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Paleomagnetism of the Duke Island, Alaska, ultramafic complex revisited

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Abstract. The Duke Island ultramafic intrusion was emplaced into the Alexander terrane immediately preceding development of a regional mid-Cretaceous thrust belt. Paleomagnetic samples were collected from exposures of ultramafic rock with cumulate layering northwest of Judd Harbor and northwest of Hall Cove. Thermal demagnetization results were analyzed using principal component analysis to isolate the characteristic remanent magnetization. Site-mean characteristic directions determined from 16 sites fail the fold test at 95% confidence, indicating that cumulate layering attitudes were highly contorted at the time of magnetization, at least on a scale of tens of meters. Variations in cumulate layering attitudes probably resulted from the combined effects of thermal convection phenomena during crystallization and deformation following crystallization but prior to magnetization. Analysis of cumulate layering over larger structural domains indicates that kilometer-scale deformation produced southwest plunging folds within the Hall Cove and Judd Harbor bodies. *Bogue et al.* [1995] proposed that a compound structural correction involving unplunging of fold axes followed by unfolding of average cumulate layering could restore cumulate layering to horizontal. However, using the full set of 21 site-mean paleomagnetic directions from Duke Island (16 from the current study and 5 from *Bogue et al.* [1995]), the compound structural correction yields mean paleomagnetic directions from the Judd Harbor and Hall Cove areas that are statistically distinguishable at 99% confidence. This result indicates that even on the kilometer-scale, cumulate layering within the Duke Island ultramafic intrusion was neither coplanar nor horizontal at the time of magnetization. Observations of cumulate layering in other ultramafic intrusive rocks indicate that this layering can significantly depart from horizontal by 10°–20° even on the kilometer scale. Therefore use of cumulate layering of ultramafic rocks as a proxy for paleohorizontal is not justified, and paleomagnetic directions from the Duke Island ultramafic intrusion cannot be used to infer the Cretaceous paleolatitude of the Insular superterrane.

1. Introduction

Discordant paleomagnetic directions with clockwise rotated declinations and shallow inclinations have been observed from some mid-Cretaceous plutons of the Coast Mountains in British Columbia and the North Cascades [*Symons*, 1977; *Beck et al.*, 1981; *Irving et al.*, 1985]. These discordant directions have been interpreted to indicate either (1) systematic NE side-up tilting of Cretaceous plutons during their uplift history [*Symons*, 1977; *Butler et al.*, 1989] or (2) ~3000 km northward translation from lower mid-Cretaceous paleolatitudes accompanied by clockwise vertical axis rotation [*Beck et al.*, 1981; *Irving et al.*, 1985]. The latter interpretation has been referred to as the Baja British Columbia hypothesis because derivative paleogeographies restore portions of western British Columbia to Cretaceous locations adjacent to present-day Baja California [*Umhoefer*, 1987; *Cowan et al.*, 1997; *Hollister and Andronicos*, 1997]. Lack of direct indications of paleohorizontal in the plutonic rocks yielding the paleomagnetic data is the fundamental cause for ambiguity in interpreting those observations.

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Limited paleomagnetic data are available from layered Cretaceous rocks of western British Columbia or southern Alaska. Paleomagnetic data from the Silverquick Conglomerate and the Powell Creek volcanics [*Wynne et al.*, 1995] have been interpreted to indicate ~3000 km of post-Campanian northward transport. However, indications of synfolding components of magnetization raise some uncertainty about the reliability of this result. *Ward et al.* [1997] also observed discordant shallow paleomagnetic inclinations in marine sedimentary rocks of the Nanaimo Formation. *Panuska* [1985] also inferred a low Cretaceous paleolatitude from paleomagnetic study of Campanian/Maastrichtian marine sedimentary rocks of MacColl Ridge in southern Alaska. For these sedimentary rocks the possibility of compaction shallowing of inclination compromises the paleolatitudinal estimates derived from paleomagnetic directions [*Gordon*, 1990; *Tarduno*, 1990; *Tan and Kodama*, 1998].

Attempting to provide paleolatitudinal observations from the Insular superterrane of southeast Alaska, *Bogue et al.* [1995] studied the paleomagnetism and magnetic anisotropy of 110 Ma layered ultramafic rocks on Duke Island (Figure 1). *Bogue et al.* [1995] argued that the paleomagnetic directions pass a fold test when average attitudes of cumulate layering in these ultramafic rocks are used as proxies for paleohorizontal. The derived paleolatitude implies 3000 km of post-mid-Cretaceous northward transport with respect to interior North American. In this paper, we

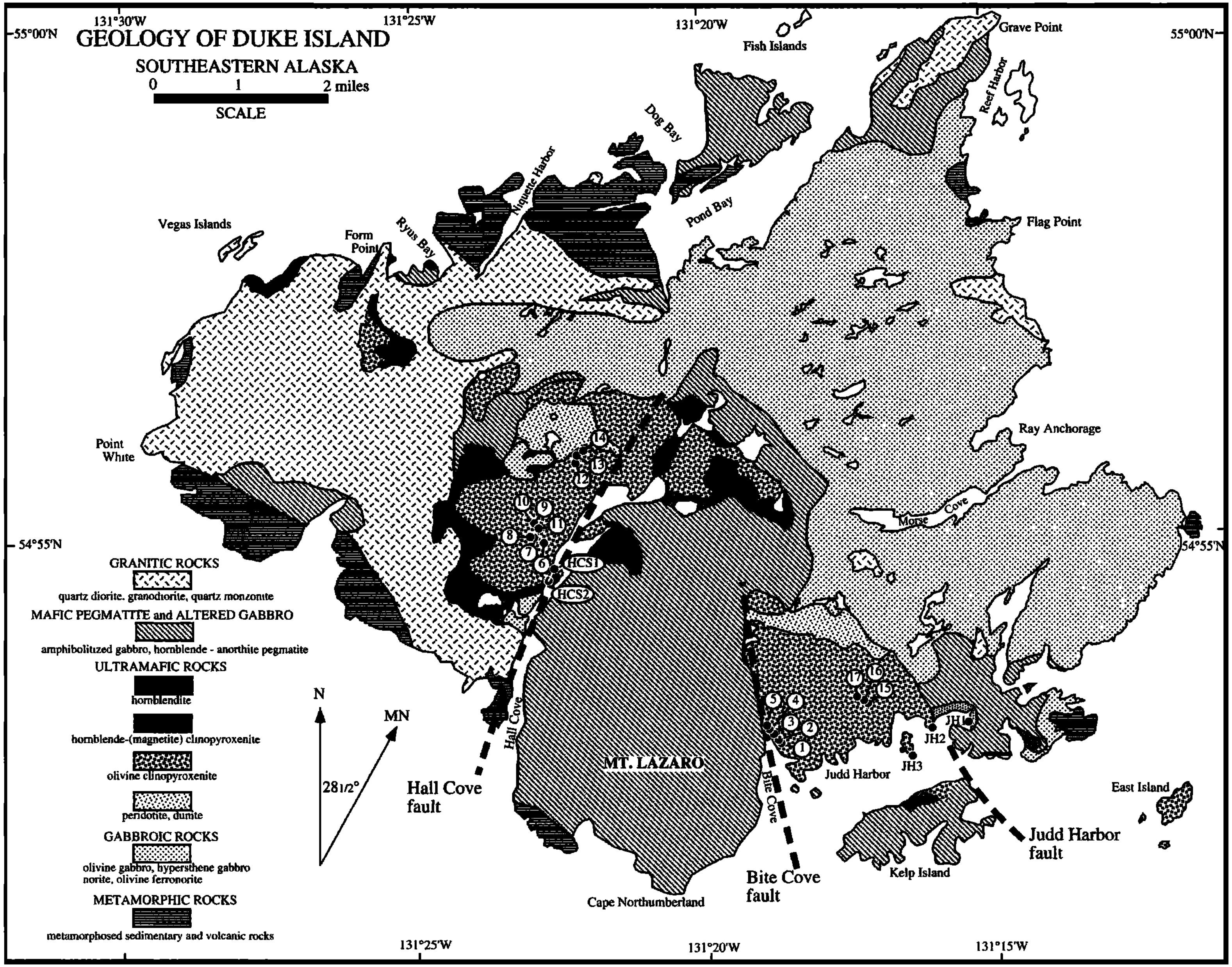

Figure 1. Generalized geological map of Duke Island modified from *Irvine* [1974] and *Saleeby* [1992]. Paleomagnetic sampling locations are indicated by circled numbers (e.g., 1 indicates site DK001).

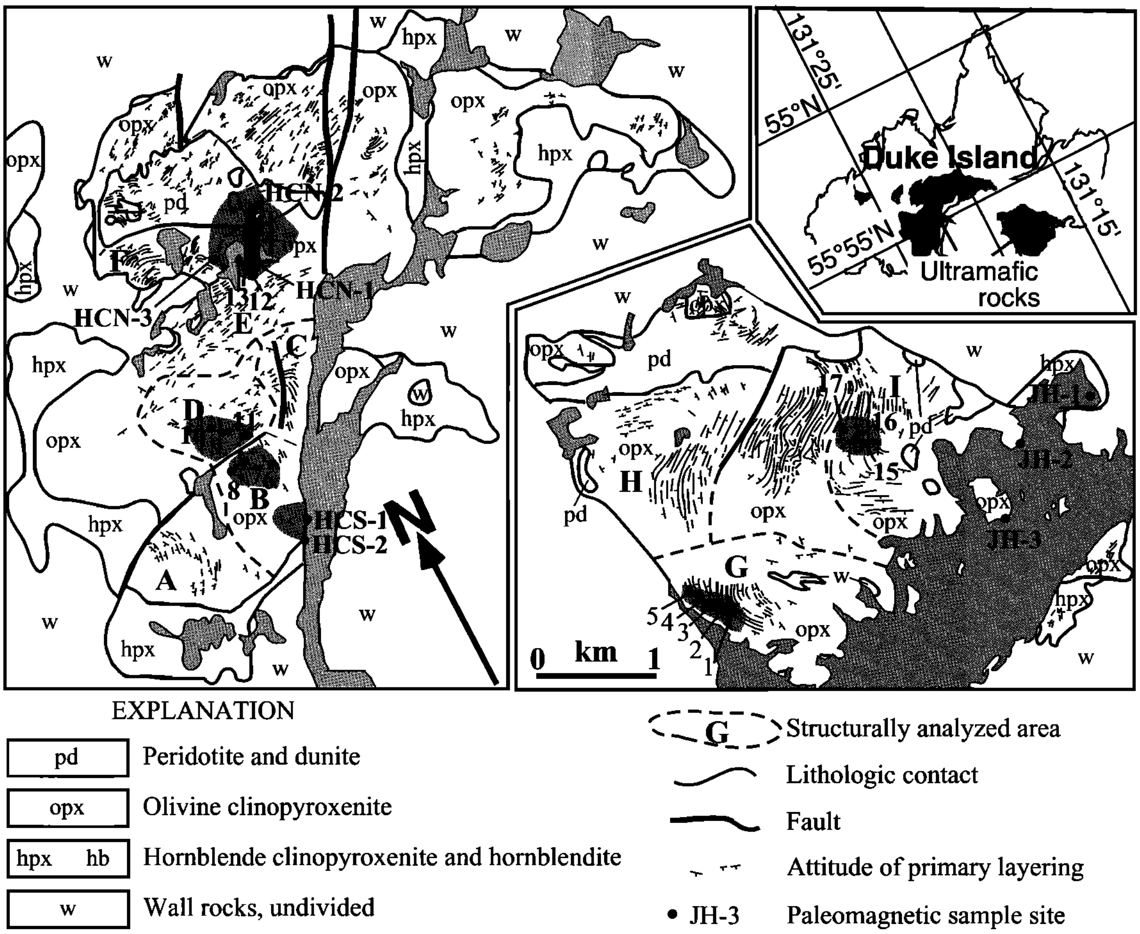

Figure 2. Geologic map of Duke Island ultramafic intrusions adapted from Plate 2 of *Irvine* [1974]. Locations of paleomagnetic sampling sites are indicated (e.g. 1 indicates site DK001 etc. of present study; sites of *Bogue et al.* [1995] are indicated by JH or HC labels). Attitudes of primary layering are indicated with tick marks pointing downdip. Dashed lines outline areas from which *Bogue et al.* [1995] analyzed cumulate layering attitudes for determinations of fold axis orientations. Gray-tone areas around paleomagnetic sites indicate regions within which cumulate layering attitudes were averaged for analysis of fold tests.

report results of additional paleomagnetic studies of Duke Island. We agree with many methods and some results described by *Bogue et al.* [1995]. However, our larger data set indicates that cumulate layering was neither planar nor horizontal at the time of magnetization and that the paleomagnetic directions cannot be used to determine the Cretaceous paleolatitude of Duke Island.

2. Geology of Duke Island

The Duke Island ultramafic intrusion was emplaced during mid-Cretaceous time into lower Paleozoic and Triassic gabbroic to tonalitic basement rocks of the Alexander terrane [*Gehrels et al.*, 1987; *Saleeby*, 1992] and is recognized as a type location of concentrically zoned ultramafic intrusions [*Irvine*, 1967, 1974; *Taylor*, 1967]. U/Pb analyses of zircons yield ages clustering between 108 and 111 Ma [*Saleeby*, 1992]. Igneous petrology and primary structures of the Duke Island intrusion were studied in detail by *Irvine* [1974]. The principal rock of the Duke Island intrusion is olivine clinopyroxenite exhibiting cumulate layering of olivine and clinopyroxene crystallized from a mafic or ultramafic magma. There are two principal exposures of the ultramafic intrusion, the Hall Cove and Judd Harbor bodies (Figures 1 and 2). Aeromagnetic and contact metamorphic features indicate that the Hall Cove and Judd Harbor bodies are connected at shallow depth. *Irvine* [1974] interprets the two bodies as upward protruding lobes connected at depth. In contrast, *Saleeby* [1992] considers the intervening roof rocks to have been displaced downward relative to the two bodies along high-angle faults related to the mid-Cretaceous thrust belt tectonics.

The magmatic and deformational history of the Duke Island ultramafic intrusion was detailed by *Saleeby* [1992]. Most crucial is evidence that substantial domains of the cumulate layering were deformed during the magmatic history of the intrusion. Igneous emplacement was immediately followed by development of a regional mid-Cretaceous thrust belt which encompasses the Duke Island area [*Rubin and Saleeby*, 1992]. This thrust belt consists of west and northwest directed brittle-ductile thrust faults and shear zones with multiple sets of cleavages and associated passive folds [*Rubin and Saleeby*, 1992; *Saleeby*, 1992]. The northeast and southwest margins of the Duke Island intrusion are either bounded by or proximal to ductile thrust zones (Figure 2 of *Saleeby* [1992]). A northeast trending metamorphic cleavage developed parallel to the Hall Cove fault and that cleavage is also observed in the Judd Harbor body where it superposes the dominant northwest trending cleavage. The northeast trending cleavage represents a shortening axis consistent with the northwest transport direction deduced from thrust faults of the region. During our paleomagnetic sampling, we searched for sites with minimal expression of cleavage. Yet in thin section each sample collected shows at least incipient cleavage formation and antigorite growth.

Four fundamental aspects of the geological development of Duke Island are critical to interpretation of paleomagnetic data from the layered ultramafic rocks. (1) What deformations affected Duke Island since intrusion, cooling, and magnetization of the ultramafic rocks? (2) To what extent can we decipher those deformations and apply appropriate structural corrections to the paleomagnetic directions from the layered ultramafic rocks? (3) Do the cumulate layers provide a proxy for paleohorizontal? (4) Over what dimensions and how accurately can cumulate layers be taken as indications of paleohorizontal at the time of magnetization? Following presentation of the paleomagnetic results, these questions will be addressed.

3. Previous Paleomagnetic Study

Paleomagnetic data were obtained from eight sampling sites in ultramafic rocks of Duke Island by *Bogue et al.* [1995]. Three sampling sites were on shoreline exposures of Judd Harbor; two sites were located on shoreline exposures of Hall Cove; and three sites were located northwest of Hall Cove. Only the outcrops sampled northwest of Hall Cove have visible cumulate layering.

Bogue et al. [1995] carefully examined the mineralogy of magnetic minerals in ultramafic rocks of Duke Island. Three populations of (titano)magnetite grains were observed through polished thin section examination. *Bogue et al.* [1995] concluded that the characteristic magnetization (ChRM) was carried by low-Ti titanomagnetite exsolved at 540°C within host clinopyroxene grains. Given the proximity of the exsolution temperature with the blocking temperatures of the ChRM, the characteristic magnetization is either entirely thermoremanent magnetization (TRM) or TRM plus high-temperature chemical remanent magnetization. *Bogue et al.* [1995] present a careful and thorough analysis of magnetite formation associated with cleavage development and serpentinization. They argue that this magnetite does not contribute substantially to the characteristic remanence. In addition, *Bogue et al.* [1995] examined anisotropy of magnetic susceptibility (AMS) and anisotropy of isothermal remanent magnetization (AIMS). Although many samples had substantial AMS and AIMS, detailed comparison of remanence directions and orientations of anisotropy axes led to the conclusion that magnetic anisotropy has no systematic effect on directions of characteristic magnetization.

To perform structural corrections of the eight site-mean ChRM directions obtained in their study, *Bogue et al.* [1995] undertook a detailed analysis of cumulate layering attitudes mapped within the Judd Harbor and Hall Cove regions by *Irvine* [1974]. *Bogue et al.* [1995] did not use cumulate layering attitudes measured directly on the outcrops sampled for their paleomagnetic study. Instead they divided the two outcrop areas of ultramafic rocks into structural domains within which cumulate layering appeared to be homogeneously deformed. These areas are shown in Figure 2. Details of the procedures and results of this structural analysis are given in *Bogue et al.* [1995] and are not repeated here. This analysis led to the conclusion that cumulate layering within the Judd Harbor and Hall Cove regions had been deformed into folds plunging moderately to the west-southwest. *Bogue et al.* [1995] performed a compound structural correction for the paleomagnetic directions which involved first unplunging the fold axes to horizontal then unfolding the layers to horizontal about the plunge-corrected strike. Because the paleomagnetic directions were significantly better clustered when compound corrected than in geographic coordinates, *Bogue et al.* [1995] concluded that the magnetization is prefolding and that the mean cumulate layering provides an estimate of paleohorizontal. In turn, it was concluded that the compound corrected paleomagnetic directions could be used to determine the mid-Cretaceous paleolatitude of Duke Island. Following presentation of the new paleomagnetic results, the analysis of cumulate layering and structural restoration of Duke Island is again examined using the expanded data sets of paleomagnetic directions and measurements of cumulate layering attitudes.

4. New Paleomagnetic Data From Duke Island

The first objective of our paleomagnetic study of Duke Island was to expand the number and spatial coverage of paleomagnetic sampling sites. In addition, we desired sample sites from outcrops which provided clear and direct measurements of cumulate layering attitudes. This sampling strategy resulted in the ability to examine fold tests of the resulting paleomagnetic directions over a range of scales. Our collections were distributed across two regions of Duke Island within which cumulate layering of ultramafic rocks is well developed (Figures 1 and 2): (1) seven sites west and northwest of Judd Harbor and (2) 10 sites west and north of Hall Cove. Sites were located in the interior of the island away from shorelines which are often controlled by faults or shear zones [*Saleeby*, 1992]. Samples were collected using standard paleomagnetic coring methods ($\geq$8 samples per site). Except for one site, which did not yield usable results, all cores were oriented by Sun compass. This is important because the high intensity of natural remanent magnetism (NRM) in these ultramafic rocks makes magnetic compass readings inaccurate. Sites were located within panels that contain cumulate layering which is planar and homoclinal over outcrop scales (tens of meters); Sun compass orientations were also used to determine the attitude of cumulate layering for each site.

Following sample preparation, all paleomagnetic samples were stored, measured, and thermally demagnetized in a magnetically shielded room with average field intensity <200 nT. Measurement of NRM was done with a three-axis cryogenic magnetometer (2G Model 755R). Initial NRM intensities ranged up to 10^2 A m^{-1}. After NRM measurements, all samples were subjected to progressive thermal demagnetization at 10 to 14 temperature steps up to 600°C. The NRM properties were similar to those observed by *Bogue et al.* [1995], who illustrate a number of examples of demagnetization behavior. A typical example of thermal demagnetization behavior from our sample collection is illustrated in Figure 3. Unblocking temperatures were generally concentrated between 450°C and 560°C, indicating that magnetite or titanomagnetite with low Ti content is the dominant carrier of NRM.

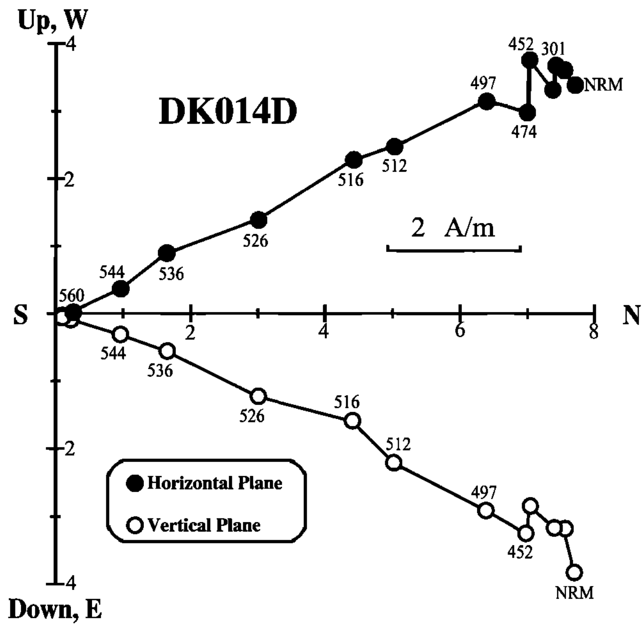

Figure 3. Vector component diagram of thermal demagnetization behavior. Open circles are projections onto vertical plane, and solid circles are projections onto horizontal plane. Numbers adjacent to data points indicate temperature (in °C). Projection is in corrected (stratigraphic) coordinates.

Table 1. Site-Mean Characteristic Remanent Magnetism Directions[a]

										Site-Mean Direction			
		Site Location		Layering						Geographic		Corrected	
Site	Area	Latitude, °N	Longitude, °W	Dip Az, deg	Dip, deg	N	J, A m^{-1}	k	α_{95}, deg	I, deg	D, deg	I, deg	D, deg
DK001	JH	54°52.89′	131°18.72′	202	44	6	33.0	56.2	5.4	18.2	82.0	33.7	103.4
DK002	JH	54°52.91′	131°18.76′	309	70	8	46.0	45.1	8.3	30.5	86.8	50.7	14.9
DK003	JH	54°52.97′	131°18.84′	275	72	7	50.0	147.2	5.0	29.1	92.3	78.7	287.1
DK004	JH	54°53.02′	131°18.91′	200	64	5	37.0	25.8	15.4	23.1	81.2	34.8	121.1
DK006	HC	54°54.94′	131°22.73′	0	0	8	19.0	13.9	15.4	52.5	23.5	52.5	23.5
DK007	HC	54°55.00′	131°22.91′	308	15	7	16.0	25.5	12.2	46.7	10.7	38.5	359.1
DK008	HC	54°55.00′	131°22.99′	278	44	5	8.3	59.8	10.0	54.2	36.0	52.3	327.6
DK009	HC	54°55.15′	131°22.93′	167	55	5	8.7	44.4	11.6	42.4	8.3	73.0	118.2
DK010	HC	54°55.20′	131°23.00′	261	49	5	8.5	48.0	11.2	37.8	12.8	38.5	330.8
DK011	HC	54°55.10′	131°22.82′	276	40	5	10.0	142.8	6.4	43.6	9.3	33.7	336.3
DK012	HC	54°55.74′	131°22.19′	207	14	7	9.1	95.3	6.2	19.7	355.3	31.3	351.5
DK013	HC	54°55.80′	131°22.18′	202	37	5	5.7	98.7	7.7	12.1	7.8	47.5	1.1
DK014	HC	54°55.90′	131°22.08′	226	65	6	6.8	116.7	6.2	31.2	5.5	53.9	296.7
DK015	JH	54°53.29′	131°17.20′	266	48	4	21.0	52.4	12.8	36.3	86.0	84.3	85.8
DK016	JH	54°53.32′	131°17.28′	253	42	5	32.0	51.5	10.8	55.9	81.3	80.6	223.0
DK017	JH	54°53.35′	131°17.39′	301	40	4	44.0	33.3	16.2	44.3	82.0	63.1	28.1

[a] Site, paleomagnetic site number; Area, JH, Judd Harbor; HC, Hall Cove; Latitude and Longitude, location of paleomagnetic site; Dip Az, azimuth of dip of cumulate layering; Dip, angle of dip of cumulate layering; N, number of samples used to determine site-mean paleomagnetic direction; J, geometric mean intensity of characteristic magnetization; k, concentration parameter (best estimate of Fisher's precision parameter); α_{95}, 95% confidence limit about site-mean direction; I and D, inclination and declination of site-mean paleomagnetic direction; Geographic, in situ direction; Corrected, paleomagnetic direction corrected for local attitude of cumulate layering.

The progression of vector end points in the 450–560°C temperature interval was analyzed using principal component analysis [*Kirschvink*, 1980] to determine the characteristic remanent magnetization (ChRM). Resulting line fits almost always had maximum angular deviation (MAD) <5°, indicating that sample ChRM directions are well determined. Following determination of sample ChRM directions, site-mean characteristic directions were calculated using standard methods of *Fisher* [1953]. Site-mean ChRM directions are listed in Table 1 and illustrated in Figure 4, both in geographic coordinates (in situ) and in "corrected" coordinates following restoration of local cumulate layering to horizontal.

5. Analysis of Cumulate Layering as Paleohorizontal

For both the Judd Harbor and Hall Cove regions, site-mean directions are more closely grouped in geographic coordinates than following restoration of local cumulate layering to horizontal. For Hall Cove sites the best estimate of the Fisher precision parameter (k) decreases from $k = 21.1$ in geographic coordinates to $k = 8.7$ after restoration of local cumulate layering to horizontal. For Judd Harbor sites, k decreases from 31.9 in geographic coordinates to $k = 5.2$ after restoration of local cumulate layering to horizontal (Figure 4). The site-mean ChRM directions from both Hall Cove and Judd Harbor fail the bedding tilt test at 95% confidence using the statistical procedure of *McElhinny* [1964]. It is noteworthy that each group of sites (1–4, 6–8, 9–11, 12–14, and 15–17) has site-mean directions which are better clustered in geographic coordinates than after restoration of local cumulate layering to horizontal. Thus no matter how results from sites are grouped, restoration of local cumulate layering to horizontal produces greater dispersion of site-mean paleomagnetic directions.

It is clear that local cumulate layering does not provide a proxy for paleohorizontal at the time of magnetization. Instead, the paleomagnetic site-mean directions fail the bedding tilt test using local cumulate layering as "bedding." This result indicates that attitudes of cumulate layering, at least on a scale ~10 m, were highly variable when the characteristic magnetization was acquired. There are two principle causes for variations in attitude of cumulate layering at the time of magnetization: (1) undulations in the cumulate layering at the time of crystallization and (2) ductile deformation following crystallization but prior to acquisition of magnetization.

Development of cumulate layers within ultramafic complexes was originally thought to be controlled by gravitational settling at the base of a magma chamber. If so, this would justify use of cumulate layering as a proxy for paleohorizontal during crystallization. Instead, detailed field observations and thermal modeling indicate that formation of cumulate layering is dominated by magmatic crystal-liquid suspension currents driven by thermal convection [*Irvine et al.*, 1998; *Norton and Taylor*, 1979]. Gravitational settling plays a role in the development of cumulate layering but does not dominate the process. There are many deflections of cumulate layering on scales of meters to tens of meters that mimic sedimentary cross bedding, on lapping, and draped morphologies. It is widely acknowledged that these structures developed during crystallization and primary formation of the cumulate layers [*Irvine*, 1974].

The Eocene Skaergaard ultramafic intrusion in east Greenland displays cumulate layering and has been studied in great detail. The Skaergaard intrusion is roughly the same dimensions as the Duke Island intrusion but with superior exposure, especially in the vertical dimension with an exposed thickness of 2500 m. *Irvine et al.* [1998] have recently summarized geological investigations and examined the origin of the cumulate layering. Their observations and analyses are sobering for those asserting that cumulate layering in ultramafic intrusions can be taken as a proxy for paleohorizontal. The Skaergaard intrusion has three major subdivisions which locally or pervasively contain cumulate layering: (1) the Upper Border Series, which crystallized from the roof contact downward; (2) the Marginal Border Series, which crystallized from the walls of the magma chamber inward and has an overall dip of 80°; and (3) the Layered Series, which accumulated from the floor of the magma chamber upward. The Layered Series has the most laterally continuous and planar cumulate layers. This series would most closely approach the idealized concept of cumulate layers formed by gravitational settling.

Irvine et al. [1998] observe many synforms and antiforms of layering that range in scale from meters to kilometers within the Layered Series [e.g., *Irvine et al.*, 1998, Figure 20]. They note that the Layered Series is broadly synformal across the 8-km east-west

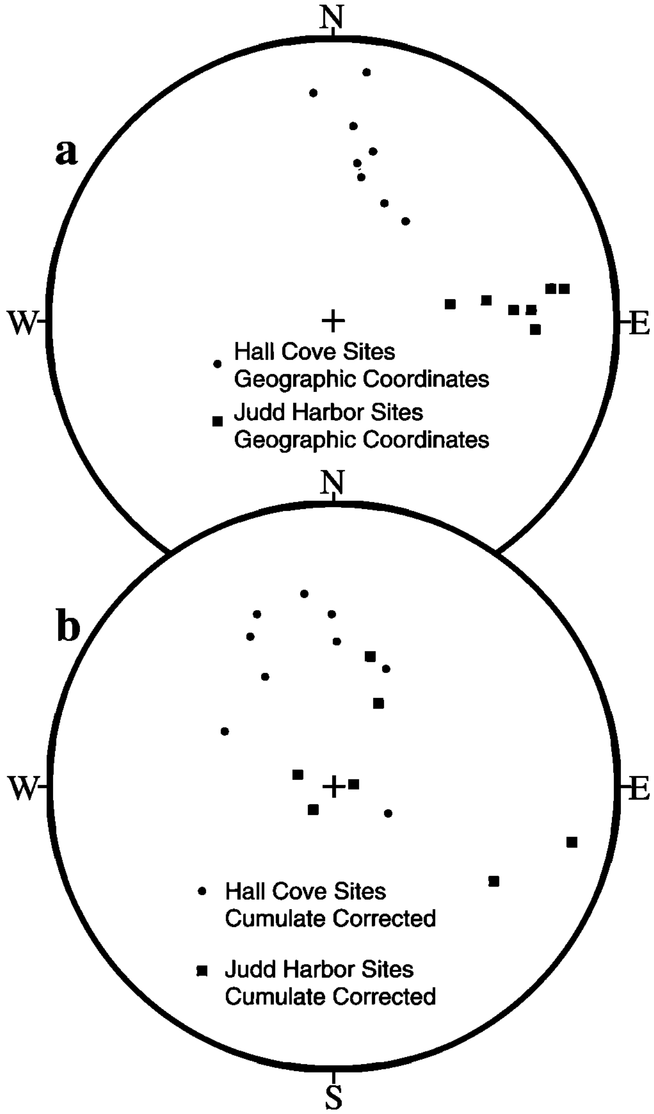

Figure 4. Equal-area projection of site-mean ChRM directions for sites collected in 1997. (a) Site-mean directions in geographic (in situ) coordinates. (b) Site-mean directions following restoration of local cumulate layering to horizontal. All directions are in lower hemisphere of the projection.

width of the intrusion and cumulate layers consistently dip >10° for distances of several kilometers [*Irvine et al.*, 1998, Figure 29]. These observations indicate that cumulate layers within an ultramafic intrusion might be roughly planar over distances approaching several kilometers. However, these layers cannot be argued to be planar over larger distances or to provide an indication of paleohorizontal to precision of even 10° to 20°. Although on the basis of a very small number of paleomagnetic samples and providing few details of the structural analysis, *Schwartz et al.* [1979] showed that paleomagnetic directions collected on a traverse across the Layered Series in the Skaergaard intrusion fail a fold test. It is clear that thermal convection can produce distortions of cumulate layering to 10°–20° over scales from meters to kilometers.

Rubin and Saleeby [1992] and *Saleeby* [1992] have documented that igneous emplacement of the Duke Island intrusion was closely followed by development of a regional mid-Cretaceous thrust belt that deformed the island and adjacent areas. Domains of the cumulate layering on Duke Island were deformed during the magmatic and cooling history of the intrusion. Failure of the fold test described above documents that cumulate layering was more contorted at the time of magnetization than could likely be accounted for by convection currents alone. It is quite likely that cumulate layers were also deformed following crystallization but prior to magnetization.

The results of the fold test described above demonstrate that cumulate layering within the Duke Island ultramafic intrusion was highly contorted at the time of magnetization, at least on a scale of tens of meters. Variations in cumulate layering attitudes at the time of magnetization probably resulted from the combined effects of thermal convection phenomena during crystallization and deformation following crystallization but prior to magnetization. Clearly, local cumulate layering cannot be taken as a proxy for paleohorizontal at the time of magnetization. Observations of cumulate layering in other ultramafic intrusive rocks suggest that this layering can significantly depart from horizontal even on the kilometer scale. Therefore use of cumulate layering of ultramafic rocks as a proxy for paleohorizontal is not justified.

6. Structural Restoration of Duke Island Ultramafic Complex

For reasons described in section 5 , we do not agree with the conclusion of *Bogue et al.* [1995] that averaged attitudes on cumulate layering in the ultramafic intrusion of Duke Island can be used as a proxy for paleohorizontal. Nevertheless, the structural restoration that they proposed did explain broad patterns in the cumulate layering and the major features of their paleomagnetic observations. In this section, we briefly examine whether the structural restoration proposed by *Bogue et al.* [1995] is supported by the expanded data sets of paleomagnetic directions and cumulate layering attitudes obtained through our study of Duke Island. In doing so, we acknowledge that this analysis is nonunique. Having argued in section 5 that convection currents and deformation affected the cumulate layering prior to magnetization, we may be overinterpreting the paleomagnetic observations in attempting this restoration. Indeed, J. B. Saleeby, who has spent the most time studying the structural geology of Duke Island, is skeptical of this analysis. We present the following analysis because it leads to interesting tentative conclusions relevant to the structural geology of the Insular superterrane and the Baja British Columbia hypothesis.

The procedures of structural analysis and restoration employed here are exactly those described in detail by *Bogue et al.* [1995]. The only differences from their analysis are the following: (1) Our measured cumulate layering attitudes were added to those previously available through the mapping by *Irvine* [1974]. (2) Rather than applying an average attitude for domain B to sites from Hall Cove south (HCS1 and HCS2 of *Bogue et al.* [1995]), only the two attitudes within 500 m of these two sites were averaged. (3) There is insufficient control on attitudes of cumulate layering to perform a useful correction for Judd Harbor sites JH1, JH2, and JH3 of *Bogue et al.* [1995], so these are not considered further. The resulting average cumulate layering attitudes and fold axis orientations are listed in Table 2, along with confidence limits calculated by applying *Fisher* [1953] statistics to the distributions of fold axes and poles to cumulate layering. Our recent work in southeast Alaska and western British Columbia supports the unplunging then unfolding order of structural corrections applied by *Bogue et al.* [1995] to arrive at their compound correction. Mid-Cretaceous thrust belt development provides a mechanism for folding the cumulate layering [*Rubin and Saleeby*, 1992; *Saleeby*, 1992]. Cenozoic extension in the Coast Mountains and the Insular superterrane involving east-side-up tilting of crustal panels can account for the west-

Table 2. Averaged Cumulate Layering and Fold Axis Attitudes[a]

Sites	Area	n	Layering Pole		Fold Axis	
			Dip Az, deg	Dip, deg	Trend, deg	Plunge, deg
DK001–DK004	JH	8	100.1	20.9	256	56
DK006–DK008	HC	12	104.7	58.9	234	36
DK009–DK011	HC	11	45.4	47.7	234	36
DK012–DK014 + HCN-1–HCN-3	HC	11	29.3	40.0	234	36
DK015–DK017	JH	8	98.8	46.3	256	56
HCS-1–HCS-2	HC	2	118.1	40.7	234	36

[a] Sites, paleomagnetic site numbers to which averaged attitudes apply; Area, JH, Judd Harbor; HC, Hall Cove; n, number of cumulate layering attitudes averaged; Layering Pole, average pole to cumulate layering in vicinity of paleomagnetic sites; Dip Az, azimuth of dip of average cumulate layering pole; Dip, angle of dip of average cumulate layering pole; Fold Axis, axis of best fit fold axis within sampling regions; Trend, trend of best fit fold axis; Plunge, dip of best fit fold.

southwest plunge of fold axes [*Rohr and Dietrich*, 1992; *Butler et al.*, 2001].

Figure 5a shows that the 21 site-mean paleomagnetic directions (16 site means from the current study plus five site means from *Bogue et al.* [1995]) are roughly distributed along a small circle, suggesting that these directions were dispersed by folding. The average fold axis orientations determined by *Bogue et al.* [1995] are also illustrated in Figure 5a. Stepwise application of the compound structural corrections to the cumulate layering and the paleomagnetic directions are detailed in Table 3. The resulting paleomagnetic directions are illustrated in Figure 5b. For the full set of 21 site-mean directions the best estimate of the *Fisher* [1953] precision parameter k increases from 6.0 in geographic coordinates to 31.4 in compound corrected coordinates. Application of the *McFadden* [1990] fold test yields a positive result at 95% confidence. However, this passage of the fold test does not necessarily indicate that the compound correction has restored the 21 site-mean directions to their original relative directions. Indeed, it is immediately evident from Figure 5b that the compound correction has not produced overlap of the distribution of site-mean directions from Judd Harbor with the distribution from Hall Cove. These sets of directions are brought closer together by application of the compound correction, but they do not overlap. Note that all inclinations from Judd Harbor sites are >70°, while all inclinations from Hall Cove sites are <70°.

The compound corrected regional mean direction from Hall Cove is declination D = 333.6°; inclination I = 55.8°, 95% confidence limit α_{95} = 5.4°, k = 52.0, N = 14, and resultant vector sum R = 13.7676. The compound corrected regional mean direction from Judd Harbor is D = 344.7°, I = 77.5°, α_{95} = 6.3°, k = 80.0, N = 7, and R = 6.9356. The 95% confidence intervals for these regional mean directions do not overlap, indicating that they are distinct at a confidence level of ≥95%. Applying the *McFadden and Lowes* [1981] method for discrimination of mean directions yields an angle between the mean directions of 22.05°, resultant vector length of 20.35, and critical confidence level for distinction between the mean directions of >99%. This calculation indicates that the compound corrected regional mean directions from the Judd Harbor and Hall Cove regions are distinct at ≥99% confidence level. The failure of the compound correction of *Bogue et al.* [1995] to converge these regional mean paleomagnetic directions indicates that this structural correction falls short of restoring cumulate layering in the Judd Harbor and Hall Cove regions to their relative orientations at the time of magnetization.

It is instructive to examine whether uncertainties in elements of the compound correction could account for the difference between the mean directions from the Judd Harbor and Hall Cove regions. It is important to realize that the difference between these mean directions is almost entirely in inclination; the mean declinations are nearly aligned. Because the plunge correction and uncertainties therein affect only the structurally corrected declination, the angular difference between the mean

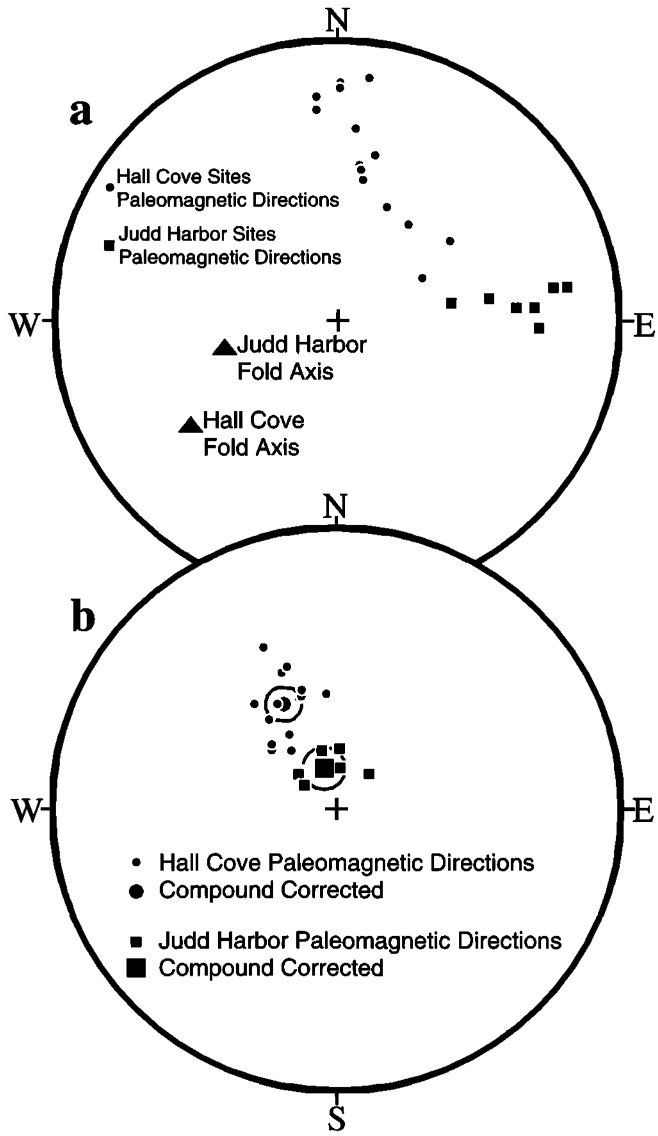

Figure 5. Equal-area projection of all site-mean ChRM directions from Duke Island. (a) Site-mean paleomagnetic directions in geographic (in situ) coordinates and fold axes for Judd Harbor and Hall Cove areas. (b) Site-mean directions following compound structural correction. All directions are in lower hemisphere of the projection. Large solid circle indicates mean direction for sites from Hall Cove. Large square indicates mean direction for sites from Judd Harbor. Circles surrounding mean directions are 95% confidence limits.

Table 3. Structural Corrections to Cumulate Layering and Paleomagnetic Directions[a]

		Geographic						Unplunged						Corrected Direction	
		Direction		Cumulate Pole		Fold Axis		Direction		Cumulate Pole		Cumulate Layer			
Site	Area	D, deg	I, deg	Trend, deg	Plunge, deg	Trend, deg	Plunge, deg	D, deg	I, deg	Trend, deg	Plunge, deg	Strike, deg	Dip, deg	D, deg	I, deg
DK001	JH	82.0	18.2	100.1	20.9	256.0	56.0	96.2	73.3	140.6	65.0	50.6	25.0	3.2	72.7
DK002	JH	86.8	30.5	100.1	20.9	256.0	56.0	148.0	80.2	140.6	65.0	50.6	25.0	315.8	74.7
DK003	JH	92.3	29.1	100.1	20.9	256.0	56.0	151.0	75.3	140.6	65.0	50.6	25.0	306.5	79.1
DK004	JH	81.2	23.1	100.1	20.9	256.0	56.0	100.0	78.2	140.6	65.0	50.6	25.0	346.6	72.3
DK015	JH	86.0	36.3	98.8	46.3	256.0	56.0	184.6	81.5	208.3	68.8	118.3	21.2	42.7	76.2
DK016	JH	81.3	55.9	98.8	46.3	256.0	56.0	248.1	67.8	208.3	68.8	118.3	21.2	313.2	75.5
DK017	JH	82.0	44.3	98.8	46.3	256.0	56.0	233.5	78.7	208.3	68.8	118.3	21.2	4.5	78.1
DK006	HC	23.5	52.5	104.7	58.9	234.0	36.0	316.3	71.8	174.8	62.3	84.8	27.7	338.3	46.7
DK007	HC	10.7	46.7	104.7	58.9	234.0	36.0	321.1	61.9	174.8	62.3	84.8	27.7	335.8	36.8
DK008	HC	36.0	54.2	104.7	58.9	234.0	36.0	315.6	79.5	174.8	62.3	84.8	27.7	343.6	53.6
DK009	HC	8.3	42.4	45.4	47.7	234.0	36.0	326.3	58.1	9.8	81.7	279.8	8.3	315.0	63.6
DK010	HC	12.8	37.8	45.4	47.7	234.0	36.0	337.1	57.7	9.8	81.7	279.8	8.3	328.0	64.3
DK011	HC	9.3	43.6	45.4	47.7	234.0	36.0	325.2	59.4	9.8	81.7	279.8	8.3	313.1	64.7
DK012	HC	355.3	19.7	29.3	40.0	234.0	36.0	337.8	34.1	354.1	68.3	264.1	21.7	330.5	54.6
DK013	HC	7.8	12.1	29.3	40.0	234.0	36.0	355.0	34.6	354.1	68.3	264.1	21.7	355.4	56.3
DK014	HC	5.5	31.2	29.3	40.0	234.0	36.0	337.5	48.8	354.1	68.3	264.1	21.7	322.7	68.8
HCN-1	HC	355.0	24.5	29.3	40.0	234.0	36.0	333.8	37.7	354.1	68.3	264.1	21.7	323.5	57.4
HCN-2	HC	1.1	15.9	29.3	40.0	234.0	36.0	345.9	34.2	354.1	68.3	264.1	21.7	342.1	55.6
HCN-3	HC	1.1	15.6	29.3	40.0	234.0	36.0	346.1	34.0	354.1	68.3	264.1	21.7	342.4	55.4
HCS-1	HC	62.2	62.0	118.1	40.7	234.0	36.0	208.9	80.9	153.6	46.2	63.6	43.8	321.7	50.8
HCS-2	HC	54.5	48.7	118.1	40.7	234.0	36.0	57.6	84.7	153.6	46.2	63.6	43.8	341.1	45.4

[a] Sites, paleomagnetic site numbers to which averaged attitudes apply; area, JH, Judd Harbor; HC, Hall Cove; I and D, inclination and declination of site-mean paleomagnetic direction; trend, trend of cumulative pole or fold axis; plunge, plunge of cumulative pole or fold axis; geographic, in-situ paleomagnetic directions or pole to cumulate layering; strike, angle of strike of unplunged cumulate layer; dip, angle of dip of unplunged cumulate layer; corrected direction, paleomagnetic site-mean direction following compound structural correction.

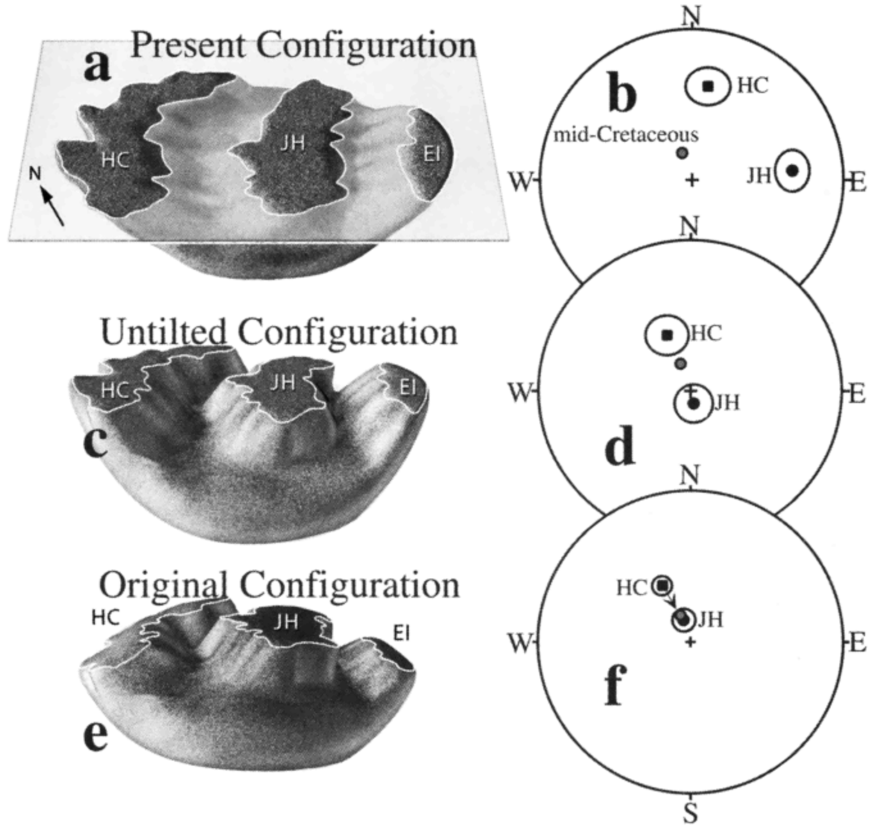

Figure 6. Stepwise restoration of Duke Island ultramafic complex to original geometry. (a) Present surface outcrops of ultramafic bodies at Hall Cove (HC), Judd Harbor (JH), and East Island (EI). (b) Present mean paleomagnetic directions from Hall Cove (HC) and Judd Harbor (JH) compared to expected mid-Cretaceous direction at a location 1000 km south of the present location of Duke Island. (c) Configuration of Duke Island ultramafic complex following unplunging of fold axes. (d) Paleomagnetic directions from Hall Cove and Judd Harbor following restoration of fold axes to horizontal. (e) Inferred original configuration of Duke Island ultramafic complex required to force coincidence of paleomagnetic directions with expected mid-Cretaceous direction. (f) Paleomagnetic directions resulting from unfolding: solid square, HC, and solid circle, JH. Arrow shows motion required to force coincidence of HC paleomagnetic direction with expected mid-Cretaceous and JH directions.

directions from Judd Harbor and Hall Cove cannot be decreased by alteration of the plunge corrections, by changing the order of the unplunging and unfolding operations, or even by elimination of the plunge correction. Only uncertainty in the cumulate layering measurements could possibly decrease the angular difference between the mean inclinations. However, it is not a simple matter to incorporate uncertainty in bedding attitudes into the fold test. Instead, fold tests assume that both paleomagnetic site-mean directions and bedding attitudes are known without error and that uncertainties arise only from dispersion of site-mean directions. Nevertheless, a rough estimate of the combined uncertainties from dispersion of paleomagnetic directions and uncertainty in the average cumulate layering attitude can be estimated from combined uncertainty of

$$\approx [\alpha_{95}^2 + {}^2]^{1/2},$$

where α_{95} is the confidence limit of the mean paleomagnetic direction and Δ is confidence limit on average cumulate layering. The values of α_{95} for both means are $\sim 6°$, and the confidence limits for the layering poles (Table 2) are $\sim 10°$. So the combined errors are $\sim 12°$ for the mean directions. Because the mean directions from Hall Cove and Judd Harbor are separated by >22°, inclusion of uncertainty in average cumulate layering could lead to minor overlap of the combined confidence limits. The mean directions from Hall Cove and Judd Harbor would still be distinct at 90% confidence and possibly at 95% confidence. Thus the difference in the regional mean paleomagnetic directions from Hall Cove and Judd Harbor cannot be explained by uncertainty in the compound structural corrections proposed by *Bogue et al.* [1995]. Instead, there must be an additional structural correction required to account for this directional difference.

We offer the model in Figure 6 as a speculative (and certainly nonunique) scenario for the structural restoration of the Duke Island ultramafic complex. We accept that post-mid-Cretaceous northward transport of the Insular superterrane could have been as much as 1000 km [*Gabrielse*, 1985; *Kapp and Gehrels*, 1998]. Accordingly, we use an expected paleomagnetic direction calculated from the North American Early to mid-Cretaceous reference pole (71.5°N,194.9°E [*Dickinson and Butler*, 1998]) at a location 1000 km south of the present location of Duke Island. Figure 6a shows the present configuration of the ultramafic complex, as drawn by *Irvine* [1974, p. 100]. (This configuration is highly simplified in comparison to that resolved by *Saleeby* [1992] through detailed mapping of structures within and surrounding the ultramafic complex.) Figure 6b shows the mean paleomagnetic directions for the Hall Cove and Judd Harbor areas in geographic coordinates. Figure 6c shows the effect of unplunging the SW trending fold axes, and Figure 6d shows attendant corrections to the paleomagnetic directions. Unfolding the cumulate layering as prescribed by the compound correction of *Bogue et al.* [1995] yields the resulting mean directions for Judd Harbor and Hall Cove shown in Figure 6f. The unfolded direction of magnetization from Judd Harbor is concordant with the expected mid-Cretaceous direction, but the Hall Cove direction is discordant and distinct from the Judd Harbor direction. To bring the Hall Cove direction into coincidence with the mid-Cretaceous and Judd Harbor directions requires an additional NW-side-down tilt of 22° about an axis with azimuth 56°. The result of this operation is that the Duke Island body restores to a slightly antiformal shape, with cumulate layering in the Hall Cove region dipping away from the central portion of the ultramafic complex (Figure 6e). We infer that the Duke Island ultramafic complex originally had a laccolith shape, with layering in the northwest portion sloping gently away from the central feeder region. The map-scale folds observed by *Irvine* [1974] could have been produced by this regional folding event. (An animation of the structural restoration of Duke Island is available at http://www.geo.arizona.edu/Paleomag/duke_ils.) Whether this speculative structural restoration of the Duke Island ultramafic complex is correct or not does not detract from our principal conclusion that the paleomagnetic directions cannot be used to infer the Cretaceous paleolatitude of Duke Island.

7. Conclusions

The primary conclusion of our paleomagnetic study is that cumulate layering of the Duke Island ultramafic complex, at least at scales up to tens of meters cannot be taken as a proxy for paleohorizontal at the time of magnetization. From the fold test using local cumulate layering, it is clear that layering on the scale of tens of meters was highly contorted at the time of magnetization. Observations of the layered ultramafic intrusive rocks of the Skaergaard intrusion, which is much better exposed than Duke Island, suggest that cumulate layering on even the kilometer scale can significantly depart from horizontal. Therefore any attempt to use paleomagnetic directions directly or indirectly restored to "horizontal" using cumulate layering of the ultramafic rocks is either demonstrably wrong or highly questionable. We further conclude that the compound correction of *Bogue et al.* [1995] does not fully restore the Hall Cove and Judd Harbor regions to their relative orientations at the time of magnetization and the compound corrected average cumulate layering does not serve as a proxy for paleohorizontal. We thus do not agree with the derivative conclusion by *Bogue et al.* [1995] that the paleomagnetic directions can be used to determine the mid-Cretaceous paleolatitude of Duke Island.

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