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E/I corrected paleolatitudes for the sedimentary rocks of the Baja British Columbia hypothesis

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Abstract

Paleomagnetic inclinations from sediments of the western terranes of Canada are consistently too shallow for their reconstructed paleogeographic positions. Two contradicting explanations for these discrepancies are: (1) terranes have been displaced northward with respect to the stable American craton by several thousands of kilometres between the Late Cretaceous (~75 Ma) and the Eocene (~50 Ma) and (2) sedimentary inclination error has caused a shallow bias in the paleomagnetic directions. Here, we apply the elongation/inclination (E/I) method to paleomagnetic data sets from sedimentary rocks of supposedly allochtonous terranes of western North America to correct for inclination flattening. Our results indicate that the paleomagnetic directions from the continental Silverquick sediments (95–92 Ma) of southern British Colombia are not seriously affected by inclination error, because the magnetic signal most likely concerns a chemical remanent magnetisation (CRM). In contrast, the marine sediments of the Nanaimo Group (84–72 Ma) of Vancouver Island region appear seriously affected by inclination flattening ($f=0.7$) and the E/I corrected mean inclinations are about 9° steeper than the original data. We arrive at corrected inclinations/paleolatitudes of $I^{**}=57°/\lambda=38°$N for the Silverquick and $I^{**}=55°/\lambda=36°$N for the Nanaimo sediments. Our corrected paleolatitudes indicate that the Canadian terranes were indeed located adjacent to the Baja Californian margin during the Late Cretaceous, thus supporting the Baja BC hypothesis.

Keywords: paleolatitude; terranes; paleomagnetism; sediments; inclination error; British Columbia

1. Introduction

A variety of paleomagnetic data from sedimentary rocks of different regions of the Earth show inclinations that are significantly shallower than predicted from their expected paleolatitudinal positions. Non-dipole components in the Earth's magnetic field and inclination errors in the paleomagnetic data are two potential explanations for these anomalously shallow inclinations, but large-scale latitudinal transport of terranes and (micro)plates is also put forward, especially in tectonically active regions. Northward terrane displacement was for instance proposed for Southern California [1–3], Central Asia [4] and the East Mediterranean [5,6], but paleomagnetic correction methods later showed that the shallow bias in these studies was likely caused by sedimentary inclination errors [7–10].

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The Baja BC hypothesis of western North America is another key example of the ongoing debate on the origin of shallow inclinations (e.g., [11]). Late Cretaceous paleomagnetic directions from both plutonic and sedimentary rocks of the western terranes of Canada and the USA commonly reveal inclinations that are much shallower than those calculated from coeval rocks of the North American craton [12–22]. Paleomagnetic results from British Columbia suggest that several Canadian terranes were located ~3000 km south of their present position (Fig. 1), which would bring them to the same paleolatitude as Baja California in the Late Cretaceous (e.g., [15, 17]). Paleomagnetic results from the Eocene Flores volcanic rocks on Vancouver Island indicate that the terranes had arrived at their current position by ~50 Ma [23]. Consequently, the Canadian terranes must have been displaced northward with respect to the stable American craton by several thousands of kilometres between the Late Cretaceous (~75 Ma) and the Eocene (~50 Ma) through dextral strike-slip movement [23]. This scenario is called the Baja British Columbia (Baja BC) hypothesis and the proposed mechanism of movement is similar to that of present-day Baja California and the San Andreas Fault [24,25].

The hypotheses of large-scale northward terrane displacement were countered by a number of geological and paleomagnetic arguments. Geological field correlations have been put forward to reject these hypotheses, mainly because the observed fault systems could only account for minor displacements [26]. In addition, the anomalously shallow inclinations in plutonic rocks have been explained by systematic errors in tilt correction, which would require smaller orogen-parallel displacements [27–29]. Data from sedimentary rocks have been countered by studies showing that anomalously shallow inclinations could also be explained by inclination flattening during compaction [7,8]. Cowan et al. [11] evaluated the hypotheses of large-scale coastwise displacement using a number of “critical geological tests”. These are as yet inconclusive, so controversies concerning the paleolatitudinal position of the suspect

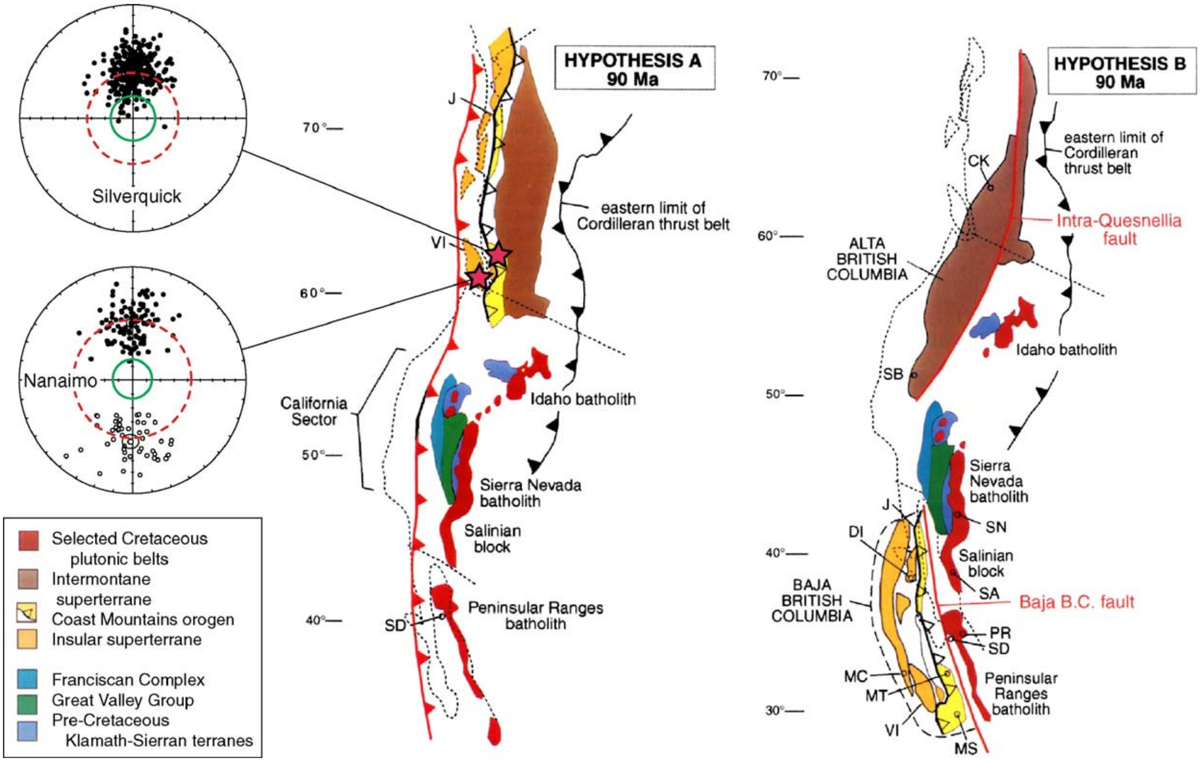

Fig. 1. Two hypotheses for the Late Cretaceous paleogeography of the western margin of North America (after Cowan et al. [11]). Hypothesis A assumes that the Insular (orange color) and Intermontane (yellow and brown) superterranes both lay north of California, such that their total post-Late Cretaceous northward displacement with respect to California and the North American craton is <1000 km. Hypothesis B, the so-called “Baja BC hypothesis”, postulates that parts of the Insular and Intermontane superterranes used to lie at least 2400 km south of their current position, relative to stable North America, in the Late Cretaceous. Equal area projections are paleomagnetic directions of sediments from the Silverquick conglomerate [18,20] and the Nanaimo Group [19,35]. Dashed red circles indicate mean inclination of the raw paleomagnetic data, solid green circles indicate expected inclinations according to the reconstruction of Besse and Courtillot [37], assuming no terrane displacement took place.

terranes of western North America in the Cretaceous have not yet been resolved.

Here, we apply the elongation/inclination (E/I) correction method of Tauxe and Kent [9] for inclination flattening to the paleomagnetic data sets of the sedimentary rocks of Baja BC, which mainly come from two different units (Fig. 1); the continental Silverquick red beds of southern British Colombia [18,21] and the marine Nanaimo rocks of Vancouver Island region [19,20]. We will evaluate how much E/I correction can compensate the shallow bias in the Baja BC sediments, and we will provide corrected estimates on the original paleolatitudinal position of the Canadian terranes in the Late Cretaceous and thus on the amount of northward transport.

2. The E/I method to correct for inclination flattening

Fine-grained sedimentary rocks can suffer from paleomagnetic inclination flattening either during initial deposition (e.g., Tauxe and Kent [30]) or during the post-depositional process of burial compaction (e.g., Tauxe [31]). During sedimentation, magnetic grains remain free to move and align with the Earth's field, but at some point become "locked in", and unable to realign with the field. The directions can be too shallow from a sub-horizontal bias in alignment of elongate magnetic particles (e.g., King [32]), or by subsequent compaction related processes [31].

A theoretical model that can recognize and correct for inclination errors in sedimentary rocks has been developed by Jackson et al. [33]. This model assumes that inclination flattening is determined by a function of the bulk magnetic anisotropy of the remanence carrying grains and the magnetic anisotropy of the individual grains, because the orientation distribution of magnetic grains in sediments changes in a regular way during compaction. Experimental studies have shown that the anisotropy of anhysteretic remanence (AAR) can be successfully used to identify and correct inclination flattening (e.g., [34]).

Recently, a statistical geomagnetic field model (TK03.GAD) was developed by Tauxe and Kent [9], that can be used to predict distributions of paleomagnetic field vectors as a function of paleolatitude, assuming that the Earth's magnetic field was on average that of a geocentric axial dipole (GAD). The shape of the distribution of directions ranges from elongate at the equator to circular at the poles. Because elongation decreases and inclination increases with increasing latitude, there is a unique value of elongation with respect to inclination predicted by the field model (Fig. 2). The elongation/inclination (E/I) method of Tauxe and Kent [9] assumes that when inclination error occurs, the directional dispersion can also be predicted. The well known inclination error formula $\tan I_o = f^* \tan I_f$ [32], where I_o is the observed inclination, I_f is that of the applied field, and f a "flattening factor", can be used to "unflatten" a given directional data set by the formula $\tan I^{**} = (1/f) \tan I_o$, where I^{**} is the estimated original field direction assuming a value of f. The E/I method determines the optimum value of f that simultaneously gives values for the average I^{**} and E of the unflattened distribution that are consistent with TK03.GAD.

It should be noted that the E/I method will only work properly if there are enough observations to adequately represent the statistical distribution of the geomagnetic field. The E/I method requires a data set large enough to have sampled secular variation of the geomagnetic field and one in which the average value of f can reasonably be estimated. Tauxe and Kent [9] argued that at least 100 sites are necessary to represent the distribution of directions drawn from plausible models of the geomagnetic field.

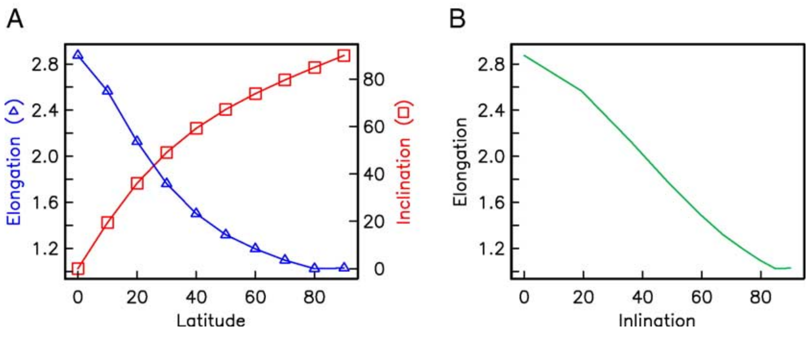

Fig. 2. A) Variations of elongation and inclination as a function of (paleo)latitude from realizations of the TK03.GAD statistical model for the geomagnetic field [9]. B) Variation of elongation as a function of inclination.

3. The Silverquick sediments (southern British Colombia)

The continental sediments of the Silverquick conglomerate form an essential element to the Baja BC hypothesis as they provide solid paleomagnetic data from sedimentary rocks that imply more than 3000 km of northward transport of the Insular and Intermontane superterranes [18,21] (Fig. 1). The Silverquick sediments are of Cenomanian age (95–92 Ma) and reveal shallow inclinations/paleolatitudes at two different localities; $I=57°/\lambda=38°$N at Mount Tatlow (51.3°N; 236.2°E) [18] and $I=56°/\lambda=36°$N at Churn Creek (51.4°N; 238.4°E) [21]. Near Mount Tatlow, the Silver-

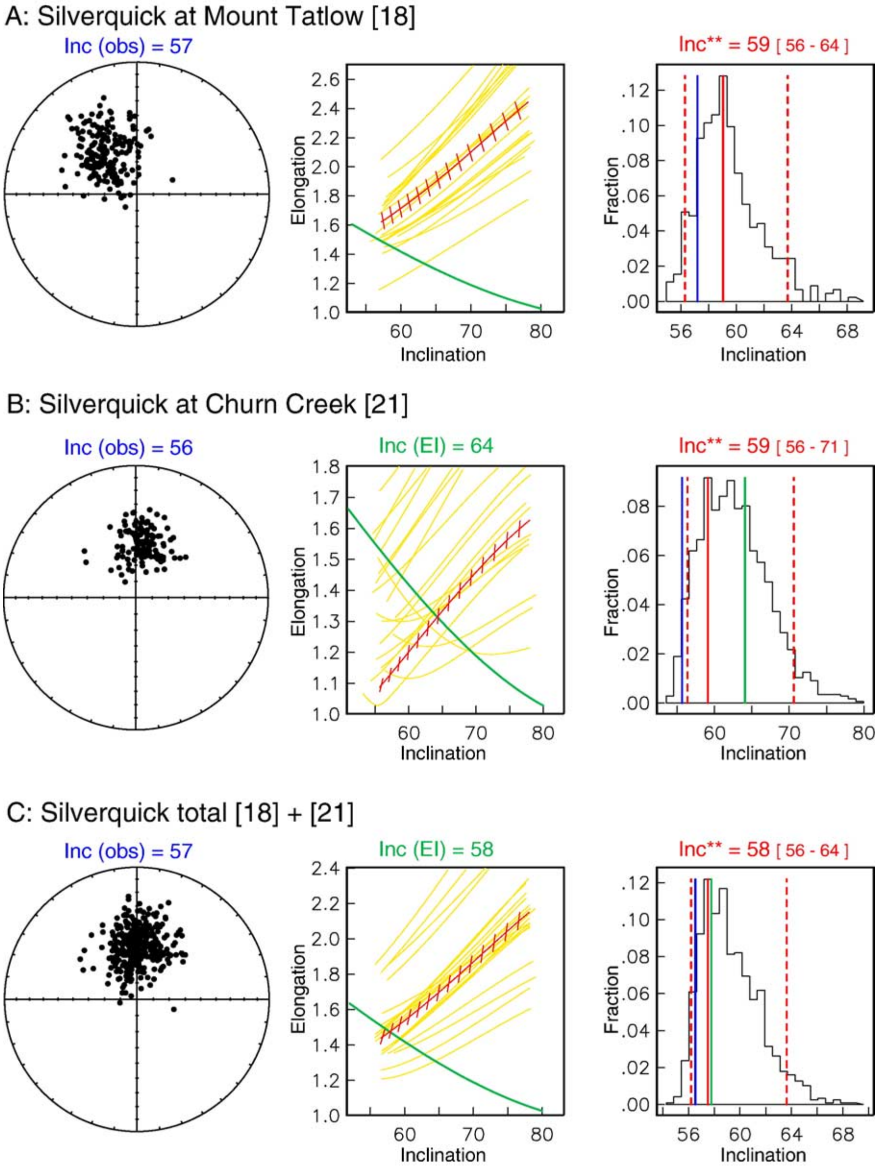

Fig. 3. Left: equal area projections of paleomagnetic directions of the Silverquick sediments from A) Mount Tatlow [18], B) Churn Creek [21], C) combined Mount Tatlow + Churn Creek. Middle: elongation versus inclination plots for the TK03.GAD model (dashed line) and for the paleomagnetic data (barbed line) for different values of f. The barbs indicate the direction of elongation with horizontal being E–W and vertical being N–S. Also shown are results from 20 bootstrapped datasets (yellow lines). The crossing points represent the inclination/elongation pair most consistent with the TK03.GAD model. Right: histograms representing crossing points from 5000 bootstrapped datasets. Blue line represents the original data, green line the TK03-corrected inclination of the original dataset and red line the most frequent inclinations after bootstrapping with dotted the 90% confidence bounds.

quick sediments are predominantly fluvial in origin, consisting of channelized sandstone and conglomerate, but also contain planar-laminated overbank deposits of siltstone and mudstone from which the paleohorizontal surfaces can be determined with precision [18]. The strata occur in a syncline, allowing a rigorous fold test to be made. At Churn Creek, a sequence of complexly interfingering conglomerates and sandstones is correlated to the Silverquick conglomerate/Powell Creek Group [21].

If inclination flattening plays a role in the Silverquick sediments, it may significantly change the geodynamic interpretations of Baja BC terrane displacement during the Cretaceous. To establish the original paleolatitude at the time of deposition, we apply the E/I correction method of Tauxe and Kent [9] to the paleomagnetic data set of the Silverquick rocks. We obtained the specimen directions for all Silverquick sites of Mount Tatlow from E. Irving and for all Silverquick/Powell Creek Group sites of Churn Creek from R. Enkin, but only incorporated those directions obtained from sediments with a characteristic remanent magnetisation (ChRM) that revealed high unblocking temperatures and passed the tilt test. This resulted in data sets of 176 samples from 15 sites of Mount Tatlow [18] and 129 samples from 16 sites of Churn Creek [21].

We want to emphasize that a total number of 305 independent registrations of the Earth's magnetic field from the Silverquick sediments is nearly ideal for the application of the E/I method. The 305 samples have likely sampled the field randomly, even if only at 31 distinct sites. In classical paleomagnetism, 31 sites are generally considered as 31 datapoints, because classical paleomagnetism requires that secular variation (SV) be averaged out. On the contrary, a field model (TK03.GAD) requires that SV NOT be averaged out. Instead, it requires an optimal distribution of individual directions that sufficiently samples snapshots of the field. Here, "optimal" means that sampling should be directed at sampling the field over a long enough time interval, e.g., several times the typical SV time scale, and in high enough resolution. This is typically what occurs in paleomagnetic sampling of sediments. To average out SV, one takes samples—even at the site level—at (slightly) different horizons. Thus, in practice, individual samples (cores, specimens) of a sedimentary site randomly sample SV, contrary to individual lava flows, which represent spot (~1 yr average) readings of the field.

We applied the E/I method to the individual results of Mount Tatlow and Churn Creek by systematically unflattening the paleomagnetic directions with values of f ranging from unity to 0.3 (Fig. 3A,B). At each unflattening step, we evaluate the mean inclination and elongation as defined by Tauxe and Kent [9]. We repeat the analysis on 5000 bootstrapped pseudo samples of the original data in order to estimate the uncertainty. The crossing point of a given elongation/inclination versus f curve with the model curve gives a unique E/I pair consistent with the field model. The histogram of all inclinations derived from the bootstrapped crossing points as well as the 95% confidence bounds shows that

Table 1

Summary of the paleomagnetic data from key-sites of the Baja BC controversy, with Lat/Long = latitude/longitude of the sample locality, N = the number of sites, D/I are the observed declination/inclination, k = precision parameter, α95 = 95% cone of confidence, I(e/i)/lat(e/i) = the corrected inclination/paleolatitude after E/I correction, plat/plong = latitude/longitude of the North American pole according to the reconstruction of [37], I_p = the predicted inclination, lat(NA) = the predicted latitude of the locality assuming no displacement with respect to North America, Ref = EPSL reference number

Formation/group	Age	Lat	Long	N	D	I	k	α95	I(e/i)	lat (e/i)	plat	plong	I_p	lat (NA)	Ref
Silverquick															
Mount Tatlow	95–92	51.3	236.2	176	322.9	57.2	20.7	2.4	58 [56–63]	39 [37–45]	75.3/76.4	196.4/197.7	74–75	60–62	[18]
Churn Creek	95–92	51.4	237.5	129	6.8	55.7	36.0	2.1	60 [56–70]	41 [37–54]	75.3/76.4	196.4/197.7	74–75	60–62	[21]
Total	95–92	51.4	237.5	305	360.0	56.5	25.2	1.6	57 [56–64]	38 [37–46]	75.3/76.4	196.4/197.7	74–75	60–62	
Nanaimo															
Pender/Spray	84–72	49.5	235.0	60	30.5	41.8	17.7	4.5	50 [42–61]	31 [24–42]	73.4/73.5	209.7/220.5	76	64	[19]
Northumberland	~75	49.5	235.3	83	6.0	50.9	20.4	3.5	61 [51–69]	42 [32–53]	73.4/75.7	209.7/197.6	74–76	60–64	[35]
Total	84–72	49.5	235.0	143	360.0	47.1	18.3	2.8	55 [48–63]	36 [29–45]	73.4/73.5	209.7/220.5	76	64	
Volcanics															
Spences Bridge	104	50.5	239.0	14	53.5	70.3	27.6	7.7		54 [44–67]	81.7/76.8	198.3/191.5	73	58	[39]
Mount Stuart	91	48.0	239.0	11	354.2	46.2	87.2	4.6	51 [47–55]*	32 [28–36]	75.3	196.4	72	57	[22]
Flores	51–50	49.0	234.0	12	349.8	69.6	41.0	7.0		53 [44–65]	79.3	170.3	69	53	[23]

the mode is $I^{**}=58–60°$ for both data sets (Fig. 3A,B; Table 1).

Since the individual results for Mount Tatlow and Churn Creek appeared to be in very good agreement, we also combined the two studies by rotating each data set to have an average declination of zero degrees. Application of the E/I method to the total paleomagnetic data set of Silverquick sediments revealed a mode of $I^{**}=57°$. The E/I pair of the total data set that is consistent with TK03.GAD is achieved with a flattening value f of 0.95 (Fig. 3C), indicating that the continental sediments of the Silverquick Formation are hardly affected by inclination flattening due to compaction. This strongly supports the suggestion that the Silverquick sediments have acquired their magnetization at a paleolatitude of 38°N in the Late Cretaceous.

4. The Nanaimo sediments (Vancouver Island)

Anomalously shallow inclinations from Baja BC sediments have also been reported from marine rocks of the Nanaimo Supergroup of the Vancouver Island region, which belongs to the Insular Superterrane [19,20,35] (Fig. 1). The Nanaimo Group comprises a sequence of Upper Cretaceous (~90–65 Ma) sedimentary rocks deposited in a marine shelf of a submarine fan environment. It consists of interbedded mudstones, siltstones and sandstones that provide clear evidence of paleohorizontal. Unfortunately, many strata appeared unsuitable for paleomagnetic research because of low unblocking temperatures and a pervasive remagnetisation [19,20].

Two sections on Texada (Pender Formation; ~83–78 Ma) and Hornby Island (Spray Formation; ~75–70 Ma), however, contain ammonite and inoceramid bivalve fossils composed of unaltered aragonite containing organic macromolecules [19]. The presence of such unaltered fossil material is an indication that thermal and chemical remagnetisation is minimal to absent [36]. Paleomagnetic data from these unaltered outcrops of the Nanaimo Group were mainly collected from silty mudstones and showed very shallow paleomagnetic inclinations ($I=42°$), suggesting about 3500 km of northward displacement of Vancouver Island with respect to the stable North American craton [19]. This would place the Insular Superterrane at even lower latitude (25°N) than the results from southern British Columbia.

The Nanaimo Group has been widely re-sampled, with 67 sites spread over 150 km, at sedimentary rocks of Santonian to Maastrichtian age (~85–65 Ma) [20]. Inclination-only analysis resulted in a mean inclination of $I=55°$, which is significantly steeper than the $I=42°$ of Ward et al. [19], but still requires over 2000 km of northward transport. A recent paleomagnetic study of the Upper Nanaimo Group on Hornby Island (Northumberland Formation; ~75 Ma), sampling mainly concretions and fine-grained rock (shales, siltstone and sandstone), resulted in a mean inclination of $I=51°$ [35].

Because clay content may play an important role in causing anomalously shallow inclinations during burial compaction, there is a possibility that compactional processes in these marine rocks have caused the lower inclination observed in the Nanaimo Group. We thus applied the E/I method to the dataset of Ward et al. [19] to test for possible inclination shallowing. We only incorporated the most reliable results that were interpreted as demagnetization lines, thereby neglecting the data obtained from great circles. Application of the E/I method to the directional distribution ($N=60$) reveals that the most consistent E/I pair is obtained when a flattening parameter f of 0.60 transforms the directions to a mean inclination $I^{**}=50°$, with 42–61° as 95% confidence bounds (Fig. 4A; Table 1).

The specimen directions of the Nanaimo localities from the Northumberland Formation on Hornby Island [35] were kindly provided to us by K. Kodama. We applied the E/I method to the $N=83$ individual directions of the complete paleomagnetic dataset ($I=51°$), which was derived from mudstones, siltstones, sandstones and concretions [35]. This resulted in a flattening factor f of 0.65 and a significantly higher corrected inclination mode $I^{**}=61°$ (Table 1). We also applied the E/I method to the directional data from the mudstones only and obtained an inclination of $I^{**}=59°$ [47–69], although the number of independent horizons ($N=24$) is far too low for any significant conclusion.

We realize that neither of these two independent Nanaimo case studies fulfill the requirement by Tauxe and Kent [9] of a dataset with at least 100 samples. Hence, we combined the directional Nanaimo data of Ward et al. [19] with those of Kim and Kodama [35] to enlarge our data set to 143 independent directions. This was done by rotating each data set to have an average declination of zero degrees; the combined data set has a mean inclination of $I=47.1°$. Application of the E/I method to the combined directional Nanaimo distribution reveals that the most consistent E/I pair is obtained when a flattening parameter f of 0.68 transforms the directions into a mean inclination $I^{**}=55°$, with 48–63° as 95% confidence bounds (Fig. 4C; Table 1).

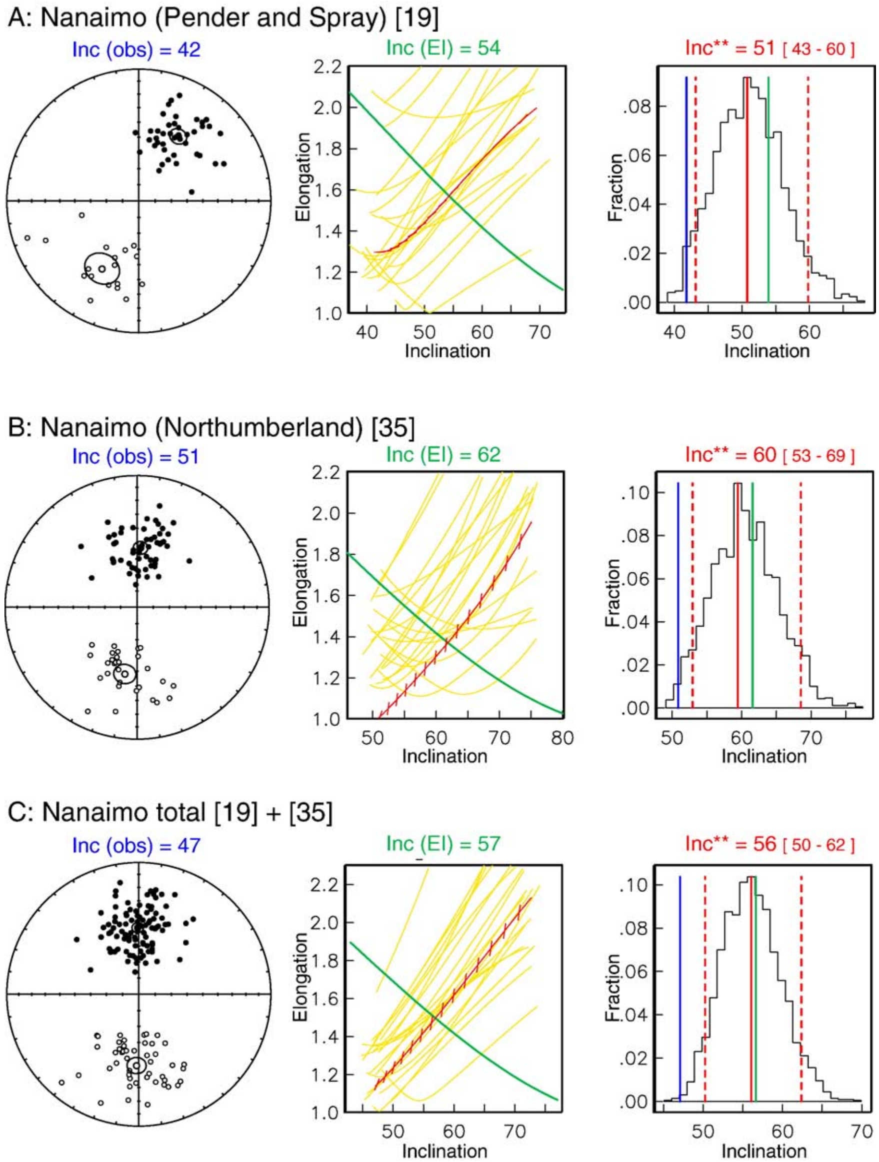

Fig. 4. Left: equal area projections of paleomagnetic directions of the Nanaimo sediments from A) Ward et al. [19], B) Kim and Kodama [35], C) combined dataset. Middle: elongation versus inclination plots for the TK03.GAD model (dashed line) and for the paleomagnetic data (barbed line) for different values of f. The barbs indicate the direction of elongation with horizontal being E–W and vertical being N–S. Also shown are results from 20 bootstrapped datasets (yellow lines). The crossing points represent the inclination/elongation pair most consistent with the TK03.GAD model. Right: histograms representing crossing points from 5000 bootstrapped datasets. Blue line represents the original data, green line the TK03-corrected inclination of the original dataset and red line the most frequent inclinations after bootstrapping with dotted the 90% confidence bounds.

Combining the individual results of two independent studies by rotating each data set to an average declination of zero degrees does not, however, rule out the possibility that there may in fact have existed small, unrecognized, rotations within the study regions. Clearly such differential rotations could have an effect on the data elongation and consequently also on the corrected inclinations. However, the outcome of the E/I method is insensitive to small differential ($<5^\circ$) rotations.

All these results support the suggestion that the sediments of the Nanaimo Group are affected by inclination flattening ($f=\sim0.7$). Application of the E/I method provides in all cases corrected inclinations that range between 51° and 60°, and that are ~9° steeper than the observed inclinations. This result indicates that the Nanaimo sediments have acquired their magnetization at paleolatitudes between 29° and 45°N.

5. Discussion

5.1. No inclination flattening in the Silverquick sediments

Wynne et al. [18] argued cogently against the possibility that the shallower inclinations of the Silverquick sediments are related to compaction processes by appealing to the similarity of paleomagnetic directions measured in fine-grained sedimentary rocks and in concretions. These arguments have been considered equivocal because at least some concretions have been shown to have a flattened AAR fabric [35]. Enkin et al. [21] also argued against compaction shallowing in their paleomagnetic directions from Churn Creek because they did not observe a significant magnetic foliation anisotropy.

Application of the E/I method to the paleomagnetic data from the Silverquick conglomerate confirms that these continental sediments were not significantly affected by inclination flattening. It is possible that the Silverquick magnetization is a chemical remanent magnetization (CRM), which would also explain the similar inclination results obtained in widely varying lithologies. When applied to a CRM, the E/I method will not result in corrected inclinations that are significantly different from the observed inclinations.

Our E/I corrected results ($I^{**}=57°$) indicate that the Silverquick sediments have acquired their magnetization at a paleolatitude of 38°N, with 95% confidence bounds between 37°N and 46°N (Fig. 3). An additional check on the validity of these shallow inclinations and paleolatitudes from the Silverquick sediments can be attained by comparison with paleomagnetic data from volcanic rocks of the same region, as inclination flattening through compaction is certainly not an issue there. Near Mount Tatlow, the Silverquick sediments are overlain by subaerial andesitic to basaltic lava beds of the Powell Creek volcanics ($^{40}Ar/^{39}Ar$ ages between ~92 and 79 Ma), from which four massive lavas and one breccia have been sampled spanning a stratigraphic thickness of approximately 200 m [18]. These volcanic rocks yielded excellent demagnetization diagrams. Line fitting results revealed pre-tilt inclinations of $51.5° \pm 8.0°$ ($N=5$), which are even shallower, but in reasonably good agreement with the sedimentary data. The inclinations from the Silverquick sediments and Powell Creek volcanics are furthermore in good agreement with the aluminum-in-hornblende (AH) barometry corrected paleomagnetic results ($I=51°/\lambda=31°$N) from the Upper Cretaceous igneous rocks (~91 Ma) of the Mount Stuart batholith (47.4°N; 239.0°E). This significantly strengthens the hypothesis of large-scale (>2000 km) northward terrane displacement of the Canadian superterranes [13,16,22].

5.2. Inclination flattening in the Nanaimo rocks

Application of the E/I method to the paleomagnetic directions of the Nanaimo Group show that these marine sediments were probably affected by inclination error, and that the most consistent E/I pair is obtained when a flattening parameter f of 0.7 is used. Our E/I results on the separate and combined datasets of Ward et al. [19] and Kim and Kodama [35] indicate that the corrected mean inclinations are consistently about 9° steeper than the original data (Fig. 4; Table 1). Rock magnetic and AAR measurements earlier showed that the Nanaimo rocks indeed had typical compactional fabrics with minimum principal axes oriented perpendicular to the bedding. Correction for inclination shallowing according to the AAR method increased the average inclination by 10° [35]. Other attempts to correct for inclination error in Cretaceous marine sedimentary rocks by the AAR method obtained correction values of 9–12° for the Pigeon Point Formation [8] and 10–15° for the Ladd Formation and Point Loma Formation [7]. The similarity of results obtained by the E/I and AAR correction methods gives us confidence that the observed inclinations and estimated paleolatitudes from the Nanaimo sediments were indeed biased shallow, and should be steeper by approximately 10°.

Our E/I corrected results ($I^{**}=55°$) thus suggest that the Nanaimo sediments have acquired their magnetization at a paleolatitude of 36°N, with 95% confidence bounds between 29°N and 45°N (Fig. 4). This paleolatitudinal position ($\lambda=35°$N at ~75 Ma) for the Insular Superterrane is in excellent agreement with the results from the Silverquick sediments ($\lambda=38°$N at ~90 Ma) and indicates that this terrane had not moved significantly northward during a ~15 Myr time period.

We realize, however, that the available paleomagnetic datasets from the Nanaimo group are not ideal for the application of the E/I method. The Nanaimo rocks are notoriously difficult for paleomagnetic studies because many samples have low unblocking temperatures and strong present-day field components. In addition, the number of independent directions from the two available paleomagnetic studies [19,35] is in both cases lower than required by the E/I method according to Tauxe and Kent [9]. We therefore recommend the Nanaimo Group be re-sampled in great detail, in accordance to the requirements of the E/I method with at least several hundred directions at one locality, to obtain a statistically more robust value on the corrected inclination and paleolatitude.

5.3. Implications for the Baja BC hypothesis

Now that we have established the original paleolatitude of the key sedimentary sites of the Baja BC hypothesis by correcting for inclination flattening, we can also estimate the offset from the predicted paleolatitude if the terranes had been attached to the North American craton (thus implying zero terrane displacement). The apparent polar wander path (APWP) for the North American craton has recently been updated [37]. This APWP is at present the most consistent way to calculate the predicted paleolatitude of our sites, allowing us to determine the latitudinal difference between the terranes and the stable continent (Fig. 5). For simplicity, we did not indicate the rotation of the North American continent in the figure (up to 15°).

Application of the E/I method to the paleomagnetic data from the Silverquick conglomerate (~95–92 Ma) reveals an average inclination $I^{**}=57°$ and corresponding paleolatitude $\lambda=38°$N (Fig. 5). We have furthermore shown that the marine sediments of the Nanaimo Group (~84–72 Ma) have a mean inclination after correction of $I^{**}=55°$, corresponding to a paleolatitude $\lambda=36°$N. The corrected paleolatitudes are in good agreement with the paleomagnetic results from the Powell Creek volcanics [18] and the AH-barometry corrected results from Mount Stuart [13,22]. All these results thus indicate a paleolatitude of 35–38°N for the Insular/Intermontane Superterrane in the Late Cretaceous (~90–75 Ma), i.e., at the paleolatitude of Baja California, while the neighbouring craton was at 57–61°N (Fig. 5).

At Churn Creek, the Silverquick sediments unconformably overlie the Mid-Cretaceous (105–100 Ma) volcanic deposits of the Spences Bridge Group [21,38]. Two independent results of these volcanic rocks revealed much steeper inclinations ($I=70°$) [39,40], which make the displacement history of the combined Insular/Intermontane Superterrane even more complicated (Fig. 5). These results suggest that ~2500 km southward transport is required between 100 and 90 Ma [21]. If this is true, reliable age control will also become a key element in future research to verify and better constrain the displacement of the suspect terranes of North America. The ongoing controversies regarding

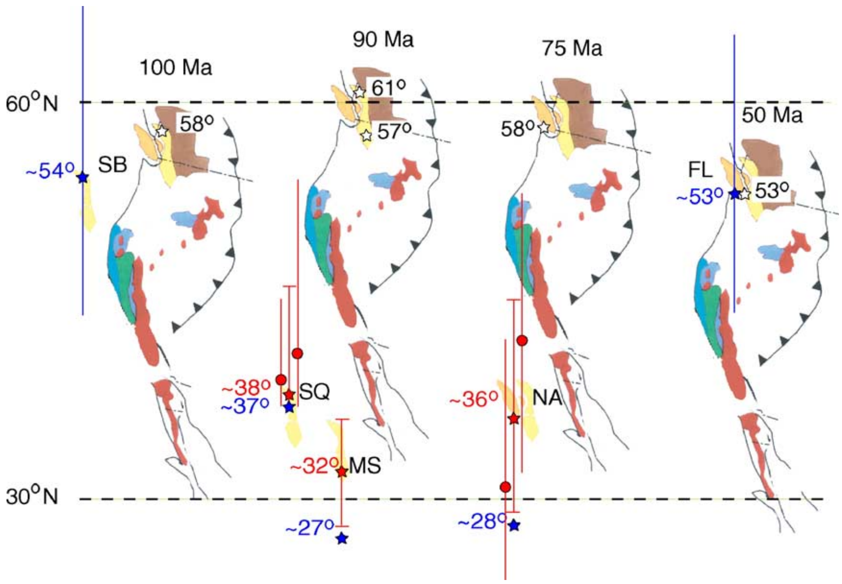

Fig. 5. Paleogeographic reconstruction of the western North American margin during the Late Cretaceous to Eocene based on corrected paleomagnetic results. White stars indicate expected paleolatitudinal values for the key sites SB=Spences Bridge group, SQ=Silverquick conglomerate, MS=Mount Stuart, NA=Nanaimo Group, FL=Flores volcanics. Blue stars indicate the paleolatitudical position estimated from the original paleomagnetic data, and red stars indicate paleolatitudinal position after correction for inclination errors (see Table 1). Our reconstruction shows that the suspect Canadian terranes were located adjacent to the Baja Californian margin during 90 and 75 Ma, thus still supporting the Baja BC hypothesis. Inclination data from the Spences Bridge Group make the Cretaceous paleogeographic reconstruction of the North American margin even more complicated by implying that the Baja BC terranes were located ~2500 km more northward at ~100 Ma. Data from Eocene rocks (~50 Ma) indicate that all major terrane displacement had ceased. This clearly emphasizes the importance of obtaining reliable age control for the Late Cretaceous rocks of the western American margin, since opposing scenarios will now have to be reviewed in different time windows.

the Baja BC hypothesis essentially resulted in two opposing scenarios (e.g., [11]) will than have to be reviewed in different time windows. The northern option implying that Baja BC was positioned north of California could have been the situation for the rocks of 120–100 Ma, while the southern option postulating that Baja BC was positioned adjacent to Baja California could be true for the rocks that formed between 100 and 75 Ma. It should be noted, however, that this geodynamic scenario is not supported by our current knowledge of plate motions in the Pacific basin.

Paleomagnetic results from the Eocene Flores volcanic rocks (Table 1) indicate that Vancouver Island had arrived at its current position at ~50 Ma [23]. The timing of terrane displacement along the North American margin is thus restricted to the period between 75 and 50 Ma (Fig. 5). Our E/I corrected results indicate a paleolatitude of 37–38°N for the Insular/Intermontane Superterrane in the Late Cretaceous (~90–75 Ma), while the neighbouring craton was at 57–61°N (Fig. 5). It would thus require between 2000 and 2500 km northward transport to bring the Baja BC landmasses to their present position during the Late Cretaceous to Eocene. As a consequence, relative plate tectonic displacement rates between the Insular Superterrane and the North American craton must have been of the order of 8–10 cm/yr to the north in the period between 75 and 50 Ma.

6. Conclusions

Application of the E/I method to correct for potential inclination errors in the paleomagnetic data sets of sedimentary sequences from the Insular Superterrane show that the corrected inclinations are still in favour of the Baja BC hypothesis. The continental sediments of the Silverquick conglomerate (95–92 Ma) of the Canadian Coastal Mountains are hardly affected by inclination error ($f=0.95$). The results of the E/I method give a corrected mean inclination of $I^{**}=57°$, which implies that this unit was formed at a paleolatitude of 38°N. This is in good agreement with paleomagnetic data from the Powell Creek volcanic rocks (~92–79 Ma; $I=51°$) and the igneous rocks of the Mount Stuart Batholith (~91 Ma), which reveal an average inclination of $I=51°$ and paleolatitude $\lambda=31°$N, after correction for tilt by AH-barometry [22]. All this confirms that the so-called “Baja BC terrane” at ~90 Ma was indeed located at the same paleolatitude as Baja California.

The marine sediments of the Nanaimo Group (84–72 Ma) of Vancouver Island are seriously affected by inclination error ($f=0.68$), and the corrected inclination $I^{**}=55°$ corresponds to a paleolatitude $\lambda=36°$N. Our results indicate that the corrected mean inclinations are about 9° steeper than the original data [19,35], which is in excellent agreement with the 10° correction obtained by the AAR method [35]. Correcting for inclination error clearly does not compensate entirely for the anomalously shallow inclinations and suggests that at ~80–70 Ma the Baja BC terrane was located at about the same paleolatitude as at ~90 Ma. It would require between 2000 and 2500 km northward transport, and displacement rates of the order of 8–10 cm/yr, to bring the Baja BC landmasses to their present position during the Late Cretaceous to Eocene.

We conclude that inclination flattening during compaction of the paleomagnetic data from sedimentary rocks of the suspect Canadian terranes cannot be used as an argument to refute the Baja BC hypothesis. Consequently, the controversies regarding the amount of northward terrane displacement of Baja BC have still not been resolved.

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