Paleomagnetism of the 70 Ma Carmacks Group at Solitary Mountain, Yukon, confirms and extends controversial results: Further evidence for the Baja British Columbia model

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Abstract

Results of paleomagnetic investigations of volcanic strata in the uppermost Cretaceous Carmacks Group (70 Ma), in south-central Yukon, have proven controversial. Anomalously shallow paleomagnetic inclinations imply large (~2000 km) amounts of translation with respect to stable North America. This result is in conflict with offsets observed across known major strike-slip faults in the Canadian Cordillera that suggest far less (<1000 km) post–mid-Cretaceous dextral offset. One such structure, the Teslin fault, separates the Solitary Mountain volcanic suite on the east from the lithologically similar Carmacks Group to the west. Using lithostratigraphy, geochronology, and geochemistry, the Solitary Mountain volcanic suite is shown to be correlative to the rest of the Carmacks Group. The magnetic remanence of samples collected near the peak of Solitary Mountain is severely affected by lightning, but samples from below the main peak retain a stable magnetization. The mean inclination (–73.6° ± 3.6°, 15 sites) is not significantly different from that determined *for the Carmacks Group elsewhere (–69.1° ± 3.8°, 26 sites). We combine inclinations from the 41 Carmacks Group sites from 4 localities to infer a translation of 1950 ± 600 km from the south with respect to cratonic North America. Feeder plutons, which hold steeper remanences, are interpreted to have tilted, rendering them inadequate for refining paleolatitude history. The Carmacks paleomagnetic data set is repeatable and robust and therefore must be considered in evaluating paleogeographic models of the Cretaceous development of the Canadian Cordillera.*

Résumé

Les résultats d'études paléomagnétiques sur des strates volcaniques du Groupe de Carmacks datant de la fin du Crétacé (70 Ma), dans le centre-sud du Yukon, se sont avérés controversés. Des inclinaisons paléomagnétiques anormalement peu profondes laissent supposer de vastes quantités (environ 2000 km) de translation par rapport à l'Amérique du Nord stable. Ce résultat est en conflit avec les déplacements observés le long des principaux décrochements connus dans la Cordillère canadienne qui suggèrent un déplacement dextre, postérieur au Crétacé moyen, beaucoup moins important (<1000 km). Une telle structure, la faille Teslin, sépare la suite volcanique de Solitary Mountain, à l'est, du Groupe de Carmacks, qui est lithologiquement semblable, à l'ouest. En utilisant la lithostratigraphie, la géochronologie et la géochimie, la suite volcanique de Solitary Mountain est présentée comme étant corrélative au reste du Groupe de Carmacks. La rémanence magnétique des échantillons prélevés près du sommet de Solitary Mountain a été grandement modifiée par la foudre, mais les échantillons prélevés sous le sommet principal conservent une magnétisation stable. L'inclinaison moyenne (–73,6°???3,6°, 15 sites) n'est pas sensiblement différente de ce qui a été déterminé pour le Groupe de Carmacks à d'autres endroits (–69,1° ??3,8°, 26 sites). Nous combinons les inclinaisons des 41 sites provenant de quatre emplacements dans le Groupe de Carmacks pour interpréter une translation de 1950???600 km à partir du sud, par rapport à l'Amérique du Nord cratonique. Les plutons nourriciers, qui présentent des rémanences plus accentuées, sont interprétés comme ayant basculé, ce qui les rend inappropriés pour raffiner l'histoire paléolatitudinale. L'ensemble des données paléomagnétiques de Carmacks est reproductible et robuste, et doit donc être pris en compte dans l'évaluation des modèles paléogéographiques du développement de la Cordillère canadienne au Crétacé.

INTRODUCTION

Several large dextral strike-slip faults of Late Cretaceous and Paleogene age are known in the Canadian Cordillera (Gabrielse, 1985; Struik, 1994). These faults indicate that the western part of the Cordillera was transported northward at the same time the Foreland fold-and-thrust belt was being formed (Price and Carmichael, 1986). It is important to quantify the amount and timing of this motion in order to delineate the geodynamic history of this mountain chain and to understand the orogenic processes at play.

Fortunately, the Cordillera was aligned approximately north-south during the Cretaceous, so paleomagnetism (which offers a quantitative method of determining paleolatitude) promises to be an ideal method for determining amounts of along-strike translations of crustal blocks. Several paleomagnetic studies have previously suggested large translations of such blocks (>1000 km), which led to the "Baja British Columbia" model (Irving, 1985). However, such large translations have proven difficult to reconcile with amounts of offset recognized along known faults, and discussion of this problem has generated what is now called the Baja British Columbia controversy.

As the principal evidence for very large lateral translations in the northern Cordillera is from paleomagnetism, it is essential that paleomagnetic studies be designed to avoid the pitfalls which undermine paleogeographic reliability. In orogenic systems, where almost all rocks are tilted, paleomagnetic directions must be rotated back to the paleohorizontal before they can be used for paleogeographic analysis. Plutons, from which most paleomagnetic data in the Canadian Cordillera have been obtained, usually hold a strong and stable paleomagnetic record; unfortunately, however, they allow only imprecise measurements of paleohorizontal. Furthermore, they provide few field tests of paleomagnetic stability. Fortunately, paleomagnetic studies of layered rocks provide more reliable paleogeographic constraints.

In this paper, we present paleomagnetic results from the Solitary Mountain volcanic suite (SMVS), a >1 km thick volcanic succession considered to be correlative with the 70 Ma Carmacks Group (Tempelman-Kluit, 1974, 1981). This group is an erosional remnant of flood basalts which originally covered much of the Whitehorse Trough and parts of the Yukon-Tanana terrane. Marquis and Globerman (1988) published initial paleomagnetic results from 18 flows in the Carmacks Group, 5 of which are now assigned to an older volcanic unit by subsequent dating. A second study provided results from an additional 13 flows (Johnston *et al.,* 1996; Wynne *et al.,* 1998). Together, these studies have suggested latitudinal movement of 1900 ± 700 km. While this is not the largest translation inferred from rock-paleomagnetism studies of Baja British Columbia, the result has been particularly controversial because of the relatively young age of the Carmacks Group, and because of its close proximity to the ancient craton margin preserved in the easternmost Cordillera.

The SMVS is separated from the rest of the Carmacks Group by the crustal-scale Teslin fault (Fig. 1), an enigmatic structure which has been interpreted both as a dextral strike-slip fault (Gabrielse, 1985), or a sinistral strike-slip fault (de Keijzer *et al.,* 2000). The 109 Ma Deadman Creek batholith intrudes and thus evidently pins the Teslin fault in the Teslin Lake area, near the Yukon-British Columbia border (Gordey *et al.,* 1998). Two major faults separate Solitary Mountain rocks from those deposited on the ancient continental margin to the east. These faults are the d'Abbadie fault, which is intruded by a mid-Cretaceous pluton and is therefore older than the SMVS (Harvey *et al.,* 1997), and the Tintina–Northern Rocky Mountain Trench fault. The latter accommodates 400–430 km of Eocene strike-slip movement (Gabrielse *et al.,* this volume), an amount that is far less than that inferred from the first two paleomagnetic studies of the Carmacks Group.

Our study addresses the following discrepancy: the Solitary Mountain volcanic suite is apparently correlative with the Carmacks Group, whose shallow paleomagnetic remanence suggests 1900 km of northward translation, but it overlies rocks interpreted on the basis of geological markers offset across the Tintina fault to have undergone only ~425 km of post-depositional displacement. If the SMVS is truly part of the Carmacks Group, it should have an indistinguishable paleomagnetic signature. On the other hand, if geological arguments for limited translation are correct, then Solitary Mountain should be paleomagnetically indistinguishable from cratonic North America.

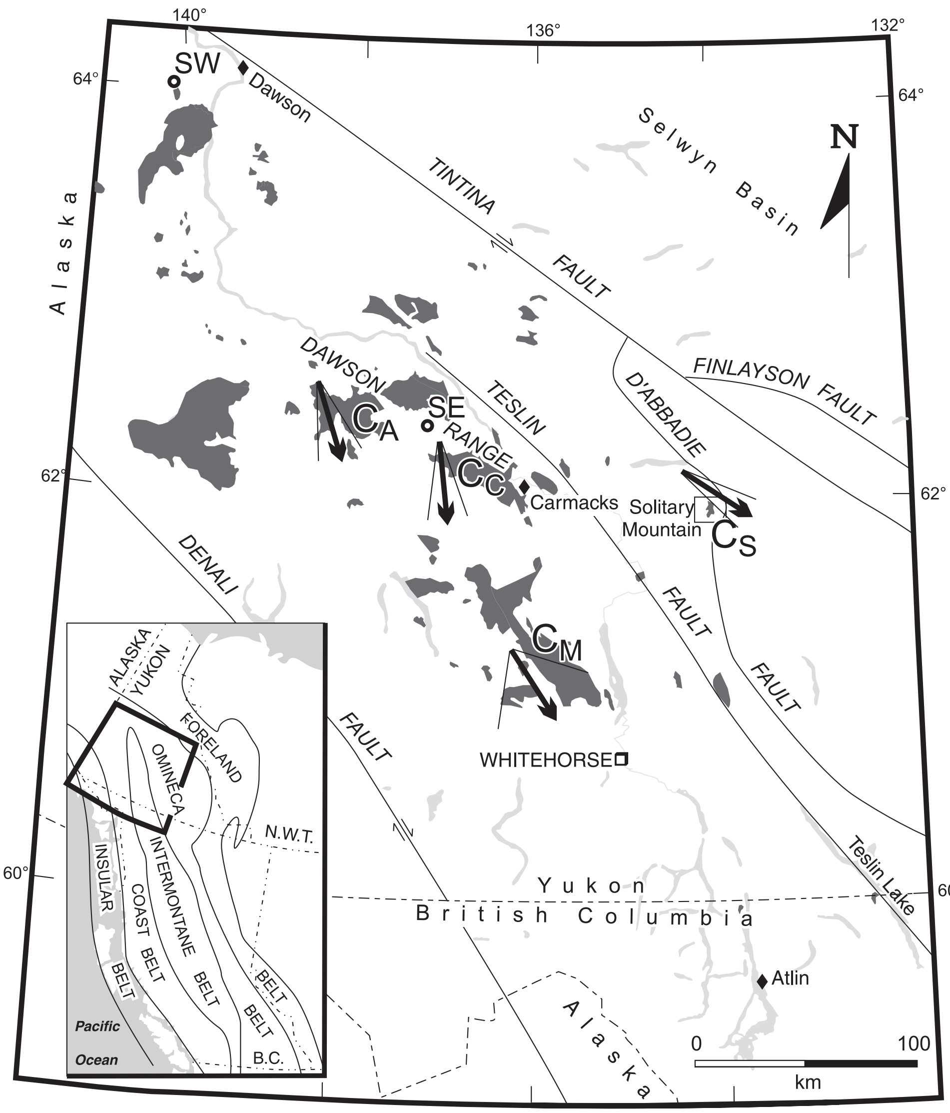


Figure 1. *The distribution of the Carmacks Group (dark areas) in Yukon and northern British Columbia, after Wheeler and McFeely (1991). The four localities of Carmacks Group sampling (C_A = Apex Mountain; C_C = Carmacks town region; C_M = Miners Range; and C_S = Solitary Mountain) are marked with arrows showing mean paleomagnetic declination and its 95% confidence bounds. Feeder plutons (SE = Seymour Stock; SW = Swede Dome) are marked with open circles. The location map shows the geomorphic belts of the Canadian Cordillera.*

GEOLOGY

The Solitary Mountain volcanic suite is located in east-central Yukon (61.9°N, 134.1°W). It is an anomalous outcrop of Cretaceous volcanic strata disconformably overlying schist of the Yukon-Tanana terrane (YTT). The volcanic suite is divisible into two units (Fig. 2). The lower unit consists of locally vesicular mafic to intermediate fragmental volcanic flow deposits with local welded tuffs, lahars, and lapilli conglomerates. The upper succession consists of ankaramitic flood basalts with pervasive well-developed columnar jointing. Euhedral phenocrysts of olivine and clinopyroxene within the ankaramites are small- to medium-grained (up to 3 mm in size) with smaller (up to 2 mm) magnetite crystals common locally.

Although situated well to the east of the main outcrop area of the Carmacks Group, and separated from it by crustal-scale structures such as the Teslin fault (Fig. 1), the SMVS was correlated with the Carmacks Group on the bases of lithostratigraphy, geochemistry, and geochronology studies undertaken during 1:25,000-scale mapping (Tempelman-Kluit, 1974, 1981). Radiometric age determinations for the Solitary Mountain volcanic suite are within error of those determined for the Carmacks Group. Ar-Ar step heating ages of 70.42 ± 0.74 Ma and 70.7 ± 0.74 Ma have been measured for ankaramite near the summit of Solitary Mountain (D. Francis, unpub. data, 2001; Johnston *et al.,* 2001). K-Ar age data on the Carmacks Group suggests a depositional period between 72 and 69 Ma with the majority of magmatism concentrated around 69–70 Ma (Grond *et al.,* 1984; Lowey *et al.,* 1986; Hart, 1995). The combined age of the Carmacks Group and the Solitary Mountain succession is 69.9 ± 0.7 (Johnston *et al.,* 2001).

Precise thicknesses of the SMVS units are not well constrained. Outcrop patterns of the top and bottom of the lower unit suggest it is ~700 m thick. The top of the upper unit is not exposed, but estimates based on outcrop patterns suggest the upper unit is at least 750 m thick. Given this thickness and the range of lithologies, deposition likely occurred over an interval of at least several thousand years.

A syndepositional east-side-down normal fault runs just west of Solitary Mountain. In the hanging wall, which includes the mountain, YTT rocks are disconformably overlain by the lower unit of the Solitary Mountain volcanic suite and then capped by the upper SMVS unit. The footwall consists of upper SMVS rocks resting disconformably on YTT with no intervening lower unit. We interpret the fault as having been active during the deposition of the Lower Carmacks Group, with the bulk of the lower unit being deposited in a trough developed above the downdropped side of the fault. Subsequent Upper Carmacks flood basalts flowed across and postdated displacement on the fault.

The metamorphic grade of the SMVS is at or below zeolite facies and recent weathering is restricted to a <1 cm thick rind. Thin-section observations show primary igneous textures and no evidence of hydrothermal alteration or fluids. Zeolites were not observed, but are inferred to be present from samples which exploded on heating during paleomagnetic thermal demagnetization. The rare examples of quartz and calcite veins, minor gold mineralization, and agate amygdules suggest local hydrothermal alteration.

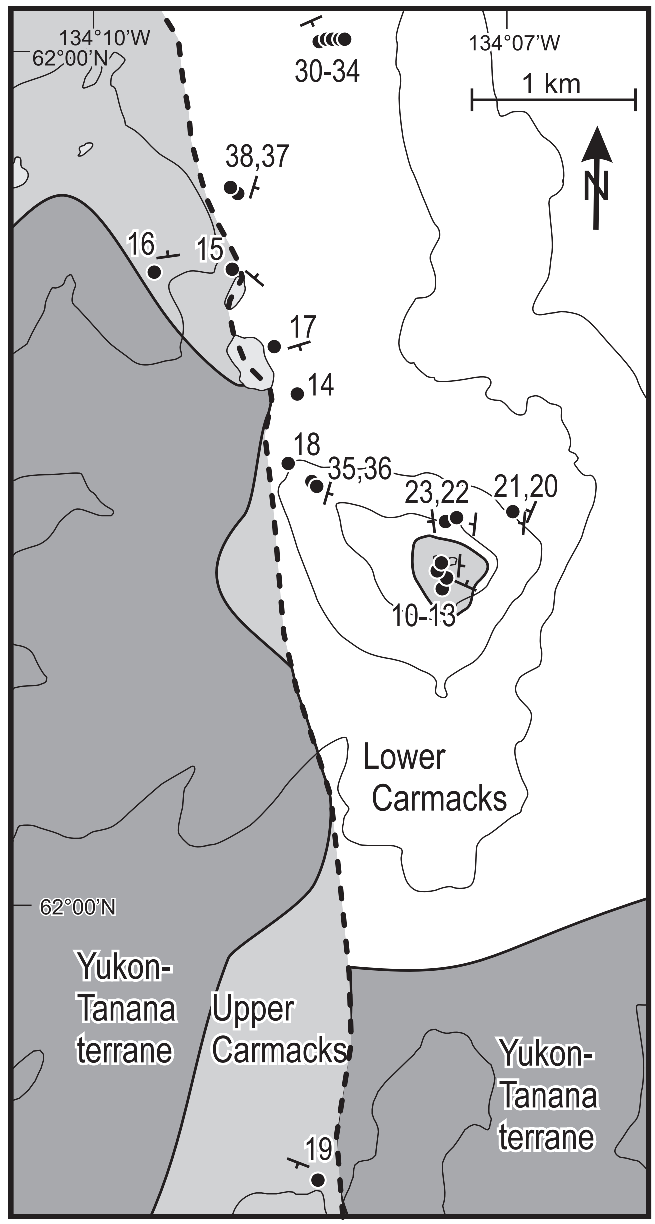


Figure 2. *Site locations (dots) on the geological map of Solitary Mountain, with Upper Carmacks Group flows (light grey), Lower Carmacks Group fragmental units and flows (white), and basement Yukon-Tanana schists (dark grey). Topographic contours (thin grey lines) are spaced at 500 feet.*

PALEOMAGNETISM

Twenty-one flows were sampled on and around Solitary Mountain (Table 1). Sites consist of 6 to 8 cores (2.5 cm diameter, 4 to 15 cm long) sampled with a gas-powered diamond-tipped drill. Cores were oriented using both magnetic and sun compasses. When the sun's shadow was not present, orientations were checked by a magnetic compass sighted from a distance. Deviations between the two methods were extreme near the mountain top (not surprising for a "solitary" mountain which acts as a lightning rod). Sites were surveyed with the two compasses to locate areas which were least affected by lightning.

Paleohorizontal was established through direct bedding measurements taken from welded tuffs and lahars within the lower fragmental unit, and from the attitudes of columnar joints in the upper unit. Flood basalts, such as are found in the Deccan province, are almost entirely characterized by vertical columnar joints (Misra, 1999). Columnar joints develop when lava pools and cools slowly, which does not occur on sloped surfaces. For example, Hawaiian basalts do not exhibit columnar jointing unless they are allowed to pool, suggesting that the relatively gentle slopes of shield volcanoes are too steep for columnar joint development. This adds to the credibility of using columnar jointing as a proxy for paleohorizontal control.

Rather than use tilt measurements from each site individually, the gentle tectonic structure was exploited by averaging tilts within 5 panels or groups of sites (Fig. 2), defined by lithology, proximity, and structure, to give more reliable estimates. Sites 30 through 34 on the northern face of the study area comprise the first panel. The next two panels consist of sites north of the mountain, east and west of the normal fault that runs the length of the study area. The fourth panel includes sites taken on the mountain itself. Flow layering recorded at sites 20 and 21 on the northeast flank of the mountain was found to be uncharacteristically steep compared with the rest of the mountain. We infer that these two sites hold a primary slope, and thus we do not include the

Table 1. Site data

Site	BD (°)	BDDA (°)	*n*	D_G (°)	I_G (°)	D_S (°)	I_S (°)	*k*	α_{95} (°)	Comment
30	3.7	155.7	12	124.0	-67.0	118.7	-70.1	233.0	2.8	
31	3.7	155.7	11	144.6	-69.2	142.3	-72.8	62.5	5.8	
32	3.7	155.7	12	121.3	-67.6	115.4	-70.5	129.4	3.8	
33	3.7	155.7	11	136.6	-69.2	132.8	-72.7	7.3	18.1	x
34	3.7	155.7	10	99.9	-71.4	89.8	-73.2	64.3	6.1	
14	4.7	131.5	7	219.7	-53.3	226.0	-53.2	3.9	35.0	L
17	4.7	131.5	11	163.7	-70.2	172.4	-74.0	177.4	3.4	
37	4.7	131.5	10	139.9	-72.7	142.9	-77.3	170.6	3.7	
38	4.7	131.5	12	134.1	-73.3	135.1	-78.0	194.0	3.1	
15	6.0	22.2	12	123.5	-60.9	133.5	-59.2	376.4	2.2	
16	6.0	22.2	10	117.3	-65.4	129.8	-64.2	364.3	2.5	
11	3.5	73.2	11	12.5	-68.7	4.0	-70.2	8.6	16.5	L
12	3.5	73.2	11	78.0	-75.4	79.5	-78.9	3.4	29.4	L
13	3.5	73.2	10	258.4	-73.8	257.5	-70.3	4.8	24.6	L
18	3.5	73.2	8	119.6	-65.0	125.6	-67.3	60.6	7.2	
20	3.5	73.2	10	113.1	-72.0	121.2	-74.5	202.6	3.4	
21	3.5	73.2	8	93.8	-77.9	101.6	-81.1	204.5	3.9	
22	3.5	73.2	6	297.1	-54.2	294.0	-51.6	13.8	18.7	L
23	3.5	73.2	8	80.6	-79.6	84.3	-83.1	7.2	22.1	L
35	3.5	73.2	8	67.3	-61.8	66.5	-65.3	28.0	10.6	
36	3.5	73.2	11	99.6	-67.2	103.9	-70.3	50.3	6.5	
19	9.0	200.8	6	158.5	-60.1	145.1	-66.1	368.3	3.5	
Mean of Sites			**15**	**121.8**	**-70.0**			**59.0**	**5.0**	
						122.9	**-72.5**	**66.5**	**4.7**	

Notes: BD, BDDA = Bedding dip and down-dip azimuth; *n* = number of specimens; D, I = declination, inclination with subscript G, S for geographic, stratigraphic coordinates; *k* = Fisher concentration; α_{95} = 95% confidence interval; comment: L for lightning, x for dispersion >15°.

measurements from them in the panel mean. Site 19, collected 4 km south of Solitary Mountain, constitutes alone the fifth panel.

Cores were cut into 2.2-cm-long cylinders in the laboratory. Remanence was measured on an Agico JR5-A spinner magnetometer and stepwise demagnetizations were performed using a Schonstedt GSD-5 alternating field demagnetizer with tumbler (8 steps to 100 mT), or an ASC TD48 thermal demagnetizer (7–9 steps to 600°C). In an attempt to avoid the effects of lightning, several samples were demagnetized by alternating field to 20 mT, followed by thermal demagnetization to 600°C. Characteristic directions were calculated using principal component analysis on segments defined by at least 4 steps and almost always directed to the origin (using programs written by the first author, available at www.pgc.nrcan.gc.ca/people/renkin_e.php).

Figure 3 illustrates the range of remanence characteristics determined from this collection. The data suggest that sites sampled on the mountain all suffered from lightning strikes – the remanences from these sites are exceedingly strong and soft and have random directions (*e.g.* Fig. 3A). A reverse polarity hard component could be observed in most of these sites, but these directions have high dispersion.

In the surrounding region, the remanences display the characteristics of primary volcanic thermo-remanent magnetization. Thermal unblocking is negligible until the rocks are heated above 200°C. At higher demagnetization steps, the unblocking temperatures are sharply defined (*i.e.,* square-shouldered decay). Magnetite (*e.g.* Fig. 3B), with an unblocking temperature below 600°C, and, in some cases, pyrrhotite (*e.g.* Fig. 3C and D), with an unblocking temperature below 400°C and coercivity above 100 mT, were observed.

Site means are given in Table 1 and Figure 4. Sites with 95% confidence interval >15° were rejected, all but one of which were affected by lightning. The other dispersed site, Site 33, is from a coarse-grained fragmental bed which has a mean direction similar to those for the other sites, but its high dispersion ($k = 7.3$, $\alpha_{95} = 18.1°$) is attributed to the influence of large grains that did not align during deposition. This site constitutes a weak yet positive conglomerate test of paleomagnetic stability. If the area were affected by a pervasive remagnetization event, these large grains would have been remagnetized along with fine grains in neighbouring rocks.

The dispersion of site mean directions is reduced on full untilting of strata (Table 2), compatible with a positive tilt test. With such shallow paleohorizontal dips (<9°), however, the distribution of site mean directions does not change significantly on tilt correction, making the tilt test indeterminate. For example, optimal concentration is obtained on 91% ± 121% untilting (Direction-Correction method, Enkin, 2003), a range which includes both 0% and 100% untilting.

Sites that are not contaminated by lightning hold a mean remanence direction of $D = 122.96°$, $I = -72.5°$, $k = 66.5$, $\alpha_{95} = 4.7°$, $N = 15$, after correction for bedding tilt. This direction is considered to be primary because: (a) the rocks are unaltered; (b) the hard magnetite and pyrrhotite demagnetization signature show that the rocks contain very stable paleomagnetic carriers; (c) the polarity is reverse and the direction is distinct from that expected for any younger age; and (d) there are weak yet positive-tending conglomerate and tilt tests.

INTERPRETATION

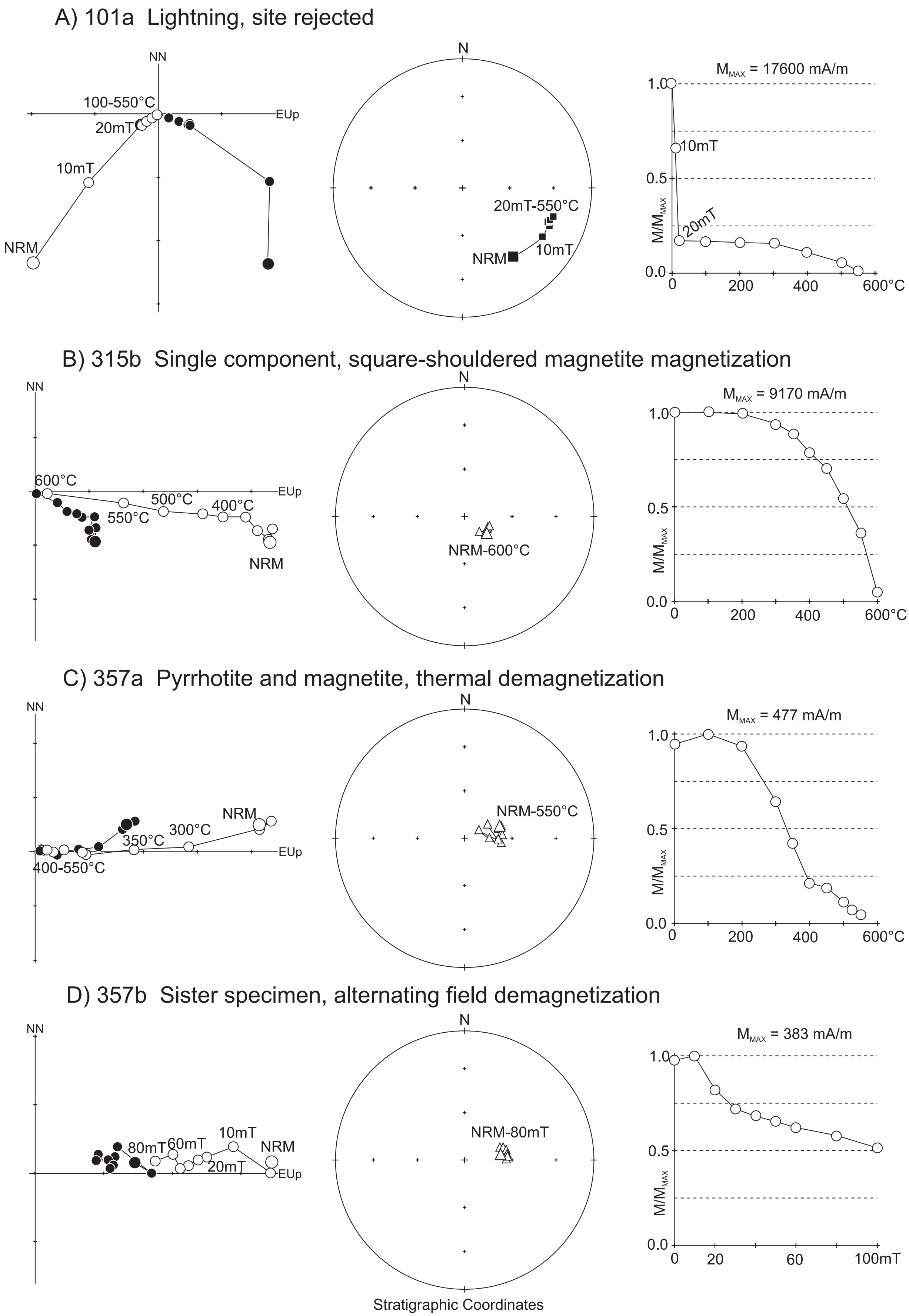
Carmacks Group

The primary goal of this study was to determine whether the SMVS is part of the Carmacks Group with its relatively shallow paleomagnetic inclination (~70°), or is consistent with cratonic North America by having a steeper inclination (~80°). The paleomagnetic means from each Carmacks locality and from Solitary Mountain are given in Table 2 and Figure 5. In order to account for differences in sampling location, site directions were projected onto a common point, 62.1°N, 136.3°W at the Carmacks townsite. The minor differences between our results and those of previous publications (Marquis and Globerman, 1988; Wynne *et al.,* 1998) are due to the choice of reference point. The four localities all have overlapping inclination distributions around 70°. The difference in mean inclinations west and east of the Teslin fault is an insignificant 4.0 ± 5.2°, which suggests the SMVS is indeed part of the Carmacks Group.

The inclination differences observed east and west of the Teslin fault correspond to an insignificant ($P = 0.05$) paleolatitude difference of 6.1° ± 7.9° or 700 ± 900 km of dextral strike-slip (assuming the fault to have been oriented paleonorth-south). Although the Teslin fault conceivably may have accommodated post-70 Ma dextral displacement on the order of 700 km, it appears that the fault was locked prior to 70 Ma because it was intruded by an undeformed mid-Cretaceous pluton (Gordey *et al.,* 1998). We suggest that differences in the remanent magnetism on either side of the fault are most likely the result of statistical sampling, and our data preclude interpretation of the Teslin fault as having been the structure that accommodated the northward transport required by paleomagnetic studies of the Carmacks Group. This result indicates that a structure, or structures, must lie to the east of Solitary Mountain.

The fact that underlying Jurassic and Triassic formations in the Whitehorse Trough were remagnetized after tilting with this same 70° inclination suggests that a large

Figure 3. *(facing page) Demagnetization characteristics of the collection. Alternating field (thermal) demagnetization steps labelled with "mT" ("°C"). Left column: orthogonal plots with horizontal (vertical) projection marked with dots (open circles). Centre column: Stereographs with lower (upper) hemisphere marked with closed squares (open triangles). Right column: Intensity plots.*


A) 101a Lightning, site rejected
NN
EUp
100-550°C
20mT
10mT
NRM
N
20mT-550°C
10mT
NRM
M_{MAX} = 17600 mA/m
1.0
0.5
0.0
M/M_{MAX}
10mT
20mT
0
200
400
600°C
B) 315b Single component, square-shouldered magnetite magnetization
NN
EUp
600°C
500°C
400°C
550°C
NRM
N
NRM-600°C
M_{MAX} = 9170 mA/m
1.0
0.5
0.0
M/M_{MAX}
0
200
400
600°C
C) 357a Pyrrhotite and magnetite, thermal demagnetization
NN
NRM
300°C
350°C
EUp
400-550°C
N
NRM-550°C
M_{MAX} = 477 mA/m
1.0
0.5
0.0
M/M_{MAX}
0
200
400
600°C
D) 357b Sister specimen, alternating field demagnetization
NN
10mT
80mT
60mT
NRM
20mT
EUp
N
NRM-80mT
M_{MAX} = 383 mA/m
1.0
0.5
0.0
M/M_{MAX}
0
20
60
100mT
Stratigraphic Coordinates

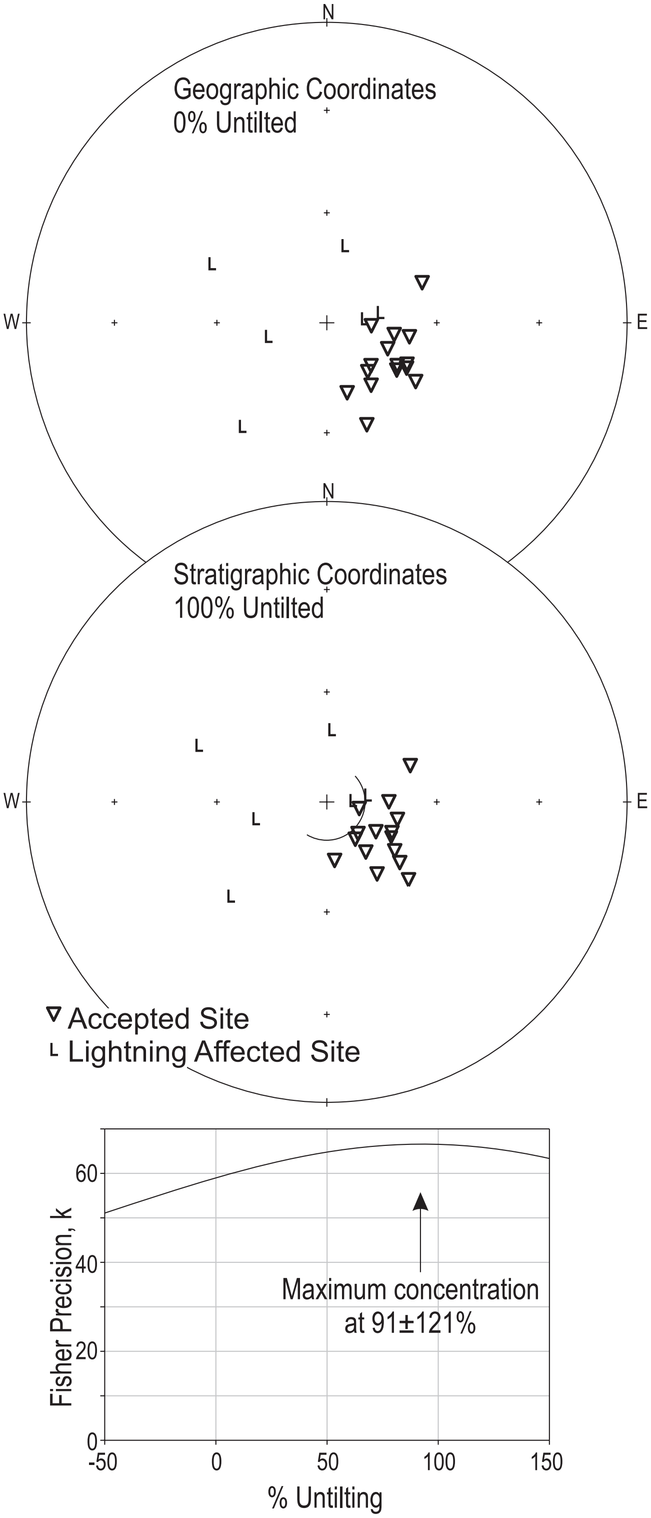


Figure 4. *Upper hemisphere stereographs of site means with present attitude ("Geographic coordinates") and after bedding correction ("Stratigraphic coordinates"). Site means indicated by an "L" are contaminated by lightning. Arc at 81° shows the expected inclination were the region attached to cratonic North America at the time of deposition, showing the site means to be consistently shallow. Bottom graph show the increase in site mean direction concentration with bedding correction, compatible with a positive tilt test.*

hydrothermal system may have been in place beneath the Carmacks Group volcanic rocks as they erupted (Wynne *et al.,* 1998). This observation indicates that the present outcrop of the Carmacks Group is a small erosional remnant of a large flood basalt province, and adds confidence that the 70° inclination is a reliable measure of the geomagnetic field direction in this region at 70 Ma.

Most of the Carmacks Group sites exhibit reverse polarity, which corresponds well with the Global Polarity Timescale. Using the most recent compilation (Cande and Kent, 1995), the bulk of Carmacks Group extrusion occurred during reverse polarity chron C31r between 71.1 and 68.7 Ma. The only normal polarity sites were found at the top of the Apex Mountain and Miners Range sections, suggesting eruption during chron C31n between 68.7 and 67.7 Ma at the end of this volcanic event.

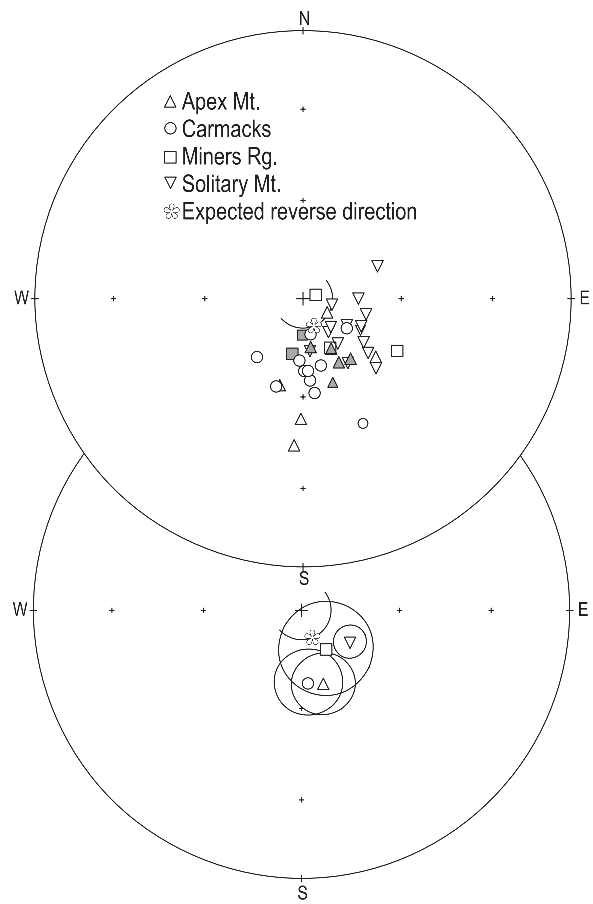


Figure 5. *Stereograph of all Carmacks Group site means (top) and locality means (bottom). Open symbols are reverse polarity, while solid symbols mark the antipode of the normal polarity direction. Arc at 81° shows the expected inclination were the region attached to cratonic North America at the time of deposition, showing the site means to be consistently shallow.*

There are declination differences between the localities (Fig. 6 and 1) that we interpret as the result of relative vertical axis rotations. The Solitary Mountain region has undergone a counter-clockwise rotation of 43.4° ± 14.6° with respect to the localities west of the Teslin fault, which do not record significant rotations. Note that today, in eastern and central Alaska, ongoing clockwise rotation of crust northeast of the active dextral Denali fault is being accommodated by a series of northeast-trending sinistral faults in eastern and central Alaska (Ellanna, 1995). Northeast-trending sinistral faults in the Dawson Range cut and postdate the Carmacks Group (Johnston, 1995), and their presence indicates that similar clockwise rotations are probable in the Dawson Range. Therefore, declination differences between the Solitary Mountain and Dawson Range region may be attributable to recent and ongoing clockwise rotation of crust in the Dawson Range. The grand mean inclination allows for differential rotation of the localities by using Block Rotation Fisher analysis (Enkin and Watson, 1996), giving -70.6° ± 2.7°, and corresponding to a paleolatitude of 54.8° ± 4.1°.

Table 2. Mean inclinations and paleogeographic implications (reference point 62.1°N, 136.3°W)

Ensemble	Sites	Bl	Inclination (°)	Paleolatitude (°N)	Lat Change (°)	Distance Change (km)
Localities						
Apex Mountain	10	1	66.0 ± 6.5	48.3 ± 8.7	23.8 ± 9.4	2666 ± 1055
(62.4°N, 138.0°W)					*21.9 ± 9.2*	*2453 ± 1027*
Carmacks region	11	1	67.8 ± 5.1	50.8 ± 7.1	21.3 ± 8.0	2386 ± 892
(62.2°N, 136.7°W)					*19.4 ± 7.7*	*2173 ± 859*
Miners Range	5	1	76.1 ± 9.6	63.7 ± 16.4	8.4 ± 16.8	941 ± 1881
(61.0°N, 135.5°W)					*6.5 ± 16.6*	*728 ± 1865*
Solitary Mountain	15	1	73.1 ± 3.6	58.7 ± 5.7	13.4 ± 6.7	1501 ± 755
(61.9°N, 136.3°W)					*11.5 ± 6.4*	*1288 ± 716*
Summary						
West of Teslin	26	3	69.1 ± 3.8	52.6 ± 5.5	19.5 ± 6.6	2184 ± 736
62.1°N, 136.3W					*17.6 ± 6.2*	*1971 ± 696*
All sites	41	4	70.6 ± 2.7	54.8 ± 4.1	17.3 ± 5.5	1938 ± 611
62.1°N, 136.3W					*15.4 ± 5.0*	*1725 ± 562*
All localities	4	4	71.1 ± 4.6	55.6 ± 7.0	16.5 ± 7.8	1848 ± 882
62.1°N, 136.3W					*14.6 ± 7.6*	*1635 ± 849*

Notes: Bl = Blocks used in Block Rotation Fisher (BRF) inclination analysis; Inclination = mean BRF inclination after adjusting site directions to reference point; Paleolatitude calculated assuming geocentric axial dipole field geometry; Latitude and Distance Change: calculated using global reference pole for 80 to 60 Ma (77.5°N, 194.9°E, α_{95} = 5.1°, N = 10 studies) followed in italics with results using previously used average of North American poles (79.2°N, 189.9°E, α_{95} = 4.2°, N = 5 studies) (Wynne *et al.*, 1992).

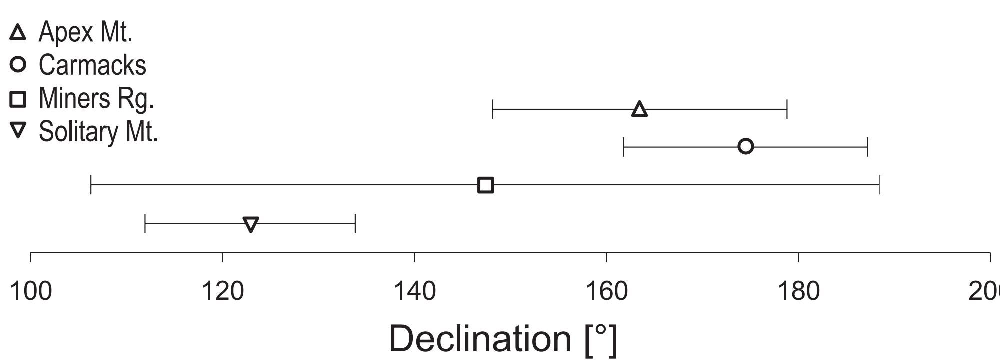


Figure 6. *Mean declinations with 95% confidence intervals of the 4 Carmacks Group localities, showing Solitary Mountain to have been rotated counter-clockwise with respect to the localities west of the Teslin fault.*

Paleomagnetic studies (McCausland *et al.,* 2001; McCausland, 2002) have been undertaken on two small (km-scale) plutons, Seymour stock and Swede Dome stock, which were likely feeders to the Carmacks Group volcanic strata west of the Teslin fault. The plutons hold indistinguishable paleomagnetic inclinations (83.6 ± 3.4° and 83.3 ± 2.5°) which these authors interpreted to provide a reliable estimate of the region's paleolatitude. They furthermore interpreted that the Carmacks Group paleomagnetic inclinations, around 70°, are anomalously shallow. We accept the paleomagnetic directions determined from these two plutons, but argue that they most probably tilted during their rise to the surface following the setting of their paleomagnetic remanence. The aluminum-in-hornblende geobarometry from these plutons shows that crystallization occurred 4 to 9 km below the surface and thus the absence of tilt in nearby subaerial outcrops cannot be used to estimate the tilt of the plutons. Second, the two stocks hold significantly different remanence directions, with a declination difference of 122° ± 34°. The vertical axis rotation implied by the declination of the Seymour stock is in excess of 90°CCW, which, if correct, can only have affected a small region. There is no geological evidence for such a large vertical axis rotation. It is simpler and geologically more reasonable to interpret that the plutons and coeval Carmacks Group volcanic strata were initially magnetized in the same direction, but that the Seymour stock tilted 20° to the north and the Swede Dome stock tilted 15° to the northwest. Such tilts are geologically reasonable, as the Carmacks Group volcanic strata are observed to have tilts up to 30°.

Paleogeographic Interpretation

In order to test the paleogeographic relationship of the Carmacks Group paleolatitude with cratonic North America, it is necessary to have a reliable paleopole of the appropriate age for the craton. Late Cretaceous poles from cratonic North America all lie in a region north of Alaska; however, these poles apparently jump back and forth about 10° in an unrealistic pattern, suggesting there are problems with statistical sampling and systematic errors. For our previous publications on this subject, we have used the compilation of Wynne *et al.* (1992) of 5 poles dated within 10 m.y. of 70 Ma. In the companion review paper (Enkin, this volume), reliable poles are selected from all major cratons and transferred onto North America using ocean kinematics, following the

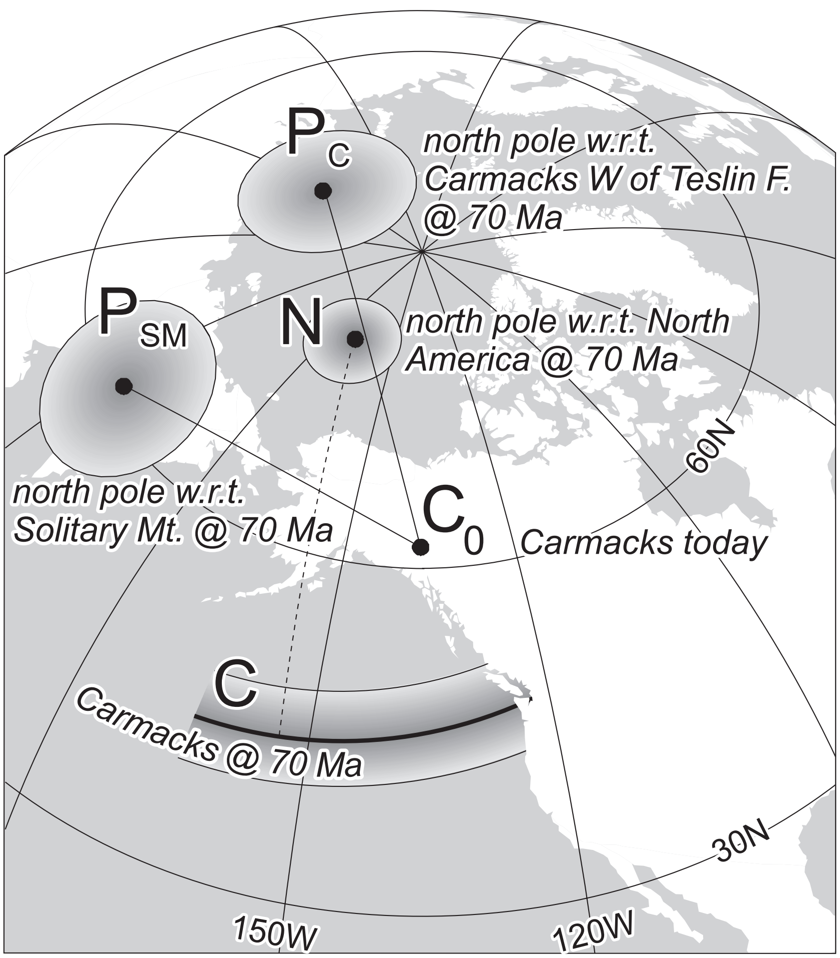


Figure 7. *The reference pole for North America (N) is closer to the sampling region than any of the poles determined from the Carmacks Group. Despite different azimuths on either side of the Teslin fault, the paleolatitudes are compatible and a single paleogeographic swath for the region is indicated 1950 ± 600 km south of its present location.*

methods of Besse and Courtillot (1991, 2002). The pole has not changed significantly (angular separation 2.0° ± 4.6°), but it leads to an increase of inferred translations by only about 200 km. Paleolatitude difference estimates will be given using both reference poles for comparison, but we favour results using the global compilation pole.

The Carmacks Group holds paleomagnetic inclinations shallower than would be expected had the region been attached to cratonic North America (Fig. 5). All localities (except for the poorly defined Miners Range locality) are significantly shallower, and 38 of the 41 site means are shallower. Transforming the inclinations to paleolatitude and using a central reference point near Carmacks (62.1°N, 136.3°W) , the combined Carmacks Group result is 17.3 ± 5.5 or 1950 ± 600 km south of its present relative position to North America (Fig. 7) (15.4° ± 5.0° or 1750 ± 550 km using the older reference pole).

Accounting for this paleolatitude discrepancy is difficult when available geological evidence is taken into account. The only major dextral strike-slip structure known to separate the displaced region from the craton is the Tintina-Northern Rocky Mountain trench fault (Roddick, 1967), with a well-constrained post-Cretaceous displacement of 400–430 km (Gabrielse *et al.,* this volume). This is a major fault, observable in topography and seismology. Yet it apparently accounts for less than one-quarter of the displacement we infer from rock paleomagnetism. As a result of this study, we can no longer appeal to structures within or west of the more complicated region west of the Tintina trench to accommodate the necessary translation; if there is a paleogeographic solution, it must therefore lie to the east. Stratigraphic ties throughout the Finlayson region prohibit a major crustal fault in this area. We thus hypothesize that hidden latest Cretaceous to Paleocene structures are present in or east of the eastern margin of the Selwyn basin.

Our findings require a reappraisal of the Baja British Columbia concept. Paleomagnetic data have been used previously to infer that the far-travelled crust included only the western part of the Intermontane domain and the more westerly Insular domain (Irving *et al.,* 1996). This narrow crustal strip, which was referred to as Baja British Columbia, was commonly inferred to have been a fore-arc sliver that migrated north in response to oblique subduction (Cowan, 1994). Our new data imply that the far-travelled domain includes not only the Insular and Intermontane belts, but also parts of the Omineca and Foreland belts, in other words, much of the Canadian Cordillera, a region more than 1000 km wide. These findings refute interpretations of the far-travelled domain as a fore-arc sliver, and call for a re-evaluation of previously enunciated "crucial tests" of paleogeographic models of the Cordillera (Cowan *et al.,* 1997). In particular, the eight predictions enunciated by Cowan *et al.* (1997) explicitly refer to the two paleogeographic hypotheses of their Figure 2, whereas our paleomagnetic data suggest that neither hypothesis is valid. The displaced region appears from our results to be much wider.

Evidence for large-scale northward translation in the Canadian Cordillera is found in Alaska, which has been interpreted to consist of a series of oroclines which formed as a response to northward translation of a ribbon continent, referred to as SAYBIA (Johnston, 2001). SAYBIA included much of the Cordillera extending east into the Foreland domain (Gladwin and Johnston, this volume). The oroclines are defined by the bent traces of belts of mid-Cretaceous and older strata and are unconformably overlain by Eocene sedimentary sequences, limiting orocline formation to the Late Cretaceous to Paleocene. These timing constraints are consistent with the interpretation, based on paleomagnetic and structural data, of deformed Upper Cretaceous and Cenozoic sedimentary and volcanic rocks within the hinge regions of the oroclines having been deposited during orocline formation (Coe *et al.,* 1985; Plumley *et al.,* 1989; Johnston, 2001).

CONCLUSION

The Solitary Mountain volcanic suite is part of the Carmacks Group volcanic succession, based on lithostratigraphic, geochemical, and geochronologic data, and now paleomagnetic analysis. Fifteen sites hold a primary remanence that is insignificantly steeper (4.0° ± 4.7°, corrected for site location) than the direction from 26 Carmacks Group sites west of the Teslin fault, although they have rotated counter-clockwise (43.4° ± 14.6°) with respect to the sites west of the fault.

The mean paleomagnetic inclination is shallow with respect to the expected Late Cretaceous direction from the cratonic North American pole, implying 1950 ± 600 km post-68 Ma translation with respect to North America. While ~425 km of this motion could have been accommodated by the Tintina fault, we infer that the remainder was accommodated by unidentified structures east of the Selwyn basin.

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