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Comment on "Paleomagnetism and Geochronology of the Ecstall Pluton in the Coast Mountains of British Columbia: Evidence for Local

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Comment on "Paleomagnetism and geochronology of the Ecstall pluton in the Coast Mountains of British Columbia: Evidence for local deformation rather than large-scale transport" by R. F. Butler et al.

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1. Introduction

[1] The ongoing work to resolve outstanding questions regarding the Cretaceous paleogeography of the North American Cordillera has spawned a healthy, and sometimes heated, examination of the geologic and paleomagnetic data on which conflicting interpretations of the amount of large-scale northward translation of terranes are based. *Butler et al.* [2002] (hereinafter referred to as BEA) interpret paleomagnetic data from the granitic Ecstall pluton, located near Prince Rupert, British Columbia, as evidence that the body was deformed via large-scale folding after acquiring its remanent magnetization in the late Mesozoic. This inference is then used by BEA to conclude that, after accounting for this folding, the Ecstall pluton records a unique magnetic inclination that can be used to rule out large-scale translation hypotheses such as "Baja BC" [i.e., *Irving et al.*, 1996]. In this comment, we recognize the value of the BEA study, which points out some very real complications in the magnetization history of this pluton. We wish to discuss the evidence for the fold postulated by BEA, to point out that there is little evidence to support its existence, and that the pattern of dispersion of the paleomagnetic data presented by BEA offers an alternate interpretation that provides a superior fit to the data, and also is consistent with the Baja BC hypothesis.

[2] The paleomagnetism of the Ecstall pluton was first investigated by *Symons* [1974], who found that it recorded an inclination of remanent magnetization that was too shallow relative to expected directions for its age and location based on apparent polar wander of North America. This observation, which conformed to a general orogen-wide pattern, was used by *Beck* [1980], *Irving et al.* [1996], and others, as evidence that portions of the western edge of the North American Cordillera had been transported relatively northward with respect to the interior of the continent, through distances exceeding several thousand kilometers, during latest Cretaceous and early Tertiary time. However, BEA reject this interpretation and instead regard their results as evidence that the pluton formed essentially in situ and acquired its suspiciously low inclination through local tectonics. The correct interpretation of the Ecstall shallow inclination has important tectonic implications.

[3] Although paleomagnetic results for the Ecstall pluton are only a small (and far from straightforward) piece of the Cordilleran puzzle, they assume much greater consequence in light of their subsequent interpretation. For instance, evidence of folding of the Ecstall pluton is used by *Butler et al.* [2001] to propose that a miscellany of unrelated causes (local deformation, compaction shallowing in sedimentary rocks, remagnetization, etc.) rather than northward translation is the correct explanation for all of the consistently shallow inclinations in Cretaceous rocks from the western Cordillera. In turn, *Butler et al.* [2001] is cited by *Dickinson* [2003] to characterize northward transport as a "geomyth" and later, in a single sentence, to dismiss the results of 40 years of Cordilleran paleomagnetism [*Dickinson*, 2004]. Other examples of the tectonic importance of the Ecstall results exist.

[4] In this discussion we take another look at the Ecstall paleomagnetic results. In agreement with BEA we conclude that the paleomagnetic evidence requires folding of the pluton about a NW trending axis sometime after it acquired its remanent magnetization. However, we show that this is fully compatible with an origin far to the south, and that in fact the latter interpretation fits the evidence much better than the tectonic scenario advanced by BEA. We do agree with BEA that because of internal folding it is not possible to use the Ecstall pluton's paleomagnetism to uniquely determine its latitude of origin.

[5] Field and laboratory methods are well described in BEA. We agree that Ecstall granitic rock retains a well-defined, ancient direction of magnetization. The Ecstall results are unusually scattered (Figure 1), but they record two polarities which are nearly antiparallel, and the entire data set is clearly nonrandom. Figure 1 includes two reference poles: the mid-Cretaceous pole of *Housen et al.* [2003] (essentially identical to that used by BEA) and the late Cretaceous–early Tertiary pole of *Beck and Housen* [2003]. Because data comprising the mid-Cretaceous refer-

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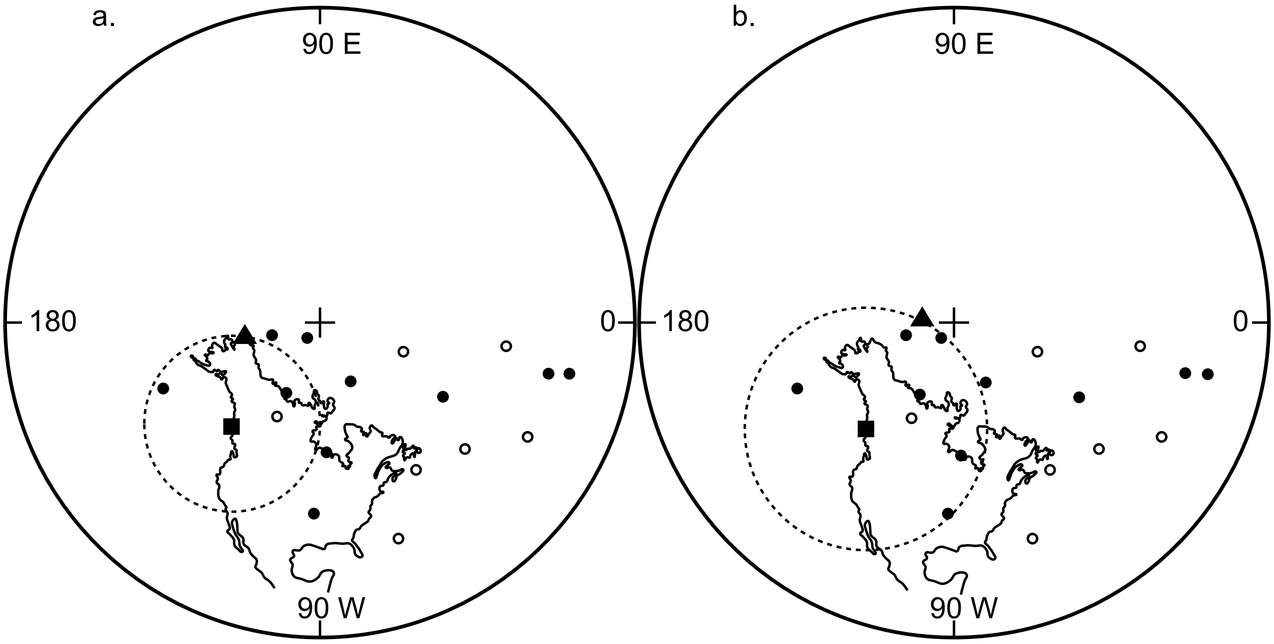

Figure 1. Site-mean virtual geomagnetic poles (VGPs) for the Ecstall pluton, from *Butler et al.* [2002]. Square, sampling location. Triangle, reference pole. (a) Mid-Cretaceous [*Housen et al.*, 2003] and (b) late Cretaceous–early Tertiary [*Beck and Housen*, 2003]. Circles are centered on the sampling location and pass through the reference pole; any VGP lying outside the circle has an anomalously shallow inclination.

ence pole all have normal polarity but the Ecstall pluton has many reverse polarity sites, we prefer the younger reference; however, our conclusions are valid whichever pole is used.

[6] From Figure 1 it is obvious that most site-mean virtual geomagnetic poles (VGPs) are rotated clockwise with respect to either reference pole. This is in keeping with most western Cordilleran paleomagnetic results. Also, the nominal paleolatitudes of most sites are lower than expected, using either reference pole. This also is not unusual. Treating the entire Ecstall pluton as an undisturbed whole and applying conventional concordance/discordance statistics, the Ecstall pluton's mean pole (59.0°N, 304.0°E, K = 6.4, A_{95} = 14.9°) shows a poleward transport of 15.5 ± 12.1° with respect to the mid-Cretaceous reference pole, and 7.2 ± 12.3° with respect to the late Cretaceous–early Tertiary pole. Both calculations indicate large, statistically significant clockwise rotations.

[7] BEA advanced beyond this standard interpretation by noticing that there is a gradient in inclination across the batholith; sites near its eastern margin have steep inclinations, grading to very shallow inclinations at its western margin. BEA subdivided their data into four subsets on the basis of location within the batholith to obtain the group means shown in Figure 2. Apparently "by eye" they fitted a fold axis to these data, interpreting the obvious small-circle distribution so obtained to folding about a horizontal axis trending 338°. (The actual best fit small circle to these data implies an axis plunging 20.5° in a direction 353.1°). BEA then conclude that the eastern sites with steep inclination are undisturbed (presumably because their steep inclinations approximate the Cretaceous expected direction), hence lie on or near the fold axis. Thus the BEA interpretation of these data is that the part of the Ecstall pluton they sampled is the western half of an NW trending anticline, and that the shallow inclinations found on its western margin are due to rotation with respect to a fold axis coincident with the easternmost exposures.

2. Testing the Fold

[8] In their discussion, BEA conclude that their postulated fold within the Ecstall pluton was consistent with the available data. As is also pointed out by *Hollister et al.*

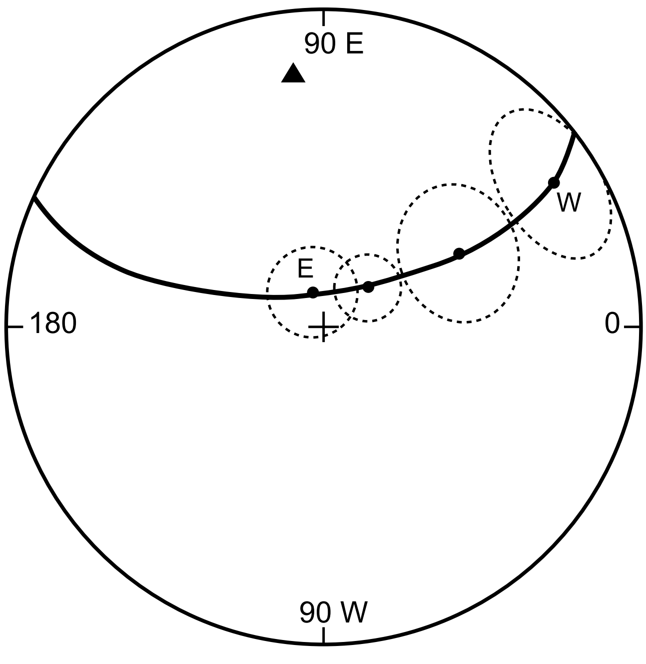

Figure 2. Locality means, from *Butler et al.* [2002], with circles of 95% confidence. Curve is best fit small circle, centered at D = 353.1°, I = 20.5°.

[2004], field evidence from the pluton itself [*Chardon*, 2003] does not appear to support the existence of this structure. The magmatic fabrics reported by *Chardon* [2003] indicate that relatively uniform, and fairly horizontal, foliations occur in the Ecstall pluton throughout the BEA sampling area. If the pluton was folded, these foliations should show some observable structural evidence of this deformation. Anisotropy of magnetic susceptibility (AMS) also was measured by BEA; such fabrics are often very sensitive indicators of mineral fabrics in plutonic rocks that are difficult to measure in the field [see *Bouchez*, 1997]. As an example, the NE portion of the Mount Stuart Batholith, in the Cascade Range (Washington State) has AMS fabrics that clearly indicate folding of magmatic foliations [*Benn et al.*, 2001], even though that portion of the Mount Stuart was folded through a smaller interlimb angle than is proposed for the Ecstall Pluton by BEA. The AMS results in BEA are not presented at a site level, so it is difficult to evaluate the structural significance of these fabrics. It is clear, however, that the large degree of folding called for by BEA is not supported by their fabric data. A smaller amount of folding (perhaps 20 degrees of tilt of each ''limb'') appears to be possible based on a visual examination of the AMS fabrics presented in BEA. Thus available structural data appear to rule out the possibility of the fold proposed by BEA.

[9] Still other data from BEA itself belie their preferred interpretation. Figure 3 of BEA shows the results of geobarometric determinations, made using the aluminum-in-hornblende method. Values shown range from 7.4 to 8.4 kb and do not vary in any obviously systematic way across the sampling area. BEA used the pattern of relatively uniform geobarometric results to rule out the possibility of large-scale tilt of the Ecstall pluton. Yet the folding of the pluton, based on their paleomagnetic evidence, requires a truly prodigious rotation ($\sim$75°) to convert the mid-Cretaceous expected direction (D = 327.8°, I = 77.9°) into a direction similar to that found near the western edge of the batholith. As the western sites are $\sim$11 km from the putative fold axis, one would expect to find that rocks currently exposed at the earth's surface originated at a level within the batholith some 10.5 km (11*(sin 75°) above the sites currently exposed at the batholith's eastern margin. Thus, if the folding hypothesis is correct there should be an obvious pressure gradient with an amplitude of $\sim$3 kb across the batholith. Also, the plunge mentioned earlier should produce a deep-to-shallow gradient from south to north. Neither of these patterns is present. As will be shown, this is largely because of the choice of reference direction and axis location made by BEA.

3. Example of an Alternative Interpretation

[10] Assume that the Ecstall pluton originated far south of its present location. Estimates of northward displacement of various mid-Cretaceous plutons, sedimentary strata, and volcanics in the Washington and Canadian Cordillera are $\sim$3000 km [*Cowan et al.*, 1997; *Housen and Beck*, 1999; *Enkin et al.*, 2003]. Because the Ecstall pluton appears to have acquired its magnetization a bit later than the mid-Cretaceous, further assume that its northward transport was 2500 km. Also assume that it traveled along the margin of North America. The northward displacement chosen would place it at about the location of San Diego, California, At that location, in late Cretaceous time, it would have acquired a direction of magnetization of D = 350.9°, I = 53.8°.

[11] The next step in this alternative scenario is northward transport. This we model as a rotation along the edge of North America of $\sim$48°, about a point located at 48.7°N, 78.2°W, which is arbitrarily chosen to match the pole of relative motion between the Pacific and North American plate (from NUVEL-1 [*DeMets et al.*, 1990]). Various transforms (small circles) related to this pole define much of the western outline of North America, hence motion northward along the continental margin is tantamount to rotation about this pole, to a first approximation. (Clearly, we do not mean to imply that the Ecstall pluton was displaced as part of the Pacific plate). Upon arrival at its present location the pluton would have a direction of remanent magnetization of D = 21.5°, I = 53.8°. Because observed directions within the body carrying that inclination have a declination of 50–60° (BEA, Table 2) we invoke a further (totally arbitrary) clockwise rotation of 33.5° to arrive at a starting in situ direction of D = 55°, I = 53.8°. We justify this latter step by noting that apparently in situ clockwise rotations of this magnitude are very common along the western edge of the continent [e.g., *Beck*, 1980].

[12] The final step in this scenario is to fold the pluton about an axis trending 353.1° and plunging 20.5°. For the location of the fold axis we chose the center of the batholith, where observed inclinations are approximately 50–60°. Using this starting location and original direction, to obtain the extreme inclinations along the margins of the pluton requires rotations of about 45°. Thus we model the BEA sampling area as a symmetrical anticline plunging 20.5° in a direction 353.1°. With these smaller rotation angles (and shorter axis-to-margin distances) the total structural relief after folding and planning off to present sea level is only about 3.9 km, equivalent to $\sim$1 to 1.5 kb Thus with this model one would expect very little variation in geobarometric determinations across the pluton, exactly as observed (BEA's Figure 3).

[13] This result shows that one cannot use the paleomagnetism of the Ecstall pluton as an argument against large-scale northward transport. Note that the various assumptions made are irrelevant; any reasonable choice of transport distance or original in situ declination will yield a similar conclusion. A least astonishment scenario places original magnetization of the pluton far to the south of its present position, but how far is anybody's guess.

[14] In a paper that appeared while this was being written, *Hollister et al.* [2004] suggest another reason for doubting the significance for terrane transport of the Ecstall paleomagnetic results. *Hollister et al.* [2004] regard the remanent magnetization of the Ecstall pluton as largely thermochemical, acquired in the Eocene by partial reheating, then cooling of exsolved ilmenohematite below 390°C; they apparently regard the appearance of internal folding as fortuitous. We agree that much or all of the magnetization in the pluton could be post-Cretaceous, but disagree about the significance of folding; the fit to a small circle shown in Figure 2 seems entirely too precise to be entirely accidental. Also, partial remagnetization would produce a great circle distribution of site-mean directions R = 90°, whereas the actual radius of the best fit small circle is 61°. *Hollister et al.*

[2004] also imply that their proposed method of remagnetization may have application to other plutons. In this they may be correct. However, regarding the Mount Stuart batholith, which they mention specifically, recent work [*Housen et al.*, 2003] has shown that magnetization is dominated by single-domain magnetite, and is entirely of normal polarity. Furthermore, the shape of the distribution of Mount Stuart site-mean VGP precludes significant internal deformation. Thus the interpretation of the Mount Stuart results, $\sim$3000 km of northward displacement, remains valid. The Ecstall pluton may have shared in this displacement.

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