Paleomagnetism of the Upper Cretaceous Nanaimo Group, southwestern Canadian Cordillera[1]

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Abstract: The Baja B.C. model has the Insular Superterrane and related entities of the Canadian Cordillera subject to >3000 km of northward displacement with respect to cratonic North America from ~90 to ~50 Ma. The Upper Cretaceous Nanaimo Group (on and about Vancouver Island, British Columbia) is a prime target to test the model paleomagnetically because of its locality and age. We have widely sampled the basin (67 sites from seven islands spread over 150 km, Santonian to Maastrichtian age). Most samples have low unblocking temperatures (<450°C) and coercivities (~10 mT) and strong present-field contamination, forcing us to reject three quarters of the collection. Beds are insufficiently tilted to provide a conclusive fold test, and we see evidence of relative vertical axis rotations. However, inclination-only analysis indicates pretilting remanence is preserved for many samples. Both polarities are observed, and reversals correlate well to paleontological data, proving that primary remanence is observed. The mean inclination, 55 ± 3°, is 13 ± 4° steeper than previously published results. Our new paleolatitude, 35.7 ± 2.6° is identical to that determined from the slightly older Silverquick and Powell Creek formations at Mount Tatlow, yet the inferred displacement is smaller (2300 ± 400 km versus 3000 ± 500 km) because North America was drifting southward starting around 90 Ma. The interpreted paleolatitude conflicts with sedimentologic and paleontologic evidence that the Nanaimo Basin was deposited near its present northern position.

Résumé : Selon le modèle Baja BC, de ~90 à ~50 Ma, le superterrane insulaire et les entités associées de la Cordillère canadienne se sont déplacés de plus de 3000 km par rapport au Bouclier canadien. Étant donné sa localisation et son âge, le Groupe de Nanaimo, du Crétacé supérieur (sur et autour de l'île de Vancouver en Colombie-Britannique), est une cible de choix pour faire l'essai du modèle paléomagnétique. Nous avons échantillonné le bassin sur une grande échelle (67 sites sur 7 îles, répartis sur 150 km, du Santonien au Maastrichtien). La plupart des échantillons ont de basses températures de dé-blocage (<450 ºC) et des coercivités faibles (~10 mT). De plus, la forte contamination du champ présent nous force à rejeter les ¾ de la collection. Les lits ne sont pas assez inclinés pour fournir un essai de plissement concluant et nous voyons des preuves de rotation des axes verticaux. Toutefois, une analyse de l'inclinaison seule indique que la rémanence avant inclinaison est bien préservée dans plusieurs échantillons. Les deux polarités sont observées et les inversions de polarité corroborent bien les données paléontologiques, prouvant ainsi que c'est la rémanence primaire qui est observée. L'inclinaison moyenne 55º ± 3º est 13º ± 4º plus abrupte que ce qui a été publié antérieurement. Notre nouvelle paléoaltitude, 35,7º ± 2,6º est identique à celle déterminée à partir des formations légèrement plus âgées de Silverquick et Powell Creek au mont Tatlow, mais le déplacement inféré est moindre (2300 ± 400 km par rapport à 3000 ± 500 km) parce que la dérive de l'Amérique du Nord vers le sud a débuté il y a environ 90 Ma. La paléoaltitude interprétée ne corrobore pas l'évidence sédimentologique et paléontologique que le bassin de Nanaimo à été déposé à proximité de sa présente position septentrionale.

[Traduit par la Rédaction]

Introduction

The western part of the Canadian Cordillera contains a collage of exotic terranes, which accreted against the rifted western margin of ancient North America and have been interacting and deforming ever since. The driving force has been subduction. A third of the Earth, ~13 000 linear km of oceanic plate, has subducted beneath the west coast of North America since 150 Ma (Engebretson et al. 1992), and a similar amount of subduction likely occurred during the previous 150 million years (Monger 1997).

The Farallon and Kula plates subducted obliquely under North America, and the mobile outer regions of the Cordillera were coupled to varying extents with the trench-parallel

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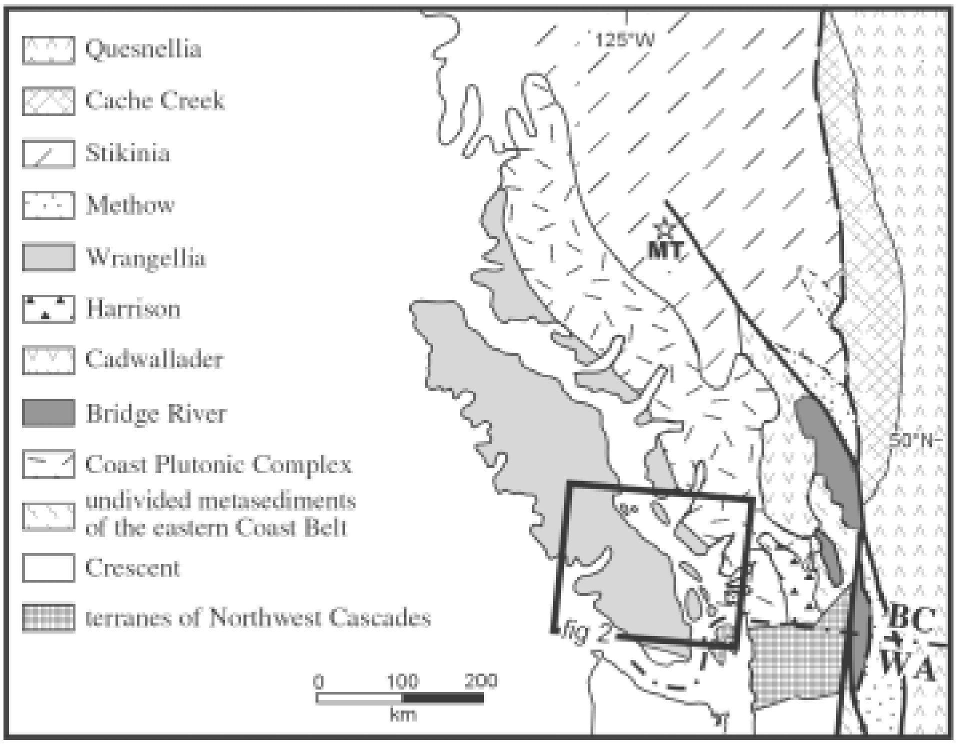
Fig. 1. Regional terrane map of southwest British Columbia (modified from Wheeler and McFeely 1991). MT, mid-Cretaceous Silverquick and Powell Creek formations sampled at Mount Tatlow (Wynne et al. 1995). The sampling region of this study is found within the box marking the location of Fig. 2.



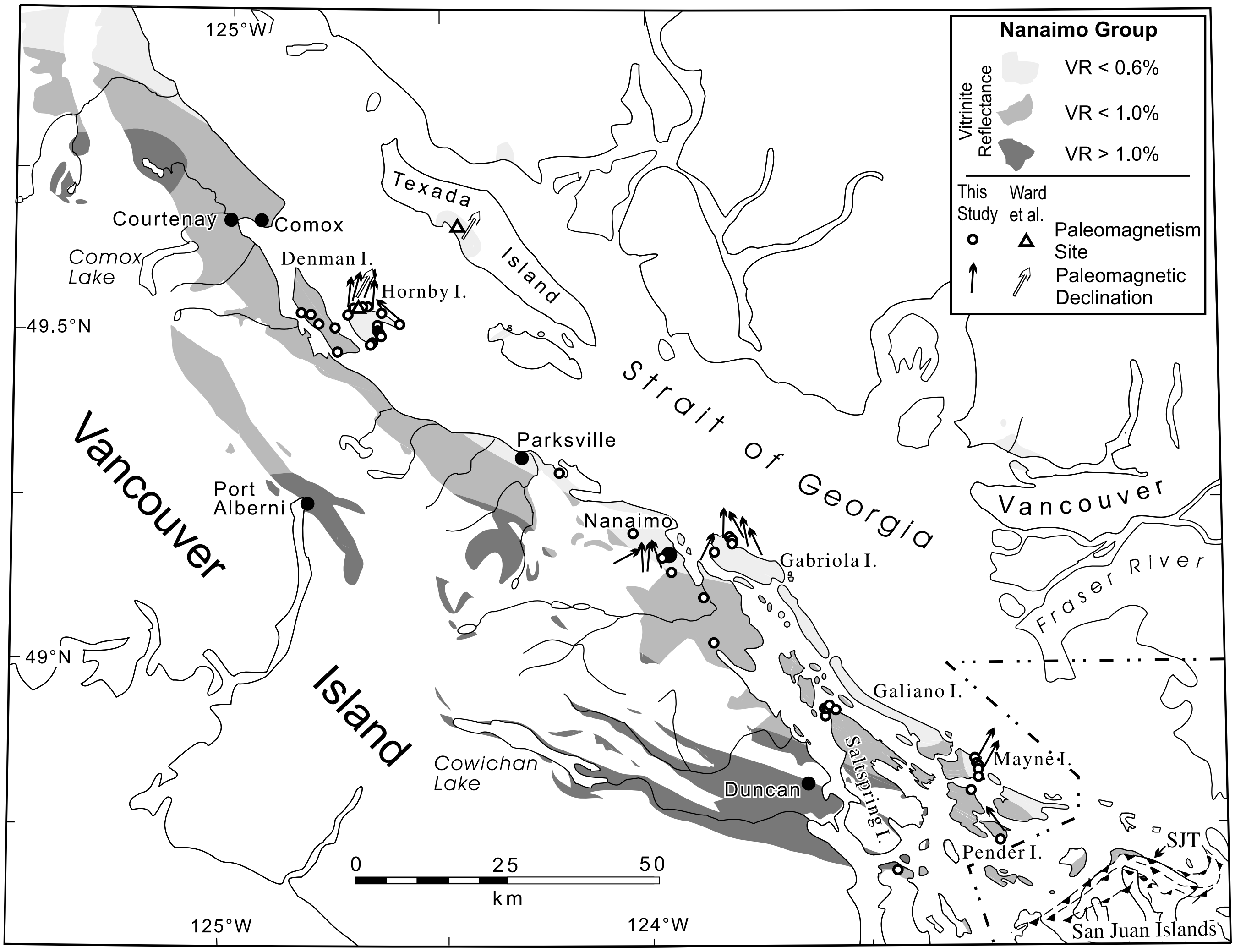
component of motion. During the Early Cretaceous, while the Farallon plate had a southerly component of motion, strike-slip faults within the Cordillera tended to have sinistral sense. Contractional faulting was the dominant deformation style between about 100 and 85 Ma. By the Late Cretaceous, when the Kula plate, and to some extent the Farallon plate, switched to northerly motion, strike-slip faults became dextral in sense (Monger 1997). The trench-parallel component of subduction is very large during the latest Cretaceous and early Tertiary. For just the period from 70 to 45 Ma, Engebretson calculated that the Kula plate displaced 3000 km towards the north (Johnston et al. 1996).

Although the strength of the couple between the western accreted terranes and adjacent oceanic plate during this period is uncertain (or even which of the Kula plate or Farallon plate were adjacent to the relevant terranes at this time), it seems reasonable that the coastal region should also show northward displacements with respect to the craton. This has been recognized in geological studies of the past 30 years (summarized in Monger and Journeay 1994*b*; Monger 1997). However, there is considerable debate over the amount of this lateral translation. Numerous independent and multidisciplinary geological studies suggest the western portion of the Canadian Cordillera has undergone only minor dextral translation (hundreds of kilometres) during Late Cretaceous – early Tertiary time (e.g., Haggart and Carter 1993; Mahoney et al. 1999; Monger and Price 1996; Mustard et al. 2000; Haggart 2000). In contrast, paleomagnetic studies from several locations in this region indicate 3000–4000 km of margin-parallel dextral translation during the same period (e.g., Beck et al. 1981; Wynne et al. 1995; Ward et al. 1997), an interpretation generally termed the “Baja B.C. hypothesis.” This contrast of interpretations continues to serve as a profound obstacle to even the most fundamental aspects of our understanding of the formation and present architecture of the Cordillera (Cowan et al. 1997; Monger 1997; Mahoney et al. 2000).

The displaced region we are considering is a large tectonic entity which roughly, but not precisely, corresponds to the Insular Superterrane of Monger et al. (1982), and for the sake of simplicity and familiarity, this designation will be used herein when describing Cretaceous to Tertiary paleogeography (similar to Cowan et al. 1997). For this paper, the Insular Superterrane refers to Wrangellia and Alexander terranes, associated pre-Eocene Coast Plutonic Complex, and associated late Mesozoic overlap assemblages including the Nanaimo Group (Fig. 1). By 90 Ma, the Methow, Bridge River, and Cadwallader terranes are linked to the Insular Superterrane and Coast Belt as part of a complex thrust system (Journeay and Friedman 1993; this roughly corresponds to the Coast Mountains orogen of Cowan et al. 1997). This designation corresponds to the Coast domain of Irving et al. (1996), but incorporates long-recognized tectonic boundaries.

Paleomagnetic methods are well suited to study this paleogeographic problem (Irving et al. 1996). Because the Cordillera has been aligned roughly north–south for the last 200 million years, displacements along the orogenic strike change the latitude of the site and thus the expected geomagnetic inclination. The key to successfully measuring this motion is finding rocks of the correct age which reliably maintain their magnetic remanent direction. The Upper Cretaceous Nanaimo

Fig. 2. Outcrop extent of the Nanaimo Group (modified from Mustard 1994), with domains of vitrinite reflectance (VR) values (based on data of England 1990; Kenyon and Bickford 1990). ○, sites from this study; △, sites of Ward et al. (1997). The paleomagnetic sites were mostly collected in sites with VR < 0.6%. The arrows show the magnetic declination measured from the accepted sites. SJT, major thrusts of the San Juan thrust system in San Juan Islands.



Group, exposed on southern Vancouver Island and the Gulf Islands of British Columbia (Fig. 2), is an obvious target for paleomagnetic study. It overlaps Wrangellia Terrane and plutons of the Coast Plutonic Complex, thus tying together these regions during the time of interest. It has the potential to record the maximum displacement of any part of the orogen, since it lies outboard of almost all of the structures which could have accommodated the motion. It was also a continuously active depositional basin during the majority of the time of proposed major lateral translation, and thus should preserve evidence of significant progressive northward translation during the 25+ million year evolution of the basin. Finally, being a sedimentary sequence, it contains much less controversial measures of paleohorizontal than available for volcanic or plutonic rocks.

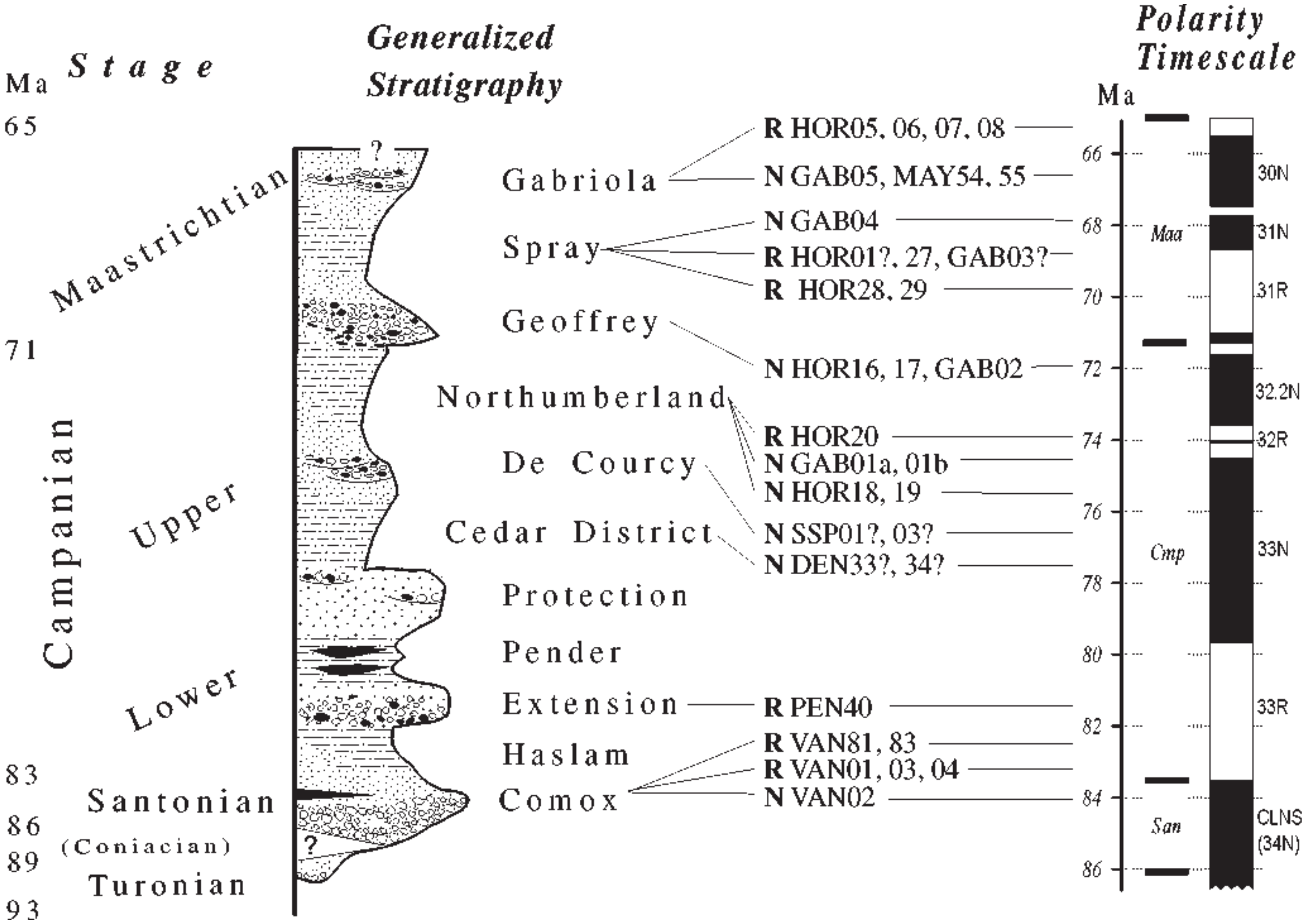
Reconnaissance sampling of the Nanaimo Group was carried out in 1980 by Ted Irving, but suitable rocks were not found. Peter Ward, who had been studying the paleontology of the Nanaimo Group, carried out magnetostratigraphic sampling first with Ken Verosub in 1992 and then with Joe Kirschvink and José Hurtado in 1995, leading to the paper by Ward et al. (1997), which seems to have become a focal point in the continuing Baja B.C. controversy (e.g., Mahoney et al. 1999; Housen and Beck 1999).

At the recommendation of Peter Ward, we started sampling in 1996, with follow-up work in 1998 and 1999. In this paper, based on the widest sampling done so far, we will characterize the paleomagnetic properties of the Nanaimo Group and discuss the paleogeographic implications.

Regional setting of the Nanaimo Basin

The Upper Cretaceous Nanaimo Group is preserved on eastern Vancouver Island, the islands of the Strait of Georgia, and the western mainland of British Columbia (Fig. 2). A comprehensive review of Nanaimo Group research and detailed analysis of the stratigraphy, sedimentology, and basin evolution is contained in Mustard (1994), with newer studies summarized in Mustard et al. (1999).

Fig. 3. Composite stratigraphic column of the Nanaimo Group (from Mustard 1994) and the accepted paleomagnetic sites in stratigraphic position. Sites yielding reverse polarity are preceded by R, and those yielding normal polarity are preceded by N. The sites are correlated to the global polarity time scale of Gradstein et al. (1995) along the right side. CLNS, Cretaceous long normal superchron.



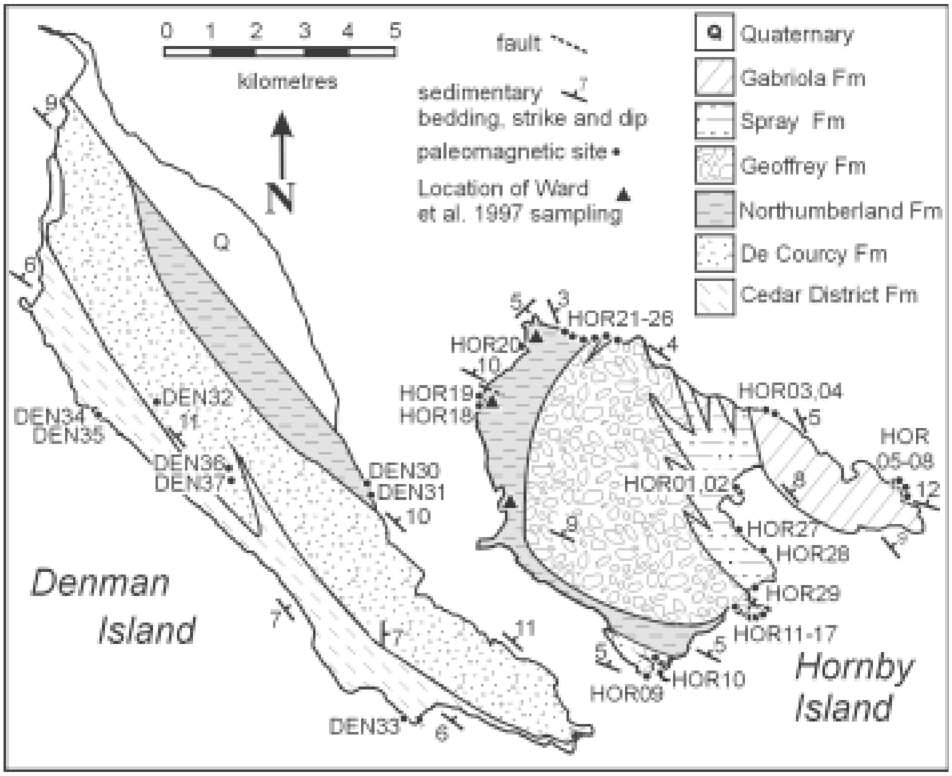
The Nanaimo Group unconformably overlies Wrangellia Terrane on its west side and the Coast Plutonic Complex on its east side and is in fault contact with the San Juan thrust system (part of the northwest Cascades terranes) to the southeast (Figs. 1, 2). It is in turn unconformably overlain in a few places by Late Paleocene to Eocene aged sedimentary rocks of the Chuckanut Group or equivalents (Mustard and Rouse 1994). Monger and Journeay (1994*a*) review the geology of these basements to the Nanaimo Group. The Nanaimo Basin was an elongate, northwest-trending depocentre, although there is no constraint on its original extent to the west or north.

A generalized stratigraphic column is given in Fig. 3. Deposition was probably continuous at least from the Santonian (~86 Ma) to some time in the late Maastrichtian (~65 Ma). The age of the Nanaimo Group strata is in most places well constrained due to an abundance of both macrofossil and microfossil data (e.g., Jeletzky 1970; Ward 1978; Haggart and Ward 1989; Haggart 1991, 1994). The exception to this is the upper part of the group, with the highest Gabriola Formation almost barren of fossil material. However, rare macrofossils and microfossils are reported from the lower part of this formation (summarized in Haggart 1991) and it overlies the Spray Formation, which in several areas contains latest Campanian and probably early Maastrichtian fauna (summarized in Haggart 1991; England and Hiscott 1992). It also contains detrital zircons of about 72 Ma (Mustard et al. 1995) and thus must be younger. These scant clues suggest the uppermost Nanaimo Group is at least in part Maastrichtian in age, but deposition may have continued into the early Tertiary (it is unconformably overlain by Late Paleocene rocks in some places (Mustard and Rouse 1994), thus is unlikely to be younger than Early Paleocene).

The basin accumulated a succession more than 4 km thick, consisting of subaerial and marine siliciclastics, with the upper two thirds of the succession represented mostly by a stacked repetition of submarine-fan complexes. Deposition occurred within a peripheral foreland basin in front of, and mostly derived from, a complex series of west- and east-vergent thrust systems active in the Coast Belt and northwest Cascades about 100 to at least 85 million years ago, although Precambrian sources farther to the east have also been suggested (Mustard 1994; Mustard et al. 1995, 2000; Mahoney et al. 1999).

Formation definitions are based on lithostratigraphic variations of fine-grained units with coarser grained and thicker bedded units dominated by sandstone and (or) conglomerate. The fine-grained units comprise mostly mudstone and thin-bedded sandstone turbidites of dominantly deep marine origin, although significant coal and other marginal marine fine-grained deposits occur in the lower Nanaimo Group. The sandstone

Fig. 4. Geological map of Hornby and Denman islands (modified from Mustard et al. 1999; Katnick 2001) and paleomagnetic site locations.



and (or) conglomerate dominate formations mostly formed by submarine-fan deposition for the upper two thirds of the group, but the lower Nanaimo Group facies generally reflect a complex mix of nonmarine alluvial and mostly shallow marine depositional environments.

Relevant to this study is the slightly diachronous nature of the formations within this relatively large basin (present extent is over 230 km along the northwest–southeast trend of the preserved group). In general, formation boundaries are conformable and gradational, but complex laterally intertonguing relationships are common. The age of any one formation tends to vary slightly through the basin. For example, the Spray Formation in the southern Gulf Islands contains numerous macrofossils and microfossils which suggest a late Campanian to early Maastrichtian age (e.g., McGugan 1982; Haggart 1991). However, 100–150 km north, on Hornby Island, the Northumberland Formation contains fossils that also suggest a late Campanian to possibly early Maastrichtian age. Thus this unit is biostratigraphically equivalent to the Spray Formation to the south, although lithostratigraphically lower. Confusion on this correlation has resulted from inferred faulting shown on maps by Muller and Jeletzky (1970), which caused McGugan (1982) and Ward et al. (1997) to misidentify part of the Northumberland Formation at the north end of Hornby Island as Spray Formation (based on the similar fossil assemblages). Newer work by Katnick (2001; see also Katnick and Mustard 2001) demonstrates that major faults do not exist and that this unit is actually all Northumberland Formation (Fig. 4). However, the inherent uncertainties in the range of biostratigraphic ages for these fossil assemblages suggest that the variations in absolute age of the formations laterally are slight, in the order of a few millions of years at most. For the purposes of this paleomagnetic study, which encompasses the entire Nanaimo Group, these minor variations do not significantly change either the relative stratigraphic positions of our samples or the interpretation in terms of the overall basin history.

The basin has been deformed by early Tertiary compression, which resulted in southwest-directed thrusting that included the Nanaimo Group (England and Calon 1991) and northwest plunging and trending folds in the Late Paleocene to Eocene age Chuckanut Formation (Johnson 1984). Recently, a younger (probably Neogene) northeast-vergent compressional event has been documented in some parts of the Nanaimo Group and its immediate basement, along with minor extensional faulting (Journeay and Morrison 1999).

The thermal maturity of Nanaimo Group rocks varies slightly within the basin. The rocks are unmetamorphosed and thus have not been deeply buried (although very low grade alteration is present in the form of zeolite minerals filling some pore spaces). Estimates for thermal maturity have been obtained from several vitrinite reflectance (VR) studies (summarized in Kenyon and Bickford 1990; and England 1990) and indirectly from studies of fossil shell compositions (Ward et al. 1997). In general, VR values are lower towards the northeastern edge of the basin (Fig. 2). VR values change suddenly across known or inferred thrust faults, suggesting that thermal maturity was reached before Eocene deformation of the basin (England and Calon 1991). Most VR values in the basin range from between about 0.4 and 1.3%, suggesting general low to moderate thermal maturities for these strata. Exceptions occur near rare Eocene intrusive bodies, where VR values up 4.6% occur, attributable to local thermal anomalies related to the specific and geographically small intrusive events.

Ward et al. (1997) picked paleomagnetic sample sites in areas where fossil ammonite and bivalve shells are still composed of unaltered aragonite. The presence of original aragonite suggests these sediments were not buried deeply enough to reach the temperature of aragonite to calcite transformation (about 100°C).

Paleomagnetic methods and sampling

We collected oriented samples from 67 sites from seven islands distributed around the basin (Table 1; Fig. 2). In general, upper Nanaimo Group formations are found on the outer Gulf Islands, and the lower formations are exposed along the basin's southwest flank on Vancouver Island. A relatively complete section through the upper Nanaimo Group was collected from Hornby and Denman islands, where we collected 37 sites from excellent coastal exposures (Fig. 4). Fieldwork was done in conjunction with new 1 : 50 000 scale mapping (Katnick and Mustard 2001). On Hornby Island, Ward et al. (1997) collected mostly siltstone from the Northumberland Formation of Katnick (2001), previously mapped as the Spray Formation (Muller and Jeletzky 1970).

Typical sites consisted of 6–10 cores distributed over a few metres of stratigraphy. In certain places, however, we adopted a magnetostratigraphic strategy, collecting samples at short intervals over a longer stratigraphic section. The cores (2.5 cm diameter, 5–12 cm long) were oriented by magnetic and sun compass. In all, we measured 746 specimens (2.2 cm long core segments).

Rocks of the Nanaimo Group are quite prone to recent weathering. We found this true even on wave-cut benches scoured yearly by winter storms. On fresh road cuts, weathering rinds extend over a metre in from the previously exposed surface. Thus we favoured fresh parts of recent road cuts for sampling where possible.

The collections of Ward et al. (1997) are dominated by the finest grained sediments because they also provide the best paleontological samples. In contrast, we focused more on fine- to medium-grained sandstones, since the shales and mudstones tend to be more fractured, more organic rich (which could lead to degradation of the magnetites), and more susceptible to compaction deformation of the primary remanence.

Following Ward et al. (1997), we attempted to sample rocks which have suffered the least thermal alteration, to optimize the chance of finding primary magnetizations. We avoided collecting sites where vitrinite reflectance is above 0.8% (~120°C) according to the survey of England (1990, his Figs. 5.1, 5.2, and 5.3).

Most Nanaimo Group strata dip gently to the north or northeast, making it difficult to set up robust fold tests. Where possible we sampled sites with counter bedding. On Hornby Island, megaclasts of several cubic metres volume containing primary bedding were deposited within large synsedimentary slump deposits, offering the potential to do a fold test using inclinations.

The magnetic remanences were generally soft, requiring careful laboratory work. Remanences were measured with an Agico JR5-A spinner magnetometer, with a noise level of ~5×10^{-5} A/m. Thermal demagnetization (using an ASC TD48 furnace) usually required 25°C steps. Alternating field (AF) demagnetization (Schonstedt GSD-1 demagnetizer with tumbler) was done with 5 or 10 mT steps. As an interlaboratory check, 25 specimens from sites which we found difficult to analyze were submitted to the California Institute of Technology paleomagnetism laboratory and measured by Tim Raub using an SCT SQUID magnetometer in a magnetically shielded room.

The degree of thermal alteration during laboratory heatings was monitored by measuring susceptibility on a Sapphire SI2B susceptibility meter. The same apparatus was used to measure anisotropy of magnetic susceptibility, as a check for compaction shallowing. Directions were fit by principal component analysis using programs developed by the first author (available on request). Site means were taken using Fisher (1953) statistics.

Results

General observations

The range of magnetic remanence behaviours is illustrated in Fig. 5. For most of the collection, the remanences were soft and noisy, making it difficult to isolate separate components. In several cases, however, we have evidence that ancient components have been retained.

The greatest challenge for paleomagnetic analysis of this collection was separating out the influence of recent viscous overprints. In theory, a present-field overprint acquired by single-domain magnetite during the recent Brunhes polarity chron should be demagnetized in the laboratory by about 200°C (Pullaiah et al. 1975), although it is often observed to be stable to higher temperatures (e.g., Kent 1983). In almost all of our collection, well over 50% of the remanence was eliminated by 200°C heating. Before thermal demagnetization, we often performed a preliminary demagnetization to clean away the least stable magnetic carriers. We found that a 5 mT AF step, immersion in liquid nitrogen (low-temperature cleaning), or even long-term (~1 year) storage in a low (<50 nT) magnetic field were equally effective, usually removing >50% of the remanence. We took care not to use steps below 200°C or 20 mT when fitting directions. In many sites, the remaining remanence was uncomfortably scattered, and possibly contaminated by the recent viscous overprint.

In many sites, there is even a low-stability magnetic component, which was acquired during core drilling, in a direction up the core barrel (Fig. 6). In some cases, this component accounted for almost all the remanence, leaving only scattered directions after 200°C or 20 mT demagnetization. This observation suggests a warning against drilling cores all in the same direction; only by drilling a site in a wide variety of directions were we able to recognize the drilling overprint.

During the laboratory procedures, the specimens were almost always held within magnetic shields. But there was a critical point during each demagnetizing step when the samples were transferred from the furnace to a shield, and highly unstable magnetic carriers could pick up a spurious magnetization in the ambient magnetic field. However, the 25 specimens demagnetized in the shielded laboratory at the California Institute of Technology displayed identical unblocking spectra and dispersion to sister specimens demagnetized in our laboratory. The ratio of the root mean square deviations from the best-fitting line through the demagnetization steps which hold most of the characteristic

Fig. 5. Demagnetization characteristics of the Nanaimo Group. For each specimen, there is an orthogonal plot, a stereograph, and an intensity plot. See text for detailed descriptions.

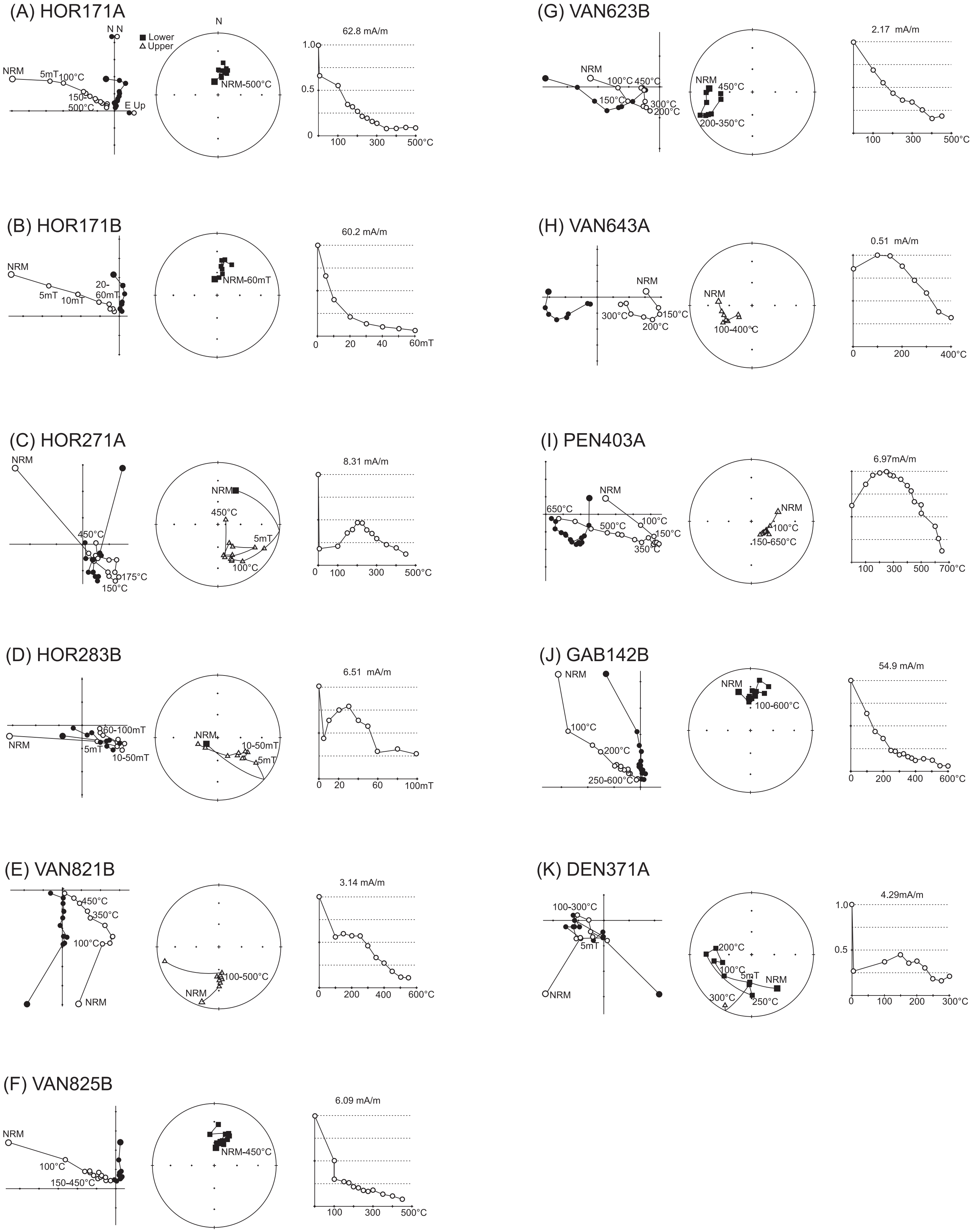


Table 1. Site details.

	Universal transverse Mercator coordinates				
Site	Easting (m)	Northing (m)	Locality	Formation	Rock type
Vancouver Island					
VAN01	428600	5446200	Jinglepot Road	Comox	Sandstone
VAN02	428600	5446200	Jinglepot Road	Comox	Sandstone
VAN03	428600	5446200	Jinglepot Road	Comox	Sandstone
VAN04	428600	5446200	Jinglepot Road	Comox	Sandstone
VAN30	411800	5461700	Northwest Bay	Haslam	Concretions
VAN31	411800	5461700	Northwest Bay	Haslam	Sandstone
VAN60	469900	5392600	Swartz Bay	Haslam	Sandstone
VAN65	436700	5432200	Near Ladysmith	Protection	Sandstone
VAN81	424600	5450800	Nanaimo	Protection	Sandstone
VAN83	429600	5443500	Nanaimo	Protection	Sandstone
VAN84	434700	5440100	Duke Point	Protection	Sandstone
Pender Island					
PEN41	480200	5405100	Hope Point	De Courcy	Mudstone, sandstone
PEN40	485200	5397600	Tilly Point	Extension	Red sandstone
Hornby Island					
HOR05	385000	5486800	St Johns Point	Upper Gabriola	Concretions
HOR06	385000	5486800	St Johns Point	Upper Gabriola	Concretions
HOR07	385000	5486800	St Johns Point	Upper Gabriola	Concretions, sandstone
HOR08	385000	5486800	St Johns Point	Upper Gabriola	Concretions, sandstone
HOR03	382100	5488400	Anderson Road	Lower Gabriola	Concretions
HOR04	382100	5488400	Anderson Road	Lower Gabriola	Concretions
HOR01	381500	5486800	Tribune Bay	Spray	Concretions
HOR02	381500	5486800	Tribune Bay	Spray	Sandstone
HOR27	381400	5485900	Tribune Bay	Middle Spray	Sandstone
HOR28	381700	5485600	Dunlop Point	Middle Spray	Concretions
HOR29	381500	5484900	Sandpiper Beach	Lower Spray	Sandstone
HOR16	381900	5484200	Downes Point	Upper Geoffrey	Sandstone
HOR17	382000	5484200	Downes Point	Upper Geoffrey	Sandstone
HOR11	381700	5484100	Downes Point	Geoffrey in Geoffrey	Breccia block
HOR12	381700	5484100	Downes Point	Geoffrey in Geoffrey	Breccia block
HOR13	381800	5484200	Downes Point	Geoffrey in Geoffrey	Breccia block
HOR14	381800	5484100	Downes Point	Geoffrey in Geoffrey	Breccia block
HOR15	381900	5484200	Downes Point	Geoffrey in Geoffrey	Breccia block
HOR24	378700	5489900	Shields Point	Lower Geoffrey	Concretions
HOR25	378700	5489900	Shields Point	Lower Geoffrey	Sandstone
HOR26	379000	5489900	Shields Point	Lower Geoffrey	Concretions
HOR22	378100	5489800	Collishaw Point	Geoffrey in Northumberland	Breccia block
HOR23	378200	5489900	Collishaw Point	Geoffrey in Northumberland	Breccia block
HOR20	377400	5489500	Collishaw Point	Upper Northumberland	Sandstone
HOR21	377700	5489800	Collishaw Point	Upper Northumberland	Concretions
HOR18	376400	5488800	Manning Point	Middle Northumberland	Sandstone in mudstone
HOR19	376500	5489000	Hornby Point	Middle Northumberland	Mudstone, sandstone
HOR09	379600	5483000	Ford Cove	De Courcy	Concretions, sandstone
HOR10	379700	5483300	Ford Cove	De Courcy	Concretions
Denman Island					
DEN30	373900	5486300	Whalebone Point	Lower Northumberland	Concretions
DEN31	374000	5486200	Whalebone Point	Lower Northumberland	Concretions
DEN36	371100	5486800	Triple Rock Drive	Middle De Courcy	Sandstone
DEN37	371100	5486800	Triple Rock Drive	Middle De Courcy	Sandstone
DEN32	369500	5488500	Near ferry	Lower De Courcy	Concretions, sandstone
DEN33	374100	5482500	Repulse Point	Middle Cedar District	Concretions
DEN34	368100	5488400	Ferry terminal	Middle Cedar District	Limestone concretions
DEN36	368100	5488400	Ferry terminal	Middle Cedar District	Sandstone dykes

BD (°)	BDDA (°)	*N*	NRM (mA/m)	χ_o ($\times10^{-5}$ SI)	Kn	% Foliation	Interpretation[a]
		Vancouver Island					
16	012	16	0.86	46	0.05	1.2	R
16	012	19	1.48	44	0.09	2.0	N with R overprint
20	045	11	0.66	48	0.03	1.3	R
20	045	11	0.51	37	0.03	0.8	R rotated
10	015	8	9.26	263	0.09	—	X
10	015	8	5.00	124	0.10	—	X
41	008	12	1.39	51	0.07	0.8	R overprint
21	070	12	0.26	37	0.05	2.7	R overprint
15	206	12	0.30	9	0.09	1.2	R scattered
15	112	10	0.43	18	0.06	0.6	R scattered
9	063	11	0.25	8	0.08	5.9	X
		Pender Island					
31	218	9	1.68	33	0.13	2.7	X
28	019	13	3.80	57	0.17	0.7	R
		Hornby Island					
11	026	9	12.10	397	0.08	3.9	R incoherent
11	026	10	8.14	317	0.06	12.8	R scattered
11	026	12	0.70	22	0.08	5.0	R scattered
11	026	9	1.03	26	0.10	8.0	R scattered
03	091	12	8.78	59	0.38	11.8	X
03	091	10	8.32	52	0.41	4.9	X
06	115	12	1.23	29	0.11	2.2	X
06	115	8	0.89	22	0.10	11.5	R? incoherent
09	061	12	8.15	96	0.21	16.1	R scattered
14	015	12	6.95	90	0.20	27.0	R
10	052	10	6.68	52	0.33	6.7	X
08	020	12	46.20	339	0.34	6.1	N
08	020	9	70.10	633	0.28	5.5	N
28	132	12	6.26	58	0.27	7.0	X
70	147	12	3.00	26	0.29	5.5	X
24	004	9	2.64	27	0.25	3.9	X
45	324	11	1.72	24	0.20	2.6	X
41	142	12	7.27	50	0.37	6.1	X
07	146	11	33.50	416	0.20	6.8	X
07	146	6	8.35	168	0.12	6.9	X
07	146	12	8.15	126	0.16	4.7	X
26	232	9	19.60	376	0.13	11.2	X
53	259	10	11.70	151	0.18	5.2	X
07	034	12	12.10	84	0.36	16.3	R incoherent
11	020	6	0.45	17	0.07	1.9	X
11	040	12	3.84	32	0.30	7.8	N
09	034	14	2.69	27	0.25	5.6	N
04	026	13	20.20	319	0.16	8.4	X
06	049	10	5.03	59	0.21	8.7	X
		Denman Island					
10	041	10	5.11	78	0.16	5.7	X
10	041	11	12.90	197	0.16	8.6	X
17	065	12	11.20	311	0.09	3.1	X
17	065	12	8.31	388	0.05	6.4	X
17	048	13	26.30	546	0.12	4.8	X
15	034	9	29.50	528	0.14	5.9	N? incoherent
10	046	11	2.05	40	0.13	2.7	N? incoherent
17	065	11	8.99	99	0.25	3.3	X

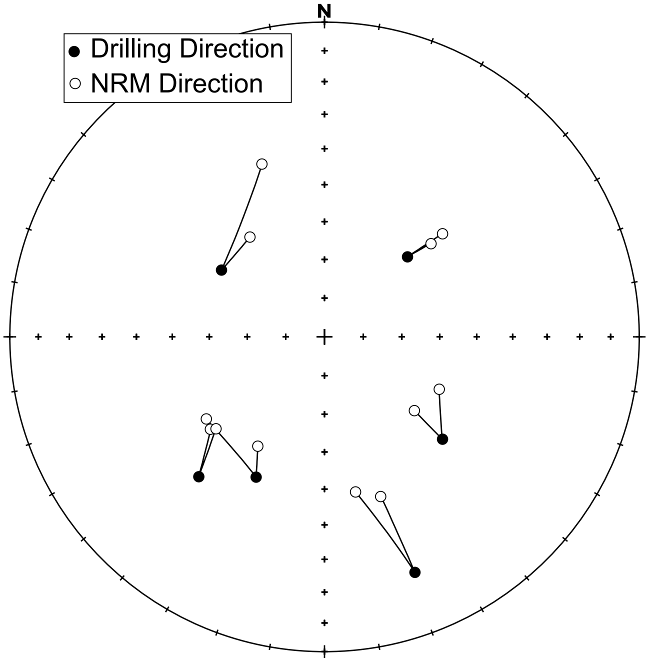
Table 1 (*concluded*).

Site	Universal transverse Mercator coordinates Easting (m)	Northing (m)	Locality	Formation	Rock type
Gabriola Island					
GAB05	440200	5450000	Clark Bay	Gabriola	Mudstone, sandstone
GAB04	437400	5447100	Descano Bay	Spray	Mudstone, sandstone
GAB03	440500	5449500	Leboeuf Bay	Spray	Sandstone
GAB02	440200	5449000	Leboeuf Bay	Geoffrey	Sandstone
GAB01a	440200	5449000	Leboeuf Bay	Northumberland	Sandstone
GAB01b	440200	5449000	Lock Bay	Northumberland	Sandstone
Mayne Island					
MAY55	481800	5410400	Campbell Bay	Gabriola	Sandstone
MAY54	481900	5410200	Bennett Bay	Gabriola	Sandstone
MAY53	481900	5409800	Seaview Drive	Spray	Mudstone
MAY52	481900	5409500	Arbutus Drive	Geoffrey	Mudstone
MAY51	482000	5408800	Aitkin Point	Northumberland	Mudstone, sandstone
MAY50	482200	5407800	Horton Bay	De Courcy and Northumberland	Coarse sandstone
Saltspring Island					
SSP01	456700	5421200	Southey Bay east	Cedar and De Courcy	Mudstone, sandstone
SSP02	456700	5420900	Southey Bay west	Cedar and De Courcy	Mudstone, sandstone
SSP03	456900	5421100	Southey Bay east	Cedar and De Courcy	Mudstone, sandstone
SSP04	456300	5419900	Southey Bay west	Cedar and De Courcy	Sandstone
SSP05	457700	5420600	Southey Bay east	Cedar and De Courcy	Mudstone, sandstone
SSP06	456400	5420900	Southey Bay west	Cedar and De Courcy	Mudstone, sandstone

Note: BD, bedding dip; BDDA, bedding downdip azimuth; *N*, number of specimens; Kn, mean Koenigsberger ratio; NRM, mean natural remanent magnetization; χ_o, mean susceptibility.

[a] N, normal polarity; R, reverse polarity; X, polarity impossible to define.

Fig. 6. Lower hemisphere stereograph showing the strong correlation between drilling direction and natural remanent magnetization (NRM) direction for site HOR11. Most sites held an observable overprint in the drilling direction, but usually it could be cleaned by low-level demagnetization.



remanence, 100–300°C, is 1.01 ± 0.47. Furthermore, the demagnetization plots of Nanaimo Group specimens measured in that same laboratory and presented by Ward et al. (1997) are not qualitatively different from ours. Thus the noise we observed is apparently intrinsic to these rocks.

Most sites contain normal-polarity remanence, which is not surprising because the Nanaimo Group was deposited during the Late Cretaceous, when the field most often had normal polarity. However, this renders it difficult to separate primary remanences from present-field overprints. We had far more confidence that we had isolated ancient remanences from the reverse-polarity sites. In the better specimens (e.g., Figs. 5C, 5E), the demagnetization path switched from the low-temperature component to the ancient reverse-polarity magnetization by 150° or 200°C. Then the remanence decayed linearly to the origin by 450° or 500°C. When we observed in normal-polarity specimens similar behaviour and relatively hard unblocking spectra, we had confidence that the present-field overprint was eliminated and that the high-temperature component is an ancient remanence. After heatings above ~450°C, we often observed significant increases in magnetic susceptibility, indicating that magnetic minerals are growing in the furnace, explaining the directional instability we see at higher temperatures.

At three sites in the lower Nanaimo Group (VAN02, VAN60, and VAN65), three components were recognized (e.g., Fig. 5G): a normal present-field overprint, a reverse-polarity intermediate-temperature component which does not go toward the origin, and a high-temperature component which often cannot be resolved. These overprint directions

BD (°)	BDDA (°)	*N*	NRM (mA/m)	χ_o ($\times 10^{-5}$ SI)	Kn	% Foliation	Interpretation[a]
		Gabriola Island					
12	308	22	48.50	505	0.25	3.5	N
13	079	11	1.94	22	0.23	5.3	N
12	308	9	1.46	25	0.15	5.5	R? incoherent
23	326	12	36.20	596	0.15	3.3	N
23	326	9	26.20	168	0.39	2.8	N
23	326	12	56.10	593	0.24	1.9	N
		Mayne Island					
25	026	12	24.70	465	0.13	3.8	N
26	032	10	17.60	288	0.15	1.7	N
22	025	10	3.79	77	0.12	5.0	X
19	029	13	0.75	17	0.11	4.2	X
24	019	13	1.59	47	0.09	2.1	X
21	008	10	0.84	18	0.11	3.0	X
		Saltspring Island					
29	038	13	1.72	310	0.14	1.4	N? incoherent
21	231	10	0.61	26	0.06	2.4	X
15	327	10	1.76	39	0.11	4.7	N? incoherent
21	231	12	2.43	42	0.15	1.7	X
21	272	11	1.69	32	0.14	3.0	X
12	244	14	122.00	24	0.13	4.2	X

are plotted in Fig. 7C. At site VAN60, from near the ferry terminal at Swartz Bay on Vancouver Island, the beds are sufficiently tilted to assert that the reverse-polarity component is a remagnetization which was not acquired before tectonic tilting, since the stratigraphically corrected direction has an inclination of only –6°, much shallower than any Cretaceous or Tertiary directions observed in the Canadian Cordillera. We may not have high confidence in the high-temperature component direction, but the fact that we can see through the effects of a late reverse-polarity overprint indicates that it is possible for these rocks to retain an ancient normal-polarity remanence.

We measured anisotropy of magnetic susceptibility (AMS) as a simple check of sediment compaction. This method measures the degree of alignment of the magnetic grains, and results are presented as an ellipsoid, where the maximum axis is aligned along the lineation and the minimum axis is perpendicular to the foliation. As is typical of fine-grained sandstones, there is usually a foliation in the bedding plane, but the mean foliation (intermediate/minimum axes) is only 5%. Site mean AMS foliations are given in Table 1. Of the whole collection, only seven sites have foliation >10%. Of these, only one site (HOR28) rendered a usable mean remanent direction, and it is not shallower than the rest of the collection. The mean lineation (maximum/intermediate axes) is only 2%, with a maximum of 8%. Usually the maximum and intermediate axes are widely distributed around the bedding plane. But there are exceptions, such as the Gabriola Island sites where sites GAB01a to GAB02 have lineation in the northeast–southwest direction, whereas the overlying sites GAB03 to GAB05 are in the northwest–southeast direction. On Mayne Island, the sites generally have lineation in the east–west direction. This fabric is presumably a result of primary current directions. The lower Nanaimo Group sites on Vancouver and Pender islands are notable for having the least anisotropy (maximum/minimum axes), almost always <3%. Upper Nanaimo Group sites usually have anisotropy between 5 and 10%.

We rejected sites when the demagnetization paths of individual specimens were too erratic to allow isolation of reliable directions or when the site's directions were so scattered that the 95% confidence interval exceeded 15°. These criteria force us to reject 75% of the sites. Even when the directions within the site are too scattered for directional analysis, we can still recognize the polarity of the characteristic magnetization, which is applicable to the magnetostratigraphic correlation of the Nanaimo Group. There is enough evidence to show that we are seeing the original remanence of these rocks.

Our detailed description of accepted results will now proceed stratigraphically from the bottom up. Stratigraphic positions are shown in Fig. 3, and site means are reported in Table 2 and Fig. 7.

Comox Formation

In the City of Nanaimo, along a recent road cut of Highway 19 at Jinglepot Road, there is a long section (Fig. 8) of the Triassic Karmutsen Formation overlain by lower Nanaimo Group conglomerates and sandstones of the Comox Formation (previously mapped as Protection Formation.). At the top of

Table 2. Site means.

Site	D_G (°)	I_G (°)	D_S (°)	I_S (°)	n_{FIT}	α_{95} (°)	*k*	Interpretation
Vancouver Island								
VAN03	122.2	–62.3	159.6	–59.9	9	5.4	91.7	R
VAN04	261.6	–73.2	242.2	–55.0	8	9.9	32.3	R rotated
VAN01	166.4	–69.9	177.1	–55.0	11	7.7	35.7	R
VAN02	359.2	70.9	004.7	55.3	9	7.7	35.4	N
VAN02	227.5	–69.6	213.0	–55.5	6	28.6	6.4	R overprint
VAN60	180.1	–47.1	182.5	–6.0	6	12	32.0	R overprint
VAN65	148.9	–56.4	180.1	–54.6	11	17.3	8.0	R overprint
VAN81	197.7	–48.3	193.8	–63.1	7	21.3	9.9	R scattered
VAN83	131.5	–69.6	167.0	–81.9	9	32.1	3.5	R scattered
Pender Island								
PEN40	98.9	–66.5	143.2	–65.2	9	5.6	86.9	R
Hornby Island								
HOR06	197.3	–71.7	200.5	–61.1	8	25.8	5.8	R scattered
HOR07	161.6	–64.6	173.5	–56.2	5	27.6	9.0	R scattered
HOR08	177.4	–62.1	184.6	–52.4	7	22.2	9.2	R scattered
HOR27	173.5	–66.0	189.7	–61.2	10	23.7	5.3	R scattered
HOR28	109.1	–59.6	130.8	–55.9	11	13.4	13.1	R
HOR16	3.0	64.1	6.5	56.5	11	6.6	49.1	N
HOR17	13.3	69.9	15.0	62.1	9	4.4	139.7	N
HOR18	15.8	58.5	21.2	48.5	11	4.9	86.5	N
HOR19	354.7	64.3	4.1	56.6	12	5.4	66.3	N
Gabriola Island								
GAB05	15.3	56.7	1.2	50.8	14	6.4	38.9	N
GAB04	8.0	60.2	26.3	53.7	9	10.7	24.1	N
GAB02	336.6	71.7	331.0	49.2	10	9.1	28.9	N
GAB01a	12.5	70.1	349.0	51.0	7	8.1	56.9	N
GAB01b	348.0	75.8	334.9	53.8	12	6.8	42.1	N
Mayne Island								
MAY55	33.7	79.7	28.7	55.1	8	9.6	33.9	N
MAY54	24.6	72.7	28.7	47.2	9	9.8	38.9	N

Note: *D* and *I*, declination and inclination, respectively, with subscript G denoting geographic coordinates and subscript S denoting stratigraphic coordinates; *k*, Fisher precision; n_{FIT}, number of specimens in the mean; α_{95}, 95% confidence interval.

the section lies a fossil bed containing inoceramid bivalves of earlier Campanian age (Haggart, Geological Survey of Canada (GSC) Fossil Report JWH-1999-02, GSC location C-304329).

The fossil shells have been altered to calcite, indicating >100°C burial heating at this site. Despite the warning of Ward et al. (1997) against using such sites, the paleomagnetic properties here were among the best observed in this study (Figs. 5E, 5F). Both normal- and reverse-polarity samples are present in this section, the reverse samples being at the top of the section, above a shell layer. A complication in this site is that some of the normal-polarity samples near the transition to the reverse-polarity section have an intermediate-temperature, reverse-polarity overprint, which is removed by 350°C demagnetization (Fig. 5G; direction plotted in Fig. 7C). Samples with the simplest properties are intermingled with poorer samples, rendering the magnetostratigraphy imperfectly defined, but we can assign polarity for most of the cores (Fig. 8). Given the paleontological constraint for the top of the section, we can unambiguously assign the reversal to be the end of the Cretaceous long normal superchron at the 83.5 Ma Santonian–Campanian boundary (time scale of Gradstein et al. 1995).

For directional analysis, this locality naturally divides itself into four sites: on the west side of the highway, the reverse-polarity samples at the top of the section (VAN01) and the normal-polarity samples below (VAN02); and on the east side of the highway two distinct outcrops (VAN03 and VAN04) separated by a broken zone. The bedding of the sites on the east side indicates that it overlies the section sampled on the west side, and indeed these sites both have reverse-polarity remanence. Mean directions are plotted in Fig. 7B. Taking the antipode of site VAN02, we see that three of the sites give similar directions, but site VAN04 apparently has suffered a clockwise vertical axis rotation. The bedding attitudes of these sites are too similar and there are too few sites to provide a robust fold test, but we note (Table 3) that the Fisher concentration of the three coherent sites increases threefold on bedding correction. The Fisher concentration of the inclination-only mean (method of Enkin and Watson 1996) of all four sites increases over fourfold from 87 to 395. Along with the correlatable magnetostratigraphy, we can confidently conclude that these sites provide reliable primary magnetizations.

Two Comox Formation sites, a few kilometres north (VAN81) and south (VAN83) of the Jinglepot Road section, also gave reverse-polarity directions. They have very low

Fig. 7. Stereographs of paleomagnetic site mean directions from accepted sites. Each point is surrounded by its 95% circle of confidence. The stereographs on the left side are uncorrected for tectonic tilts, and those on the right side are for directions with respect to bedding but likely reveal relative vertical axis rotations.

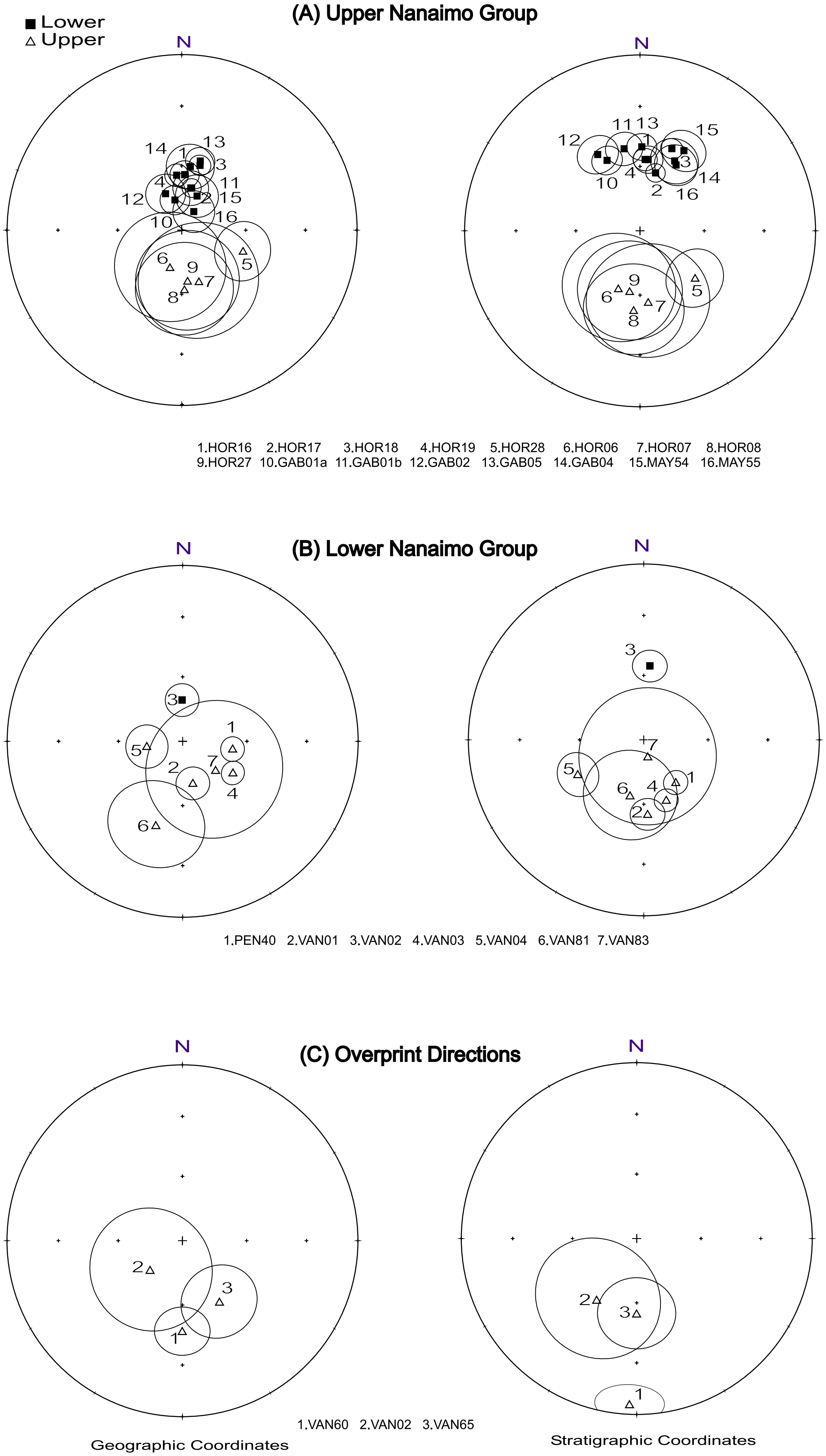
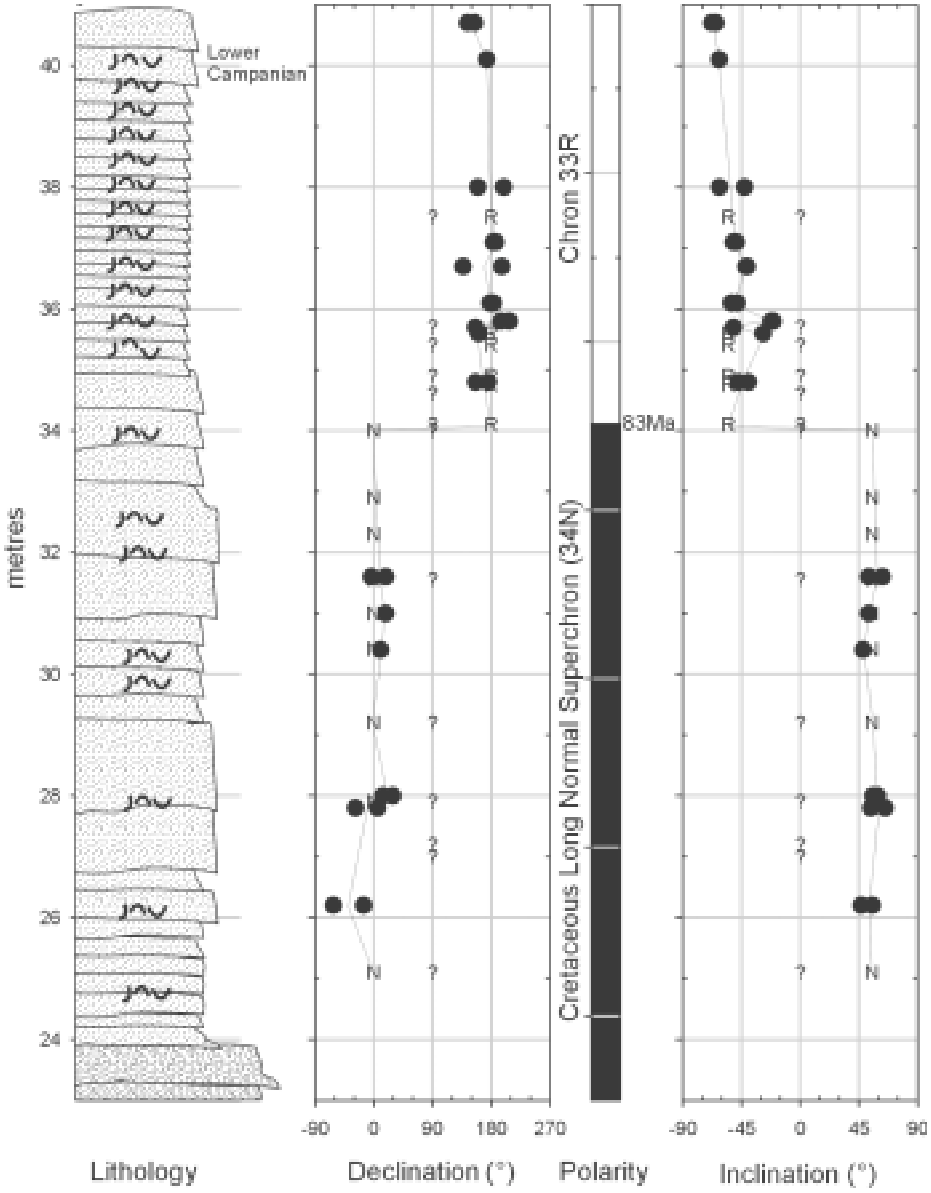


Fig. 8. The top 18 m of the Jinglepot Road section. The lower 23 m consists of conglomerate with volcanic clasts sitting on mafic volcanics of the Triassic Karmutsen Formation. The schematic of shells marks the layers containing abundant broken bivalve shells, the topmost of which yielded datable Inoceramus fossils. Most paleomagnetic specimens provided measurable remanent directions (●), whereas several could only be used to identify polarity (N, normal; R, reverse), and some gave only noise (?). The section is clearly marked by a single polarity reversal, correlated to the transition from the Cretaceous long normal superchron to chron 33R.



precision, but they confirm the dominant magnetic polarity when this formation was deposited.

Extension Formation

At Tilly Point, on the southern tip of Pender Island, is a rare red-bed site (PEN40) which is part of the Extension Formation. Most of the outcrop is conglomeratic, but medium-grained sandstone lenses exist and were sampled. Specimens that were too coarse grained (~3 mm clasts) gave random directions, providing a weak conglomerate test, which indicates that the site has not been pervasively overprinted. The sandstones retain a well-behaved reverse-polarity remanence carried by hematite (Fig. 5I, site mean in Fig. 7B).

Cedar District and De Courcy formations

Sites from these formations gave uniformly disappointing results. However, four sites (DEN33, DEN34, SSP01, SSP03) gave interpretable though scattered means, all giving normal polarity (Fig. 3).

Northumberland Formation

Northumberland Formation sites are typically quite noisy magnetically, but we did isolate useable directions from four of them (HOR18, HOR19, GAB01a, GAB01b). The polarity is solidly normal until the upper part of the formation as represented by a scattered reverse-polarity site HOR20. Note that the samples collected by Ward et al. (1997) on Hornby Island are from the same general location as sites HOR18 and HOR19.

Geoffrey Formation

The Geoffrey Formation is notable for being the most susceptible to drilling overprints (e.g., Fig. 6). The synsedimentary slumping megaclasts on Hornby Island proved completely unstable magnetically. Three sites (HOR16, HOR17, GAB02) did not suffer severe drilling overprints and held well-behaved, normal-polarity remanences.

Spray Formation

On Hornby Island, the Spray Formation (HOR01, HOR02, HOR27, HOR28, HOR29) consistently gave reverse polarity, yet the scatter was generally great, and in only one site (HOR28) could we assign a direction with a 95% confidence interval (α_{95}) of less than 15°. This site, however, is suspect because it has an exceedingly high anisotropy of magnetic susceptibility (27%), almost entirely as foliation in the bedding plane. The rock contained numerous iron-stained flattened concretions. On Gabriola Island, site GAB03 has remanences which are dominated by normal polarity. This we interpret to be a present-field overprint, because at high-temperature demagnetization steps the direction migrates toward the upper hemisphere, showing that there is a well-obscured primary reverse-polarity magnetization hiding under the overprint. The top of the formation, as represented by a large mudstone exposure (GAB04), has normal polarity.

Gabriola Formation

The Gabriola Formation exposed on Gabriola and Mayne islands has normal polarity. The sites collected on Hornby Island are from the highest Nanaimo Group strata to be found anywhere in the basin, and they hold reverse-polarity remanence, which is very useful for magnetostratigraphic correlation, but the scatter was too great for directional analysis (Fig. 7A).

Discussion

We have accomplished the most complete paleomagnetic sampling of the Upper Cretaceous Nanaimo Group. This study is now the largest paleomagnetic study of Cretaceous rocks in the Canadian Cordillera, in terms of both area covered and number of specimens measured. The justification for this major effort is that these rocks have the potential to help resolve the continuing Baja B.C. controversy, since they have the optimal age and position to observe or deny great motions along the western margin of North America.

The presence of both magnetic polarities, and especially the positive magnetostratigraphic correlation at the Jinglepot Road section, shows that these rocks are capable of retaining their primary magnetic remanence. Unfortunately, only 17 of the 67 sites we collected gave remanence means we consider useable for directional analysis (~75% rejection rate). A further 12 sites have unacceptably high dispersion ($\alpha_{95} > 15°$) but allow us to recognize polarity for magnetostratigraphic purposes. We must consider the possible causes of this very low success rate.

Contributions to unstable magnetization

Thermal alteration caused by burial certainly is one problem. The lower strata exposed along the southwest side of the basin have been uplifted from depths of up to 6 km, but we have avoided parts of the basin with higher levels of vitrinite reflectance (England 1990). The correlation between the magnetic remanence instability and organic maturity is weak. In particular, we refute the hypothesis of Ward et al. (1997) that “the degree of alteration of aragonite to calcite can be an indicator of the gradient between primary and overprinted magnetization of the Nanaimo Group (or other) strata.” Our best locality, where we observed a paleontologically constrained reversal, had fossils with calcite alteration. On the other hand, Denman Island, with VR values of ~0.7%, rendered poorer results than Hornby Island, with VR values around 0.5%. The sites with large Eocene(?) reverse-polarity overprints had VR values of 0.8 (site VAN65) or 0.9 (site VAN60).

More significant might be that the source detrital material for the Nanaimo Basin has few stable magnetic carriers in it. Apparently most of the carriers are relatively large multidomain grains which are so unstable that they are remagnetized just by drilling the rocks and can be demagnetized by very low level techniques: 5 mT AF, 100°C or low-temperature demagnetization. It is difficult to generalize about sandstone compositions for the Nanaimo Group, given our regionally and stratigraphically diverse range of sampling. Sandstone compositions range greatly, from lithic to arkosic arenites, and the lithic component is volcanic rich in some places and chert rich in others (Mustard 1994). This reflects a diversity of source areas feeding into the Nanaimo Basin and changes in sources over the 25+ million-year history of this large basin. However, the upper two thirds of the basin stratigraphy is dominated by submarine-fan deposits which received a large component of detritus from plutons of the eastern Insular Belt and the Coast Belt. This dominance of material from slow-cooled plutons might in part explain the unstable nature of the magnetic minerals.

Most of the sites we collected have a gentle (0–30°) north or northeast dip. A present-field overprint (or contamination of a primary remanence), incorrectly tilt corrected as if it were a pretilting remanence, renders a direction not greatly dissimilar from the apparent characteristic directions for these rocks. The consequence is that it is very difficult to separate a primary normal-polarity remanence from a present-field overprint. One strong argument for accepting the normal-polarity sites is that they have unblocking spectra very similar to those of the reverse-polarity sites. As well, some normal-polarity samples have a reverse-polarity overprint, showing that the normal polarity predates a partial remagnetizing event.

The fold test, relative vertical axis rotations, and inclination shallowing

We are confronted with a difficult situation for assessing the paleomagnetic fold test. If the magnetization predates

Table 3. Collected means.

		Full Fisher analysis								
		0% untilt				100% untilt				
	N	D (°)	I (°)	k	α_{95} (°)	D (°)	I (°)	k	α_{95} (°)	Maximum clustering (% untilt)
Upper Nanaimo Group	12	0.8	69.2	39.8	7.0	2.0	55.8	28.2	8.3	22±15
Lower Nanaimo Group	5	149.9	–75.9	19.0	18.0	182.6	–62.4	18.0	18.5	14±53
All	17	354.2	71.5	29.0	6.7	2.1	57.7	25.3	7.2	33±13
Normal polarity	12	7.0	68.4	85.2	4.7	5.9	54.9	42.0	6.8	17±14
Reverse polarity	5	128.8	–73.4	16.6	19.3	169.5	–64.2	13.7	21.4	<–50

Note: *N*, number of sites.

tectonic tilting, then the concentration of remanence directions should be at a maximum after 100% untilting of the bedding attitudes. This will not be apparent if some sites are contaminated by a present-field overprint. Furthermore, different regions of this fold and thrust belt may have suffered differential vertical axis rotations, making it difficult to undo the tectonic rotations.

In Table 3, we give the summary means of various groupings of sites. In most cases, the maximum concentration (method of Watson and Enkin 1993) is achieved on only partial rather than full untilting. When all the accepted sites are combined, the maximum concentration occurs at an intermediate level of untilting, significantly different from 0%, showing that we do not have a simple posttilting remanence. On the other hand, the two polarity groups are closer to antipodal after tectonic correction (12.1 ± 14.5°; method of Debiche and Watson 1995) than before (17.7 ± 12.8°), which supports a pretilting hypothesis.

The interpretation of the fold test results is that we have either a mixture of pretilting and post-tilting remanences, or that the structural corrections we have applied are wrong. It is clear from the stereographs of site means (Fig. 7, especially Fig. 7A) that after tilt correction the sites are streaked out along a circle of relatively constant inclination. Furthermore, neighbouring sites have similar declinations, as if the sites sit on rigid blocks (see the declination arrows marked in Fig. 2). Given that we have sampled several thrust sheets spread out over 150 km of strike length of the Eocene-age Cowichan fold and thrust belt, it is not surprising that differential vertical axis rotations should affect the sites.

To analyze such settings, Enkin and Watson (1996) developed the block rotation Fisher (BRF) method, which determines the mean inclination from sites sampled from regions or blocks that have suffered relative vertical axis rotations. Better than methods which consider only the site inclinations, the BRF method also uses the declinations within each individual block, providing a far more robust and geologically sound interpretation. The BRF results are summarized in Table 3. The degree of untilting necessary to give maximum concentration is usually not significantly different from 100%, indicating a pretilting remanence.

The vertical axis rotations determined by the BRF method are reasonable. The northwest-dipping strata on Gabriola Island give northwest magnetic declinations, and the easterly dipping site GAB04 has a northeast declination. The beddings do bend around the bay where this site is located, which could be the result of such a rotation. The Mayne and Hornby sites dip north-northeast, as do their declinations. The main Jinglepot Road section sites are dipping more northerly, and so does their declination. The three exceptions are (*i*) the uppermost Jinglepot Road site, VAN04, which has the same apparent bedding as site VAN03, but almost perpendicular declinations; (*ii*) the Pender Island site, PEN40, from a region that may have suffered more complicated rotations; and (*iii*) the Hornby Island site HOR28, which is highly anisotropic.

There remains the possibility that the measured inclination is anomalously shallow due to sedimentary compaction. In fine-grained sediments, inclinations can shallow by aligning the long axes of magnetic grains towards the bedding plane during deposition or compaction. According to the model of Anson and Kodama (1987), magnetite grains attached to clay grains rotate on compaction into the bedding plane. We argue that our collection has avoided the worst effects of this phenomenon, since our grand mean inclination is significantly steeper (13 ± 4°) than that measured by Ward et al. (1997). If we consider only our co-located sites (HOR18 and HOR19 versus their Hornby Island sites), our mean inclination is 12 ± 5° steeper than theirs. Whereas their collection favoured clay-rich siltstone and mudstone (85 of 103 samples), we avoided such rocks, and thus avoid the clay-related shallowing of the remanence.

Age and paleogeography

When we order all our sites stratigraphically, we get an acceptable magnetostratigraphy for the entire Nanaimo Group (Fig. 3). We recognize sites representing each of the major Late Cretaceous polarity chrons, leaving very little leeway for alternative correlations. Figure 3 enhances our confidence that we have measured primary remanences and provides refined age control on the Nanaimo Group formations. An important implication is that this correlation places the reversal in the Gabriola Formation, as observed on the north shore of Hornby Island, at the C30N–C29R transition in the Maastrichtian, just below the end of the Cretaceous. This latest Maastrichtian age is compatible with previous estimates of the age of the Gabriola Formation (e.g., Mustard 1994; Haggart 1991), which is otherwise generally undated, except by extrapolating from below using model sedimentation rates and detrital zircon ages.

Using the mean direction of all 17 acceptable sites, we could determine the paleomagnetic pole to be 79.0°N, 47.3°E, dp = 7.8°, and dm = 10.6°, where dp and dm are the 95% confidence intervals parallel and perpendicular, respectively,

Block rotation Fisher (BRF) analysis						
0% untilt			100% untilt			
I (°)	k	α_{95} (°)	I (°)	k	α_{95} (°)	Maximum clustering (% untilt)
67.6	68.7	3.9	53.7	116.4	3.0	74±27
–70.1	48.7	7.2	–58.4	94.1	5.2	104±52
68.4	67.5	3.3	55.2	108.6	2.6	74±24
68.5	73.8	3.8	53.7	117.0	3.0	75±24
–67.6	44.9	7.5	–58.5	106.1	4.9	99±54

Fig. 9. The paleomagnetic pole measured from the Nanaimo Group is far-sided with respect to (w.r.t.) the Late Cretaceous pole for cratonic North America, implying that the Nanaimo Basin was formed at the latitude of northern Mexico and southern California. The Mount Tatlow pole (Wynne et al. 1995) gives the same paleolatitude, however it is older and must be compared to the mid-Cretaceous pole for North America. The difference between the North American poles marks the southward drift of the craton. All uncertainties are plotted at the 95% confidence level. Note the small paleolongitudinal uncertainty. This reflects studies which indicate that Early and Late Cretaceous basins on the Baja B.C. entity were receiving some sand directly from North America, requiring that the basins and their basements were connected to (or very close to) North America by this time, regardless of their paleolatitude (Mahoney et al. 1999).

to the line joining the site to the pole. By taking the mean of the individual site poles we would get 79.4°N, 48.5°E, K = 12.9, and A_{95} = 10.3°. However, since we have argued for the possibility of differential vertical axis rotations, our preferred method is to calculate the mean inclination and paleolatitude with BRF analysis and use the mean declination as a first-order approximation for the whole set. In this way, we get a pole of 76.3°N, 48.8°E, dp = 2.6°, and dm =

20.6°, where dp and dm come from independent determinations of uncertainty in the inclination and declination, respectively.

There are difficulties in establishing a precise Late Cretaceous reference pole for North America (Gunderson and Sheriff 1991). In the absence of any recent studies on cratonic North America, we will use the same pole as that employed by Wynne et al. (1992, 1998): 79.2°N, 189.9°E, K = 326, $A_{95} = 4.2°$, and number of studies $N = 5$. Plotted in Fig. 9, it is clear that the Nanaimo Group pole is far-sided with respect to that expected for the North American craton. This is the signature of a terrane which has been displaced from the south. The paleomagnetically determined paleolatitude for the Nanaimo Group (35.7 ± 2.6°) is almost identical to that determined for the slightly older Silverquick and Powell Creek formations at Mount Tatlow (35.9 ± 3.5°) (Wynne et al. 1995), yet the inferred displacement is smaller (2300 ± 400 km for the Nanaimo Group versus 3000 ± 500 km for the Mount Tatlow rocks). This difference is compatible with the motion of North America southward starting around 90 Ma (compare the mid-Cretaceous (Van Fossen and Kent 1992) and Upper Cretaceous reference poles in Fig. 9).

One prediction of the Baja B.C. hypothesis is that rocks around 85–80 Ma should have lower measured paleolatitudes than rocks dated around 70–65 Ma. In this study (Table 3), the lower Nanaimo Group sites do not have a significantly different mean (BRF) inclination than the upper Nanaimo Group sites (4.7 ± 6.0° steeper). We are not confident that we have collected sufficient useable sites to differentiate these directions, but it is also possible that we are observing the southward motion of North America while the Nanaimo Basin is maintaining a constant paleolatitude. It is interesting to note that the Texada Island samples of Ward et al. (1997) give a slightly (though insignificantly) steeper inclination than the younger, stratigraphically higher samples collected from Hornby Island, in a fashion similar to that of our collection. We suggest that all of their collection has suffered compaction-related inclination shallowing, however, it does seem unlikely that the stratigraphically higher and presumably less deeply buried strata have greater compaction shallowing than the deeper strata (as speculated by Housen and Beck 1999).

Although the paleomagnetic results presented suggest a southerly paleolatitude for the Nanaimo Basin during deposition, it should be noted that all other lines of evidence from this basin do not support this interpretation. The combination of detailed facies trends, paleocurrent analysis, paleogeography, and the patterns of Precambrian detrital zircon ages suggest both that the Nanaimo Basin received some of its sediment from a source area east of the Coast Belt, which was at about the same latitude as the basin is now, and that this source area was consistent during Campanian to early Maastrichtian time, both features that support a northern position for the life of the basin and thus the subjacent Insular Superterrane and its associated entities (Mahoney et al. 1999; Mustard et al. 2000). In addition, paleontological comparisons of molluscan assemblages from the Nanaimo Group with those from Late Cretaceous basins of undisputed southern latitudes clearly demonstrate significant differences and strongly suggest a northern position for the Nanaimo Basin (Elder and Saul 1993; Haggart 2000). This basic conflict of paleomagnetic results with other evidence for paleogeographic position remains unresolved.

Conclusions

The Baja B.C. controversy continues to be a focal point for geological research in the Canadian Cordillera. Did or did not the western Canadian Cordillera displace from Mexican latitudes during the Late Cretaceous and Paleogene? On one side, it calls into question the nature of geological correlations, the power of provenance studies, the location of fault structures, and the latitudinal zonation of fossil assemblages. On the other side, it challenges our understanding of the geometry and statistical variations of the geomagnetic field, the rock magnetic mechanism responsible for recording the ancient field direction, and the paleomagnetic methods used to determine it.

Clearly, the resolution of this controversy requires more multidisciplinary geological and paleomagnetic study. The present study was attempted in this light. New mapping, along with provenance and paleontological work, has made the Nanaimo Basin one of the best understood Cretaceous basins in the Cordillera. It spans the critical age and is optimally placed to record the greatest displacement. Furthermore, road and coastal access to the basin is unparalleled, at least for the Canadian Cordillera.

Despite many difficulties, we have isolated the primary remanence direction in 17 sites, based on the positive presence of polarity reversals, a positive magnetostratigraphic correlation, and a positive inclination fold test. The stability tests of this study will be strengthened by locating more paleomagnetically stable sites with a range of bedding tilts. This should increase the resolution of both the magnetostratigraphy and paleomagnetic history of this basin.

The resulting paleomagnetic pole is far-sided with respect to the expected Late Cretaceous pole for cratonic North America but is similar in paleolatitude to that determined for mid-Cretaceous rocks in the Insular Superterrane. The interpreted latitude anomaly is 2300 ± 400 km, placing the Nanaimo Basin at the latitude of about the present Mexico–California border.

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References

Anson, G.L., and Kodama, K.P. 1987. Compaction induced inclination shallowing of the post-depositional remanent magnetization in a synthetic sediment. Geophysical Journal of the Royal Astronomic Society, **88**: 673–692.

Beck, M.E., Jr., Burmester, R.F., and Schoonover, R. 1981.

Paleomagnetism and tectonics of Cretaceous Mt. Stuart batholith of Washington: translation or tilt? Earth and Planetary Science Letters, **567**: 336–342.

Cowan, D.S., Brandon, M.T., and Garver, J.I. 1997. Geologic tests of hypotheses for large coastwise displacements — a critique illustrated by the Baja British Columbia Controversy. American Journal of Science, **297**: 117–178.

Debiche, M.G., and Watson, G.S. 1995. Confidence limits and bias correction for estimating angles between directions with applications to paleomagnetism. Journal of Geophysical Research, **100**: 24 405 – 24 429.

Elder, P.K., and Saul, L.R. 1993. Paleogeographic implications of molluscan assemblages in the Upper Cretaceous (Campanian) Pigeon Point Formation, California. *In* Mesozoic paleography of the western United States — II. *Edited by* G. Dunn and K. McDougall. Pacific Section, Society of Economic Paleontologists and Mineralogists, Book 71, pp. 171–186.

Engebretson, D.C., Kelley, K.P., Cashman, H.P., and Richards, M.A. 1992. 180 million years of subduction. GSA Today, **2**: 93–100

England, T.D.J. 1990. Late Cretaceous to Paleogene evolution of the Georgia Basin, southwestern British Columbia. Ph.D. thesis, Memorial University of Newfoundland, St. John's, Nfld.

England, T.D.J., and Calon, T.J. 1991. The Cowichan fold and thrust system, Vancouver Island, southwestern British Columbia. Geological Society of America Bulletin, **103**: 336–362.

England, T.D.J., and Hiscott, R.N. 1992. Lithostratigraphy and deep-water setting of the upper Nanaimo Group (Upper Cretaceous), outer Gulf Islands of southwestern British Columbia. Canadian Journal of Earth Sciences, **29**: 574–595.

Enkin, R.J., and Watson, G.S. 1996. Statistical analysis of paleomagnetic inclination data. Geophysical Journal International, **126**: 495–504.

Fisher, R.A. 1953. Dispersion on a sphere. Proceedings of the Royal Society of London, **217**: 295–305.

Gradstein, F.M., Agterberg, F.P., Ogg, J.G., Hardenbol, J., van Veen, P., Thierry, J., and Huang, Z. 1995. A Triassic, Jurassic and Cretaceous time scale. *In* Geochronology, time scales and global stratigraphic correlation. *Edited by* W.A. Berggren, D.V. Kent, M.-P. Aubry, and J. Hardenbol. Society for Sedimentary Geology, Special Publication 54, pp. 95–128.

Gunderson, J.A., and Sheriff, S.D. 1991. A new late Cretaceous pole from the Adel Mountains, west central Montana. Journal of Geophysical Research, **96**: 317–326.

Haggart, J.W. 1991. Biostratigraphy of the Upper Cretaceous Nanaimo Group, Gulf Islands, British Columbia. *In* A field guide to the paleontology of southwestern Canada. *Edited by* P.L. Smith. Geological Association of Canada, Vancouver, B.C., pp. 222–257.

Haggart, J.W. 1994. Turonian (Upper Cretaceous) strata and biochronology of southern Gulf Islands, British Columbia. *In* Current research 1994-A. Geological Survey of Canada, Paper 1994-A, pp. 159–164.

Haggart, J.W. 2000. Paleobiogeography of Pacific coast molluscan faunas suggests high-latitude Cretaceous tectonic setting of Insular Belt. *In* Geological Society of America, Cordilleran Section Annual Meeting, Abstracts with Programs, Vol. 32, No. 6, p. A-16.

Haggart, J.W., and Carter, E.S. 1993. Cretaceous (Barremian–Aptian) radiolaria from Queen Charlotte Islands, British Columbia: newly recognized faunas and stratigraphic implications. *In* Current research 1993-E. Geological Survey of Canada, Paper 1993-E, pp. 55–65.

Haggart, J.W., and Ward, P.D. 1989. New Nanaimo Group ammonites (Cretaceous, Santonian–Campanian) from British Columbia and Washington State. Journal of Paleontology, **63**: 218–227.

Housen, B.A., and Beck, M.E., Jr. 1999. Testing terrane transport: an inclusive approach to the Baja B.C. controversy. Geology, **27**: 1143–1146.

Irving, E., Wynne, P.J., Thorkelson, D.J., and Schiarizza, P. 1996. Large (1000 to 4000 km) northward movements of tectonic domains in the northern Cordillera, 83 to 45 Ma. Journal of Geophysical Research, **101**: 17 901 – 17 916.

Jeletzky, J.A. 1970. Biochronology. *In* Geology of the Upper Cretaceous Nanaimo Group, Vancouver Island and Gulf Islands, British Columbia. *Edited by* J.E. Muller and J.A. Jeletzky. Geological Survey of Canada, Paper 69-25, pp. 35–58.

Johnson, S.Y. 1984. Stratigraphy, age, and paleogeography of the Eocene Chuckanut formation, northwest Washington. Canadian Journal of Earth Sciences, **21**: 92–106.

Johnston, S.T., Wynne, P.J., Francis, D., Hart, C.J.R., Enkin, R.J., and Engebretson, D.C. 1996. Yellowstone in the Yukon: the Late Cretaceous Carmacks Group. Geology, **24**: 997–1000.

Journeay, J.M., and Friedman, R.M. 1993. The Coast Belt thrust system: evidence of Late Cretaceous shortening in southwest British Columbia. Tectonics, **12**: 756–773.

Journeay, J.M., and Morrison, J. 1999. Field investigations of Cenozoic structures in the northern Cascadia forearc, southwestern British Columbia. *In* Current research 1999-A. Geological Survey of Canada, Paper 1999-A, pp. 239–250.

Katnick, D.C. 2001. Sedimentology, stratigraphy and provenance of the Upper Cretaceous Nanaimo Group, Denman and Hornby islands, British Columbia. M.Sc. thesis, Simon Fraser University, Burnaby, B.C.

Katnick, D.C., and Mustard, P.S. 2001. Geology of Denman and Hornby islands, British Columbia (NTS 92F/7E, 10). British Columbia Geological Survey, Geoscience Map 2001-3, scale 1 : 50 000.

Kent, D.V. 1983 Thermoviscous magnetization in some Appalachian limestones. Geophysical Research Letters, **12**: 805–808.

Kenyon, C., and Bickford, C.G.C. 1990. Vitrinite reflectance study of Nanaimo Group coals of Vancouver Island (92F). *In* Geological fieldwork, 1989. British Columbia Ministry of Mines and Petroleum Resources, Paper 1990-1, pp. 543–552.

Mahoney, J.B., Mustard, P.S., Haggart, J.W., Friedman, R.M., Fanning, M., and McNicoll, V.J. 1999. Archean and Earliest Proterozoic zircons in Cretaceous sediments of the western Canadian and northwest U.S. Cordillera: the “Baja B.C.” hypothesis fails a “crucial test.” Geology, **27**: 195–198.

Mahoney, J.B., Tikoff, B., Maxson, J., and Haugerud, R.A. 2000. Penrose conference report: terrane accretion along the western Cordilleran margin: constraints on timing and displacement. GSA Today, **10**: 11–13.

McGugan, A. 1982. Upper Cretaceous (Campanian and Maestrichtian) foraminifera from the upper Lambert and Northumberland formation, Gulf Islands, British Columbia, Canada. Micropaleontology, **28**: 1–12.

Monger, J.W.M. 1997. Plate tectonics and Northern Cordilleran Geology: an unfinished revolution. Geoscience Canada, **24**: 189–198.

Monger, J.W.H., and Journeay, J.M. 1994*a*. Basement geology and tectonic evolution of the Vancouver region. *In* Geological hazards of the Vancouver Region, southwestern British Columbia. *Edited by* J.W.H. Monger. Geological Survey of Canada, Bulletin 481, pp. 3–25.

Monger, J.W.H., and Journeay, J.M. 1994*b*. Guide to the geology and tectonic evolution of the southern Coast Mountains. Geological Survey of Canada, Open File 2490.

Monger, J.W.H., and Price, R.A. 1996. Comment on “Paleomagnetism of the Upper Cretaceous strata of Mount Tatlow: evidence for

3000 km of northward displacement of the eastern Coast Belt, British Columbia" by P.J. Wynne et al., and on "Paleomagnetism of the Spences Bridge Group and northward displacement of the Intermontane Belt, British Columbia: A second look" by E. Irving et al. Journal of Geophysical Research, **101**: 13 793 – 13 799.

Monger, J.W.H., Price, R.A., and Templeman-Kluit, D.J. 1982. Tectonic accretion and the origin of two major metamorphic and plutonic belts in the Canadian Cordillera. Geology, **10**: 70–75.

Muller, J.E., and Jeletzky, J.A. 1970. Geology of the Upper Cretaceous Nanaimo Group, Vancouver Island and Gulf Islands, British Columbia. Geological Survey of Canada, Paper 69-25.

Mustard, P.S. 1994. The Upper Cretaceous Nanaimo Group, Georgia Basin. *In* Geological hazards of the Vancouver region, southwestern British Columbia. *Edited by* J.W.H. Monger. Geological Survey of Canada, Bulletin 481, pp. 27–96.

Mustard, P.S., and Rouse, G.E. 1994. Stratigraphy and evolution of Tertiary Georgia Basin and subjacent Upper Cretaceous sedimentary rocks, southwestern British Columbia and northwestern Washington State. *In* Geological hazards of the Vancouver region, southwestern British Columbia. *Edited by* J.W.H. Monger. Geological Survey of Canada, Bulletin 481, pp. 97–170.

Mustard, P.S., Parrish, R.R., and McNicoll, V. 1995. Provenance of the Upper Cretaceous Nanaimo Group, British Columbia: evidence from U–Pb analyses of detrital zircons. *In* Stratigraphic development in foreland basins *Edited by* S.L. Dorobek and G.M. Ross. Society of Economic Paleontologists and Mineralogists, Special Publication 52, pp. 112–127.

Mustard, P.S., Katnick, D.C., Baker, J., Enkin, R.J., and Mahoney, J.B. 1999. Multidisciplinary studies of the Upper Cretaceous Nanaimo Group, Hornby and Denman islands, British Columbia. *In* Current research, 1999-A. Geological Survey of Canada, Paper 1999-A, pp. 231–238.

Mustard, P.S., Mahoney, J.B., Fanning, C.M., Friedman, R.M., and McNicoll, V.J. 2000. Nanaimo Group, southwest British Columbia: a Late Cretaceous basin with a continuous northern provenance signature. *In* Geological Society of America, Cordilleran Section Annual Meeting, Abstracts with Programs, Vol. 32, No. 6, p. A-57.

Pullaiah, G., Irving, E., Buchan, K.L., and Dunlop, D.J. 1975. Magnetization changes caused by burial and uplift. Earth and Planetary Science Letters, **28**: 133–143.

Van Fossen, M.C., and Kent D.V. 1992. Paleomagnetism of 122 Ma plutons in New England and the Mid-Cretaceous paleomagnetic field in North America: true polar wander or large-scale differential mantle motion? Journal of Geophysical Research, **97**: 19 651 – 19 661.

Ward, P.D. 1978. Revisions to the stratigraphy and biochronology of the Upper Cretaceous Nanaimo Group, British Columbia and Washington State. Canadian Journal of Earth Sciences, **15**: 405–423.

Ward, P.D., Hurtado, J.M., Klrschvink, J.L., and Verosub, K.L. 1997. Measurements of the Cretaceous paleolatitude of Vancouver Island: consistent with the Baja – British Columbia hypothesis. Science (Washington, D.C.), **277**: 1642–1645.

Watson, G.S., and Enkin, R.J. 1993. The fold test in paleomagnetism as a parameter estimation problem. Geophysical Research Letters, **20**: 2135–2137.

Wheeler, J.O., and McFeely, P. (*Compilers*). 1991. Tectonic assemblage map of the Canadian Cordillera and adjacent parts of the United States of America. Geological Survey of Canada, Map 1712A, scale 1 : 2 000 000.

Wynne, P.J., Irving, E., Schulze, D.J., Hall, D.C., and Helmstaedt, H.H. 1992. Paleomagnetism and age of three Canadian Rocky Mountain diatremes. Canadian Journal of Earth Sciences, **29**: 35–47.

Wynne, P.J., Irving, E., Maxson, J.A., and Kleinspehn, K.L. 1995. Paleomagnetism of the Upper Cretaceous strata of Mount Tatlow: evidence for 3000 km of northward displacement of the eastern Coast Belt, British Columbia. Journal of Geophysical Research, **100**: 6073–6091.

Wynne, P.J., Enkin, R.J., Baker, J., Johnston, S.T., and Hart, C.J.R. 1998. The big flush: paleomagnetic signature of a 70 Ma regional hydrothermal event in displaced rocks of the northern Canadian Cordillera. Canadian Journal of Earth Sciences, **35**: 657–671.