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Palaeopole for the 69 Ma Prospector Mountain stock: a critique of the Carmacks/‘Baja BC’ transport estimate for Yukon, Canada

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SUMMARY

The 69 Ma Prospector Mountain stock is located in southwestern Yukon in the northern Canadian Cordillera. This massive monzonite-syenogranite stock is thought to be the intrusive volcanic centre for the surrounding coeval Carmacks Group volcanics. Anomalous palaeomagnetic data from these volcanics have provided the only evidence for the commonly posited hypothesis that the Yukon-Tanana terrane (YTT) was part of the far-travelled (1950 ± 600 km northward) ‘Baja BC’ terrane from 70 to 50 Ma. All other geologic evidence and averaged palaeomagnetic data support a northward displacement of ∼415 ± 15 km. This study provides a direct test of the Carmacks volcanics’ estimate and examines the possible causes of its anomalous results. Both the stock and volcanics are unmetamorphosed and rest unconformably on metamorphosed basement rocks of the YTT. Palaeomagnetic and mineral magnetic results from 17 of 19 tested sites (218 specimens) in the Prospector stock and its peripheral skarn isolated a stable thermoremanent magnetization (TRM) in magnetite or low-Ti titanomagnetite that was mostly determined on demagnetization between temperatures of 500 and 580 °C. The TRM has a direction of Decl. = 8.3°, Incl. = 82.4° ($N = 17$, $k = 71.9$, $\alpha_{95} = 4.2°$), providing a non-significant northwards translation estimate of 70 ± 880 km for the YTT. The normal-polarity TRM direction at Prospector Mountain provides a highly significant palaeomagnetic reversals test with the reversed-polarity TRM of the 70 Ma Swede Dome stock, another volcanic centre of the Carmacks Group about 190 km to the north. The test affirms to a high probability that both stocks carry primary TRMs and have not been tectonically tilted significantly since emplacement. Combining the palaeopoles for these two stocks with that for the 75 Ma Mount Lorne volcanic centre stock about 210 km south of Prospector Mountain yields a combined northward translation estimate of 330 ± 400 km for the YTT since ∼71 Ma. This estimate agrees closely with the 415 ± 15 km estimate from geological constraints on strike-slip motion along the inboard Tintina fault zone since ∼70 Ma, and with the palaeomagnetic estimate of 650 ± 450 km northward since ∼108 Ma from four mid-Cretaceous batholiths. In contrast, the palaeomagnetic directions from four areas of the ∼70 Ma Carmacks volcanics are poorly clustered. Nonetheless their estimates of ∼1900 km northward have been used for a quarter of a century to support a far-travelled ‘Baja BC’ tectonic model for the YTT. This paper discusses and concludes that the anomalous far-travelled estimates from the Carmacks volcanics are attributable to the unfortunate additive effects of inadequate averaging of secular variation, dipole offset error, unrecognized primary dip and other possible causes.

Key words: Palaeomagnetism applied to tectonics; Continental tectonics: strike-slip and transform; Volcaniclastic deposits; North America.

INTRODUCTION

Palaeomagnetic results from volcanic strata of the ∼70 Ma Carmacks Group have been a hallmark of the Baja British Columbia (Baja BC) hypothesis. The hypothesis postulates that the tectonic terranes that underlie the Intermontane Belt (IMB) of British Columbia and Yukon in Canada originated some 1000–4000 km to the south and were translated northward along North America’s western margin during the Palaeocene to dock with North America at ∼50 Ma (Irving 1985; Irving *et al*. 1996). Palaeomagnetic studies on the

~70 Ma Carmacks Group volcanics in Yukon by Marquis & Globerman (1988), Johnston *et al.* (1996), Wynne *et al.* (1998) and Enkin *et al.* (2006) have been used to support a northward translation estimate of 1950 ± 600 km of the Yukon-Tanana terrane (YTT) and IMB terrane between 70 Ma and ~50 Ma (Enkin *et al.* 2006). Conversely, most geologic evidence based on known fault displacements (e.g. Gabrielse 1985; Gabrielse *et al.* 2006) and most palaeomagnetic evidence from other units in the YTT and IMB support a northward displacement of ≤1000 km since ~70 Ma (Symons *et al.* 2005; McCausland *et al.* 2006). In this paper we present palaeomagnetic results from the 69 Ma Prospector Mountain pluton, a co-magmatic hypabyssal felsic pluton that intrudes the gently dipping lower Carmacks volcanic section. Our results from this pluton give a palaeopole that indicates a non-significant northward displacement of only 70 ± 880 km.

At the core of the Baja BC controversy in Yukon is a fundamental difference in the palaeomagnetic strategy being used to study the hypothesis. The proponents for large translation distances of ~1950 ± 600 km for Baja BC in Yukon cite results from only the Carmacks volcanics to support the hypothesis. They assert that palaeomagnetic samples must come from bedded strata only to get a reliable tilt corrections for the measured characteristic remanent magnetization (ChRM) direction (e.g. Enkin *et al.* 2006). Conversely, the proponents of translation distances of ≤1000 km utilize palaeomagnetic data from a score of palaeomagnetic studies, mostly but not solely from plutons. They assert that: (1) reasonably accurate tilt corrections can often be determined for plutons from methods such as geobarometry (e.g. McCausland *et al.* 2006), contact metamorphic aureoles (e.g. Irving & Archibald 1990), host rock bedding (e.g. Harris *et al.* 1999b; Symons *et al.* 2004) and other geologic evidence; (2) most unmetamorphosed or gently metamorphosed plutons are not significantly tilted since emplacement but rather underwent simple isostatic uplift; and (3) the average ChRM from multiple collections provides a more accurate translation estimate than the Carmacks volcanics only (e.g. Symons *et al.* 2005; McCausland *et al.* 2006). The consequences of these two different approaches are discussed in this paper. The latest Carmacks' estimate of 1950 ± 600 km for northward translation of the IMB and YTT from ~70 to ~50 Ma conflicts with the geological estimate 415 ± 15 km (Gabrielse *et al.* 2006) and with our mean palaeomagnetic estimate here of 330 ± 400 km from three coeval ~71 Ma plutons. Not all volcanic strata are perfect ChRM recorders. We suggest that the anomalous Carmacks volcanics estimate has been caused by the unfortunate addition of multiple error sources.

Geology

The volcanic strata of the Late Cretaceous Carmacks Group were deposited uncomformably on a diverse assemblage of older metamorphosed Mesozoic, Palaeozoic and Proterozoic rocks of the YTT and Stikine terrane of the IMB in southwestern Yukon and northernmost British Columbia between the Denali and Tintina faults (Fig. 1). The volcanic rocks crop out in numerous isolated large and small areas such that Tempelman-Kluit (1974) interpreted them to be erosional remnants of a sheet-like deposit that covered most of the region. The Carmacks Group is comprised of a lower dominantly andesitic and fragmental succession and an upper dominantly basaltic and massive flow succession. The upper flood basalts have the geochemical signature of a subcontinental lithospheric mantle origin (Johnston *et al.* 1996). By ~1995 the available K-Ar, Rb-Sr and Ar^{40}/Ar^{39} ages appeared to cluster at ~70 ± 3 Ma for the Carmacks volcanics (Hart 1995), implying a brief dramatic regional eruption event. More recently the eruption interval has been shortened to ~70 ± 1 Ma (Johnston 2001; Enkin *et al.* 2006). Also, the thickest accumulations of coarse fragmental rocks are in volcanic complexes that are cored by granitic to syenitic plutons, including the Prospector Mountain stock (Johnston *et al.* 1996).

The Prospector Mountain stock crops out over an area of ~25 km^2 in an irregular E-W trending belt (Fig. 2) in National Topographic System Map Area NTS 115I-5 and area NTS 115J-8 on the flanks of Prospector and Apex Mountains. Payne *et al.* (1987) mapped the geology of the Prospector Mountain sheet (NTS 115I-5) from which the following highly abridged description is mostly taken.

The Prospector Mountain stock is the youngest major rock unit in the map area and intrudes rocks of the YTT (Fig. 2). This terrane includes nearby, from oldest to youngest, the: Proterozoic to Palaeozoic Yukon Metamorphic Complex; Triassic (?) Klotassin hornblende-biotite granodiorite to diorite suite; Jurassic to mid-Cretaceous Big Creek hornblende diorite to biotite granodiorite of the Dawson Range Batholith and quartz monzonite of the Casino Intrusions; Mid Cretaceous Mount Nansen suite comprised of andesite-latite flows with later porphyritic latite-dacite dikes and intrusions; Mid Cretaceous Caribou Creek conglomerate and Colorado Creek breccia; and, the Late Cretaceous Carmacks Group and co-magmatic Prospector Mountain stock. The pre-Cretaceous rock units are metamorphosed whereas the Cretaceous units are unmetamorphosed (Johnston *et al.* 1996).

The Carmacks Group is composed of lower and upper volcanic sections. The lower section has a thin rhyodacitic flow at its base that is overlain by a massive unit of coarse andesitic volcaniclastics, interbedded tuffs, and flow breccias with minor andesite and basalt flows. These units weather rapidly and are found mostly in topographic lows. The upper volcanic section is composed mostly of flat to gently dipping dark green to black basalts and andesites. Some flows are up to 20 m thick, massive and resistant. Geochemically they grade upwards from andesites and basalts into ankaramites. The flows often have a crude subvertical columnar jointing where massive with an uppermost vesicular zone that has irregular fracturing. Sausseritization, bleaching, sericitization, hematization and other alteration from hydrothermal fluids are common throughout the Carmacks volcanics (Wynne *et al.* 1998). Several very minor late mafic-to-intermediate plugs, dikes and sills in the volcanics and underlying host rocks are deemed to be genetically related to extrusion of the Carmacks flows. No estimate is given for the thickness of either the lower or upper section near Prospector Mountain. Smuk *et al.* (1997) have reported Ar^{40}/Ar^{39} alteration ages of 67.8 ± 0.6 Ma for the lower andesite-basalt and 70.9 ± 0.6 Ma for the upper basalt near Apex Mountain at the western end of the Prospector Mountain stock.

The Prospector Mountain pluton is composed of massive unfoliated quartz-bearing monzonite and syenogranite. This medium- to coarse-grained rock intrudes both the lower and upper sections of the Carmacks Group that completely surround the stock (Fig. 2). The intrusive relationship is confirmed by small inliers of the lower volcanics that rest on top of the stock and by a local fine-grained porphyritic contact phase of the pluton. Quartz monzonite from the stock has given a K-Ar whole rock radiometric age of 68.2 ± 1.6 Ma (Tempelman-Kluit 1984). Recently Allan *et al.* (2013) reported an LA-ICP-MS ^{206}U-^{238}Pb zircon age of 68.9 ± 0.3 Ma from syenogranite at the Au-Ag-Cu Bonanza prospect (Fig. 2). Also, they reported two $^{40}Ar/^{39}Ar$ sericite ages on alteration in cross-cutting gold-bearing pyritic veins of 69.2 ± 0.5 Ma and 68.4 ± 0.5 Ma. The four available ages for the Prospector pluton give a mean age of 68.7 ± 0.4 Ma that is coeval with the 69.4 ± 1.6 Ma mean

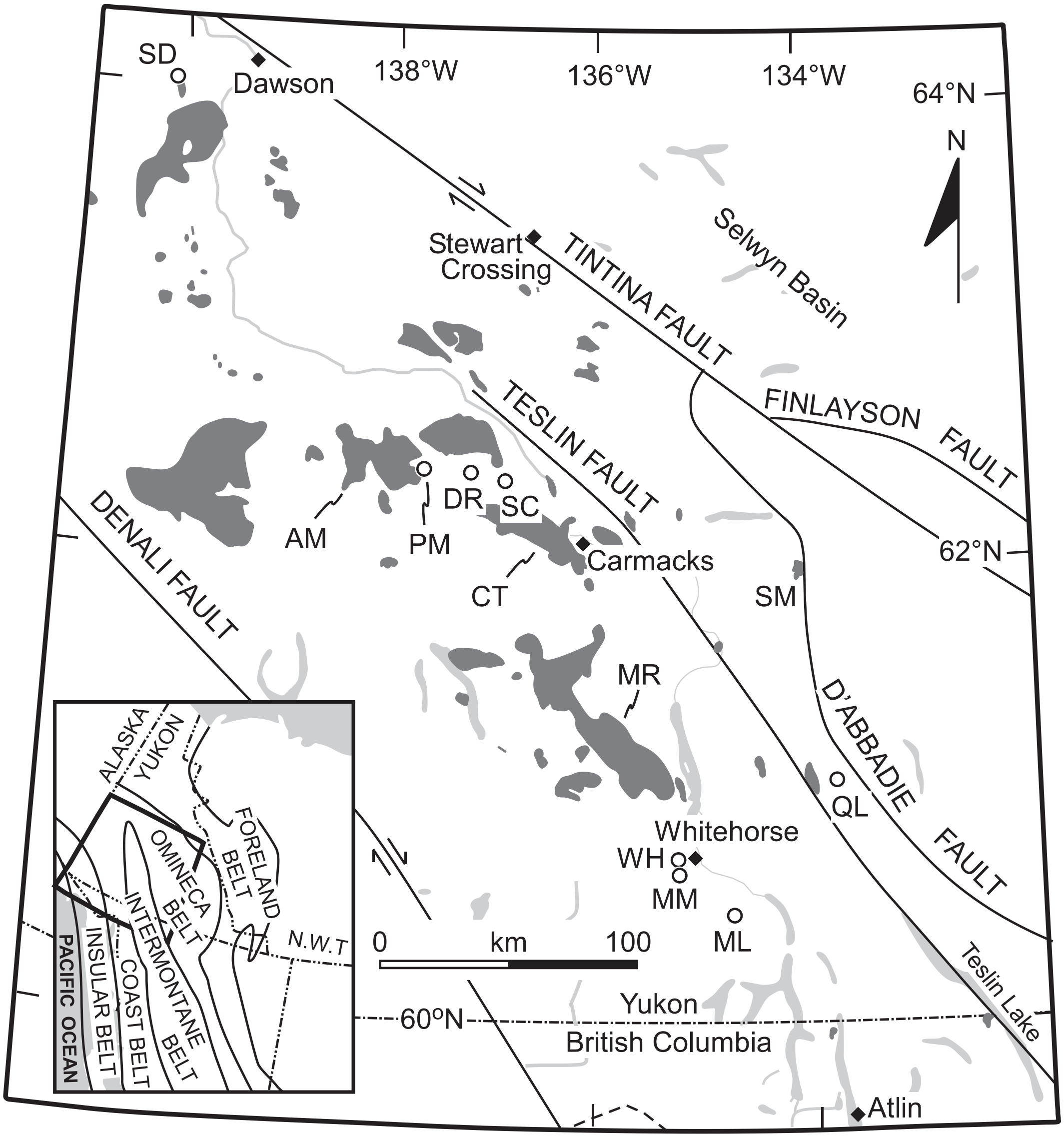

Figure 1. Map showing the distribution of the Carmacks Group volcanics (dark areas) in Yukon and northernmost British Columbia and the locations of published palaeomagnetic studies in the volcanics (AM, Apex Mountain; CT, Carmacks townsite; MR, Miners Range; SM, Solitary Mountain), in coeval volcanic centres (ML, Mount Lorne stock; PM, Prospector Mountain stock; SC, Seymour Creek stock; SD, Swede Dome stock) and in mid-to-early Cretaceous plutons (DR, Dawson Range batholith; MM, Mount McIntyre stock; QL, Quiet Lake batholith; WH, Whitehorse batholith). Inset shows broader physiographic mountain belts and other regions of the Northern Cordillera for context, with the main figure area shown in black outline. N.W.T. is North West Territories. The figure is modified from Wheeler & McFeely (1991) and Enkin *et al*. (2006).

of the two K-Ar ages reported by Smuk *et al*. (1997) for the host Carmacks Group volcanics. Some features suggest that the pluton may be a laccolith rather than a stock (Cook 2012). Fracture zones within the stock are local in extent and display minor normal fault displacements. Small fractures with quartz veins containing minor pyrite and lead-zinc-silver sulphides are found at the stock's contact zone with the adjacent Carmacks volcanics, further indicating that the stock is a high-level volcanic centre that is related to the Group's extrusion.

EXPERIMENTAL METHODS

The study area is located on the sides of Prospector and Apex mountains (Fig. 2). Both peaks are >2000 m high in the isolated and rugged Dawson Range. The sites were accessed by helicopter and, in general, two sites were drilled on each of the few available safe landing locations. All sites were in massive monzonite except for site 18 that was in a narrow skarn zone at the contact between the stock and Carmacks volcanics. Six or seven cores were drilled at each of 19 sites and oriented *in situ* using either a sun compass or magnetic compass with topographic control. From 10 to 15 oriented specimens per site were sliced from the cores, yielding 218 specimens from 112 cores (Table 1). The specimens were stored for about 1 yr in a magnetically shielded room with an ambient magnetic field of ~0.2 per cent of the Earth's field intensity to allow the specimens' unstable viscous remanent magnetization (VRM) components to substantially decay. Then the residual natural remanent magnetization (NRM) of each specimen was measured using an automated vertical-axis 2G Enterprises DC-SQUID magnetometer at the University of Windsor.

Initially, one specimen per site with typical NRM values was subjected to alternating field (AF) demagnetization in 11 steps up

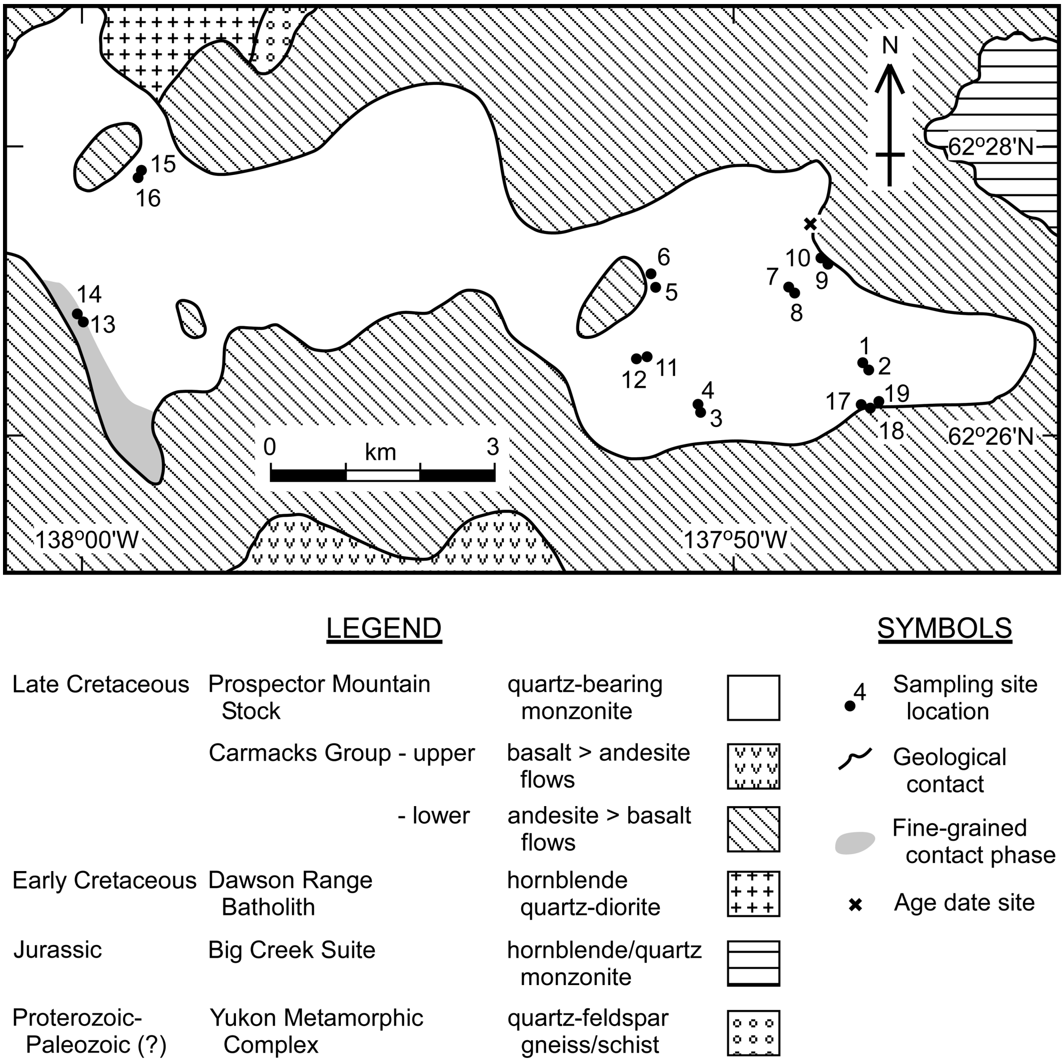

Figure 2. Geology of the Prospector Mountain stock after Payne *et al*. (1987) with palaeomagnetic sampling site locations from this study. The '×' locates the Au–Ag–Cu Bonanza prospect where U–Pb and Ar–Ar age dates are reported (Allan *et al*. 2013).

to 150 mT using a Sapphire Instruments SI-4 demagnetizer. A second typical specimen per site was tested by thermal (TH) demagnetization in 19 steps up to 675 °C using a Magnetic Measurements MMTD-1 demagnetizing oven. After assessing the results from these AF and TH pilot specimens, most of the remaining specimens were first AF demagnetized at steps of 15 and 30 mT and then TH demagnetized at steps of 450, 500, 520, 540, 560 and 580 °C, plus steps of 610, 630 and 650 °C for about half of them. Specimen ChRM directions were identified using vector density contour and component plots (Kamb 1959; Zijderveld 1967), and the directions were calculated using least-squares fitting (Kirschvink 1980) and remagnetization circle methods (Bailey & Halls 1984).

To characterize the magnetic minerals, 11 typical specimens were subjected to saturation isothermal remanent magnetization (SIRM) testing. After initial AF demagnetization at 150 mT, each specimen was magnetized in a direct field in 14 steps up to 900 mT using a Sapphire Instruments SI-6 DC pulse magnetizer, and then it was AF step demagnetized in 11 steps to 150 mT. Also, hysteresis loop measurements were obtained using a Lake Shore Cryotonics PMC Micromag vibrating sample magnetometer (VSM) model 3900–04 on two chip samples from each of sites 5, 8, 18 and 19.

RESULTS

Natural remanent magnetization

The specimens' NRM intensities span a range of about four orders of magnitude (Table 1). Overall, specimens from the 18 felsic intrusive sites yielded a median (M) NRM intensity of $M = 3.83 \times 10^{-1}$ A m^{-1} with quartile values (Q_1, Q_3) of $Q_1 = 1.81 \times 10^{-1}$ A m^{-1} and $Q_3 = 26.7 \times 10^{-1}$ A m^{-1}. The site 18 skarn specimens gave more intense values of $M = 4.71$ A m^{-1}, $Q_1 = 2.12$ A m^{-1} and $Q_3 = 9.65$ A m^{-1}.

Demagnetization

On AF step demagnetization most specimens exhibited a rapid VRM decay, thereby reducing their NRM intensity to <10 per cent by 20–30 mT as their remanence direction followed a great circle to a near-vertical to steeply northward down endpoint direction (Figs 3a and b). Although a few specimens isolated an endpoint ChRM or endpoint direction with little VRM removal (Fig. 3c), most isolated their ChRM direction in applied fields above 40 mT (Fig. 3d). On TH step demagnetization, most specimens showed a progressive

Table 1. Site mean remanence directions for the Prospector Mountain stock.

Site	Median NRM intensity (A m^{-1})	Specimens			Characteristic remanence direction			
		s	*e*	*r*	Decl. (°)	Incl. (°)	*k*	α_{95} (°)
1	0.497	12	12		346.6	80.6	122.6	3.9
2	0.423	12	11		321.4	81.1	139.9	3.9
3	4.490	12	6	4	137.7	84.8	34.8	8.3
4	3.830	10	2	5	341.1	85.9	89.4	6.4
5	0.038	11	10		38.1	63.9	105.7	4.7
6	0.153	11	8	2	44.1	78.2	18.4	11.6
7	7.770	12	7	4	350.5	83.0	24.9	9.3
* 8	18.300	12	12		3.5	22.9	1.9	44.1
* 9	1.280	10	8		158.4	57.1	28.5	10.6
10	0.170	9	8		354.1	84.3	16.1	14.2
11	0.144	14	14		333.5	88.2	43.5	6.1
12	0.195	15	15		77.5	83.4	47.1	5.6
13	0.157	11	11		301.2	81.3	12.9	13.2
14	0.136	11	10	1	37.1	87.2	61.1	5.9
15	1.200	10	3	6	15.5	74.3	64.3	6.5
16	0.340	10	10		35.9	66.5	25.5	9.8
17	9.110	12	5	6	339.9	72.2	15.9	11.8
18	4.710	12	8	4	322.5	82.5	56.3	5.8
19	0.314	12	12		302.6	84.1	210.5	3.0
Σ		(17)			8.3	82.4	71.9	4.2

* Site mean directions omitted for calculation of the collection mean direction (Σ) from 17 sites means. Specimens measured (*s*), and endpoint (*e*) and remagnetization circle (*r*) directions used to calculate the site mean characteristic remanence directions of declination (Decl.), inclination (Incl.) and radius of cone of 95 per cent confidence (α_{95}) in degrees, and the precision parameter (*k*) of Fisher (1953).

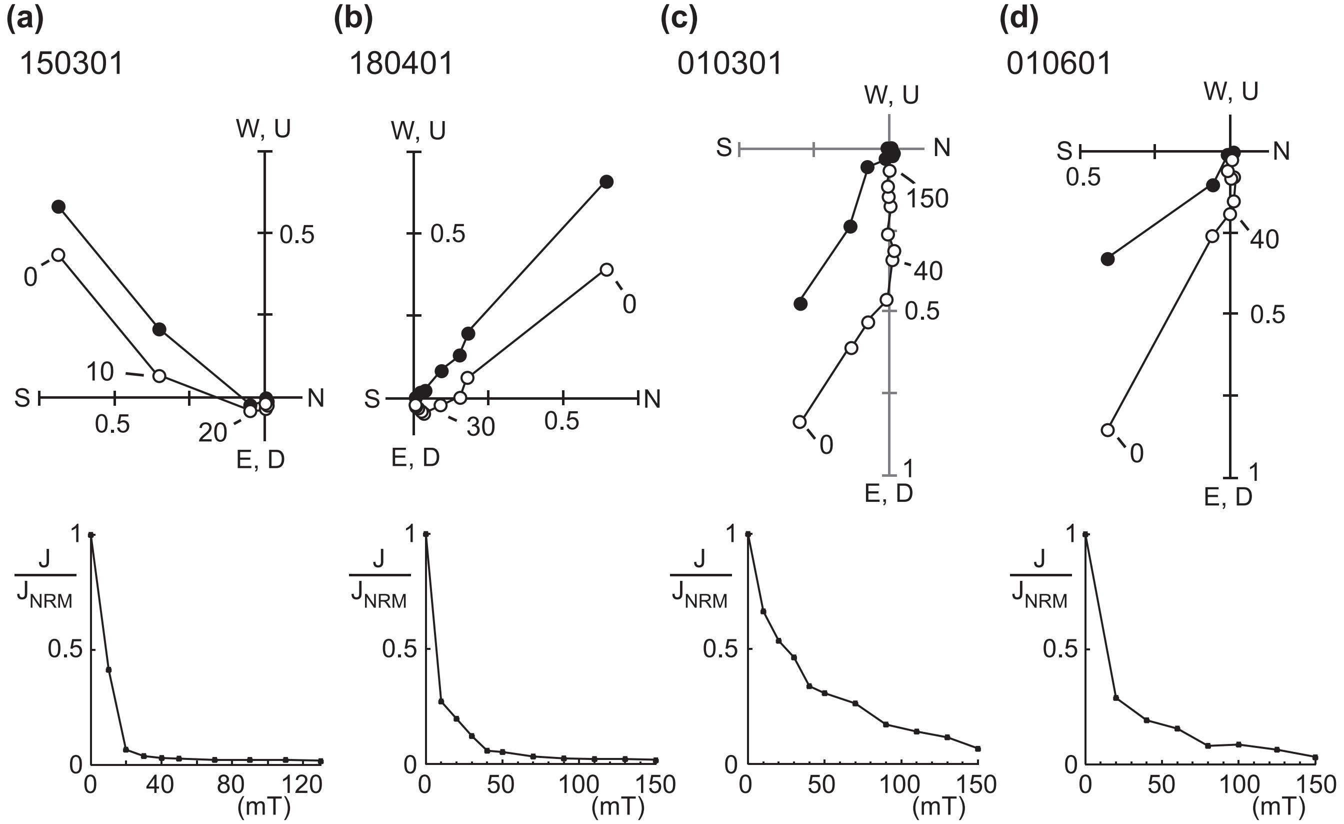

Figure 3. Vector component plots for example specimens showing the isolation of their characteristic remanent magnetization (ChRM) direction on alternating field (AF) step demagnetization. Directions in the horizontal plane (solid circles) lie in the N–E–S–W (north–east–south–west) plane and directions in the vertical plane (open circles) lie in the N–D–S–U (north-down-south-up) plane. Axial intensities are given as a ratio of the natural remanent magnetization (NRM) intensity ($J_0 = 1.0$), which are: (a) 7.75×10^{-1} A m^{-1}; (b) 1.69×10^{0} A m^{-1}; (c) 4.79×10^{-1} A m^{-1}; and (d) 3.29×10^{0} A m^{-1}. The AF intensity (*H*) and some labelled steps are in milliteslas (mT).

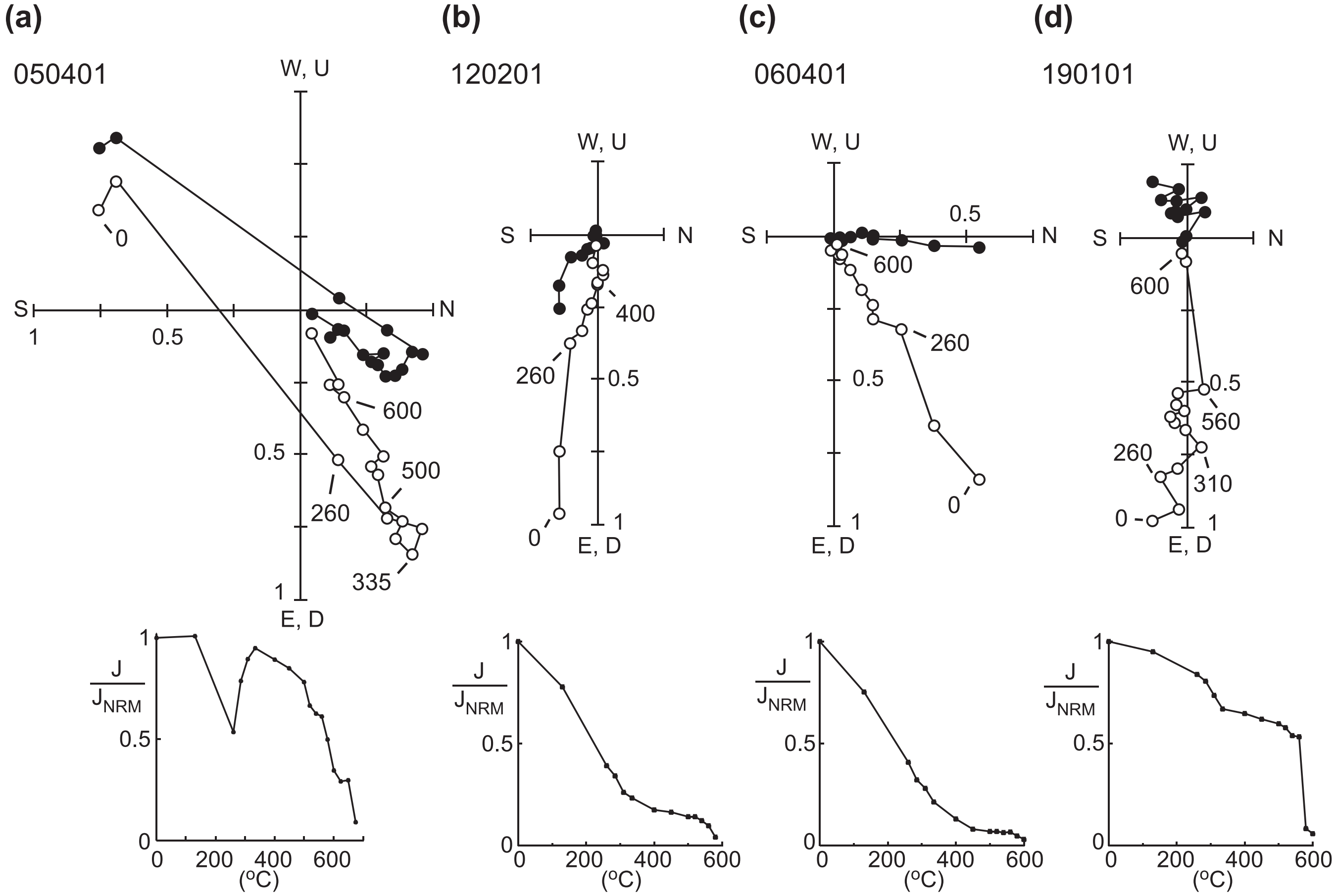

Figure 4. Vector component plots for example specimens showing the isolation of their ChRM direction on thermal (TH) step demagnetization. Plotting conventions as for Fig. 3 except the temperatures are in Celsius degrees (°C). The J_0 values are: (a) 6.55×10^{-2} A m^{-1}; (b) 2.07×10^{-1} A m^{-1}; (c) 2.72×10^{-1} A m^{-1}; and (d) 2.66×10^{-1} A m^{-1}.

loss of remanence intensity up to ~590 °C with increased rates of intensity decay in the 260–335 °C and 520–580 °C ranges that indicate unblocking of a pyrrhotite or titanomagnetite (Figs 4b and d) and magnetite (Figs 4a–d) ChRM, respectively. TH step demagnetization isolated near-vertical to steeply northward and downward ChRM directions also after the removal of VRM (Fig. 4). Given that AF step demagnetization quickly removed the VRM and that TH demagnetization best isolated the ChRM in the 500–580 °C range, AF and then TH step demagnetization was used for most specimens (Fig. 5). For nearly all specimens, the 610–650 °C steps gave very low remanence intensities with erratic remanence directions, indicating that hematite was not a significant carrier of the specimens' ChRM. The 36 specimens that had been glued together were AF demagnetized in 8 steps to 150 mT (Fig. 3d), isolating the ChRM in the 40–80 mT range.

Saturation isothermal remanent magnetization (SIRM)

All 11 test specimens acquired remanence saturation rapidly by 200 mT with a mean value of 125 ± 31 mT that is indicative of magnetite or pyrrhotite, where the remanence saturation intensity (J_{sat}) is defined as 90 per cent of the maximum intensity reached at 900 mT (J_{900}), that is, $J_{\mathrm{sat}} = 0.9\ \mathrm{J}_{900}$. The crossover points of the SIRM acquisition and demagnetization curves (Symons & Cioppa 2000) yield mean intensity values (H) of 23 ± 8 mT and residual percentages of saturation magnetization (J/J_{900}) of 31 ± 3 per cent (Fig. 6), indicate that pseudo-single to single domain magnetite is the dominant remanence carrier in 10 of the 11 specimens. The anomalous site 5 specimen gives values of 63 mT and 28 per cent, respectively, suggesting either pseudo-single domain pyrrhotite or some minor primary or secondary hematite with the magnetite (Fig. 6a).

Hysteresis measurements on six chip samples of monzonite from the Prospector Mountain stock are shown on a Day plot (Day *et al.* 1977; Dunlop 2002a,b). All six monzonite samples plot in, or almost in, the pseudo-single domain field with a curve and ratio values that are typical of magnetite or low Ti titanomagnetite (Fig. 6b). The high coercivity ratio values from skarn site 18 at the stock's contact suggest that sulphides weathered to form goethite (Peters & Dekkers 2003). No values suggest that pyrrhotite is present.

The TH step demagnetization, SIRM and hysteresis loop measurements indicate that single and pseudo-single domain magnetite and/or low Ti titanomagnetite is the major ChRM carrier in the Prospector Mountain stock, and that trace pyrrhotite is only occasionally present except perhaps in skarn samples at the stock's contact.

Characteristic remanent magnetization

Nearly all specimen vector directions are defined by demagnetization steps in either the 500–580 °C (~75 per cent) or 40–80 mT (~25 per cent) range. They were averaged to get the site mean ChRM directions (Fisher 1953; Table 1). Of the 19 site means,

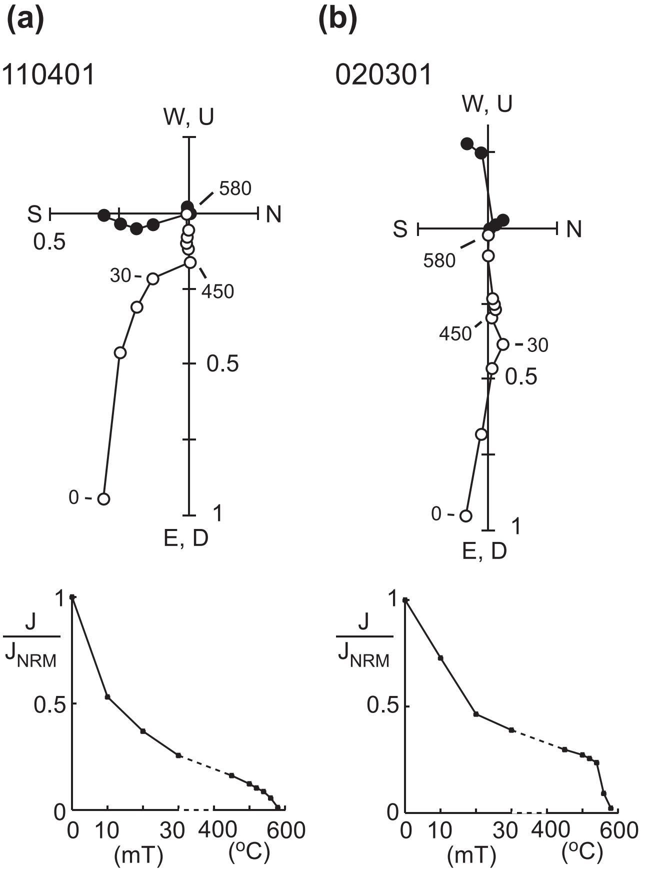

Figure 5. Vector component plots for example specimens showing the isolation of their ChRM direction on AF step demagnetization first to 30 mT and then TH step demagnetization. Plotting conventions as in Fig. 3. The J_0 values are: (a) 1.39 × 10^{-1} A m^{-1} and (b) 4.23 × 10^{-1} A m^{-1}.

17 formed a cluster (Fig. 7) and were averaged to define the unit mean ChRM direction at declination $D = 8.3°$, inclination $I = 82.4°$ (number of sites $N = 17$, precision parameter $k = 71.9$, radius of cone of 95 per cent confidence $\alpha_{95} = 4.2°$) (Fig. 7). Excluded from the unit mean was the site 8 direction because of the high dispersion of its specimen directions and the site 9 direction because it was aberrant relative to the cluster of 17 site mean directions (Table 1). In the absence of any evidence of alteration or deformation, the stock's ChRM is inferred to be a primary thermoremanent magnetization (TRM) that resides in magnetite or low-Ti titanomagnetite. Using a mean location for the 17 Prospector Mountain sites of 62.45°N, 137.86°W (or 222.14°E), the palaeopole given by the site mean ChRM direction is 77.1°N, 231.7°E (radius of cone of 95 per cent confidence, $A_{95} = 8.1°$) (Fig. 8). The Prospector Mountain stock provides a non-significant northwards translation estimate of 70 ± 880 km for the YTT with respect to North America since 69 Ma using the reference Apparent Polar Wander Path (APWP) of Torsvik *et al.* (2012).

DISCUSSION

Prior Carmacks' palaeomagnetic results

Marquis & Globerman (1988) reported palaeomagnetic results from 18 of 27 tested sites in the Carmacks volcanics from locations near Carmacks and Miners Range in Yukon and Atlin in British Columbia (Fig. 1). They calculated from their palaeopole that the volcanics had undergone a northward translation of 1500 ± 950 km and rotation of 10.2° ± 20.7° clockwise (cw) relative to North America. Thus they concluded that the volcanics were carried by the Kula plate from offshore of Washington State to Yukon between ~70 Ma and 59–54 Ma. Shortly thereafter Butler (1990) noted that Marquis & Globerman (1988) had used an older 100 ± 20 Ma reference palaeopole for North America and that simple averaging of the site mean ChRM directions might underestimate the error because adjacent flood basalt flows with colinear ChRM directions might be recording the same eruption event. Butler (1990) recalculated Marquis & Globerman's (1988) data based on cooling units and obtained a barely significant northward transport estimate of 1200 ± 1150 km that better fit the geological estimates. Replying, Marquis *et al.* (1990) defended their statistical methods but concluded that more research was needed. Both Marquis &

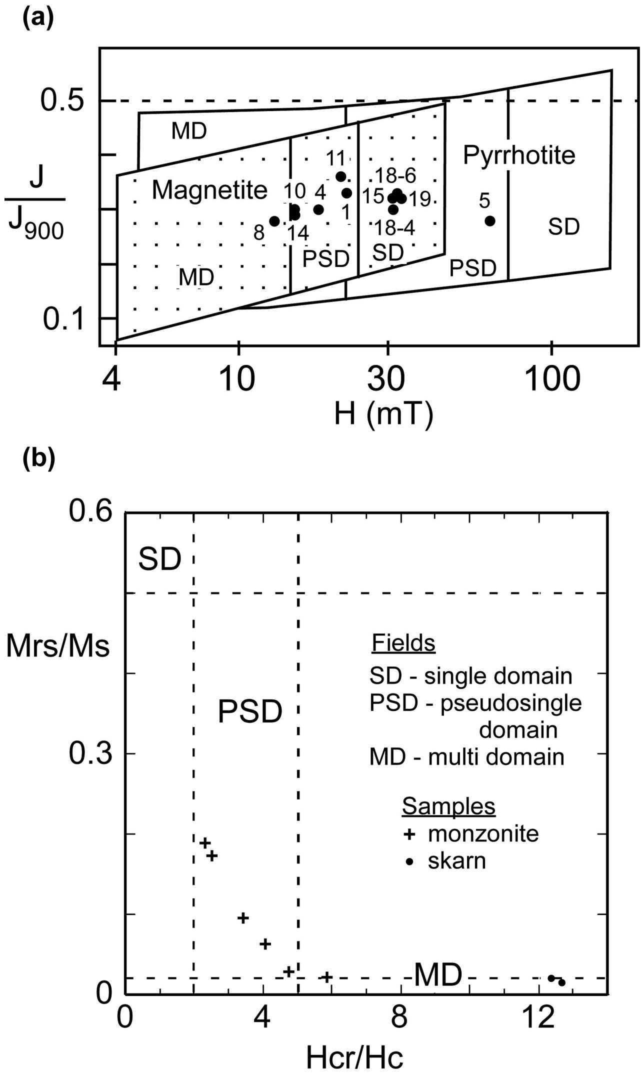

Figure 6. (a) Plot of the cross-over points for the SIRM acquisition and demagnetization curves for 11 representative specimens. J/J_{900} is remanence intensity as a ratio to the SIRM intensity acquired at 900 mT. H is the applied magnetic field intensity. SD, PSD and MD denote the expected response fields for single, pseudo-single and multidomain magnetite, respectively. The anomalous point from site 5 lies in the field for single domain pyrrhotite. The points in the SD magnetite field are from perimeter phase sites 15 and 19 and skarn site 18. (b) Day plot for selected samples from sites 5, 8, 18 and 19. +: monogranite and •: skarn.

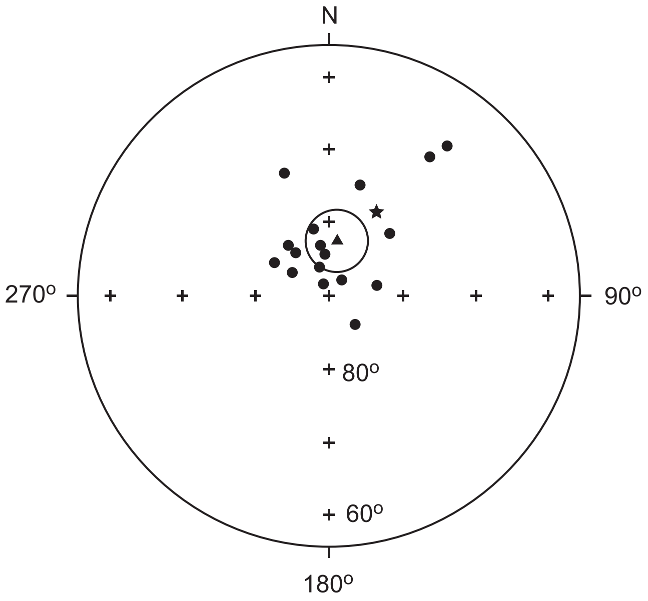

Figure 7. Mean ChRM directions for the 17 accepted sites (●) listed in Table 1. Note that the directions are plotted on the central portion of an equal-area stereograph for inclinations in the 45°–90° range. The overall mean direction (▲) is surrounded by its cone of 95 per cent confidence. The star is the present Earth's magnetic field direction.

Globerman's (1988) and Butler's (1990) estimates proved moot when Mihalynuk *et al.* (1992) determined a radiometric age of 81.3 ± 0.3 Ma for the five Table Mountain sites near Atlin to show that they were not part of the ~70 Ma Carmacks Group.

Subsequently, Johnston *et al.* (1996) reported a mean ChRM direction calculated from 13 new Carmacks Group sites near the town of Carmacks and the 13 valid sites of Marquis & Globerman (1988), which gave a northward transport distance of 1900 ± 700 km relative to North America. Noting the similar ankaramitic geochemistry, Johnston *et al.* (1996) suggested further that the Carmacks volcanics were part of a displaced terrane that originated above the projected Yellowstone hotspot volcanic trend and when it was ~1000 km offshore of Oregon in the Pacific. The palaeomagnetic data used by Johnston *et al.* (1996) came from 10 sites at Apex Mountain near sites 13–16 of this study, and from 3 sites near the town of Carmacks (Wynne *et al.* 1998; Fig. 1). Wynne *et al.* (1998) reaffirmed the 1900 ± 700 km northward estimate for Baja B.C., which Johnston (2001) used as his sole YTT data point in proposing his SAYBIA (Siberia-Alaska-Yukon-British Columbia) ribbon-continent tectonic model for the northern Cordillera. Prior and later palaeomagnetic results from the 75 Ma Mt. Lorne, 68.5 ± 0.2 Ma Seymour Creek and 69.8 ± 1.3 Ma Swede Dome stocks in the YTT and IMB (Fig. 1) gave much lower translation estimates of 1170 ± 390 km northward, 265 ± 830 km southward and 360 ± 575 km northward, respectively (Harris *et al.* 1999a; McCausland *et al.* 2001, 2005). Most recently, Enkin *et al.* (2006) accepted ChRM directions from 15 of 21 palaeomagnetic sites in the Carmacks Group from Solitary Mountain (Fig. 1). When combined with the 26 accepted site mean ChRM directions from

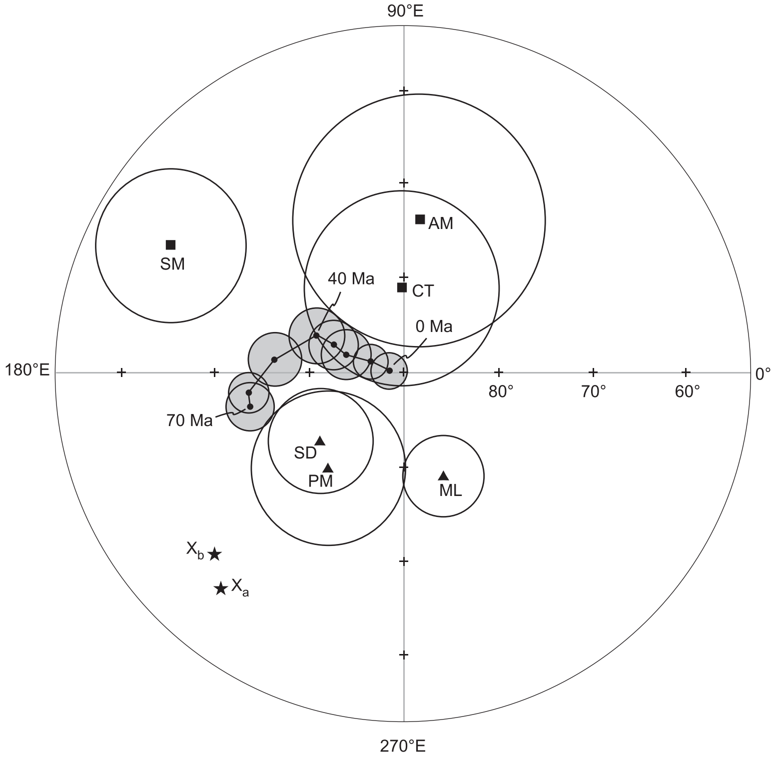

Figure 8. North polar plot for latitudes of >55°N showing the locations of the palaeopoles for the: (■) Carmacks Group volcanic sections from AM, Apex Mountain; CT, Carmacks Townsite; and SM, Solitary Mountain; and (▲) coeval volcanic centre stocks from: ML, Mount Lorne; PM, Prospector Mountain; and SD, Swede Dome, with their surrounding cones of 95 per cent confidence ($A_{95}{}^\circ$) (Table 2) after tectonic correction for 415 km of dextral translation on the Tintina fault zone. Also shown are the mean locations (stars) for the palaeomagnetic collections in the Yukon before (X_b) and after (X_a) tectonic correction (Table 2), and the reference Apparent Polar Wander Path (APWP) for North America (●) in 10 Myr increments from 70 Ma to present with their A_{95} cones from Torsvik *et al.* (2012).

Table 2. Summary of palaeomagnetic data from the Carmacks Group volcanics and coeval stocks.

Entry	Collection	Average age in Ma (Determinations)	Number of sites	Polarity, normal/ reversed	Mean site location		Mean ChRM direction				Palaeopole				References
					°N	°E	Decl. (°)	Incl. (°)	*k*	α_{95} (°)	°N	°E	*k*	A_{95} (°)	
Carmacks volcanics															
1	Apex Mountain	69.2 (2)	10	5/5	62.4	222.0	343.5	66.6	31.5	8.7	73.9	84.1		13.1	a
2	Solitary Mountain	70.6 (2)	15	0/15	62.0	225.8	302.9	72.5	66.5	4.7	62.0	151.4		7.9	b
3	Carmacks Townsite	70.2 (4)	11	0/11	62.2	223.6	354.5	68.0	46.3	6.8	78.5	60.8		10.5	ac
4	Miners Range	70.8 (2)	5	2/3	61.0	224.5	327.4	76.2	30.9	14.0	74.8	159.4		24.9	c
5	Entries 3 + 4	70.6 (6)	16	2/14	61.8	223.9	348.5	70.9	36.3	6.2	81.2	91.6		10.1	
6	Entries 1 + 2 + 5	70.3 (10)	3*	7/34	62.1	223.9					75.0	120.7	29.5	23.1	
7	Entries 1 + 2 + 5		3^{+}	7/34	59.9	229.8					75.3	134.4		21.6	
Coeval stocks															
8	Prospector Mountain	68.7 (1)	17	17/0	62.5	222.1	8.3	82.4	71.9	4.2	77.1	231.7		8.1	d
9	Seymour Creek	68.5 (1)	16	2/14	62.3	222.8	245.0	83.6	73.8	4.3	55.2	202.5		8.4	e
10	Swede Dome	69.8 (1)	17	0/17	64.2	219.6	359.9	82.7	162.8	2.8	78.6	219.5		5.5	f
11	Mount Lorne	75.3 (1)	18	6/12	60.5	225.3	24.2	75.9	201.0	2.4	78.3	290.9		4.3	g
12	Entries 8 + 9 + 10 + 11	70.4 (4)	4*	25/43	62.4	222.5					74.7	223.5	28.5	17.6	
13	Entries 8 + 10 + 11	71.1 (3)	3*	23/29	62.4	222.3					79.6	246.0	117.4	11.4	
14	Entries 8 + 10 + 11		3^{+}	23/29	60.2	228.5					77.4	249.0		12.7	

Abbreviations as in Table 1. Reversed polarity directions/converted to antipodal normal directions to compute the mean directions. References: a, Wynne *et al.* 1998; b, Enkin *et al.* 2006; c, Marquis & Globerman 1988; d, this paper; e, McCausland *et al.* 2001; f, McCausland *et al.* 2005; and g, Harris *et al.* (1999a). Number of collection mean ChRM directions averaged before (*) and after ($^{+}$) tectonic correction for 415 km of post-Cretaceous dextral displacement on the Tintina fault zone.

Marquis & Globerman (1988) and Wynne *et al.* (1998), Enkin *et al.* (2006) estimated that the Carmacks volcanics had been translated 1950 ± 600 km northward relative to North America. Further, they hypothesized that the Seymour Creek and Swede Dome stocks have ChRM directions that were similarly steepened by unrecognized tilting on uplift, thereby giving anomalously low estimates for northward transport.

The Carmacks data

Palaeomagnetic data from three studies have been used to postulate a current northward translation of 1950 ± 600 km for Carmacks Group and Baja BC (Marquis & Globerman 1988; Wynne *et al.* 1995; Wynne *et al.* 1998; Enkin *et al.* 2006). Conversely, palaeomagnetic data from four 70 ± 5 Ma plutons, including two that are comagmatic volcanic centres of the Carmacks Group, give significantly (2σ) lower northward translation distances (Harris *et al.* 1999a; McCausland *et al.* 2001, 2005; this study; Table 2).

Palaeomagnetic data from 41 sites in the Carmacks Group volcanics come from the Apex Mountain, Solitary Mountain, Carmacks townsite and Miners Range areas (Fig. 1; Table 2, entries 1–4). The Miners Range area, however, has only five sites that yield an aberrant ChRM mean direction and very poor clustering statistics, and so these sites have been included with the Carmacks townsite sites (Table 2, entry 5). The site mean ChRM directions for the three collections were converted to palaeopoles that give a mean palaeopole at 75.0°N, 120.7°E ($k = 29.5$; $A_{95} = 23.1°$) before correction for a post-extrusion dextral translation of 415 km on the Tintina fault zone and at 75.3°N, 134.4°E ($A_{95} = 21.6°$) after correction (Table 2, entries 5–7). Similarly, palaeomagnetic data are available from 78 sites in four felsic plutons that are either comagmatic or coeval with the Carmacks Group lavas, that is, the Prospector Mountain, Seymour Creek, Swede Dome and Mount Lorne stocks (Fig. 1; Table 2, entries 8–11). However, the Seymour Creek stock gives a ChRM direction that is aberrant relative to the other three stocks. This stock is adjacent to, and cut by the regional Big Creek fault that was active after the stock's emplacement. Also this stock does not intrude Carmacks Group flows whereas the other three stocks intrude, or are proximal to, such flows. Thus we agree with Enkin *et al.* (2006) that the Seymour Creek stock was likely tilted by faulting during uplift. We note in particular that Seymour Creek's ChRM declination is southwesterly whereas it is northerly for the other three stocks. Further, excluding the Seymour Creek pluton's mean ChRM direction from the overall plutonic mean direction results in a statistically significant (2σ) increase in the precision parameter (k of Fisher 1953) from 28.5 to 117.4 (Table 2, entries 12 and 13).

Radiometric age dates

There are obvious concerns with the radiometric age dating of the sampled palaeomagnetic sections in the Carmacks lavas. At Apex Mountain the upper ankaramitic basalt has given a significantly older age of 70.9 ± 0.6 Ma than the 67.8 ± 0.6 Ma age of the underlying andesitic basalt's (Smuk *et al.* 1997). The Miners Range palaeomagnetic sites are >10 km away from the nearest geochronological sites that gave significantly different 74.2 ± 2.5 Ma and 69.1 ± 2.6 Ma ages (Grond *et al.* 1984). At Carmacks townsite, the reported radiometric ages of 67.9 ± 2.3, 68.0 ± 2.2, 71.7 ± 1.7 and 73.1 ± 2.5 Ma span ∼5 Myr but none come from the palaeomagnetic site locations (Grond *et al.* 1984; Smuk *et al.* 1997). The details of the 70.42 ± 0.74 Ma and 70.70 ± 0.74 Ma ages cited for the Solitary Mountain volcanics (Enkin *et al.* 2006) have yet to be reported (Enkin, private communication, 2016). The absolute ∼6.4 Ma range of ages from 74.2 to 67.8 Ma alone suggests that the Carmacks Group was not extruded as a 70 ± 1 Ma magmatic event (Johnston 2001; Enkin *et al.* 2006). In their assessment, Allan *et al.* (2013) give a 73 Ma to 65 Ma range of ∼8 Ma for deposition of the Carmacks Group based on whole rock K-Ar ages.

Prior to ∼1995 the Carmacks Group was considered an extensive short-lived (∼70 ± 3 Ma) suite of flood volcanics that likely covered much of southwest-central Yukon (Grond *et al.* 1984; Tempelman-Kluit 1984; Lowey *et al.* 1986; Smuk *et al.* 1997). Upon

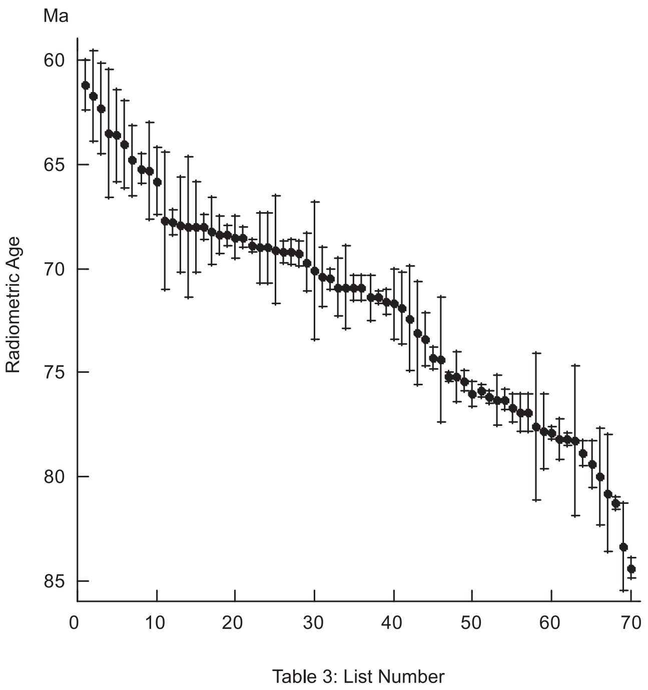

Figure 9. Plot of the radiometric age dates listed in Table 3.

compiling mid-to-Late Cretaceous radiometric age dates for Yukon and northernmost British Columbia, Hart (1995) deemed the Carmacks magmatic episode to span from 84 to 68 Ma. He was prescient in suggesting that the apparent hiatus of volcanism between the 84–78 Ma 'Windy-Table Suite' from south of Whitehorse (Fig. 1) and the 74–68 Ma 'Carmacks Suite' from north of Whitehorse could simply reflect inadequate sampling because later radiometric age determinations subsequently have infilled the hiatus (Fig. 9 and Table 3).

The 85–60 Ma radiometric ages in Fig. 9 and Table 3 come from the compilations of Hart (1995) and Smuk *et al.* (1997) and papers of Bineli Betsi & Lentz (2010), Bineli Betsi *et al.* (2012), Bineli Betsi & Lentz (2013) and Allan *et al.* (2013). The 70 ages date extrusive, intrusive and hydrothermal magmatic activity in an ~8 × 10^5 km^2 area of the YTT and IMB terranes in Yukon and northernmost British Columbia that have been attributed to Carmacks magmatism. A majority of the ages are from the Dawson Range between 62°N and 63°N latitude that hosts many prospective mineral showings and includes the Prospector Mountain area (Fig. 1). Arranged chronologically these ages show the onset of magmatic activity from ~85 to ~80 Ma, fairly constant activity from ~80 to ~65 Ma, and the waning of activity from ~65 to ~60 Ma (Fig. 9; see also Allan *et al.* 2013). Arranged geographically in latitudinal slices, these ages show a relatively even and modest level of magmatic activity throughout the region with a large peak between 62°N and 63°N that is roughly proportional to the increased sampling bias in the Dawson Range area (Fig. 10). Examination of the sampled rock types as a function of age and geography reveals some anomalies (Fig. 9 and Table 3). For example, all massive monzonitic stocks that are now considered comagmatic intrusive centres of the Carmacks volcanics give 70 ± 2 Ma ages and crop out between 62°N and 63°N. Possibly these centres coincide with the peak of Carmacks volcanism only in that latitude range. Possibly, however, some dated felsic stocks that are close to undated potential Carmacks Group lavas have simply not been recognized as volcanic centres such as the 77.5 ± 0.3 Ma Folle Mountain, 77.1 ± 0.7 Ma Wheaton Valley, 75.3 ± 2.8 Ma Mount Lorne and 69.8 ± 1.3 Ma Swede Dome stocks in other parts of Yukon (Morrison *et al.* 1979; Mortensen 1988, 1992; Hart 1995; J.K. Mortensen, private communication, 1999). Also most 80 Ma to 85 Ma age dates that come from south of 62°N in Yukon, perhaps suggesting a northward migration of mid Late Cretaceous-Palaeocene magmatism.

Historically, the 'Carmacks' name has been applied *sensu stricto* to refer to the Carmacks Group specifically and *sensu lato* to refer to mid Late Cretaceous to Palaeocene magmatic and hydrothermal events. The sweep of age dates in Fig. 9 shows that magmatic and hydrothermal activity was fairly constant and widespread throughout the YTT and IMB in Yukon from ~80 Ma to ~65 Ma. Within Yukon, the activity is both episodic and regional as Allan *et al.* (2013) have shown for the area between about 62°N and 64°30′N. The important take away for this study is that local post-70 Ma hydrothermal alteration of the Carmacks Group volcanics is a real possibility. Two other observations are merited. It is misleading to portray the Carmacks Group as a short-lived widespread intense magmatic event at 70 ± 1 Ma as described in some palaeomagnetic literature (Johnston 2001; Enkin *et al.* 2006). Also, the effects of mid Late Cretaceous to Palaeocene magmatic and hydrothermal events should not be automatically labelled as 'Carmacks' in origin.

Geologic constraints on tectonism

The survey of age dates above may not be complete but it does provide sufficient data to support some generalizations. First, the YTT and Stikine terranes of southwestern Yukon underwent fairly continuous but locally episodic intrusive and extrusive magmatic activity from ~85 to ~60 Ma that reflects variable tectonic stress. This time interval follows emplacement of large mid-Cretaceous granitic plutons inboard of the Tintina fault such as the Tungsten (~98–94 Ma), Mayo (~96–93 Ma) and Tombstone (~92–90 Ma) suites (Hart *et al.* 2004) and extrusive rocks such as the South Fork volcanics (98–96 Ma; Gordey & Makepeace 2000). The interval corresponds to emplacement of the large orogen-parallel Late Cretaceous-Palaeocene felsic plutons of the Coast Plutonic Complex just outboard and inboard of the Coast Shear Zone such as the Ecstall (~90–70 Ma) and Quotoon (~73–57 Ma) suites, respectively (Butler *et al.* 2001, 2006; Brownlee & Renne 2010). This implies that the ~85–60 Ma interval corresponds to the migration of active magmatism from inboard to outboard of the YTT and IMB terranes with scattered sporadic plutonism, volcanism and hydrothermal alteration within these terranes that peaked at ~72 ± 5 Ma as shown by the flattened linear slope from ~77 Ma to ~67 Ma in Fig. 9.

Second, at about 79 Ma the Kula plate broke from the Farallon plate and began colliding obliquely with North America (Seton *et al.* 2012). The terranes outboard of the Coast Shear Zone began moving northward rapidly, whereas the inboard terranes of southwestern Yukon were subjected to dextral transpression with much slower northward motions as North America moved westward (Engebretson *et al.* 1985; Kelley 1993; Gabrielse *et al.* 2006). From the offsets of rock units and structures, Gabrielse *et al.* (2006) concluded that the southwest side of the Tintina fault zone in Yukon underwent 415 ± 15 km of dextral offset relative to North America during the Palaeocene to mid-Eocene. They showed that this correction aligns all Upper Cretaceous and most Lower Cretaceous geological features across the Tintina fault, and also that a correction of 490 km aligns the remaining Lower Cretaceous offsets. The mean ages for the Carmacks volcanics and

Table 3. Radiometric ages for the 60–85 Ma interval in southwestern Yukon.

This list	Source list[a]	Rock type[b]	Method[c]		Age Ma	This list	Source list[a]	Rock type[b]	Method[c]		Age (Ma)
1	A1	Ia	wr	K/Ar	61.2 ± 1.2	36	B5	Vm	sc	Ar/Ar	70.9 ± 0.6
2	A2	If	fs	K/Ar	61.7 ± 2.2	37	B1	Vm	sc	Ar/Ar	71.4 ± 1.1
3	A3	If	zr	U/Pb	62.3 ± 2.2	38	D11	Ia	zr	U/Pb	71 ± 0.3
4	A4	Vm	bi	K/Ar	63.5 ± 3.1	39	D10	Ii	zr	U/Pb	72 ± 0.6
5	A5	If	wr	K/Ar	63.6 ± 2.2	40	B7	Ic	bi	K/Ar	71.7 ± 1.7
6	A6	Vi	wr	K/Ar	64.0 ± 2.1	41	C3	If	zr	U-Th/He	71.9 ± 1.7
7	A7	Ii	wr	K/Ar	64.8 ± 1.7	42	A20	Vi	wr	K/Ar	72.4 ± 2.5
8	A8	Ii	wr	K/Ar	65.2 ± 0.7	43	A21	Vm	wr	K/Ar	73.1 ± 2.5
9	A9	Vi	wr	K/Ar	65.3 ± 2.3	44	A22	Vm	wr	K/Ar	73.4 ± 1.3
10	B10	Im	bi	K/Ar	65.8 ± 1.6	45	D9	Vf	zr	U/Pb	74 ± 0.5
11	A10	If	hb	K/Ar	67.7 ± 3.3	46	A23	If	hb	K/Ar	74.4 ± 3.0
12	B4	Vm	sr	Ar/Ar	67.8 ± 0.6	47	C4	If	zr	U/Pb	75.2 ± 0.2
13	A11	Vi	wr	K/Ar	67.9 ± 2.3	48	D6	Is	mo	Re/Os	75 ± 1.2
14	B8	Vm	bi	K/Ar	68.0 ± 3.4	49	D5	If	zr	U/Pb	75 ± 0.5
15	A12	Vm	bi	K/Ar	68.0 ± 2.2	50	D7	If	zr	U/Pb	76.0 ± 0.6
16	D15	Ia	zr	U/pb	68.0 ± 0.6	51	C5	Is	mo	Re/Os	75.9 ± 0.3
17	B11	Ic	wr	K/Ar	68.2 ± 1.6	52	C6	Is	mo	Re/Os	76.2 ± 0.3
18	C1	If	zr	U/Pb	68.4 ± 0.9	53	B18	Im	sc	Ar/Ar	76.3 ± 1.2
19	D18	Ii	sc	Ar/Ar	68.4 ± 0.5	54	C7	Ia	wr	K/Ar	76.3 ± 0.5
20	B6	Vm	sc	Ar/Ar	68.5 ± 1.0	55	D8	Ia	sc	Ar/Ar	77 ± 0.7
21	D14	Vf	zr	U/Pb	68.5 ± 0.5	56	C8	Ii	zr	U/Pb	76.9 ± 0.9
22	D16	If	zr	U/Pb	68.9 ± 0.3	57	C8	Ii	zr	U/Pb	76.9 ± 0.9
23	A13	Ii	wr	K/Ar	69.0 ± 1.7	58	C9	Ii	bi	K/Ar	77.6 ± 3.5
24	A14	Ia	wr	K/Ar	69.0 ± 1.7	59	C10	If	zr	U-Th/He	77.8 ± 1.8
25	A15	Vi	fs	K/Ar	69.1 ± 2.6	60	C11	Is	mo	Re/Os	77.9 ± 0.3
26	D17	Ia	sc	Ar/Ar	69.2 ± 0.5	61	C12	If	zr	U-Th/He	78.2 ± 1.0
27	D13	If	zr	U/Pb	69.2 ± 0.6	62	C13	Is	mo	Re/Os	78.2 ± 0.3
28	D12	If	zr	U/Pb	69.3 ± 0.6	63	A25	Vi	fs	K/Ar	78.3 ± 3.6
29	A16	Ia	wr	K/Ar	69.7 ± 1.4	64	C14	Ii	bi	K/Ar	78.9 ± 0.6
30	A17	If	fs	K/Ar	70.1 ± 3.3	65	A27	Im	wr	K/Ar	79.4 ± 1.1
31	C2	If	zr	U-Th/He	70.4 ± 1.4	66	A28	Vf	wr	K/Ar	80.0 ± 2.3
32	A18	Ic	bi	K/Ar	70.5 ± 0.5	67	A29	Vi	wr	K/Ar	80.8 ± 2.8
33	B3	Vm	sc	Ar/Ar	70.9 ± 1.4	68	A30	Vp	zr	U/Pb	81.3 ± 0.3
34	B2	Vm	sc	Ar/Ar	70.9 ± 2.0	69	A32	Vf	wr	K/Ar	83.4 ± 2.1
35	A19	Ic	wr	K/Ar	70.9 ± 0.6	70	A33	Vf	zr	U/Pb	84.4 ± 0.5

[a] Source list: Reference source—A, Hart (1995); B, Smuk *et al*. (1997); C, Bineli Betsi & Lentz (2010, 2013); Bineli Betsi *et al*. (2012); D, Allan *et al*. (2013).

[b] Rock Type: I, intrusive; V, volcanic extrusive; a, altered; c, volcanic centre stock; f, felsic; i, intermediate; m, mafic; p, pegmatite; s, sulphide.

[c] Method: Mineral—bi, biotite; fs, feldspar; hb, hornblende; sc, sericite; mo, molybdenite; wr, whole rock; zr, zircon; System: Ar/Ar, argon/argon; K/Ar, potassium/argon; Re/Os, rhenium/osmium; U/Pb, uranium/lead; U-Th/He, uranium-thorium/helium.

coeval stocks of 70.3 and 71.3 Ma, respectively (Table 2), predate the Cretaceous–Palaeocene boundary at 65.5 Ma by only ∼5 Ma (Gradstein *et al*. 2004). Dextral transpression tectonism between the Tintina and Denali faults may have caused additional northward displacement on lesser faults such as the Big Salmon, d'Abaddie, Tummel, Teslin, Big Creek and Tally Ho dextral transcurrent faults that roughly parallel the Tintina and Denali faults and dissect the YTT and IMB terranes in Yukon (Colpron *et al*. 2007). For example, Gladwin & Johnston (2006) have shown that the 108 Ma Glenlyon pluton's contact aureole record a dextral displacement of ≤10 km on the Tummel fault. Displacements on these faults were mainly mid to Late Cretaceous in age and imply an additional ∼300 km of northward motion at most between the Tintina and Denali (Coast) fault zones. Only a few tens of kilometres of this displacement, however, could have affected the ∼71 Ma Carmacks Group rocks studied palaeomagnetically in the available ∼5 Myr prior to Palaeocene (Gabrielse *et al*. 2006; Colpron *et al*. 2007). Thus, the geologic evidence predicts ∼500 ± 50 km of northward displacement for Carmacks palaeopoles and host rocks.

The Yellowstone-in-Yukon model

A provocative suggestion of Johnston *et al*. (1996) and Wynne *et al*. (1998) was that the Carmacks Group was extruded as the YTT-IMB terranes crossed over the Yellowstone hotspot (mantle plume) when offshore of Oregon. The model was based on the Yellowstone and Carmacks lavas having similar ankaramitic compositions, their calculated Carmacks palaeolatitude fitting the plate tectonic model for the northeastern Pacific Ocean of Engebretson *et al*. (1985) and Kelley (1993), and the assumption that hotspot locations were fixed in the Earth's mantle. However Tarduno (2007) has shown that hotspots move with mantle flow and are not fixed relative to plate motions, thereby destroying the theoretical underpinning of the Yellowstone-in-Yukon model. Further, if the Carmacks volcanics were extruded when the Yellowstone hotspot was overridden, then a path of progressively older flows should be present in Yukon like the westward track from Yellowstone. Also, mildly to highly potassium-enriched mafic lavas of the alkali series like shoshonites and ankaramites are commonly associated with suprasubduction zone volcanics in continental fore and back arcs, such as the Cascade Range of the USA and British Columbia (Gill *et al*.

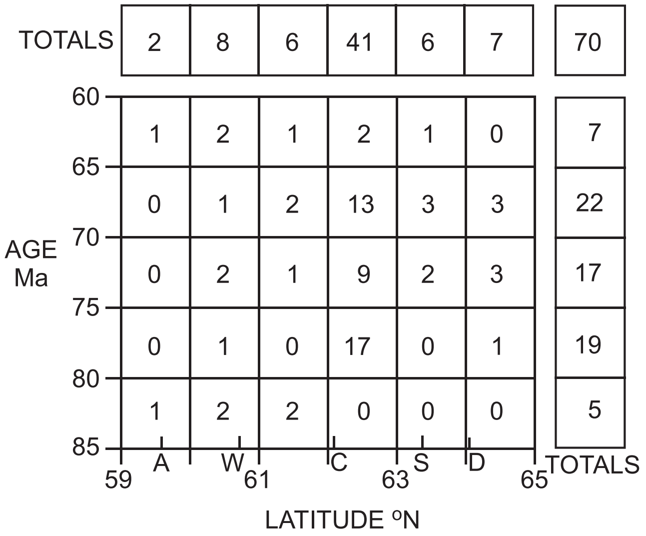

Figure 10. Geographic distribution of 85–60 Ma radiometric age dates for rocks in the Yukon-Tanana and Intermontane Belt terranes between the Tintina and Denali fault zones in Yukon and northernmost British Columbia. A, W, C, S and D indicate the latitudes of Atlin, Whitehorse, Carmacks, Stewart Crossing and Dawson City, respectively. Data are from Hart (1995), Smuk *et al.* (1997), Bineli Betsi & Lentz (2010, 2013), Bineli Betsi *et al.* (2012), and Allan *et al.* (2013).

2004). This tectonic environment agrees with the scenario described above for southwestern Yukon at ~70 Ma and has remained true through to the Neogene. Southwards from Atlin, B.C. (Fig. 1) for ~400 km are several large volcanic complexes like the Carmacks Group that rest on rocks of the YTT and Stikine terranes inboard of the Coast Plutonic Complex. They include the Pliocene-to-present Level Mountain and Mount Edziza complexes that cover ~1800 km^2 and ~400 km^2, respectively, that are peralkaline and related to local rifting (Souther & Symons 1974; Hamilton & Evans 1983). In summary, the Yellowstone-in-Yukon model for Carmacks suite volcanism lacks geologic credibility.

Tectonic transport and rotation

The ChRM directions for the Carmacks volcanics and coeval volcanic centre stocks form significantly different populations at 95 per cent confidence (Table 2, entries 6 and 12; Fig. 8) and give incompatible estimates for the tectonic transport and rotation of the YTT and Stikine terranes in Yukon. From 32 palaeopoles worldwide that were rotated into North American co-ordinates if necessary, Torsvik *et al.* (2012, their table 11) located the 70 Ma reference palaeopole for North America at 73.6°N, 192.4°E ($A_{95} = 2.5°$). Following Demarest (1983), the mean palaeopoles for the Carmacks volcanics and volcanic centre stocks (Table 2, entries 6 and 12) provide northward (poleward) translation estimates of 18.1° ± 18.6° and 3.0° ± 9.3°, respectively, before correction for 415 km of dextral motion on the Tintina fault, and of 14.9° ± 17.4° and −0.5° ± 10.4° after correction. Since only three collection means are being averaged, the ± errors are unreasonably high. When the 41 volcanic flow and 52 stock site mean ChRM directions are averaged, they give palaeopoles A_{95} values 6.8° and 3.8° and northward translation estimates of 18.1° ± 5.8° and 3.0° ± 3.6°, respectively. After correction for 415 km of dextral offset on the Tintina fault, the volcanics provide a significant northward translation estimate of 1660 ± 645 km and the stocks a non-significant southward translation of 60 ± 400 km. Clearly the Carmacks intrusive volcanic centres provide an excellent fit to the geological estimate whereas the volcanics themselves provide a significantly different estimate at ≫95 per cent confidence. Following is a discussion of several aspects of this substantial palaeomagnetic and geologic dilemma for southwestern Yukon and for the Baja BC hypothesis inboard of the Denali Fault - Coast Shear Zone.

Secular variation and cooling units

Secular variation in the Earth's magnetic field is a major problem for palaeomagnetic studies of lava sequences. Secular variation refers to the angular dispersion of the geomagnetic field or short term random meandering of the north magnetic pole about the Earth's north geographic pole or spin axis by up to ~15° of arc in any direction over a period of ~2000 yr (Merrill & McElhinny 1983). The problem arises because shield volcanoes erupt spasmodically, issuing numerous flows over short time intervals and then becoming quiescent for long time stretches. For example, on 1943 February 20th, a fissure opened in a cornfield in the Trans-Mexican Volcanic Belt of southwestern Mexico. In 1 yr, the Paricutin volcano grew explosively to a height of 336 m, composed mostly of pyroclastic rocks. Over the next 7 yr it erupted in a series of relatively quiet lava flows over an area of ~25 km^2 and reached a height of 424 m (Luhr 1993). Paricutin's height, aspect and lithology are broadly similar to Solitary Mountain where Enkin *et al.* (2006) sampled.

When discussing the ChRM of a volcanic sequence that tracks secular variation versus the ChRM of a pluton, the concept of 'cooling units' is important (Butler 1990). The primary remanence in igneous rocks is normally carried by magnetite or titanomagnetite with the ChRM being acquired on cooling through the 585–475°C range. For fast-cooling lava flows, depending on thickness, the ChRM is 'locked in' within a few hours or days after extrusion. Thus a thick sequence of flows that accumulates within a few years will not provide a series of independent readings of the palaeofield direction, but will instead give only one point on the field's meandering secular variation path. To obtain a reliable palaeopole that averages out the short-term effects of secular variation, a reasonably random sampling of a time period of ≥2000 yr in necessary (Merrill & McElhinny 1983). At Solitary Mountain, as but one possible example, Carmacks flows at adjacent sites 30–32 give very similar ChRM directions (Enkin *et al.* 2006) and may well be only one 'cooling unit' that gives just one estimate of the secular variation path. The discussion and reply of Marquis & Globerman's (1988) original Carmacks volcanics' results highlighted this problem (Butler 1990; Marquis *et al.* 1990). In contrast, a stock like Prospector Mountain that outcrops over an area of ~25 km^2, even if emplaced at depths of only a few kilometres, will take centuries to millennia to cool. Thus the specimens from each site lock in their ChRM over both a long time and a large temperature range that substantially averages out secular variation to provide a better estimate the Earth's geomagnetic palaeopole. The estimation error in a palaeopole's location is proportional to the area of its cone of 95 per cent confidence. The much larger cones for the three Carmacks volcanic collections relative to those for the three stock collections illustrates this very important difference between the ability of volcanic flows and intrusive volcanic centres to successfully average secular variation (Fig. 8). Unlike suites of volcanic flows, intrusions typically give a tight 95 per cent confidence cone on a mean direction exactly because they cool slowly through magnetization blocking temperatures on the timescale of secular variation and so do a good job of averaging it. Simply put, it is necessary to measure many more flow sites in a volcanic sequence than plutonic sites in a stock to average out the directional bias caused by secular variation. For example, it took the palaeomagnetic analysis of specimens from 84 and 50 flow sites, respectively, from the nearby Mount Edziza and Level Mountain volcanic complexes to decrease the radii of their cones of 95 per cent confidence about their mean ChRM directions to 4.5° and 4.0° (Souther & Symons 1974; Hamilton & Evans 1983), respectively. These are about the same A_{95} values as given by the least well-clustered of the Carmacks volcanic centre stocks using only ∼17 sites (Table 2).

Dipole offset error

Palaeomagnetists have long known that unit mean ChRM directions give palaeopoles that are offset from the Earth's geographic spin-axis pole and far-sided from the collection location (e.g. Wilson 1971). The bias has commonly been attributed mostly to inclination error in clastic sedimentary rocks. Recently, however, Pavón-Carrasco *et al*. (2016) have shown from a robust database of palaeopoles that volcanic rocks worldwide extruded in the past 400 yr have a mean inclination that is about 3° lower than the measured reference geomagnetic field predicts. This result implies that palaeomagnetic estimates of a terrane's tectonic displacement from volcanic lavas will be in error by ± 330 km depending on the site-palaeopole geometry. For the Carmacks volcanics, the dipole offset error adds ∼300 km to the estimate. This error source has not yet been shown to be present in large plutons.

Tilt corrections

All of the sites reported in previous studies for the Carmacks volcanics had their ChRM directions corrected for tilt. However, nearly all of the applied tilt corrections were obtained, not by direct measurement on lava contact horizons, but by use of various indirect proxy measurements (Marquis & Globerman 1988; Wynne *et al.* 1998; Enkin *et al*. 2006). The rationale that only layered strata should be studied palaeomagnetically to obtain reliable tectonic transport estimates is the tacit assumption that only such strata provide reliable bedding tilt corrections. This assumption is true in general, but it is not true for the Carmacks Group. These lava flows occur mostly in low-lying areas of mountainous terrane and are poorly exposed under a lush forest cover. There are few roads so that a helicopter is required for palaeomagnetic collecting with few safe landing locations. There are no known stratigraphic sections of the Carmacks Group that are even as promising palaeomagnetically as those tested to date.

In Yukon, mafic volcanics weather rapidly so that good exposures with true attitudes are hard to find. Further, lavas and ash flows on the flanks of a composite stratovolcano of the Carmacks type commonly have irregular primary dips of up to 15°–30° (Holmes 1965). Thus flow top vesicular, amygdular, brecciated or oxidized zones or flow bottom brecciated and chill zones, even if present, typically have substantial primary dips. Similarly, when ash falls on a volcano's flank, it typically forms a fairly even layer on the older sloping surface to record a substantial primary dip. Jointing in mafic flows is often used as a bedding-perpendicular proxy. However, 'basalt' columns are initiated at the top of a cooling flow and propagate downward perpendicular to the sloping cooling front that mimics the attitude of the flow top initially. Until a flow is several metres thick, the 'vertical' joints record some or all of the flow's primary dip. Similarly, a column's polygonal convex transverse joints will have a primary dip on average when unloaded that is about perpendicular to the 'vertical' joints. Also, the sampling of a basalt column is problematic because it yields scattered ChRM and anisotropy of magnetic susceptibility directions, presumably because of stress build-ups during cooling (Symons 1967; Almqvist *et al*. 2012).

Virtually all of the existing palaeomagnetic sites in the Carmacks volcanics have had their 'palaeohorizontal' estimated using these various proxy methods or by projection from distant outcrops (Marquis & Globerman 1988; Wynne *et al*. 1998; Enkin *et al*. 2006). The high variability of these dip-proxy measurements is well illustrated at Solitary Mountain where Enkin *et al.* (2006) opted to average the measured proxy values in presumed tectonic panels over as many as 10 sites after omitting some steeper inclinations as assumed 'primary dips'. Even with these smoothing attempts, the resulting tilt test on the volcanics' ChRM at Solitary Mountain gave a non-significant and notably non-determinative result of 91 ± 121 per cent pre-tilting.

Remagnetization

Mafic volcanic rocks are more prone to remagnetization by lightning strikes and by meteoric or hydrothermal fluids than felsic plutons because their iron content is about five times greater on average. Mafic stratavolcanoes form as topographic highs and act as prominent lightning rods to ground until eroded and buried (Enkin *et al.* 2006). Lightning strikes intensely remagnetize the volcanics by induction and heat in random directions with a decreasing intensity away from the strike site. Palaeomagnetists identify a recently struck site in Yukon by the specimen's high mostly normal polarity NRM intensities and scattered NRM directions. Enkin *et al.* (2006) identified and rejected 6 of 21 sites (29 per cent) at Solitary Mountain on this basis. Valid ∼70 Ma ChRM directions in Yukon have steep inclinations of either normal or reversed polarity. The addition of randomly directed lighting-induced remanence component, if not identified and entirely removed, will inherently shallow a normal ChRM inclination in most cases and will almost always shallow a reversed ChRM inclination in Yukon. The potential for not identifying and removing such added biasing components is increased significantly if only TH demagnetization methods are used.

Remagnetization by oxidation or reduction is another likely source of preferentially shallowed ChRM inclinations in the Carmacks volcanics relative to their felsic volcanic centre stocks. Wynne *et al*. (1998) wrote for the Carmacks strata at Miners Range, Carmacks townsite and Apex Mountain that 'Alteration, including saussuritization, bleaching, and sericite and hematite alteration, is common'. This extensive alteration must postdate their deposition at ∼70 Ma.

Mafic volcanics typically have extensive horizontal porosity in vesicular flow tops and vertical transmissivity through columnar joints. Therefore they are thoroughly accessible to later meteoric or hydrothermal fluids. Thus their relatively high content of magnetite, pyrite and other ferrous minerals make them an easy target for extensive hematization. In contrast, felsic stocks are typically massive and much less reactive chemically, and so they are relatively impervious to fluid flow until unloading joints develop at surface after uplift. Excluding primary exsolution hematite that carries a very stable and desirable primary ChRM, hematite is commonly found only in the thin modern weathering rind at surface of felsic plutons in Yukon, which is easily avoided in sample preparation (e.g. McCausland *et al*. 2006). Obviously also these felsic rocks have relatively low contents of ferrous minerals that are amenable to hematization.

Remagnetization has been a substantial problem in the Carmacks volcanics that has led to a high rejection rate of site mean ChRM directions from the palaeopole calculations. Marquis & Globerman (1988) rejected the directions from 8 of 21 sampled Carmacks volcanics sites, Wynne *et al.* (1998) excluded 2 of 15 sites, and Enkin *et al.* (2006) excluded data from 7 of 21 sites as insufficiently well clustered or aberrant in direction. Thus 17 of 57 sites overall (30 per cent) of the collected sites were deemed unfit. By comparison the ChRM directions from only 6 of the 58 sites (10 per cent) collected in the three accepted felsic volcanic centre stocks of the Carmacks Group were similarly excluded (Harris *et al.* 1999a; McCausland *et al.* 2005; this study).

Post-depositional hydrothermal and/or thermal remagnetization may have altered some ∼70 Ma Carmacks Group ChRM directions. There is abundant radiometric evidence for hydrothermal activity from ∼70 to ∼60 Ma (Fig. 9 and Table 3) that continued through the Cenozoic. For example, the 53.6 ± 0.2 Ma Flat Creek granitic stock with 51.1 Ma andesitic dikes crops out over ∼100 km^2 and intrudes the Carmacks Group (Symons *et al.* 2004). The Carmacks sites of Marquis & Globerman (1988) are located ∼4 km north of the stock and likely overlie its outward-dipping shoulder (Hart 1997). The stock and the tilt-corrected volcanics have nearly identical mean mixed-polarity ChRM directions of $D = 345.2°$, $I = 76.8°$ and $D = 327.4°$, $I = 76.2°$, respectively. Thus it is plausible that intrusion of the Eocene stock may have remagnetized, uplifted and tilted the volcanics northward at ∼54 Ma. If true, then the *in situ* ChRM direction of the volcanics is recording the same non-significant post-Eocene northward translation of 90 ± 500 km as the stock.

Remagnetization in the Carmacks volcanics would likely shallow its ChRM inclinations. The palaeopole for North America was located north of Alaska at 70 Ma, travelled along a bending arc to the present north pole (Torsvik *et al.* 2012; Fig. 8). Any stable secondary remagnetization component that adds to, or replaces, the volcanics primary ChRM from lightning, oxidation or hydrothermal alteration after 50 Ma, especially if it is Recent in origin, will have the time-referenced APWP direction. On average this addition or remagnetization will cause the ChRM of the volcanics to be shallowed up to 10° and the declination to be rotated up to ∼25° clockwise (Fig. 8). The resulting possible ∼10° decrease in palaeolatitude would add an error of up to ∼1100 km of additional northward translation to the estimated northward translation of the Carmacks volcanics, potentially explaining much of the difference in translation estimates between the volcanics and stocks. Note also the apparent ∼25° ± 5° of clockwise declination rotation reported for the Apex Mountain (AM) and Carmack's townsite (CT) palaeopoles (Enkin *et al.* 2006). Further, it would be hard to detect any remagnetization bias palaeomagnetically if it is a residual stable remanence from lightning strikes that predate the last century or if it is from hematite oxidation isolated in the last few steps by either AF or TH step demagnetization.

In summary, remagnetization and scatter of the ChRM directions are potentially significant problems in obtaining reliable ChRM directions from the Carmacks volcanics because nearly all of the likely effects preferentially shallow the inclination and increase the translation estimate. Conversely, remagnetization is much less of a likely problem in the coeval Carmacks volcanic centre stocks.

Reversals

Palaeomagnetic sites with antiparallel normal and reverse polarity ChRM directions provide the data for the important 'reversals' test in palaeomagnetism (Irving 1964). Antiparallel directions show that the primary ChRM direction has not been biased by a later secondary magnetization component. If present between two comparable collections from different areas in a region, a positive test shows the absence of a remagnetization bias. Further, if all of the site mean ChRM directions are well clustered when the reverse site mean directions are switched to their antiparallel normal direction, they provide strong support for the rationale that secular variation has been averaged out of the data set to truly isolate the palaeopole of the Earth's geomagnetic axial-dipole field at the time of ChRM formation.

For the Carmacks suite both normal and reverse site mean ChRM directions were found in the Apex Mountain and Miners Range volcanic collections and in the Mount Lorne stock collection (Table 2). All three collections passed the reversals test, meaning that the two populations of site mean directions are not statistically significantly different at 95 per cent confidence using the test statistics of McFadden & Lowes (1981, Table 4). This test, however, is unimpressive for the two volcanics collections because: (1) the radii of their cones of 95 per cent confidence (α_{95}) are very large for both the normal (14.1°) and reverse (25.5°) populations at Miners Range and for the reverse (18.9°) population at Apex Mountain; and (2) the mean ChRM directions by polarity are 15.7° and 9.2° off antiparallel for the two collections, respectively (Table 4). By comparison, the normal and reverse mean ChRM directions for the Mount Lorne collection are impressive, having α_{95} values of 4.2° and 3.2°, respectively, that are only 2.8° off antiparallel.

The final column in Table 4 provides an estimate of the relative strictness of the reversal test for each collection. Normal and reverse mean ChRM directions that both have A_{95} values of 5.0°—which would be considered reasonably well clustered by most palaeomagnetists—and that are up to 5.8° off antiparallel, would just pass the McFadden & Lowes (1981) test. This standard has been given a value of 1.00 (Table 4). As the value goes up or down, it describes how much proportionately larger or smaller the reversals' test area becomes on the Earth's spherical surface. Clearly the large A_{95} confidence errors determined for the Miners Range and Apex Mountain volcanics make their reversals test areas so large that the tests are virtually meaningless. These test results provide additional evidence also that secular variation has not been truly averaged out of the palaeopoles for these two collections. Conversely, the Mount Lorne stock has given highly clustered antiparallel ChRM directions that pass the reversals test to a very high standard, which indicates that secular variation bias has been substantially averaged out of its palaeopole. Note also that the coeval Seymour Creek stock has a symmetrical reversal in two of its 16 sites, showing that the stock retains a primary ChRM although it has been tilted and so is not included in this analysis.

There is also a highly positive reversals test between the normal-polarity Prospector Mountain and reverse-polarity Swede Dome stocks (Table 4). These stocks are ∼190 km apart (Fig. 1), have overlapping ages of 68.2 ± 1.6 Ma and 69.8 ± 1.3 Ma, respectively, and both were emplaced into flat-lying unmetamorphosed Carmacks volcanics on YTT basement. The plutons' antiparallel ChRM directions lie within each other's cone of 95 per cent confidence (Fig. 8), and yield a highly positive reversals test (Table 4). This result asserts strongly that: (1) both of these unmetamorphosed stocks retain a primary ChRM that has not been significantly altered by remagnetization or tilting; and (2) that the YTT in southwestern Yukon has behaved as an essentially coherent tectonic package since ∼70 Ma. Conversely, the Carmacks volcanic collections do not provide any robust reversals tests, while explanation of their palaeomagnetic results does require: (1) a major hypothetical tectonic rotation

Table 4. Results of positive palaeomagnetic reversals tests.

Collection	Polarity	Number sites	Mean ChRM direction Decl. (°)	Incl. (°)	k	α_{95} (°)	Angular separation (°)	Relative test area size
Miners Range volcanics	Normal	2	7.1	76.0	316	14.1		
	Reverse[a]	3	306.1	73.1	26	25.5	15.7	17.98
Apex Mountain volcanics	Normal	5	334.1	69.3	175	5.8		
	Reverse[a]	5	351.3	63.2	17	18.9	9.2	7.82
Mount Lorne pluton	Normal	6	15.8	75.8	251	4.2		
	Reverse[a]	12	28.4	75.8	187	3.2	2.8	0.56
Prospector Mountain Swede Dome plutons	Normal	17	8.3	82.4	72	4.2		
	Reverse[a]	17	359.9	82.7	165	2.8	1.2	0.51

[a]The measured direction is antiparallel to the direction given here. Relative size of the test area on a sphere using the McFadden & Lowes (1981) test. A size of 1.00 is given by normal and reverse populations that are reasonably well clustered with α_{95} values of 5.0° and that are 5.8° off antiparallel to give a marginal positive–negative test result.

to explain the Solitary Mountain results in particular; and (2) about 1500 km more northward translation than the known 415 km geological offsets in contacts and faults can justify (Gabrielse *et al.* 2006).

Inclination shallowing error?

Marquis & Globerman (1988) stated clearly that they sampled either basalt or andesite at each of their Carmacks volcanics sites. Wynne *et al.* (1998) stated clearly that seven of their sites (W09–W12, W61–W63) were collected from basalt but stated imprecisely that other sites (W01–W08) came from intercalated volcaniclastics and basalt flows. Similarly Enkin *et al.* (2006) reported that the 18 sites from the lower Carmacks unit at Solitary Mountain came from 'vesicular mafic to intermediate fragmental volcanic flow deposits with local welded tuffs, lahars and lapilli conglomerates'. If volcaniclastic strata were sampled rather than rare lava flows, then two issues arise. First, volcaniclastic rocks tend to be very porous so that they could have been remagnetized by later fluid flows. Second, like all clastic sediments, they would be susceptible to inclination error from mechanical compression on burial loading or to bedding error from primary detrital processes. Both mechanisms cause systematic decreases in ChRM inclination of up to ∼20° (Dunlop & Özdemir 1997; Bilardello & Kodama 2010; Bilardello *et al.* 2011), which would cause the northward translation estimate to increase by many hundreds to low thousands of kilometres. In the absence of a clear lithologic description for each site, the potential for an overestimate resulting from inclination shallowing error is difficult to assess.

Other Cretaceous palaeomagnetic data

If the ∼70 Ma Carmacks Group volcanics record ∼1950 km of northward displacement relative to North America rather than ∼415 km as the geology indicates (Gabrielse *et al.* 2006), then all other Cretaceous units in the YTT and IMB terranes of Yukon should also record a ∼1950 km or slightly greater displacement palaeomagnetically. This, however, is not the case. The 96 ± 4 Ma Dawson Range batholith, 109 ± 1 Ma Mount McIntyre stock, 112 ± 4 Ma Whitehorse batholith and 114.7 ± 1.1 Ma Quiet Lake batholith (Fig. 1) that have given northward (poleward) translation estimates of 1.9° ± 7.7°, 11.9° ± 6.1°, 8.0° ± 5.7° and 1.4° ± 5.1°, respectively (Harris *et al.* 1999a,b; McCausland *et al.* 2006; Symons *et al.* 2015). The tectonic consequences of the palaeopoles obtained for these four plutons have been discussed recently (Symons *et al.* 2015) and are not repeated here except to make two observations. First, these four plutons give an average displacement of 5.8° ± 4.4° or 650 ± 450 km northward since ∼108 Ma, which agrees with the geological estimate of ∼490 km since the Early Cretaceous (Gabrielse *et al.* 2006) and with the 330 ± 400 km northward estimate obtained here from the three ∼71 Ma volcanic centre stocks (Table 2). Of the seven Cretaceous plutonic estimates, the largest by far is 11.9° ± 6.1° from the Mountain MacIntyre stock, and even it is significantly less at ∼93 per cent confidence than the 17.6° ± 5.4° from Carmacks volcanics' estimate of Enkin *et al.* (2006).

Gladwin & Johnston (2006) noted that the 108.5 ± 1.1 Ma Glenlyon batholith (Rasmussen 2013) in Yukon appeared to pin the accreted terranes of Baja BC to the continental assemblages of North America. Therefore, if the overlying Late Cretaceous Carmacks volcanics were translated 1950 ± 600 km northward, they argued that the inboard Selwyn Basin assemblages must also have been translated ∼1950 km northward with the volcanics. Subsequently, Johnston (2008) argued that the Selwyn Basin and the outboard Cassiar platform beside the IMB were allochthonous and part of a 'ribbon continent' that he named 'SAYBIA'. He postulated that SAYBIA docked with North America along a cryptic suture beside and subducting under the Mackenzie Mountains platform. Thus, the only palaeomagnetic data from Yukon that support the SAYBIA model come from outside the Selwyn Basin with support from the pinning point interpretation. Four palaeomagnetic studies from within the basin contradict the SAYBIA model. They are discussed in detail by Kawasaki & Symons (2014) and summarized next.

Palaeomagnetic studies of the 97 Ma Ragged stock and the 98 Ma Mine Stock and abutting Cantung W-Cu ore deposit in the southeastern Selwyn Basin have given concordant palaeopoles for North America (Symons *et al.* 2008; Kawasaki & Symons 2014). The Howards Pass Zn-Pb deposits are hosted in Early Silurian black shales of the eastern Selwyn Basin. They carry a Middle Jurassic post-folding metamorphic ChRM that gives a palaeopole that is concordant with the Middle Jurassic North American reference palaeopole (Kawasaki & Symons 2012). This result is consistent with the Selwyn Basin being autochthonous or para-autochthonous, but remains less conclusive until the age of metamorphism is radiometrically determined. The fourth palaeomagnetic study was on the 92 Ma Deadman stock in the extreme northwestern corner of the Selwyn Basin (Symons *et al.* 2006). The stock's palaeopole was discordant by 7° ± 4° relative to the North American reference palaeopole. The discordance was attributed to a rotation of the pluton from being pushed up the curving frontal ramps of the North Fork and Dawson thrust faults. Even if the ramp rotation interpretation is incorrect, the maximum displacement is still only 770 ± 440 km or significantly less than SAYBIA's 1950 ± 600 km estimate. Stated simply, there is no palaeomagnetic evidence from the Selwyn Basin or elsewhere in Yukon that supports either the Carmacks volcanics' 1950 ± 600 km displacement estimate or the SAYBIA ribbon continent tectonic model although it continues to be postulated (e.g. Shaw & Johnston 2016).

Irving *et al*. (1985) noted that the then available palaeopoles from the IMB and Coast Plutonic Complex gave similar estimates for Baja BC northward displacement. They concluded that large plutons sampled away from known structural complications provided 'a reasonable approximation to palaeohorizontal'. From ∼1995 to ∼2005 palaeomagnetic data from large plutons in southwestern Yukon became increasingly available and gave palaeopoles that formed a coherent pattern that showed the region had not been translated by >1500 km northward from 70 to 50 Ma (Symons *et al*. 2005; McCausland *et al*. 2006). Proponents of the anomalous Carmacks volcanics estimates opted to either: (1) ignore the plutonic data (Wynne *et al*. 1995); (2) claim that all older units had been remagnetized by Carmacks hydrothermal fluids (Wynne *et al*. 1998); or (3) suggest that the plutons had been tilted in such a way as to give a uniformly discordant palaeopoles' bias (Enkin 2006; Enkin *et al*. 2006). Recently Symons & Kawasaki (2011) analysed palaeopoles from Palaeocene to mid Eocene units in the Coast Plutonic Complex from inboard of the Coast Shear Zone and from the IMB and YTT terranes from the northern Cordillera and Alaskan panhandle. Of the six 56–50 Ma (52 ± 4 Ma average) available palaeopoles for the IMB-YTT, Symons & Kawasaki (2011) showed that the four palaeopoles from volcanic flow sequences are closely concordant with the two palaeopoles from plutons. Similarly these six palaeopoles are concordant with nine 59 Ma to 46 Ma (51 ± 4 Ma average) palaeopoles from plutons in the eastern Coast Plutonic Complex after excluding three additional widely divergent palaeopoles from around the Hawkesbury Warp. These results support the original surmise of Irving *et al*. (1985) that plutons sampled away from known structural complications provide a reasonable approximation of horizontal that implies simple regional isostatic uplift only. Further the 15 palaeopoles in both populations combined record a non-significant post-Palaeocene southward translation of 130 ± 540 km for terranes inboard of the Coast Shear Zone (Symons & Kawasaki 2011).

Inclination-only block rotation method

Enkin *et al*. (2006) used the inclination-only block rotation (IOBR) method to calculate their Carmacks volcanics' northward translation estimate. This method considers each of the four palaeomagnetic Carmacks collection areas to be a separate tectonic block that is free to rotate about a vertical axis (Enkin & Watson 1996). After a small correction (<2°) in the site mean ChRM directions to adjust them to a mean site location, the site palaeoinclinations are calculated along the mean palaeodeclination of each block. The final step is to rotate the four populations of block palaeoinclinations to a common palaeodeclination and then to calculate the overall 'average' palaeoinclination. Use of the IOBR method has led Enkin *et al*. (2006) to combine data sets that are statistically significantly different in ChRM direction (e.g. Solitary Mountain with the other three areas) and to combine collection populations with significantly different dispersions (e.g. Miners Range with the other three areas) to obtain at their northward translation estimate of 1950 ± 600 km.

There are other problems with the IOBR method. First, by ignoring the ChRM declinations, the method inherently overestimates the translation distance. This bias is easily seen. If one calculates ChRM directions listed in Table 2, the 1950 km translation distance is reduced by about 180 km because palaeodeclination dispersion is substantially eliminated by block rotation. Second, the IOBR method provides no information on where a terrane originated. The method simply locates each collection block on a small circle of palaeolatitude about the 70 Ma reference palaeopole and therefore it does not provide real tectonic information or even indicate if the four blocks of Carmacks Group volcanics were resting on a quasi-coherent YTT at 70 Ma!

Third, use of the IOBR method has led Enkin *et al*. (2006) to hypothesize major tectonic rotations for which negligible geologic evidence can be cited. The ChRM declinations for the four volcanics 'tectonic blocks' range from 303° to 355° (Table 2). Using the IOBR method required applying clockwise (+) rotation corrections of +43°, +14°, +2° and −8° for the Solitary Mountain, Miners Range, Apex Mountain and Carmacks townsite 'blocks', respectively, about a vertical axis. In reality it would be very difficult geologically for flat-lying unmetamorphosed volcanics lying on a stable metamorphic crust within a region the size of southwestern Yukon to be rotated so significantly without also being tilted significantly.

Fourth, describing the four Carmacks collection areas as 'tectonic blocks' is misleading. The sites in the Carmacks townsite block come from a 15 km N–S × 90 km E–W strip that is cut by many faults including the regional Teslin and Semenof faults (Fig. 1). The Miners Range 'block' has two normal and the three reversed polarity sites that are not antiparallel and are separated by a fault (Marquis & Globerman 1988). The Solitary Mountain 'block' straddles the regional d'Abbadie fault system (Fig. 1). Detailed geologic mapping at even a 1:50 000 scale is not yet available for the Apex Mountain 'block'. In their geologic summary of the tectonics of the region, Allan *et al*. (2013) observed that there is little evidence for significant deformation in the YTT during the Palaeocene-Eocene. In summary, it is ironic that Wynne *et al*. (1998) and Enkin *et al*. (2006) eschewed the use of averaged plutonic ChRM data that may have undergone a few degrees of random tilt individually on uplift, yet have willingly incorporated such large hypothetical vertical-axis tectonic corrections into their northern translation estimate.

Reference poles

Rather than use the IOBR method discussed above, we think that the best approach to calculating terrane tectonic motions is the traditional palaeomagnetic method, which is to use both the ChRM declinations and inclinations of dated rock units to build an APWP for the terrane. Had only inclinations been used, it is unlikely that reliable APWPs would have been built to provide a basis for the plate tectonic revolution of the past half century! Also, we think it preferable to use a reference palaeopole drawn from the most recent and widely accepted reference APWP of the day. Both Wynne *et al*. (1998) and Enkin *et al*. (2006; see also Enkin 2006) chose to construct their own North American Mesozoic-to-present APWP and 70 Ma reference palaeopole based mostly on selected mostly North American palaeopoles. Thus their 70 Ma reference palaeopole suffered from problems due to its small source dataset of only 10 palaeopoles, being at 77.5°N, 194.9°E ($A_{95} = 5.1°$). By contrast the 70 Ma reference palaeopole of Torsvik *et al*. (2012) is located at 73.5°N, 192.6°E ($A_{95} = 2.5°$) and based on 32 palaeopoles. These two 70 Ma 'reference' palaeopoles are ∼4° apart, and, depending on the geometry of the sampling site and poles, could change an estimated translation distance by as much as ±440 km. For the Carmacks Group, switching the two reference palaeopoles results in a change of ∼165 km in the northward translation estimate and

~11° in the rotation estimate. We advocate using the most robust APWP of the day as a reference for terrane tectonic motion studies.

CONCLUSIONS

The 68.7 ± 0.4 Ma Prospector Mountain volcanic centre stock intrudes the coeval 69.4 ± 1.6 Ma Carmacks Group volcanics. The stock has yielded a tightly clustered population of 17 site mean ChRM directions with a mean of $D = 8.3^\circ$, $I = 82.4^\circ$ ($k = 71.9$, $\alpha_{95} = 4.2^\circ$). The ChRM of this unmetamorphosed monzonite-syenogranite stock is interpreted to be a primary TRM that resides in magnetite or titaniferous magnetite with unblocking temperatures in the 500–580 °C range. Importantly, Prospector Mountain's normal-polarity 69 Ma TRM direction provides a statistically highly significant positive palaeomagnetic reversals test with the 69 Ma Swede Dome's reversed polarity TRM direction (McCausland *et al*. 2005). Given that Swede Dome is another unmetamorphosed volcanic centre stock in the YTT that is coeval with adjacent flat-lying Carmacks Group volcanics some ~190 km to the north of Prospector Mountain, the test affirms that both plutons retain an untilted unbiased primary ChRM.

The existing palaeomagnetic data from the Carmacks Group volcanics of Marquis & Globerman (1988), Wynne *et al*. (1998) and Enkin *et al*. (2006) are evaluated. The relatively low number of volcanic cooling unit sites (compared with e.g. Souther & Symons 1974; Hamilton & Evans 1983), the large scatter in the ChRM directions both within and between the four collection areas, dispersion differences between normal and reversed sites, and the lack of definitive fold or reversals tests suggest clearly that secular variation has not been successfully averaged out of the palaeomagnetic data. This is a problem that Butler (1990) first identified a quarter of a century ago. Other potential problems in the data appear to include dipole offset error, inaccurate tilt corrections, a high rejection rate of 'remagnetized' sampling sites, the questionable Yellowstone-in-Yukon genetic model, and possibly systematic clastic bedding inclination errors. These potential problems are predisposed in general to preferentially shallow the measured ChRM inclinations and thereby increase erroneously the calculated northward translation distance. Further, the 1950 ± 600 km estimate for northward translation of the YTT between ~70 Ma and ~50 Ma obtained from the volcanics by Enkin *et al*. (2006) is significantly greater than the 415 ± 15 km geologic estimate of Gabrielse *et al*. (2006). The 1950 ± 600 km estimate is also notably greater than the estimates from >20 other Cretaceous to mid Eocene palaeopoles from plutons and volcanic rocks in the YTT, IMB and Coast Plutonic Complex inboard of the Denali-Coast Shear Zone. Overall each of these >20 rock units would have to have an unrecognized average structural tilt of ~12° NNW downward at all sites to match the 1950 km translation estimate given by the Carmacks Group volcanics!

Combining the ChRM directions of the Prospector Mountain, Swede Dome and Mount Lorne felsic volcanic centre stocks yields an average northward transport distance for the YTT of 330 ± 400 km since 71 ± 5 Ma, which is consistent with the 415 ± 15 km geological estimate of Gabrielse *et al*. (2006). The non-significant difference between the palaeomagnetic and geologic estimates provides strong support for the accuracy of the geologic estimate. This result supports the notion also that the YTT and Stikine terranes in Yukon were not part of Baja BC's posited northward translation trek since the mid-Cretaceous.

Acceptance of the tenet that only bedded strata should be used to provide palaeomagnetic estimates of tectonic motions is a failing strategy in Yukon (and elsewhere). This is true because the best of the known Carmacks Group volcanic sections at Apex Mountain have now been tested palaeomagnetically in this co-located study, and because the magnetic remanence in most pre-Cretaceous volcanic and sediment exposures in Yukon have been variably metamorphosed. Massive felsic plutons, which are relatively resistant to metamorphic processes compared to volcanic and sedimentary units, can preferentially provide additional viable palaeomagnetic targets for tectonic research in the YTT-IMB terranes of southwestern Yukon.

Finally, the traditional palaeomagnetic method of averaging palaeopoles to develop an APWP for a terrane is a much better method than the IOBR method of Enkin & Watson (1996) for estimating a terrane's translation from multiple palaeopoles. The traditional method has the potential advantage of providing real information on the terrane's tectonic motion history from matching poles and/or APWPs. Also the IOBR method inherently overestimates the translation distance and underestimates its error limits by minimizing the real declination dispersion. The method may also require its user to postulate tectonic block rotations about vertical axes for which there is little or no geologic evidence. An example is the hypothesized 43° rotation correction used by Enkin *et al*. (2006) for the Carmacks Group volcanics in Solitary Mountain's 'tectonic block'.

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