted to show that the cumulate layering in the ultramafic rock at Duke Island was not initially horizontal and so could not serve as a datum for restoring the paleomagnetic remanence to its original orientation.

[4] We present here a reanalysis of available structural and paleomagnetic data from the Duke Island ultramafic complex. Because the cumulate layering at Duke Island has been folded about two distinct and spatially separate fold axes, it is possible to infer the original orientation of the remanence without the assumption that the layering was initially nearly horizontal. We show that restored this way, the best estimate of the mid-Cretaceous paleolatitude of Duke Island (and the Insular superterrane it intrudes) is virtually identical to that reported by *Bogue et al.* [1995] and supportive of the Baja BC hypothesis. Moreover, we will update a comparison [*Bogue et al.*, 1995] placing the result from Duke Island in the context of paleolatitudes established (with control on paleohorizontal) for seven middle and Late Cretaceous formations of the Insular and Intermontane superterranes.

2. Geologic Setting

[5] The geologic framework of the Baja BC debate has been thoroughly described elsewhere [*Cowan et al.*, 1997], and so only the most essential features will be repeated here. At issue is the mid-Cretaceous disposition of three geologic belts (from west to east, the Insular superterrane, Coast Mountains Orogen, and Intermontane superterrane) that now constitute the western Cordillera of North America between latitudes 48° and 62°N (Figure 1). As defined by *Irving* [1985], Baja BC included all these units; more recent versions of the hypothesis [e.g., *Cowan et al.*, 1997] restrict the term to the Insular superterrane and Coast Mountain Orogen (which were together by 90 Ma) because their travel history apparently differs from that of the Intermontane superterrane. A key question in any version of the Baja BC hypothesis is the position of the Insular superterrane relative to North American craton at 90 Ma. Was it within several hundred kilometers of its present relative position (as in hypothesis A of *Cowan et al.* [1997], equivalent to the "moderate translation" hypothesis of *Butler et al.* [2001a])? Was it at some intermediate position (e.g., implying relative translation of 1600–1800 km as suggested by *Umhoefer* [2003])? Or, was the Insular superterrane some 20° (2100 km or more) farther from the pole than the western margin of the craton? Paleomagnetic results from mid-Cretaceous units in the Insular superterrane or Coast Mountains Orogen indicating 20° or more of discordance relative to cratonic North America [e.g., *Beck et al.*, 1981; *Bogue et al.*, 1995; *Irving et al.*, 1985; *Wynne et al.*, 1995] are fully compatible with the third alternative (the Baja BC hypothesis) but not the other two.

[6] The geology of Duke Island has been described in detail by *Irvine* [1974] and *Saleeby* [1992] and summarized as background for paleomagnetic studies by both *Bogue et al.* [1995] and *Butler et al.* [2001b]. The ultramafic complex (Figure 2), which constitutes ~15% of the island's surface, crops out as two main bodies (Hall Cove to the NW and Judd Harbor to the SE) which are likely connected at depth [*Irvine*, 1974]. The intrusion exhibits a crude concentric zoning, with a dunite core surrounded in succession by zones of olivine clinopyroxenite and hornblende clinopyroxenite. Plagioclase is completely absent from all the ultramafic rock types. The ultramafic rock, which has been dated (U/Pb in zircon) at 108–111 Ma [*Saleeby*, 1992],

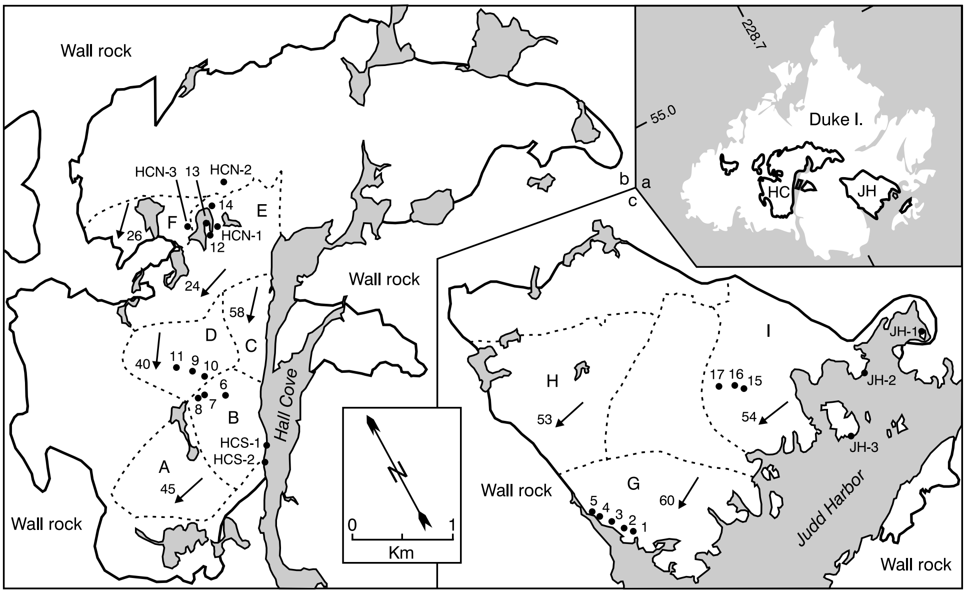

Figure 2. Partial geologic map of (a) Duke Island, showing the (b) Hall Cove (HC) and (c) Judd Harbor (JH) lobes of the ultramafic intrusion moved together for convenience (simplified from *Bogue et al.* [1995, Figure 2]). Shown with dots are the paleomagnetic sites of *Bogue et al.* [1995] (e.g., HCS-1, HCN-1, and JH-1) and those of *Butler et al.* [2001b] (numbered 1–17). Geological contacts are from *Irvine* [1974, Plate 2]. Numbered arrows show direction and amount of plunge of fold axes in structurally homogeneous areas (labeled A–I) as defined by *Bogue et al.* [1995] and used by *Butler et al.* [2001b].

intruded Paleozoic gabbros of the Alexander terrane [*Irvine*, 1974; *Saleeby*, 1992]. The Alexander terrane is a major element of the Insular superterrane, and so a mid-Cretaceous paleolatitude from Duke Island applies to both it and the Coast Mountains Orogen.

[7] From the standpoint of paleomagnetic study the key feature of the ultramafic intrusion at Duke Island is the spectacular cumulate layering displayed by all lithologies. Numerous features (e.g., slump blocks, drape folds, cross bedding, and graded bedding) provide strong evidence that the layering was formed by gravitationally controlled deposition of olivine and clinopyroxene grains on or near the bottom of the magma chamber [*Irvine*, 1974]. As described below, both this study and *Butler et al.* [2001b] interpret the paleomagnetic results as evidence that the layering at Duke Island formed within 20° of horizontal. The cumulate layering exhibits both short-wavelength (outcrop-scale) contortions and larger (kilometer-scale) open folding. As discussed in more detail in section 3, the short-wavelength structures predate the paleomagnetic remanence [*Bogue et al.*, 1995; *Butler et al.*, 2001b] while the larger-scale folds (perhaps better termed tilts) postdate the characteristic remanence [*Bogue et al.*, 1995; *Butler et al.*, 2001b]. For clarity, we will refer to these two scales of structure in section 3 as "early" and "later" to emphasize their temporal relation to the remanence even though both formed in mid-Cretaceous time.

3. Previous Paleomagnetic Studies

[8] The first paleomagnetic study of the ultramafic rocks on Duke Island [*Bogue et al.*, 1995] was based on a small set of eight sample sites collected in 1979 to address rock magnetic rather than tectonic issues. Demagnetization experiments isolated a remanence characterized by high-median destructive fields and unblocking temperature (T_b) distributions narrowly concentrated near 540°C. Examination of thin sections cut from the paleomagnetic cores revealed that clinopyroxene grains contained two sets of crystallographically oriented opaque lamellae that are essentially magnetite and that formed at temperatures very close to the T_b of the characteristic remanence [*Bogue et al.*, 1995]. Because other forms of magnetite observed in thin sections were either too coarse grained (with low coercivity) or clearly secondary (and therefore postdating the later folding), *Bogue et al.* [1995] inferred that these magnetite lamellae in silicate hosts carried the primary (prefolding) remanence. *Bogue et al.* [1995] also demonstrated that the very strong magnetic anisotropy of the ultramafic rocks had no systematic effect on either the direction or the dispersion of the primary remanence and was likely associated with secondary magnetite that was the product of minor serpentine formation.

[9] In an attempt to restore the cumulate layering to the orientation it had prior to the later and larger-scale folding, *Bogue et al.* [1995] examined the map data of *Irvine* [1974] and divided the ultramafic exposure into a set of nine structural domains as shown in Figure 2. In each domain (typically 1 km^2 in size) the layering appeared to be folded coherently about a well-defined fold axis. Fold axes from structural domains were consistently oriented within both the Hall Cove and Judd Harbor outcrop areas, but the mean fold axes of the two bodies were distinct, differing by 22° in trend and 20° in plunge (Figure 3). A paleomagnetic tilt test using a "compound correction" (removing the plunge of the fold axes and correcting for the tilt of the cumulate layering

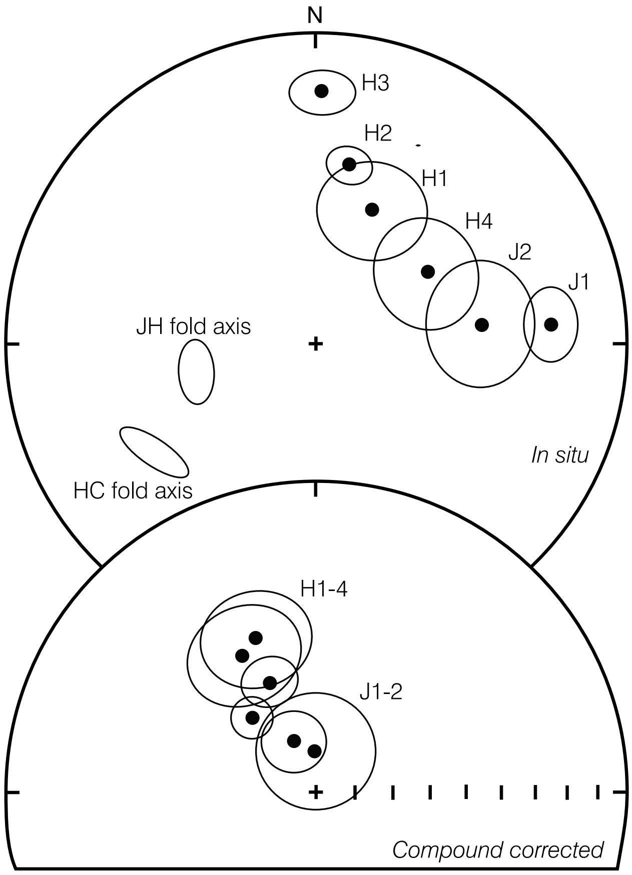

Figure 3. Paleomagnetic tilt test. Equal-area plots show paleomagnetic group means before and after compound structural correction. Groups J1 and J2 are from the Judd Harbor outcrop area; H1–H4 are from the Hall Cove outcrop area (see Table 1 for sites constituting each group.) Circles show 95% confidence regions [*Fisher*, 1953] about mean remanence directions. Also shown in southwest quadrant of Figure 3 (top) are ellipses centered on mean fold axes for Hall Cove (trend = 256, plunge = 56) and Judd Harbor (trend = 236, plunge = 36). Ellipses were sketched by eye around central 95% of distributions shown in Figure 5.

after areal averaging in the vicinity of site clusters) was highly positive; the precision parameter k [*Fisher*, 1953] improved from 3.0 to 31.9. This result clearly showed that the remanence predated the later (i.e., kilometer-scale) deformation and was likely primary. The mean remanence direction, restored using the assumption that the areally averaged layering was originally horizontal, was declination (D) = 320°, and inclination (I) = 66°. Compared to the reference direction for North America, the result implied that the ultramafic complex on Duke Island (and therefore the Insular superterrane it intrudes) had moved some 3000 km poleward relative to North America since 110 Ma, consistent with the Baja BC hypothesis.

[10] The result of *Bogue et al.* [1995] was derived from an average of eight site mean directions but only three distinct structural corrections (one each for the northern and southern groups of Hall Cove sites and a much less certain rotation for the three sites at Judd Harbor). In order to test the key assumption that the areally averaged cumulate layering was initially horizontal and to better assess the significance of the tilt test, *Butler et al.* [2001b] obtained a new collection of oriented samples from 17 sites (shown in Figure 2) that complemented the coverage of *Bogue et al.* [1995]. Unlike the previous work this new paleomagnetic study was aimed specifically at the issue central to the Baja BC hypothesis: the mid-Cretaceous latitude of Duke Island. *Butler et al.* [2001b] only collected from outcrops where the orientation of the cumulate layering could be accurately measured, although they eventually concluded (as had *Bogue et al.* [1995]) that the layering at outcrop scale was a poor indicator of paleohorizontal.

[11] *Butler et al.* [2001b] found that the remanence of the ultramafic rocks was well behaved and isolated characteristic remanence directions for all sites in a straightforward manner. They also found that the dispersion of site means improved dramatically (the precision parameter k increased from 6.0 to 31.4) after applying a compound structural correction based on areally averaged layering attitudes. For this restoration, *Butler et al.* [2001b] used the mean fold axes for Hall Cove and Judd Harbor calculated by *Bogue et al.* [1995] and their own picks (based on published map data [*Irvine*, 1974] plus their field observations) of mean layering attitudes near six groups of paleomagnetic sites. Included in their analysis were the five sites of *Bogue et al.* [1995] from Hall Cove. Like *Bogue et al.* [1995], *Butler et al.* [2001b] concluded that the remanence of the ultramafic complex "passes" the tilt test and was therefore acquired before the later deformation. *Butler et al.* [2001b] observed further that after structural correction the 14 site means from Hall Cove formed a cluster that was statistically distinct (22°) from the cluster of seven site means from Judd Harbor. Figure 3 and Table 1 show this result in a slightly different way using the mean directions of each of the six groups of paleomagnetic sites associated with a particular structural correction. *Butler et al.* [2001b] presented an approximate evaluation of errors and argued that the difference in overall mean directions between the structurally corrected sites from Hall Cove and Judd Harbor could not be fully ascribed to uncertainties in the paleomagnetic or structural measurements. They finally concluded that the cumulate layering, even averaged over hundreds of meters, was not initially horizontal, that the prefolding inclination could not be determined, and that the pluton could therefore provide no information about the mid-Cretaceous paleolatitude of the Insular superterrane.

[12] At Duke Island, failure or success of the paleomagnetic tilt test depends entirely on the scale at which it is carried out. Combining our original data with that of *Butler et al.* [2001b], we have found that if individual outcrop-by-outcrop data are used, then the tests fail when applied at the scale of single traverses in the case of Butler et al.'s data or within single homogeneous areas as *Bogue et al.* [1995] tried originally but did not report. If the same information is used for a single test covering all sites in both ultramafic bodies, the result is null, i.e., no significant change in the concentration parameter k (S. Grommé, unpublished data, July 1998). Layering attitudes at this scale almost certainly represent structures associated with cross bedding, draping, or other early, "soft sediment" like deformation of cumulate layering.

Table 1. Compound Structural Correction on Domain-Averaged Paleomagnetic Directions, Duke Island Ultramafic Complex

Site Group	Sites	Layering Pole	Fold Axis	Group Mean	Compound Corrected Group Mean	α_{95}	Original Layering
J1	1–4	100.1, 20.9	256, 56	085.4, 25.3	336.4, 75.7	8.3	63.2, 13.4
H1	6–8	104.7, 58.9	234, 36	022.7, 51.6	338.8, 45.8	13.6	252.8, 16.6
H2	9–11	045.4, 47.7	234, 36	010.2, 41.3	318.7, 64.3	5.4	131.3, 6.8
H3	12–14, HCN 1–3	029.3, 40.0	234, 36	001.0, 19.9	336.9, 58.5	7.1	258.9, 3.9
J2	15–17	098.8, 46.3	256, 56	083.4, 45.5	359.7, 79.3	15.3	51.0, 18.4
H4	HCS 1–2	118.1, 40.7	234, 36	057.7, 55.4	331.9, 48.5	(14)	238.2, 13.9

Site group designates group of paleomagnetic sites receiving the same compound correction. J1 and J2 are from Judd Harbor area; H1–H4 are from Hall Cove area. Sites are paleomagnetic site names. HCN 1–3 and HCS 1–2 are from *Bogue et al.* [1995]; all others are from *Butler et al.* [2001b]. Layering pole is trend and plunge (in degrees) of pole to areally averaged cumulate layering. Fold axis is trend and plunge (degrees) of fold axis used in compound correction. Group mean is declination (degrees east) and inclination (positive downward) of mean in situ remanence direction for site group. Compound corrected group mean is declination and inclination of mean compound-corrected remanence direction. The α_{95} column is the 95% confidence region [*Fisher*, 1953] about mean remanence direction (and for H4, in parentheses, the angle between the two site mean directions). Original layering is inferred strike and dip (degrees) of cumulate layering prior to deformation. Fisher mean of in situ domain-averaged paleomagnetic directions is $D = 42.3$, $I = 45.6$, $k = 6.6$, and $\alpha_{95} = 28.2$. Fisher mean of structurally corrected domain-averaged paleomagnetic directions is $D = 334.8$, $I = 62.3$, $k = 31.0$, and $\alpha_{95} = 12.2$; Bingham mean is $D = 334.7$, $I = 62.3$, major semiaxis = 13.3, minor semiaxis = 3.7, pole to great circle through major semiaxis is $D = 242.4$, and $I = 1.2$. Mean of six equivalent VGPs is latitude = 72.0°N, longitude = 119.8°E, $k = 18.4°$, and $\alpha_{95} = 16.0°$. Mid-Cretaceous paleolatitude is 43.9° ± 16°. Mid-Cretaceous paleolatitude anomaly with respect to North America is (reference pole of *Housen et al.* [2003]) 21.2° ± 11.5°.

[13] If structural attitudes are averaged for each traverse or each part of a homogeneous area surrounding a single site, the number of independent structural blocks from which we have data reduces to six, and the result of the tilt test is strongly positive. The larger scale and younger tilts made evident by this averaging are associated with mid-Cretaceous thrusting [*Saleeby*, 1992], a regional deformation affecting much of the western Coast Mountains [*Rubin et al.*, 1990]. The dependence of the tilt test on scale is the natural result of the facts that deformation of the Duke Island ultramafic bodies occurred progressively during solidification and cooling and that the magnetization of the rocks was acquired relatively late in this process at a time when deformation amounted to broad-scale block tilting. These blocks approximate the homogeneous areas as originally defined [*Bogue et al.*, 1995]. In this context it is significant to recall that we (Gromme, in 1984) originally delineated these homogeneous areas partly on the basis of bands of little or no outcrop, faults, and linear areas full of small lakes as shown by *Irvine* [1974, Plate 2] (compare with *Bogue et al.* [1995, Figure 2].) These boundaries, marked by subdued topography, faults, or both, are almost certainly underlain by comminuted rock, perhaps mylonites in part.

4. Structural Correction With Two Fold Axes

[14] As discussed in more detail below, we agree with *Butler et al.* [2001b] that the paleomagnetic data from Duke Island provide evidence that the areally averaged cumulate layering was not necessarily horizontal when the remanence was acquired. We do not agree, however, that it is impossible to infer the predeformation remanence direction. An interesting aspect of the later broad folding or tilting affecting the cumulate layering at Duke Island is that it occurred about two distinct fold axes, one for the Hall Cove outcrop area and one for the Judd Harbor outcrop area [*Bogue et al.*, 1995]. This circumstance makes possible an alternative way to restore the paleomagnetic directions to their original, pre-late-folding orientation that involves less restrictive assumptions than usual. In particular, this alternative technique does not require that the layering (at the time its magnetization was acquired) was everywhere perfectly horizontal. It does require that prior to the later folding the layering was sufficiently planar that the axes about which the folding or tilting occurred are identifiable and that folding or tilting occurred about horizontal axes.

[15] Consider two rock units, both with the same prefolding paleomagnetic remanence. Folding about horizontal axes affects both units, but the azimuth of the fold axis differs between the two units. For rock unit 1 the folding disperses the remanence directions along a particular small circle. The pole of this small circle is fold axis 1; the tilted remanence directions (see Figure 4) define its radius. For rock unit 2 the tilted remanence directions are distributed along a different small circle; its pole is fold axis 2, and the paleomagnetic directions (Figure 4) define its radius. Because the fold axes are distinct, one direction common to both small-circle distributions will be the original, prefolding remanence direction. In general, the pair of small circles will define two possible prefolding remanence directions. If

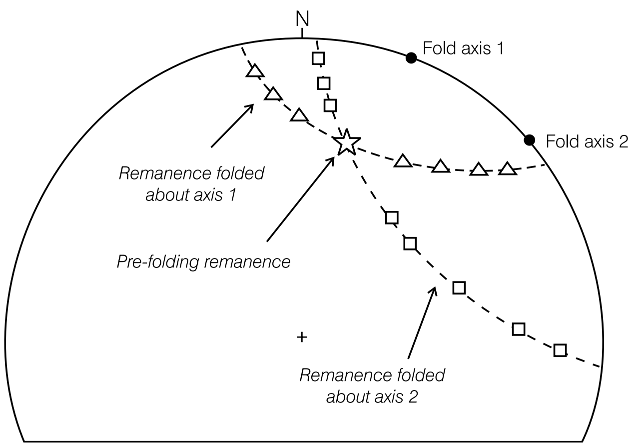

Figure 4. Hypothetical paleomagnetic remanence folded about two axes. Folded remanence directions (squares and triangles) are distributed along small circles centered on each fold axis (dots). The two small circles intersect at the prefolding remanence direction (star).

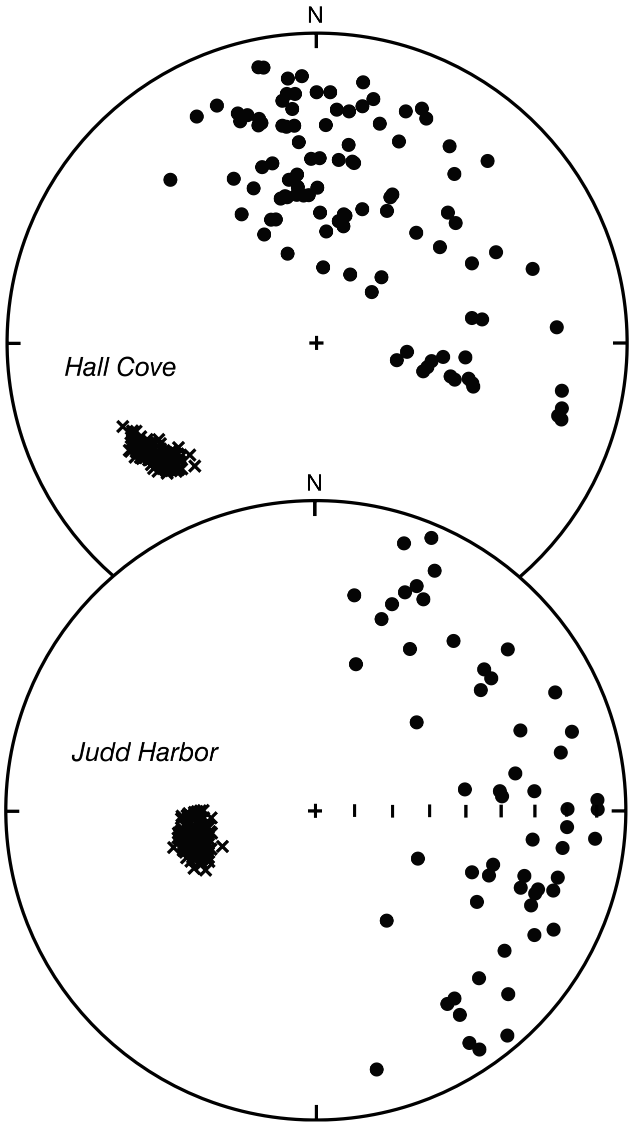

Figure 5. Observed poles to layering (dots) and distribution of 200 best fit fold axes (crosses) found by bootstrap resampling technique for Hall Cove and Judd Harbor outcrop areas.

one of the two choices can be eliminated on independent grounds, then the technique yields a unique determination of the prefolding direction. Notice that the two–fold axis technique makes no assumption about horizontality of layering (averaged over any scale) at the time of magnetization. Instead, it follows from the much less restrictive assumption that prefolding layering attitudes were not so variable that fold axis orientations are indeterminate; i.e., that the layering on the scale of the folds was approximately planar.

[16] In order to apply this technique to the structural and paleomagnetic observations from Duke Island, it is essential to establish that the two axes associated with the later folding or tilting are well determined and distinct. Figure 5 shows the result of bootstrap resampling experiments exploring the uncertainty associated with the mean fold axes for the Hall Cove and Judd Harbor bodies. The structural data used here, layering attitudes picked off the map of *Irvine* [1974], are the same as those used to calculate mean fold axes by both *Bogue et al.* [1995] and *Butler et al.* [2001b]. The procedure for Hall Cove (with 102 poles to bedding) was as follows: (1) Construct a pseudosample set by drawing a random set of 102 poles from the list. In a typical pseudosample set, several of the sample poles will be represented more than once, and several will not be represented at all. (2) Find the great circle that best fits (in a least squares sense) the pseudosample distribution, and take its pole as an estimate of the Hall Cove fold axis. (3) Repeat steps one and two 199 times, the result being 200 estimates of the Hall Cove fold axis. The essence of the bootstrap method is to take the variation of poles generated by this pseudosampling scheme as representative of the variation one would find by estimating sample means from the actual distribution of bedding poles.

[17] It is apparent in Figure 5 that the fold axes for both Hall Cove (N = 102) and Judd Harbor (N = 60) are well determined, with somewhat more variation in azimuth than plunge. It is also clear from the plots that the two fold axes are quite distinct; there is no overlap between the two distributions. The plots also show that the folds affecting the cumulate layering are roughly cylindrical; i.e., the layering poles appear to be distributed along and about great circles. We assume that the fold axes were close to horizontal when tilting occurred as expected in shallow crustal stress fields, as is commonly observed in active folding, and as is done for the standard paleomagnetic tilt test. We also assume that the moderate southwesterly plunges of the fold axes postdate magnetization. As discussed by *Bogue et al.* [1995], the paleomagnetic data provide observational support for these assumptions; the tilt-corrected site mean directions cluster much more tightly if the fold axes are restored to horizontal than if they are not. Finally, there is good reason to believe that the Hall Cove and Judd Harbor bodies originally had the same prefolding remanence direction. Indeed, geophysical evidence [*Irvine*, 1974] suggests the two bodies are actually connected at depth, a single pluton that acquired a homogeneous magnetization as it cooled.

[18] Figure 6 shows the paleomagnetic site means from the Hall Cove body after the rotation (about a horizontal axis) that brings the Hall Cove fold axis to horizontal. The curve passing through the paleomagnetic data is the small circle about the Hall Cove fold axis that best fits the paleomagnetic data. The true ancient field direction should lie somewhere along this small circle. The plot also shows the results of a bootstrap-style simulation of the errors inherent to this particular small-circle fit. We incorporated site level paleomagnetic errors (assuming an average precision parameter of k = 66 for site level dispersion) and the errors in the fold axis determinations illustrated on Figure 5 to produce an artificial distribution of small-circle fits. To create each small circle in the distribution, we simulated a new set of paleomagnetic site means by drawing random samples from artificial Fisher distributions centered on the observed site means. We then randomly picked a fold axis from the bootstrapped distribution shown on Figure 5, rotated it to horizontal (applying the same rotation to the site mean directions), and calculated the small circle about the fold axis that best fit the simulated paleomagnetic data.

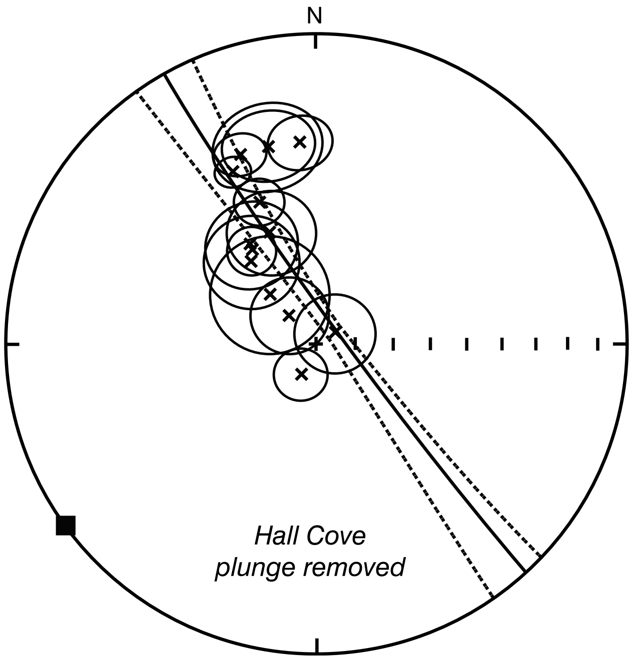

Figure 6. Small circle (solid line) about Hall Cove fold axis that best fits the Hall Cove site mean remanence directions (crosses with 95% confidence circles). All data are shown after rotation to remove plunge of fold axis shown as a square. Dashed lines show inner two thirds of range of small circles found by bootstrap technique described in text.

The hourglass-shaped band about the best fit small circle on Figure 6 encloses the inner two thirds of 200 small circles generated by this procedure. It shows the range (approximating ± one standard deviation) in small-circle fits that might be expected if someone were to redo the structural and paleomagnetic measurements 200 times.

[19] Figure 7 shows the corresponding best fit small circle and error simulation for the Judd Harbor body (after the fold axis has been restored to horizontal). The paleomagnetic data on the plot include the Judd Harbor sites of *Bogue et al.* [1995]. The lack of observable layering attitudes in the vicinity of *Bogue et al.*'s [1995] three Judd Harbor sites that precludes their use in the standard tilt correction [see *Butler et al.*, 2001b] is irrelevant in this reconstruction. Notice that structural data alone define the fold axis and hence the pole of the best fit small circle. Paleomagnetic data alone define the radius of the best fit small circle about the specified pole. Directly fitting a small circle to the paleomagnetic data would be practical only if the variation in tilt affecting the paleomagnetic sites greatly exceeds other effects that disperse the paleomagnetic site mean directions. In the case of Duke Island, however, the abundant measurements of the cumulate layering provide a much stronger constraint on fold axis orientation than do the paleomagnetic data.

[20] Figure 8 (top) shows the intersection of the small-circle fits to the data from Hall Cove and Judd Harbor. This intersection (D = 337.3°, I = 61.0°) represents the only plausible ancient field direction common to both structural and paleomagnetic data sets. (The other intersection of these small circles corresponds to an upward direction and is not a plausible prefolding remanence direction because (1) all the actual data are in the lower hemisphere and (2) the ultramafic complex acquired its remanence during the Cretaceous Normal Superchron.) To characterize the uncertainty in this intersection point, we simulated the effect of structural and paleomagnetic errors by calculating 200 intersections of randomly selected pairs of small circles from the simulated small-circle distributions described above and shown (inner two thirds only) on Figures 6 and 7. The irregular curve about the intersection point on Figure 8 encloses 83% of the simulated distribution of small-circle intersections. The distribution is irregular in shape (with more variation in inclination than in declination) and is skewed toward directions with steeper inclinations. If one ignores these details and models the simulated data as a Bingham distribution [*Onstott*, 1980], the mean is virtually identical to the intersection of the best fit small circles for Hall Cove and Judd Harbor (see Figure 8).

[21] The azimuths of the two fold axes from Duke Island are ~90° from the declination of the inferred remanence direction. As a result the assumption that the fold axes were originally horizontal, while reasonable, hardly affects the inferred inclination (and corresponding paleolatitude) of the ancient field direction. For example, if the later folding had occurred about axes with the same azimuths but plunging 10° either SW or NE, then the inferred ancient field inclination would change by less than a degree; the assumption of steeper initial plunges would yield a shallower ancient field direction. More critical is the assumption that the two fold axes originally had the same plunge. The standard tilt test itself provides support for this assumption: The precision parameter k for domain means is 17.3 if the difference in plunge is not removed and 32.0 if the plunges are assumed to have been

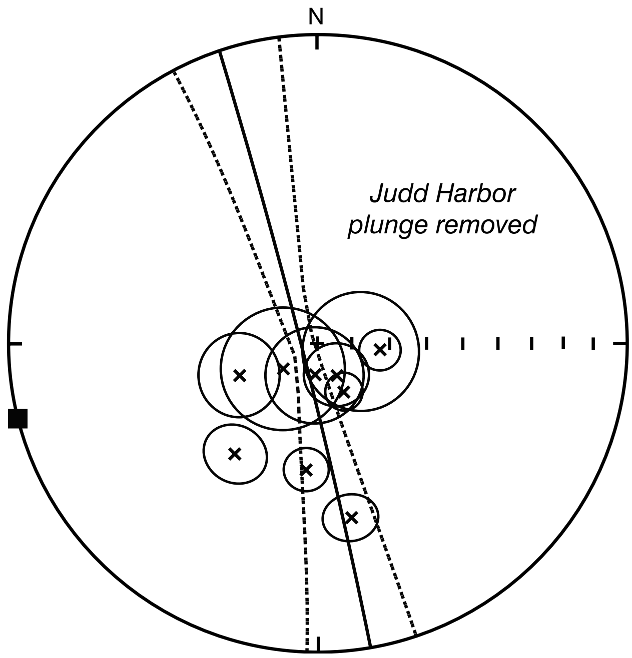

Figure 7. Best fit small circle (solid line) and error estimate (dashed line) for Judd Harbor structural and paleomagnetic data (plunge removed). See Figure 6 for further explanation.

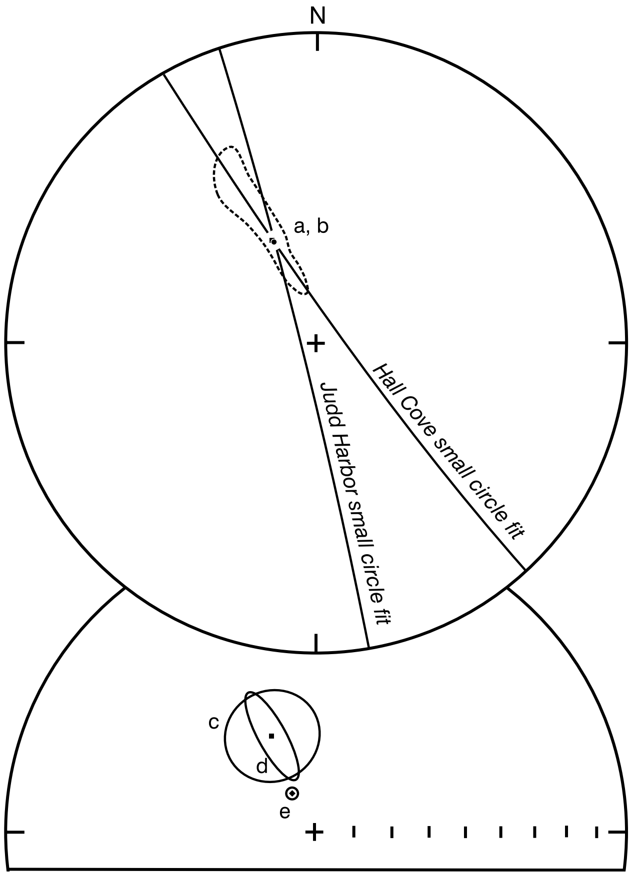

Figure 8. Two estimates of the prefolding ancient field direction for Duke Island ultramafic complex. (top) Equal-area plot shows ancient field direction inferred by intersecting small circles. Solid lines show small-circle fits to structural and paleomagnetic data from Hall Cove and Judd Harbor areas; their intersection (point a) is the inferred ancient field direction. Dotted line encloses 83% of a simulated distribution incorporating structural and paleomagnetic errors of 200 small-circle intersections. Point b is the mean of the simulated data assuming they follow a Bingham distribution. (bottom) Equal-area plot shows paleomagnetic estimate of ancient field direction. Dot is the grand mean with 95% confidence region (c, assuming a Fisher distribution; d, assuming a Bingham distribution) of compound-corrected domain mean directions shown on Figure 3. Point e is the mid-Cretaceous field direction and 95% confidence region for Duke Island assuming no translation relative to North America (reference pole of *Housen et al.* [2003]).

equal. Also critical is the assumption that the 20° difference in fold axis azimuths between Hall Cove and Judd Harbor reflects a real difference in the way the two bodies were folded. An alternative possibility is that the fold axes originally had the same azimuth but became distinct by a later vertical axis rotation between the two parts of the intrusion. The paleomagnetic data do not provide a sensitive test of this hypothesis, but such a rotation is clearly not responsible for the angular difference (which is similar in magnitude but almost entirely in inclination) between the mean compound-corrected directions from Hall Cove and Judd Harbor (see Figure 3).

5. Revised Paleolatitude Estimate

[22] The small-circle intersection shown in Figure 8 (top) is very close (1.8°) to the grand paleomagnetic mean (D = 334.8°, I = 62.3°) one obtains by summing the compound-corrected mean directions (Figure 3 and Table 1) from each of the six structural domains determined by *Butler et al.* [2001b]. This paleomagnetic mean, along with 95% confidence regions calculated assuming the data are from either a Fisherian or Bingham distribution, is shown in Figure 8 (bottom). We prefer the Bingham error ellipse because it better expresses the dispersion of the domain means, which vary more in inclination than in declination. A grand mean calculated from structural domain means (N = 6) has a larger (and, in our view, more realistic) confidence region than one calculated (assuming either a Fisher or Bingham distribution) by assigning unit weight to each of the site means (N = 21) listed by *Butler et al.* [2001b, Table 3].

[23] Because the two-fold-axis technique yields the same mean direction as the mean of the six compound-corrected domain mean directions, we accept the latter (and its associated Bingham 95% confidence region) as the best estimate of the ancient field direction from the Duke Island ultramafic body. Essentially, we are taking the agreement between this mean and estimate derived from intersecting small circles as evidence that effects of initial dips on the structural corrections are self-canceling and therefore not seriously biasing our estimate of the ancient field direction. We discuss this fortuitous circumstance in more detail below. For comparison, Figure 8 (bottom) also shows the ancient field direction (D = 78.4°, I = 327.1°, α_{95} = 1.5°) that would be expected at Duke Island had the site remain fixed with respect to North America since the mid-Cretaceous (reference pole of *Housen et al.* [2003]; pole longitude = 191.2°E, pole latitude = 70.1°N, α_{95} = 2.7°). There is no overlap between the 95% confidence regions about the grand paleomagnetic mean and the reference direction nor in the inclination extrema of the confidence regions; the directions are distinct, even when only their inclinations are compared.

[24] The mean of the six VGPs (assumed Fisherian) corresponding to the structurally corrected domain means (Table 1) yields a paleolatitude of 43.9° (±16.0°). The expected paleolatitude (using the North American reference pole of *Housen et al.* [2003]) is 68.0° (±3.7°). The paleolatitude anomaly with respect to North America is 21.2°, with the 95% confidence interval equal to ±11.5° calculated using the method of *Debiche and Watson* [1995]. There are no significant differences between these values and those calculated assuming the VGPs follow a Bingham distribution. For comparison, the paleolatitude anomaly calculated directly from the inclination of the small-circle intersection point is 25.6° but with an uncertainty that is not straightforward to evaluate. As discussed above, a simulated distribution of 200 small-circle intersections incorporating structural and paleomagnetic errors shows that the confidence region about the small-circle intersection is irregularly shaped and not centered on the intersection. What can be said is that 94% of the simulated intersections have inclinations shallower than

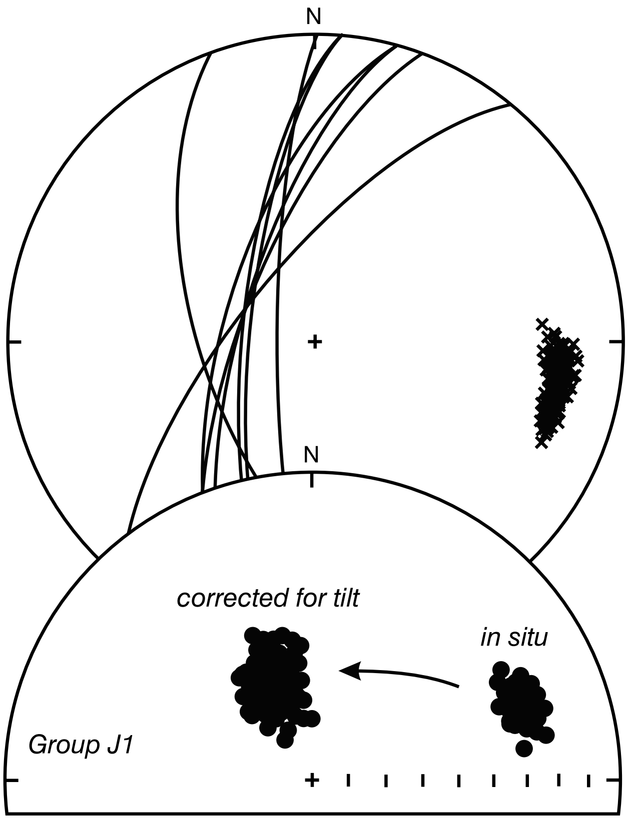

Figure 9. Expected dispersion of compound-corrected J1 group mean remanence directions from paleomagnetic and structural errors. (top) Solid lines showing observed layering in vicinity of paleomagnetic sites. Crosses show distribution of 200 mean layering poles found by bootstrap resampling of the data. (bottom) Artificial Fisher distribution (labeled "in situ") expressing within-domain paleomagnetic errors and distribution (labeled "corrected for tilt") of compound-corrected group mean directions incorporating errors in determining the fold axis, mean layering, and paleomagnetic group mean direction. See text for fuller explanation.

the shallowest directions in the 95% confidence region about the reference direction. Furthermore, the irregular curve enclosing 83% of the intersections (see Figure 8) is distinct in inclination from the 95% confidence region about the reference direction. Although it is not possible to calculate a formal confidence interval on the paleolatitude anomaly derived from the small-circle analysis, the two observations above suggest that the paleolatitude anomaly based only on the small-circle intersection is significant at a high (83–94%) level of confidence. Because the grand paleomagnetic mean yields a similar (and slightly smaller) paleolatitude anomaly but with straightforward confidence limits, we regard it as the best estimate of the mid-Cretaceous paleolatitude of Duke Island.

6. Discussion

6.1. Magnitude of the Initial Dips

[25] The key conclusion of *Butler et al.* [2001b] was that the cumulate layering in the ultramafic complex at Duke Island, even averaged over hundreds of meters, was never horizontal. They estimated that up to approximately half the difference between the mean remanence directions from the Hall Cove and Judd Harbor bodies could be attributed to known paleomagnetic and structural errors, with the rest arising from the presumed falsity of the assumption that the areally averaged cumulate layering was originally horizontal. To better quantify the way that initial dips contribute to the errors, we performed numerical experiments using the bootstrap technique to simulate the combined effect of three kinds of known errors affecting the structurally corrected directions: uncertainty in the fold axis orientation, uncertainty in the estimate of domain mean layering, and within-domain paleomagnetic scatter. The idea was to isolate the effect of initial dips by seeing how much of the observed dispersion can be accounted for by all other sources.

[26] The bootstrap technique and results for estimating errors on the fold axis determinations were described above and are shown in Figure 5. Figure 9 shows the results of bootstrap resampling experiments performed on the poles to bedding and site mean paleomagnetic directions from the structural domain comprising paleomagnetic sites 1–4 of *Butler et al.* [2001b]. Figure 9 (top) shows 200 estimates of the mean layering attitude based on bootstrap resamplings of the eight layering attitudes used to calculate the domain mean layering. The data for these calculations are the same as those used by *Butler et al.* [2001b] for their structural corrections; they include values picked from *Irvine*'s [1974] map and new field measurements. Figure 9 (bottom) shows an artificial Fisher distribution (labeled "in situ") with precision parameter k equal to the observed scatter of paleomagnetic site means within the domain. The center of this artificial distribution is an "ideal" domain mean direction that the compound structural correction will take exactly to the grand mean corrected direction of $D = 334.8°$ and $I = 62.3°$. Random samplings of this distribution will display dispersion similar to that observed for the actual paleomagnetic sites but will have means that scatter about the grand mean direction. Figure 9 also shows the result of picking a fold axis from the distribution shown in Figure 5, a domain mean layering pole from the distribution in Figure 9 (top), and an estimate of the group mean direction found by sampling the "in situ" distribution shown on the plot, performing the compound structural correction with these values, and then repeating the process 199 times. The cloud of points labeled "corrected for tilt," which by design centers on the grand mean direction, shows the variation in the compound-corrected domain mean direction that arises from uncertainty in the structure and the within-domain paleomagnetic errors.

[27] The final step is to randomly pick mean directions from distributions created this way for each of the six structural domains and compute their angular dispersion. The calculated scatter of the six structurally corrected ideal domain means, which averaged $\sim 7°$ in the 200 trials, arises solely from within-domain dispersion and uncertainty in the structural corrections. The difference between the simulated dispersion (7°) and the observed value (13°) is $\sim 11°$ (i.e., $(13^2 - 7^2)^{1/2}$), which represents the contribution from the one source of error not present in the simulation: differences between the (structurally corrected) domain mean directions. Assuming that the ancient, prefolding remanence was

uniform across the intrusion, these differences almost certainly reflect the domain-scale departures of the cumulate layering from horizontal. If random in orientation, then premagnetization dips would have to average $\sim 17°$ to produce the observed dispersion of structurally corrected domain mean directions.

[28] This statistical estimate of the magnitude of initial dips may be compared to ones based on direct comparisons between the compound-corrected domain mean directions (which assume the layering was initially horizontal) and the ancient field direction inferred from the two-fold-axis technique (which makes the less restrictive assumption that the fold axes were initially horizontal). For each domain mean direction we simply found the prefolding layering attitude needed to bring the observed remanence direction to the inferred ancient field direction. *Butler et al.* [2001b] performed this same exercise using an ancient field direction consistent with the assumption that Duke Island was 1000 km south of its present position relative to North America in the mid-Cretaceous. In our reconstruction, cumulate layering originally dipped away from the center of the intrusion at comparable dips (an average of 10° to the NW for Hall Cove and 16° to the SE for Judd Harbor; see Table 1). This pattern of roughly opposing dips explains why the compound-corrected mean direction (which is susceptible to bias from initial dips) is virtually identical to that found by the two-fold-axis method (which is relatively immune to problems from initial dips). The reconstruction of *Butler et al.* [2001b] shows a more asymmetrical pattern; they inferred that the layering in the Judd Harbor body was initially horizontal while that in the Hall Cove body dipped 22° to the NW. Both reconstructions appear plausible, and we know of no geological evidence that might help decide between them. As judged by the dispersion they introduce to either structural reconstruction, the areally averaged initial dips of cumulate layering at Duke Island are of the order of 15°. This value is clearly large enough to significantly affect (if not recognized and dealt with) a paleomagnetic estimate of paleolatitude but also small enough to explain why the later folding is so well expressed.

6.2. Lessons From Other Layered Intrusions

[29] As described above, paleomagnetic observations support our hypothesis that the cumulate layering at Duke Island was subhorizontal and roughly planar over large areas. This finding is consistent with *Irvine*'s [1974] conclusion that the features and orientation of the layering were primarily controlled by gravity. A variety of features (e.g., graded beds and spectacular cross bedding) strongly suggest that magmatic density currents originating on steep magma chamber walls form the layering. These currents, which flow across the magma chamber floor at speeds of several kilometers/hour [*Irvine*, 1980], deposit grains as they slow on the shallow slopes characteristic of the magma chamber floor. Density currents of this sort are physically plausible because both major cumulate minerals (olivine and pyroxene) have a significant positive density contrast (of order 500 kg/m^3) with the host magma.

[30] Igneous layering in many other well-studied plutons, mostly mafic and ultramafic, has been extensively described and summarized by *Wager and Brown* [1968]. Of these examples the most spectacular exhibition of gravity-dominated deposition by magmatic density currents is the layered series of the early Eocene Skaergaard gabbro intrusion in east Greenland [*Irvine*, 1998; *Wager and Brown*, 1968]. Mistakenly referring to it as an "ultramafic intrusion," *Butler et al.* [2001b] called attention to the paleomagnetic investigation of the Skaergaard by *Schwarz et al.* [1979]. In that study of a transect spanning most of the layered series, Schwarz and coworkers found that between-site dispersion of paleomagnetic directions increased after tilt correction, whether the correction was made on a site-by-site basis (one oversize core per site) or on a more generalized basis using the geologic map originally made by L. R. Wager and W. A. Deer [see *Wager and Brown*, 1968]. Moreover, Schwarz and coworkers showed that the in situ paleomagnetic directions agreed rather well with the limited number of paleomagnetic directions available from coeval or slightly older lava flows in east Greenland. From this they concluded that tilting of the Skaergaard gabbro intrusion, as measured by the south-southeast dips of the enclosing lavas [see *Wager and Brown*, 1968, Figures 7a and 7b] had occurred after its solidification but before it had cooled through the Curie temperature. The temperature interval was from $\sim 1000°$ to 580°C, which corresponded to a time interval of 250,000 years or less [*Schwarz et al.*, 1979]. This conclusion is well supported by contemporary and subsequent paleomagnetic investigations of early Eocene basalts in both east and west Greenland [*Faller and Soper*, 1979; *Riisager et al.*, 2003]. It differs from the interpretation of *Butler et al.* [2001b], who ascribe the negative result of the tilt test at Skaergaard to distortion of the cumulate layering by thermal convection.

[31] At Skaergaard, pretilting layering is observed to dip away from opposite walls toward a low point in the magma chamber floor with dips ranging from 2° to $\sim 17°$ [*Wager and Brown*, 1968]. At Duke Island, paleomagnetically inferred predeformational layering dips as evaluated in this study or by *Butler et al.* [2001b] are very similar. One key difference between the two plutons is that plagioclase is present as a cumulate phase at Skaergaard and completely absent at Duke Island. Unlike pyroxene and olivine, plagioclase is very close to neutrally buoyant in mafic magma. There is good reason, therefore, to expect that gravity's role in creating the layering at Duke Island was at least equal to or probably somewhat greater than it was at Skaergaard. The initial dips inferred in our reconstruction (which range from 4° to 18°) are entirely consistent with this conclusion.

6.3. Comparison With Other Published Results for Baja BC

[32] In Figure 10 we show the revised paleolatitude for Duke Island relative to the most recently published Cretaceous reference paleomagnetic pole for the North American craton [*Housen et al.*, 2003]. The revised value, shown as the difference between the observed and expected paleolatitude (21.2° ± 11.5°) is somewhat less than the 27° ± 12° shown by *Bogue et al.* [1995, Figure 14] but has much better determined error limits. The Duke Island paleolatitude difference with its 95% confidence limits is among the largest of those determined from other Cordilleran superterranes, as befits its position as the most outboard of them. It is consistent with the Baja BC hypothesis and precludes hypothesis A of *Cowan et al.* [1997] or the "moderate translation" hypothesis of *Butler et al.* [2001a]. An inter-

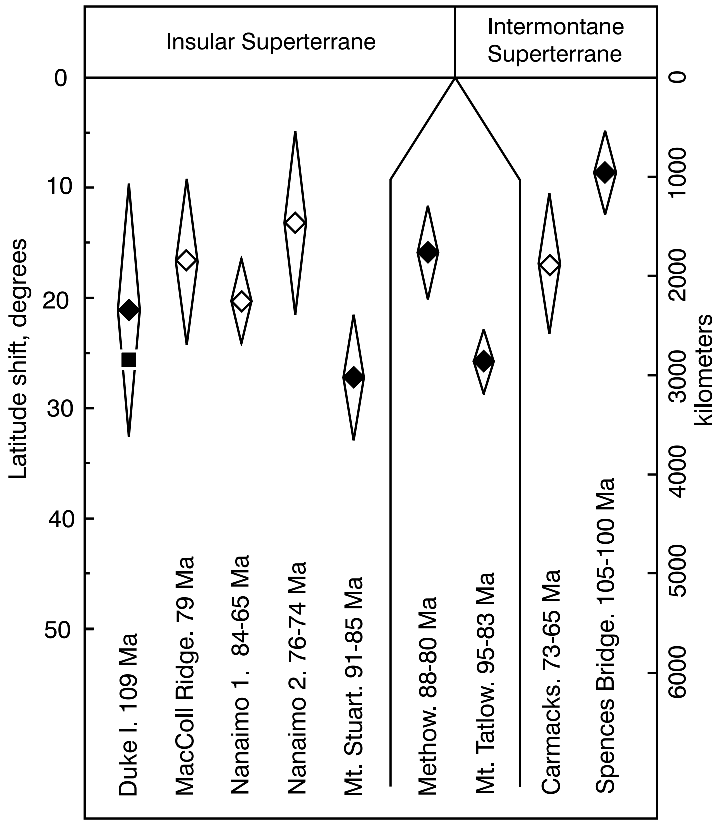

Figure 10. Paleolatitude difference diagram for Cretaceous rocks of the Canadian Cordillera and southern/southeastern Alaska. Post-Cretaceous northward latitude shifts are the differences between the observed paleomagnetic paleolatitudes and those predicted from the appropriate reference pole for the North American craton, calculated either using the method of *Debiche and Watson* [1995] or using the multiplier 0.78 from *Demarest* [1983]. Only data from rocks in which the original horizontal can be estimated directly are included; data from plutonic rocks other than the Duke Island ultramafic intrusion and the Mount Stuart batholith are omitted. Solid diamonds refer to the 125–85 Ma pole of *Housen et al.* [2003]; open diamonds refer to the 80–63 Ma pole of *Wynne et al.* [1992]. Tapered areas about symbols are 95% confidence intervals about the latitude differences that schematically represent the diminishing probabilities of values farther from the means. For comparison, the solid square depicts the latitude shift derived directly from the small-circle intersection technique as described in the text. The diagram shows results from the following studies: Duke Island, this study; MacColl Ridge, *Stamatakos et al.* [2001]; Nanaimo Group 1, *Enkin et al.* [2001]; Nanaimo Group 2, *Kim and Kodama* [2004]; Mount Stuart, *Housen et al.* [2003, and references therein]; Methow block, *Enkin et al.* [2002, and references therein]; Mount Tatlow strata and correlatives, *Enkin et al.* [2003, and references therein]; Carmacks Group, *Wynne et al.* [1998, and reference therein]; Spences Bridge Group, *Haskin et al.* [2003, and references therein]. The Methow block and the Mount Tatlow strata and correlatives are geographically within the Intermontane superterrane but were assigned to the Insular superterrane by *Haskin et al.* [2003], who showed that the two superterranes were stratigraphically linked by mid-Cretaceous time. The labels WEST and EAST denote relative positions of study areas compared with the North American craton, but note that the study areas are distributed over 16° of present latitude from northwestern Washington state through westernmost Canada to south central Alaska.

mediate offset of 1600 to 1800 km (i.e., a latitude shift of ~15°) as postulated by *Umhoefer* [2003] lies within the 95% confidence limits and so is compatible with, but not strongly supported by, the paleomagnetic result from Duke Island.

[33] The paleomagnetic evidence for the original statements of the Baja BC hypothesis [*Beck et al.*, 1981; *Irving et al.*, 1985] was derived entirely from five plutonic rock bodies in which, at that time, there was no way of determining the original horizontal; this condition has resulted in prolonged debate in the literature as discussed in section 1. All these results were illustrated by *Bogue et al.* [1995, Figure 14] along with all the results from bedded rocks that were available at that time. In Figure 10 we have omitted four of the five pluton-derived paleolatitudes. We retain Mount Stuart because of the exhaustive restudy of the paleomagnetism of that pluton by *Housen et al.* [2003] and because of the convincing use of the aluminum-in-hornblende geobarometer to establish the tilt of the pluton (see references in that publication). The other six rock

formations represented in Figure 10 are all bedded and have incontrovertible evidence of original horizontal. Of these six the paleomagnetic data for four are derived mainly or entirely from volcanic rocks, either tuffs, in the case of MacColl Ridge, or lavas, in the cases of Mount Tatlow, Carmacks, and Spences Bridge, and all four provide positive fold tests. The Methow data were obtained from red beds, and the analysis of their paleomagnetism was correspondingly complex [*Enkin et al.*, 2002]. The Nanaimo Group rocks occupy a critical place and time with respect to the evidence for the movement history of Baja BC; they are late Cretaceous and are sandwiched between Vancouver Island and mainland Canada (Figure 1). Although the Nanaimo Group rocks could be expected to show paleomagnetic evidence over their stratigraphic span for the movement history of Baja BC, they have proved to be exceptionally problematic paleomagnetically because they are entirely sedimentary and not at all volcanogenic. Of the three investigations of these rocks, we show in Figure 10 results of the two most recently published. They are shown separately because the laboratory procedures and the statistical methods of analysis differ greatly but also as an illustration of the difficulties inherent in attempting to get paleomagnetic data from all the bedded rocks of Baja BC. The study by *Enkin et al.* [2001] labeled Nanaimo 1 spans 140 km along the length of the Gulf Islands in the Strait of Georgia. Because the rocks are nearly homoclinal, no definitive fold test was possible. No correction was made for possible shallowing of paleomagnetic inclination because the authors of that study carefully avoided sampling rocks containing appreciable clay. The investigation by *Kim and Kodama* [2004] (Nanaimo 2 in Figure 10) was restricted to only one of the Gulf Islands, and for the same reason no fold test was feasible. On the basis of elaborate rock-magnetic experiments in their laboratory, *Kim and Kodama* [2004] applied an empirical correction to their data to account for the shallowing of paleomagnetic inclination that may result from compaction and lithification of clay-rich sediment. In the context of Figure 10 we find using the method of *Debiche and Watson* [1995] that the application of this compaction correction decreased the overall mean latitude shift from 22.1° ± 7.7° to 13.3° ± 8.4°. The two paleolatitude differences for the Nanaimo Group illustrated in Figure 10 do not differ significantly at better than 95% confidence, and both are significantly different from what would be predicted assuming no northward post-magnetization transport. Moreover, as befits their late Cretaceous age, the Nanaimo rocks studied by both investigators exhibit antiparallel normal and reversed paleomagnetic polarities.

[34] In summary, the paleolatitude differences shown in Figure 10 represent 22 different investigations, only the most recent of which are cited directly in the caption. In nearly all cases the later investigators have confirmed the earlier results and interpretations. Even after eliminating all the data from plutons for which tilting cannot be properly evaluated, we are left with the inescapable observation that the Cretaceous rocks of Baja BC show paleomagnetic latitudes that are significantly farther south than would be predicted for that time. All the authors cited in the caption for Figure 10 have provided abundant descriptions of how their paleomagnetic data were obtained and evaluated. For comprehensive reviews of the conflict between paleomagnetic and geologic evidence, the reader is referred to the original publications, especially those by *Haskin et al.* [2003] and *Enkin et al.* [2002, 2003].

7. Summary of Conclusions

[35] In cases where separate areas of uniformly magnetized rock are folded about two different axes, it is possible to infer the predeformation remanence direction without the usual assumption that the layering was originally horizontal. The technique works because the folded remanence directions lie along small circles centered on each of the two fold axes, the intersection of which defines the prefolding direction. We applied this technique to published structural and paleomagnetic data from the ultramafic complex exposed near Hall Cove and Judd Harbor on Duke Island [*Bogue et al.*, 1995; *Butler et al.*, 2001b]. Like *Butler et al.* [2001b] we infer that the cumulate layering at Duke Island was subhorizontal (initial dips of order 15°) and that the remanence clearly predates the kilometer-scale folding of mid-Cretaceous age. Structural observations from the two outcrop areas reveal that this later folding occurred about two axes that are well defined and distinct. Small circles about these fold axes that best fit the paleomagnetic data intersect at $D = 337.3°$ and $I = 61.0°$. This direction lies 1.8° from the grand mean of the average remanence directions from each of the six structural domains defined by *Butler et al.* [2001b]. Both these estimates of the ancient field direction at Duke Island are distinct at a high level of confidence from what would be expected if Duke Island had remained fixed with respect to North America since the mid-Cretaceous. Using the grand mean paleomagnetic direction (preferable because conventional confidence limits can be calculated), we find the mid-Cretaceous paleolatitude to be 43.9° ± 16° (Table 1).

[36] The 21.2° ± 11.5° of poleward translation of the Insular superterrane implied by this result is consistent with the Baja BC hypothesis which posits 20° of relative offset since 90 Ma between the Insular superterrane and the North American craton. We show this consistency in Figure 10, where we have used, with one exception, only data from investigations of layered or bedded rocks in which the paleohorizontal could be accurately or at least reasonably determined. Note that the 95% confidence interval for Duke Island is larger than any of the others; this difference encompasses the difference in paleomagnetic inclinations between the Hall Cove and Judd Harbor parts of the ultramafic intrusion. Although *Butler et al.* [2001b] had concluded that the paleomagnetism of the Duke Island ultramafic intrusion could not be used to infer its mid-Cretaceous paleolatitude, our new analysis of the combined data is in agreement with our earlier conclusion [*Bogue et al.*, 1995] that it can be so used and that the result is concordant with southerly paleolatitudes determined by many other workers from bedded rocks of terranes farther inboard in the Insular and Intermontane superterranes.

[37] **Acknowledgments.** We thank Robert Butler and George Gehrels who informed us early on of their intention to extend our original paleomagnetic study of the ultramafic complex on Duke Island, shared all the new data with us as it emerged from Bob's laboratory, and engaged us in an extended and lively discussion of whether these rocks provide a

trustworthy measure of the mid-Cretaceous paleolatitude of the Insular superterrane. We are also thankful for the comments of Paul Umhoefer, an anonymous reviewer, and Randy Enkin that led to substantial improvements in the paper.

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