The big flush: paleomagnetic signature of a 70 Ma regional hydrothermal event in displaced rocks of the northern Canadian Cordillera[1]

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Abstract: The 70 Ma Carmacks Group, a subaerial volcanic succession which once covered much of central southwest Yukon, has a paleomagnetic remanent direction which passes the fold test and the reversal test. A new collection of 13 sites, combined with 13 sites from a previous study, renders a pole (088.6°E, 78.4°N, $A_{95} = 7.8°$) which is far-sided with respect to the pole for cratonic North America and implies a displacement from the south of 1900 ± 700 km. Late Triassic Mandanna Member red beds and Early Jurassic Nordenskiöld Formation tuffs, deformed in the Late Jurassic, fail the fold test and conglomerate test but pass a contact test with Eocene dykes. The postdeformational remanent direction is identical to that isolated from the Carmacks Group. The magnetic signature contained in these older formations is probably an overprint produced by an extensive hydrothermal system active during Carmacks extrusion. Geological work indicates that the Carmacks Group is plume related. Given its paleomagnetic latitude and geological nature, we hypothesize that the Carmacks Group is a displaced segment of the Yellowstone hot-spot track, and the hydrothermal system which remagnetized the older rocks was established by mantle upwelling below the region.

Résumé : Le Groupe de Carmacks, âgé de 70 Ma, est une succession volcanique subaérienne qui couvrait jadis la majeure partie du centre sud-ouest du Yukon, il possède une direction paléomagnétique rémanente certifiée par le test du pli et le test des inversions. Une nouveau groupe de 13 sites, combiné à 13 sites d'une étude antérieure, fournit un pôle (088,6°E, 78,4°N, $A_{95} = 7{,}8°$) qui est considérablement éloigné par rapport au pôle du craton de l'Amérique du Nord et qui implique un déplacement à partir du sud de 1900 ± 700 km. Les couches rouges du Membre de Mandanna, du Trias tardif, et les tufs du Formation de Nordenskiöld, du Jurassique précoce, qui subirent une déformation durant le Jurassique tardif ont échoué le test du pli et le test de conglomérat, mais ils ont passé avec succès le test de contact avec les dykes de l'Éocène. La direction rémanente post-tectonique est identique à celle isolée du Groupe de Carmacks. La signature magnétique qui caractérise ces formations plus anciennes est probablement une réaimantation produite par un système hydrothermal étendu qui fut actif durant l'extrusion de Carmacks. L'étude géologique révèle que le Groupe de Carmacks est apparenté à un panache. Étant donné sa latitude paléomagnétique et sa nature géologique, nous avançons l'hypothèse que le Groupe de Carmacks représente un segment déplacé du tracé du point chaud de Yellowstone, et que le système hydrothermal qui a réaimanté les roches les plus anciennes est dû à l'ascension du manteau sous la région étudiée.

[Traduit par la Rédaction]

Introduction

The allochthonous terranes accreted to North America since the Jurassic have not remained immobile since they docked. The Cordillera features many large strike-slip faults roughly parallel to the orogen with Late Cretaceous to early Cenozoic dextral motion, indicating northward displacement with respect to North America. Paleomagnetic studies since the early 1970s (summarized by Irving et al. 1996) indicate that these northward motions were large and differed in places ranging from 1000 to 4000 km. This interpretation has proven controversial, since geological estimates of displacement fall far short of the paleomagnetic estimates.

Marquis and Globerman (1988) reported results from a paleomagnetic study of the Late Cretaceous Carmacks Group in central southwest Yukon. They measured a predeformational magnetization with a mean direction of declination $D = 166.7°$, inclination $I = -71.4°$ (Fisher precision $k = 53$, 95% confidence interval $\alpha_{95} = 4.8°$) and a corresponding paleopole of 109.4°E, 82.1°N ($K = 21$, $A_{95} = 7.8°$, $N = 18$ sites). This paleopole is far-sided with respect to the 70 Ma reference paleopole of cratonic North America and they concluded that the discrepancy between the two was the product of 1500 ± 950 km of northward displacement of the Whitehorse Trough. They speculated, using a model developed by Umhoefer (1987), that the northward motion was a product of the tectonic

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interaction along the transpressional margin between the Kula plate and the western edge of the North American plate.

Butler (1990) reworked data from Marquis and Globerman (1988), averaging together adjacent sites which had similar directions. He argued that these sites were not time-independent samplings of the paleomagnetic field. Marquis et al. (1990) argued that the physical and geological basis of Butler's argument was weak. The paleopole and northward displacement he calculated were not statistically different from those given by Marquis and Globerman, but have a larger confidence limit ($A_{95} = 10.3°$), reflecting the lower number of sites used. Our new data allow us to decide the merits of these arguments.

In southern British Columbia, the 104 Ma Spences Bridge Group (Irving and Thorkelson 1990; Irving et al. 1995) yielded a paleomagnetic estimate of 1100 ± 600 km displacement with respect to North America. This displacement is smaller than that observed from the Carmacks Group. Based on the discrepancy between the paleolatitudes observed in the north and south, Irving et al. (1995) suggested that the Intermontane Belt stretched by strike-slip elongation and dismemberment during its northward transport.

The aim of this study was to improve constraints on paleogeographic models of the northern Cordillera by adding to the Marquis and Globerman (1988) sampling of the Carmacks Group. Also, in an attempt to provide new temporal constraints on the paleogeography of the Cordillera, we sampled two older units, the Triassic Mandanna Member and the Jurassic Nordenskiöld Formation.

Geological setting of central southwest Yukon

The main geological elements in central southwest Yukon are the arc-dominated Stikinia and the pericratonic Yukon–Tanana terranes. Stikinia, which underlies the northernmost Intermontane Belt, consists of the Middle Triassic Joe Mountain volcanic complex, the Late Triassic Lewes River Group, and the Early Jurassic Laberge Group. Mafic submarine volcanic rocks of the Joe Mountain volcanic complex, including thick sections of pillow basalt, form the basement to the trough and are either oceanic crust or attributable to seamount magmatism. These rocks are similar to and lie along strike from volcanic rocks included in the Cache Creek terrane (Hart and Hunt 1994; Hart and Orchard 1996). The Lewes River Group consists of thick sequences of isotopically juvenile andesitic volcanic rocks and flow breccia, and coeval volcanoglomerates which are equivalent to the Stuhini Group of British Columbia. These rocks are overlain by a 7 km thick sequence of strata which make up the Whitehorse Trough. The strata include sandstone, siltstone, and reefal carbonates of the upper Lewes River Group, and immature clastic sedimentary rocks of the Mandanna Member and Laberge Group. The Laberge Group is dominated by polymictic molasse shed eastward into the basin and derived from erosion of the Lewes River Group (Hart et al. 1995; Johannson et al. 1997). Interbedded with the clastic strata of the Laberge Group are tuff and volcanogenic sandstone of the Nordenskiöld Formation.

Stikinia narrows and pinches out to the north. Rocks of the metamorphic Yukon–Tanana Terrane which surrounds much of northern Stikinia are dominated by Paleozoic and older continental margin sedimentary and continental arc sequences. It is difficult to accommodate the Yukon–Tanana Terrane within the geomorphological belts recognized in the central and southern portions of the Canadian Cordillera. The eastern portion of the terrane was previously included in the para-authochthonous Omenica Belt. However, the Yukon–Tanana Terrane is faulted against and distinguished from adjacent rocks of ancient North America on the basis of its distinct stratigraphy and structure (Mortensen 1992; Johnston and Erdmer 1995*a*, 1995*b*). In addition, the terrane apparently wraps around the northern termination of Stikinia and extends >500 km south along the west margin of the Intermontane Belt (Johnston et al. 1996). Thus the terrane lies, in part, outboard of exotic oceanic rocks of the Cache Creek terrane. The origin of this problematic geometry remains a matter of conjecture and debate (Mihalynuk et al. 1994).

The main phase of post-Triassic deformation in the Whitehorse Trough occurred from the late Middle to Late Jurassic, probably during the obduction of the Cache Creek terrane to the west over Stikinia (Ricketts et al. 1992).

Cretaceous sedimentary and volcanic rocks overlie and plutonic rocks intrude the Whitehorse Trough and the Yukon–Tanana Terrane. Mid-Cretaceous volcanic rocks consist of andesitic feldspar porphyry flows and tuffs of the Mount Nansen Group. Felsic volcanic rocks deposited across south-central Yukon between 84 and 78 Ma, including pyroclastic flows and flow-banded rhyolite, are included in the Windy–Table Suite (Mihalynuk et al. 1992; Hart 1995). Voluminous sequences of subaerial volcanic rocks deposited across central Yukon between 72 and 69 Ma, including extensive flood basalts, are included in the Carmacks Group (Tempelman-Kluit 1974; Grond et al. 1984).

Paleomagnetic field and laboratory procedures

Drill cores (typically six) or hand samples (three) were collected at each site and oriented using both magnetic and solar compasses. The solar and magnetic bearings agreed within 2° except where the rocks had been hit by lightning and were, as a consequence, strongly magnetic. Solar bearings were used for these rocks.

Specimens were measured in the laboratory using a robotized Schonstedt DSM1 fluxgate magnetometer or a Geofyzika JR5A spinner magnetometer. Specimens were demagnetized using five to 10 demagnetization steps, using a Schonstedt TSD-1 thermal demagnetizer or Schonstedt GSD-5 alternating field demagnetizer with tumbler. Magnetic components were isolated using principal component analysis. Site means are listed in Table 1.

Carmacks Group

Geology and sampling

Thick, isolated accumulations of subaerial volcanic rocks exposed across southwest central Yukon between Whitehorse and Dawson (Fig. 1) make up the Carmacks Group (Tempelman-Kluit 1974). The group is divisible into a lower fragmental unit and an upper flood-basalt unit, and commonly overlies a basal conglomerate. There is a paucity of related intrusions. K–Ar age determinations constrain Carmacks

Table 1. Site averages.

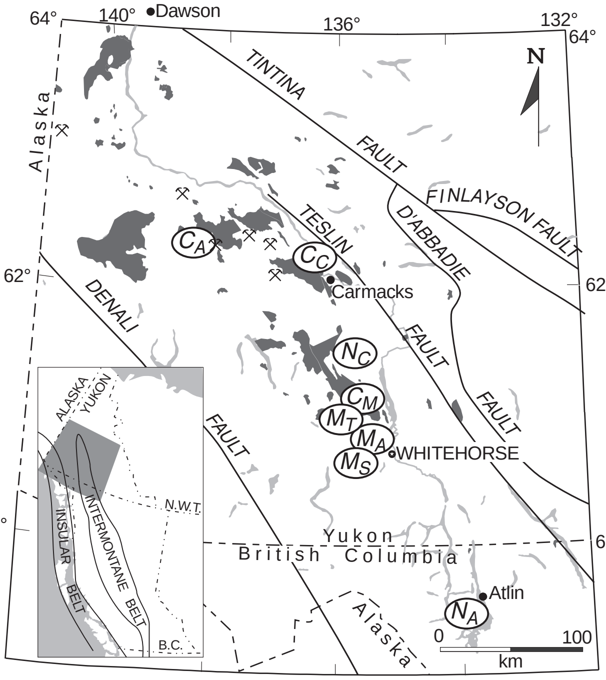
Site	Lat. (°N)	Long. (°W)	BD (°)	BDDA (°)	n	D_G (°)	I_G (°)	D_S (°)	I_S (°)	k	α_{95} (°)
Carmacks Group (72–69 Ma) at Apex Mountain, in stratigraphic order from the bottom up											
W01	62.46	138.05	08	030[a]	10	325.6	67.5	340.3	63.0	216	3.3
W02	62.46	138.05	00	000[a]	10	330.4	72.6	330.4	72.6	224	3.2
W03	62.46	138.05	00	000[a]	10	331.5	67.8	331.5	67.8	203	3.4
W04	62.46	138.05	00	000[a]	8	350.8	75.2	350.8	75.2	280	3.3
W05	62.46	138.05	00	000[a]	6	321.5	66.7	321.5	66.7	63	8.5
W06	62.41	138.10	20	135	8	168.0	–37.5	181.0	–53.1	56	7.5
W08	62.41	138.10	18	112	12	166.3	–55.8	195.0	–62.7	50	6.6
W07	62.41	138.10	18	112	10	169.5	–36.5	183.5	–44.4	95	5.0
W09	62.37	138.01	22	120	10	119.9	–59.6	119.7	–81.6	190	3.5
W10	62.38	138.02	10	115	Lightning						
W11	62.39	138.02	15	230	9	156.4	–60.9	128.6	–61.6	218	3.5
W12	62.40	138.05	22	118	Lightning						
Carmacks Group (72–69 Ma) at Carmacks											
W61	62.17	136.30	25	260	7	182.3	–48.0	154.3	–47.2	113	5.7
W62	62.18	136.27	28	003	9	2.4	–80.8	183.3	–71.2	105	5.1
W63	62.18	136.27	28	003	11	308.2	–74.2	218.3	–67.4	195	3.3
Nordenskiöld (183–188 Ma) at Cinnamon Bun Row											
J75	61.37	135.68	32	038	11	0.2	88.5	36.7	56.9	40	7.3
J76	61.37	135.68	32	038	9	85.0	81.7	48.2	52.0	74	6.0
J77	61.37	135.68	32	038	12	55.6	78.1	43.5	46.6	74	5.1
J78	61.37	135.68	32	038	11	107.7	86.7	44.0	56.8	31	8.4
J79	61.37	135.68	32	038	16	308.7	76.3	13.7	55.8	22	8.0
J81	61.38	135.67	32	038	11	344.7	84.2	30.4	54.4	210	3.2
J82	61.38	135.67	32	038	16	64.6	87.1	40.7	55.5	107	3.6
J83	61.38	135.67	32	038	9	270.7	87.7	34.8	59.5	189	3.8
J84	61.38	135.67	32	038	6	201.3	73.8	54.7	73.0	29	12.6
J85	61.38	135.67	32	038	9	209.3	84.1	40.5	63.9	198	3.7
Nordenskiöld (183–188 Ma) at Atlin Lake											
J91	59.30	133.98	94	033	7	151.8	–75.3	199.9	10.9	158	4.8
J92[b]	59.30	133.98	94	033	9	194.1	–66.8	204.9	25.8	7	21.3
J93	59.30	133.98	94	033	10	143.2	–65.1	189.2	12.0	80	5.4
J94[b]	59.30	133.98	94	033	9	224.6	–67.9	217.8	25.7	3	36.7
J95	59.30	133.98	94	033	18	138.0	–63.9	187.5	10.2	49	5.0
J96	59.30	133.98	94	033	5	150.8	–57.4	182.9	18.1	59	10.0
J97	59.30	133.98	94	033	15	115.7	–76.9	200.0	2.2	30	7.1
Mandanna (208–212 Ma) at Alaska Highway											
T81	60.82	135.32	22	357	11	356.6	67.3	356.8	45.3	56	6.2
T82	60.82	135.32	22	357	9	322.6	76.6	343.4	56.2	49	7.4
T84	60.82	135.32	22	357	20	333.9	59.9	340.8	38.7	8	12.6
T85	60.82	135.32	22	357	12	329.6	75.9	345.8	54.9	15	11.4
T86	60.82	135.32	16	357	9	313.6	64.6	328.8	51.5	108	5.0
T87	60.82	135.32	16	357	11	317.0	68.5	332.9	54.8	64	5.8
T88	60.82	135.32	17	352	12	340.2	78.3	346.9	61.6	34	7.6
T90	60.82	135.32	17	351	21	340.1	79.3	346.7	62.4	29	6.0
T66	60.82	135.32	17	351	20	353.0	60.6	352.4	43.5	7	13.5
Mandanna (208–212 Ma) at Sid's Quarry											
T91	61.39	135.31	38	115	7	175.7	–64.1	250.3	–57.2	63	7.7
T92	61.39	135.31	42	092	8	152.8	–74.8	249.5	–53.4	113	5.2
T93	61.39	135.31	42	092	3	159.5	–73.1	246.3	–51.8	294	7.2
Mandanna (208–212 Ma) at Takhini											
T70	60.88	135.37	67	271	10	324.9	61.0	294.2	4.5	26	9.6
T71	60.88	135.37	67	271	7	5.0	58.1	305.4	21.5	27	11.8
T72[b]	60.88	135.37	67	271	7	61.8	56.4	296.0	50.4	15	16.2

Notes: BD, bedding dip; BDDA, bedding downdip azimuth; *n*, number of specimens; *D* and *I*, declination and inclination of the mean, respectively, with subscript G denoting geographic coordinates with respect to present horizontal and subscript S denoting stratigraphic coordinates with respect to paleohorizontal; *k*, Fisher precision; α_{95}, 95% confidence interval.

[a] Well-defined bedding.

[b] α_{95} >15°, so site not used in mean.

Fig. 1. Simplified geologic map, after Wheeler and McFeely (1991), of central southwest Yukon and northwest British Columbia showing the distribution of the Carmacks Group (dark areas) and sampling localities: Carmacks Group at Apex Mountain (C_A), Carmacks region (C_C), and Miner's Range (C_M); Nordenskiöld Formation at Cinnamon Bun Row (N_C) and Atlin Lake (N_A); Mandanna Member at Takhini (M_T), Alaska Highway (M_A), and Sid's Quarry (M_S). The crossed hammers mark mineral deposits which have been dated at Carmacks ages. Figure location and physiographic belts are shown in the inset map.



Group deposition to between 72 and 69 Ma (Grond et al. 1984; Lowey et al. 1986; Hart 1995). Recent ^{40}Ar–^{39}Ar studies are consistent with the bulk of volcanism occurring from 70 to 69 Ma (D. Francis, unpublished data).

Fragmental rocks of the lower unit of the Carmacks Group include coarse olivine, pyroxene, and feldspar porphyritic volcanoclastic and volcanoglomeratic rocks, laminated felsic and mafic tuff, shale, and mudstone. Subordinate flows of andesite and basaltic andesite are interbedded with the fragmental rocks. Isolated rhyodacite flows are locally present at the base and the top of the unit. Alteration, including saussuritization, bleaching, and sericite and hematite alteration, is common. Quartz chalcedony forms agates, lines and fills cavities, coats individual clasts, and fills crosscutting fractures. The thickest, coarsest accumulations of fragmental volcanic rocks define a number of volcanic complexes that are commonly cored by small (1 km^2) granitic to syenitic intrusions.

The areally extensive flat-lying flows of the upper flood-basalt unit overlie the fragmental unit along a small (<10°) angular unconformity. These flows consist primarily of olivine- and clinopyroxene-phyric flows that grade upward from basalt and basaltic andesite to primitive ankaramites which contain olivine (Fo_{93}) megacrysts (Francis and Johnston 1996*a*). Individual flows vary from 1 to 10 m thick and can be distinguished on the basis of flow-bottom and flow-top breccias, vesicle distribution, columnar jointing patterns, and lithological variation.

Fig. 2. Field photograph of fine-grained bedding present in some localities of Carmacks volcanics. Note glove for scale.

The Carmacks lavas range from high-potassium basalts to high-Si, low-Al primitive shoshonites. Pyroxene tuffs and olivine phyric flows range up to 15% MgO, requiring a high liquidus temperature (1400°C at 1 bar (100 kPa), dry). The lavas are characterized by calc-alkaline trace element signatures including enrichment in large ion lithophile elements (e.g., Rb, Ba, and K) and light rare earth elements (REE), relative depletion in high field strength elements (e.g., Nb, Zr, and Ti), and flat heavy REE patterns (Francis and Johnston 1996*a*). These features are consistent with melting of metasomatized subcontinental lithospheric mantle in response to elevated mantle temperatures (Francis and Johnston 1996*a*, 1996*b*; Johnston et al. 1996).

The stratigraphy, volume, and geochemistry of the Carmacks Group suggest that this basaltic province is attributable to melting above a hot spot (Johnston et al. 1996; Francis and Johnston 1996a). Though now deeply eroded, the Carmacks Group probably once covered much of southwest central Yukon, an area of 100 000 km^2, and includes extensive flood basalt. Much of this large basaltic province resulted from a short-lived (~1 Ma), highly productive magmatic event. The Carmacks Group was erupted during a "cusp" in Cordilleran magmatic activity (Armstrong 1988) and cannot be correlated with any coeval magmatic arc activity. The paucity of related intrusive bodies, a common characteristic of flood-basalt provinces, cannot be easily attributed to the current level of exposure, as the basalts are commonly deeply eroded. Locally, erosion has exposed the plutonic roots of the younger Sloko arc, a Tertiary volcanic succession which locally overlies the Carmacks Group. The anomalously high liquidus temperature required by the primitive basalts is consistent with the presence of an upwelling mantle plume, a hot spot. The geochemical character of the basalts suggests that impingement of the hot spot resulted in melting of enriched, subcontinental lithosphere. The resulting alkalic basalts are similar to the basal successions of other large continental flood-basalt provinces (e.g., the Paraná-Etandeka, Gibson et al. 1995).

Cretaceous volcanic rocks south of Whitehorse in Yukon and British Columbia also include the Windy–Table Suite which were previously included in the Carmacks Group (Wheeler and McFeeley 1991). Recent mapping and geochronological studies demonstrate that this volcanic succession includes thick felsic pyroclastic deposits and rhyolite flows and was deposited between 85 and 78 Ma (Mihalynuk et al. 1992; Hart 1995) and therefore is distinguishable from the Carmacks Group. During their paleomagnetic study of the Carmacks Group, Marquis and Globerman (1988) collected samples from five sites at Table Mountain near Atlin Lake in northern British Columbia. Volcanic rocks at these sites, which yielded a U–Pb zircon date of 81.3 ± 0.3 Ma (Mihalynuk et al. 1992), are now included in the Windy–Table Suite and therefore predate the Carmacks Group.

In this study, 15 sites were collected from two principal areas (Apex Mountain and the region just north of Carmacks) over two summers. Sites are listed in Table 1 in stratigraphic order. Generally shallow bedding (paleohorizontal) was inferred from the alignment of fragments, drawn-out vesicles, planar partings, breccia horizons assumed to represent flow-top and flow-bottom breccias, lithological contacts, and the averaged orientation of columnar joints. Five sites (W01–W05) were collected from a well-exposed sequence of intercalated finely bedded volcaniclastics (Fig. 2) and massively bedded pyroxene-phyric basalt flows on the north-facing cirque of Apex Mountain. Three sites (W06–W08) were collected from a homoclinal sequence of thick to massive bedded volcaniclastics and pyroxene and plagioclase-phyric basalt flows overlooking the Klotassin River. These sites span approximately 400 m of stratigraphy. Exposure consisted of isolated 3–5 m high outcrop steps punctuating the north-facing slope down to the Klotassin River. Four sites (W09–W12) were collected from high on the plateau that stretches south from Apex Mountain. Isolated outcrops of massively bedded pyroxene-phyric basalt flows with 5 mm glomeroporphyritic knots of plagioclase crystals were sampled. Three sites (W61–W63) were collected from isolated outcrops along the Klondike Highway north of Carmacks. The cores from the Carmacks Agate Quarry (site W61) are relatively unaltered, finely crystalline basalt with 0.2–5 cm quartz-filled amygdules. The other two sites on the highway are finely crystalline pyroxene-phyric basalt which is oxidized and vesicular.

Paleomagnetism

Examples of the typical response of the Carmacks Formation to demagnetization are shown in Fig. 3. At low temperatures (<300°C) or alternating fields (<20 mT), a small component, probably due to the present field, is removed. The characteristic magnetization has an unblocking temperature between 500 and 575°C and is removed by 80–90 mT alternating field (AF). Given the unblocking temperatures and coercivity spectrum of these specimens, the principal magnetic carrier is presumed to be single-domain titanomagnetite. Orthogonal plots show a straight-line decay to the origin which corresponds to a stable, unwavering end point in stereonet projections. Individual sites have well-clustered directions and correspondingly small 95% confidence circles. In one case (site W08), the present field component contaminated the characteristic direction, but the site mean could be isolated by locating the intersection of sector-constrained great circle demagnetization paths (method of McFadden and McElhinny 1988). Both normal (five sites) and reversed (eight sites) polarities were observed.

Specimens from two sites (W10, W12) high on the plateau south of Apex Mountain and four individual specimens from two other sites had enormous natural remanent magnetization (NRM) intensities (50–150 A/m), distributed unblocking temperatures (between 100 and 500°C), low coercivities, and anomalously shallow directions. This is the typical magnetic signature of rocks which have been hit by lightning. These specimens have been omitted from our analysis.

Site mean directions are summarized in Table 1. In Table 2, the site averages are combined in several ways. The mean direction obtained from our new data (indicated as "This study" in Table 2) is not significantly different ($P = 0.05$) from the direction obtained by Marquis and Globerman (1988) (see also Table 2). This direction is a recalculation of the average given by Marquis and Globerman (1988), leaving out data obtained from the five Table Mountain sites from the older Windy–Table Suite. The mean directions of the three localities are statistically indistinguishable (Miner's Range, Carmacks region, and Apex Mountain in Table 2), and the polarity means are antipodal to within 4.2 ± 8.6° (normal and reversed in Table 2). Combining all 26 sites, we obtain our preferred direction, $D = 166.3°$, $I = -69.3°$ ($k = 14$, $\alpha_{95} = 4.9°$) (Fig. 4; indicated as "All" in Table 2).

These sites pass the fold test; at 98 ± 6% unfolding there is maximum precision (k) and minimum 95% confidence circle radius (method of Watson and Enkin 1993). The bedding control available at some sites was less than optimal. To test whether poor bedding control had introduced an artificial shallowing of directions, we calculated the mean of just those sites from two localities (five sites from Millers Ridge, Marquis and Globerman (1988); five sites from Apex Mountain, this study) with the best bedding control (indicated as "Most reliable bedding" in Table 2). No fold test is possible because the contrast in attitudes between the two localities is insufficient. The mean direction of the remaining 16 sites (indicated as "Less reliable bedding" in Table 2) is not significantly different ($P = 0.05$)

Table 2. Formation and locality means.

		Geographic coordinates				Stratigraphic coordinates			
	N	D_G (°)	I_G (°)	k	α_{95} (°)	D_S (°)	I_S (°)	k	α_{95} (°)
Carmacks Group									
All	26	161.4	–71.6	18.8	6.7	166.3	–69.3	34.8	4.9
This study	13	160.0	–66.2	14.7	11.2	167.0	–66.2	28.8	7.9
Marquis and Globerman[a]	13	163.9	–76.7	29.7	7.7	165.4	–72.2	45.0	6.2
Most reliable bedding	10	161.9	–69.7	128.6	4.3	163.4	–69.1	128.7	4.3
Less reliable bedding	16	161.1	–72.8	12.0	11.1	168.2	–69.3	23.2	7.8
Miner's Range	5	117.4	–85.1	29.7	14.3	147.4	–76.2	30.9	14.0
Carmacks region	11	176.1	–73.8	20.9	10.2	174.5	–68.0	46.3	6.8
Apex Mountain	10	155.9	–61.0	27.1	9.5	163.5	–66.6	31.5	8.7
Normal polarity	7	337.9	75.2	60.6	7.8	340.8	71.7	107.7	5.8
Reverse polarity	19	162.5	–70.2	14.9	9.0	168.1	–68.3	27.7	6.5
Mandanna Member									
All	14	338.8	69.5	70.8	4.8	347.4	54.9	6.9	16.3
Alaska Highway	9	334.5	70.8	75.4	6.0	344.0	52.4	68.2	6.3
Sid's Quarry	3	164.9	–70.9	133.8	10.7	248.6	–54.1	709.8	4.6
Takhini	2	345.9	61.1			299.6	13.1		
Nordenskiöld Formation									
All	15	323.4	82.6	34.7	6.6	25.6	37.1	5.3	18.4
Cinnamon Bun Row	10	11.4	89.7	78.6	5.5	38.1	57.8	78.9	5.5
Atlin Lake	5	142.1	–68.1	74.0	9.0	192.0	10.8	74.0	9.0

Notes: *N*, number of sites in mean. Other terms as defined in Table 1.

[a] Recalculation from Marquis and Globerman (1988) study with five sites from what are now known to be pre-Carmacks Group rocks removed.

Fig. 3. Thermal (top) and AF (bottom) demagnetization characteristics of Upper Cretaceous Carmacks Group magnetization. The directions have been corrected for bedding orientation. In orthogonal plots, the horizontal and vertical projections are marked with solid and open circles, respectively. In stereographs, the lower and upper hemispheres are marked with solid and open symbols, respectively. Temperatures are in °C, and peak AF intensities in mT. The Carmacks Group has the magnetic signature of single-domain magnetite.

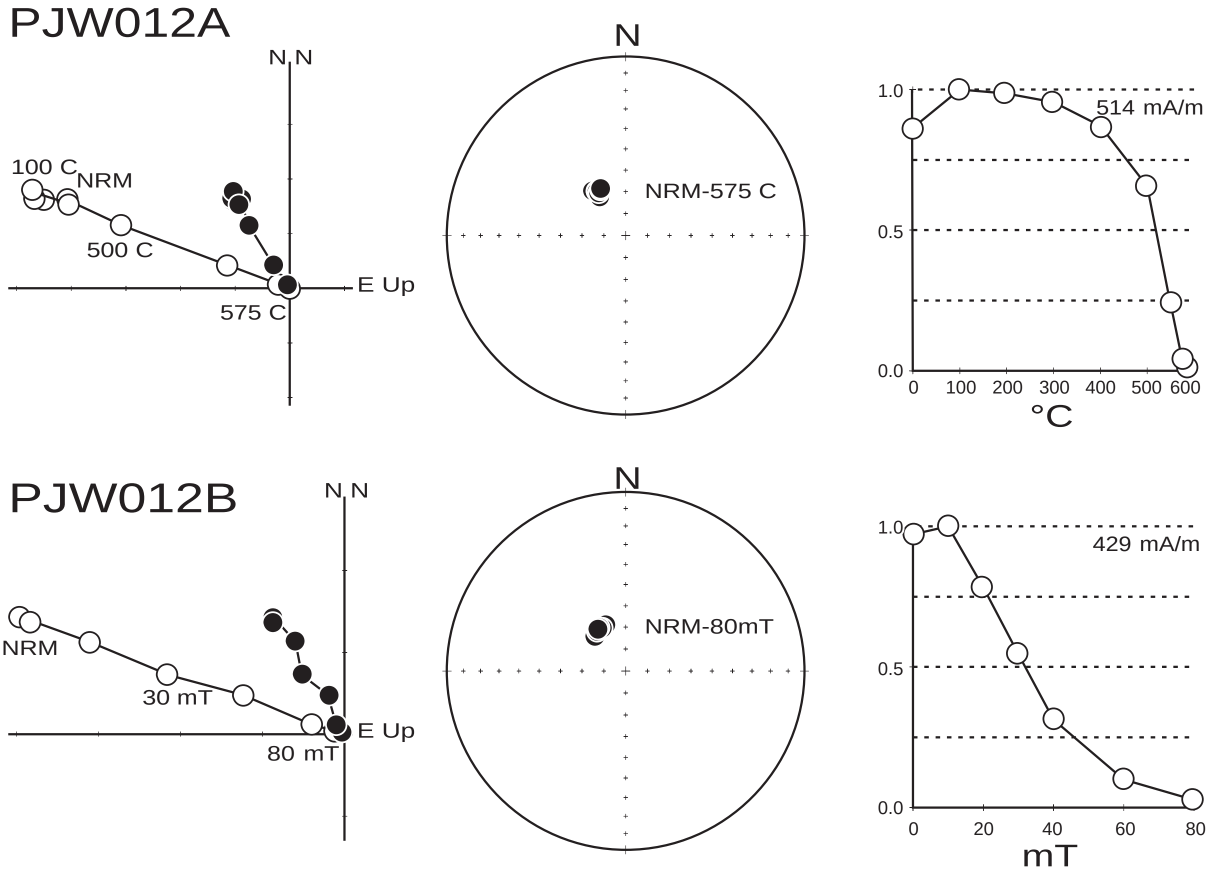
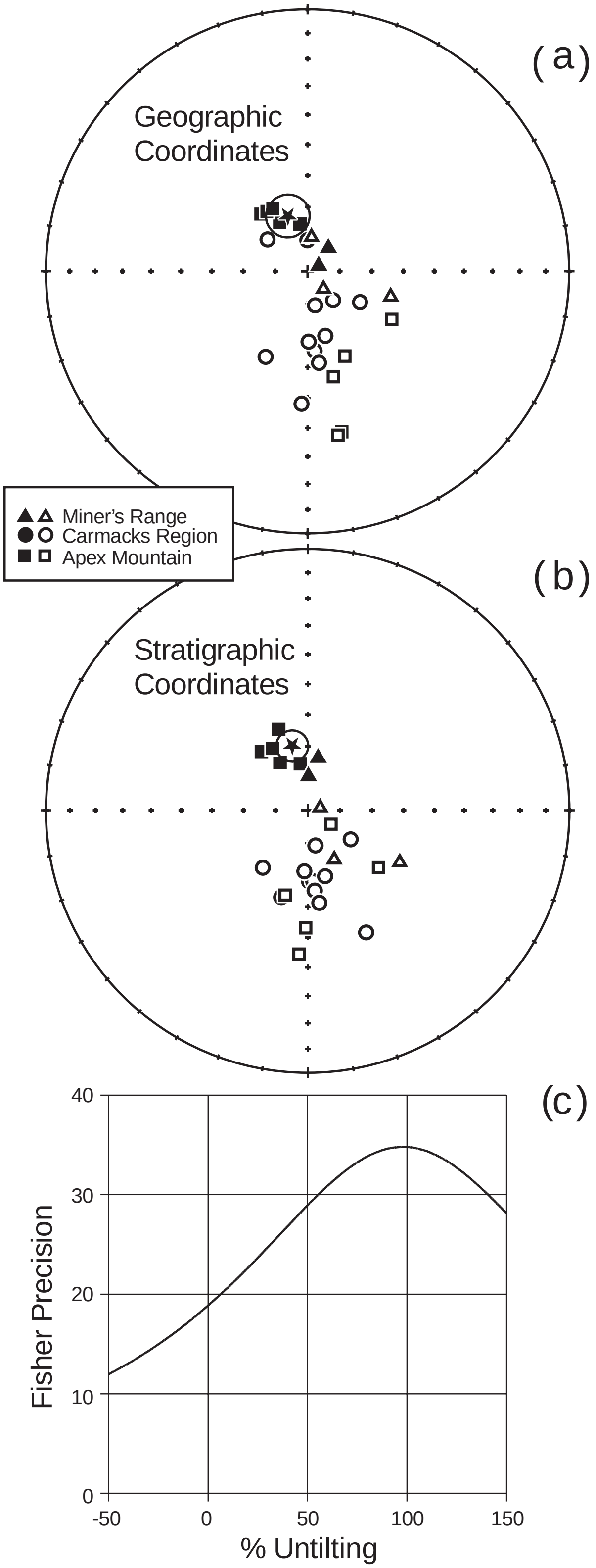


Fig. 4. Carmacks Group site directions from three localities, and their mean (denoted by ★). The lower and upper hemispheres are marked with solid and open symbols, respectively. (*a*, *b*) Stereographs showing directions before and after tectonic correction. (*c*) Graph showing that maximum concentration of the site mean directions occurs on full tectonic correction (98 ± 6% untilting), indicating a positive fold test.



from the mean to the 10 best controlled sites. Therefore, we are confident that the effects of poor bedding control are random and have not skewed our results. In the discussion that follows the $N = 26$ average, using all sites, will be used.

Mandanna Member

Geology and sampling

Mandanna Member strata include up to a kilometre thick section that occurs at the top of the Lewes River Group in the western Whitehorse Trough. The member is dominated by well-bedded arkosic and tuffaceous sandstone, and mudstone with subordinate conglomerate. All lithologies are characterized by a distinctive maroon colour, although green-coloured beds are not uncommon. Locally clasts of the oxidized maroon material occur as clasts in the green beds, indicating syndepositional oxidation, consistent with a lagoonal to intertidal deposition (Hart 1997).

Cores were collected from three localities (Table 1). Bedding is well established at all localities. The nearly flat-lying Alaska Highway locality (nine sites) is cut by three andesitic dykes, thus allowing a contact test. The Takhini locality (three sites) has interbedded conglomeratic units which allow for a conglomerate test, and the third locality (three sites) near Scout Lake (Sid's Quarry) has a significantly different attitude which permits a regional fold test.

Paleomagnetism

The red colour of these rocks is characteristic of hematite. At 100 mT AF, 25–75% of the NRM intensity remains. This high coercivity is typical of hematite. Alternating field demagnetization fails to define the characteristic direction of magnetization and consequently the majority of the specimens were thermally demagnetized. The specimens with the best defined single component magnetizations have orthogonal plots with straight-line decays to the origin with a well-defined end point. These specimens have sharp, square-shouldered demagnetization curves with unblocking temperatures above 600°C (Fig. 5, YUT812B). Many of the Mandanna Member specimens also contain some magnetite (possibly detrital), which is seen in sloping demagnetization curves between 100 and 600°C. The characteristic magnetization for most specimens was isolated, using line fitting between 100 and 680°C.

Contact test

At the Alaska Highway locality, the Mandanna Member is cut by three dykes of probable Eocene age. Similar dykes mapped 18 km west yielded a K–Ar whole rock age of 52.1 ± 2.6 Ma (Hart 1997). The dykes are 0.4–1.3 m wide, weakly altered, fine to medium grained, and mafic in composition, with small granite and shale xenoliths and less than 5% phenocrysts (plagioclase and pyroxene). They trend north–south and have subvertical margins.

At this locality, the rocks distant from the dykes all contain normal polarity remanence and have magnetization characteristics typical of Mandanna Member rocks at other localities (e.g., Fig. 5, YUT812B). The dykes also have normal polarity (e.g., Fig. 5, YUT894A). Surprisingly, rocks in the contact zone (less than a quarter of a dyke width away, Fig. 6) are overprinted in a reversed direction (e.g., Fig. 5, YUT904A).

Fig. 5. Demagnetization characteristics of Upper Triassic Mandanna Member magnetization. See Fig. 3 for symbol conventions. The bottom specimen, YUT812B, shows typical characteristics of the majority of specimens, with a hematite magnetic signature. In the contact zone of Eocene dykes, e.g., YUT904A, there is a total overpint in a reversed direction. Farther away from the dykes, e.g., YUT906A, there is a partial overprint in the reverse direction (400–550°C). The dykes, e.g., YUT894A, have low magnetic stability and merely record the present field direction.

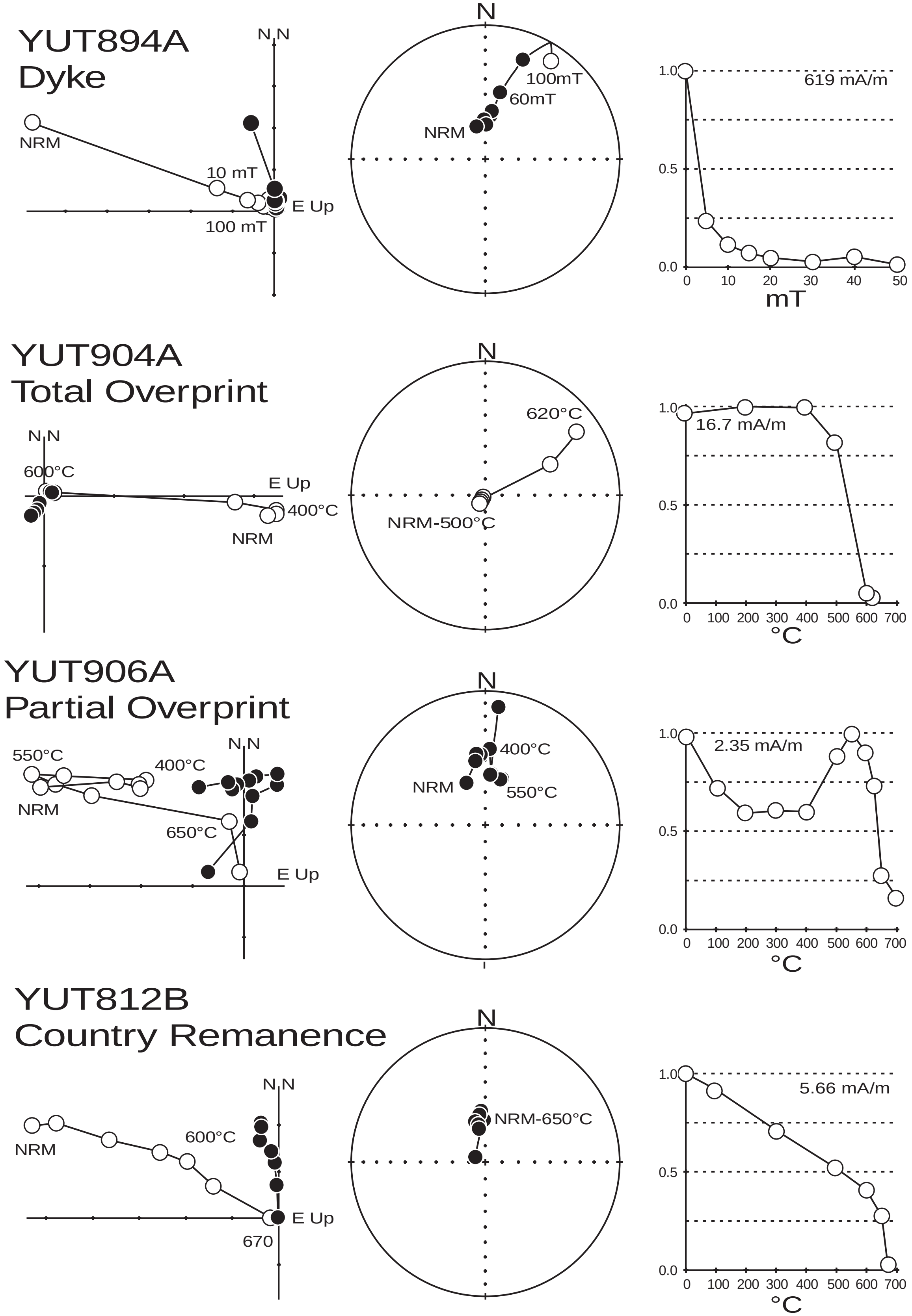
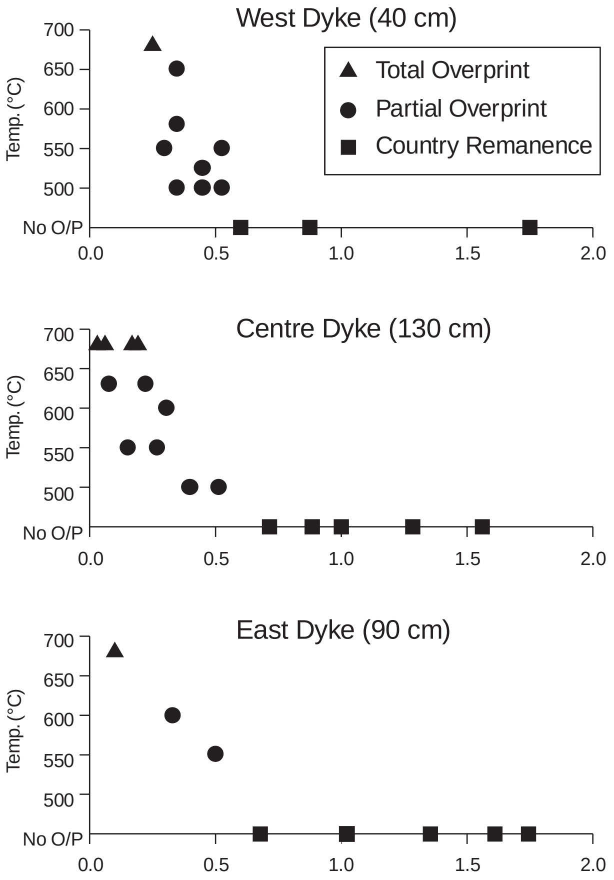


Fig. 6. Maximum unblocking temperature of the reverse polarity overprint observed in the contact zones of three dykes cutting the Mandanna Member. Rocks within one-quarter dyke width are totally overprinted. Outside one-half dyke width, there is no observed contact effect. The unblocking temperature in the partial overprint zone decreases with distance from the dykes. Despite the lack of an ancient remanence in the dykes, the thermal signature of the contact zone renders a positive contact test. No O/P, no overprint.

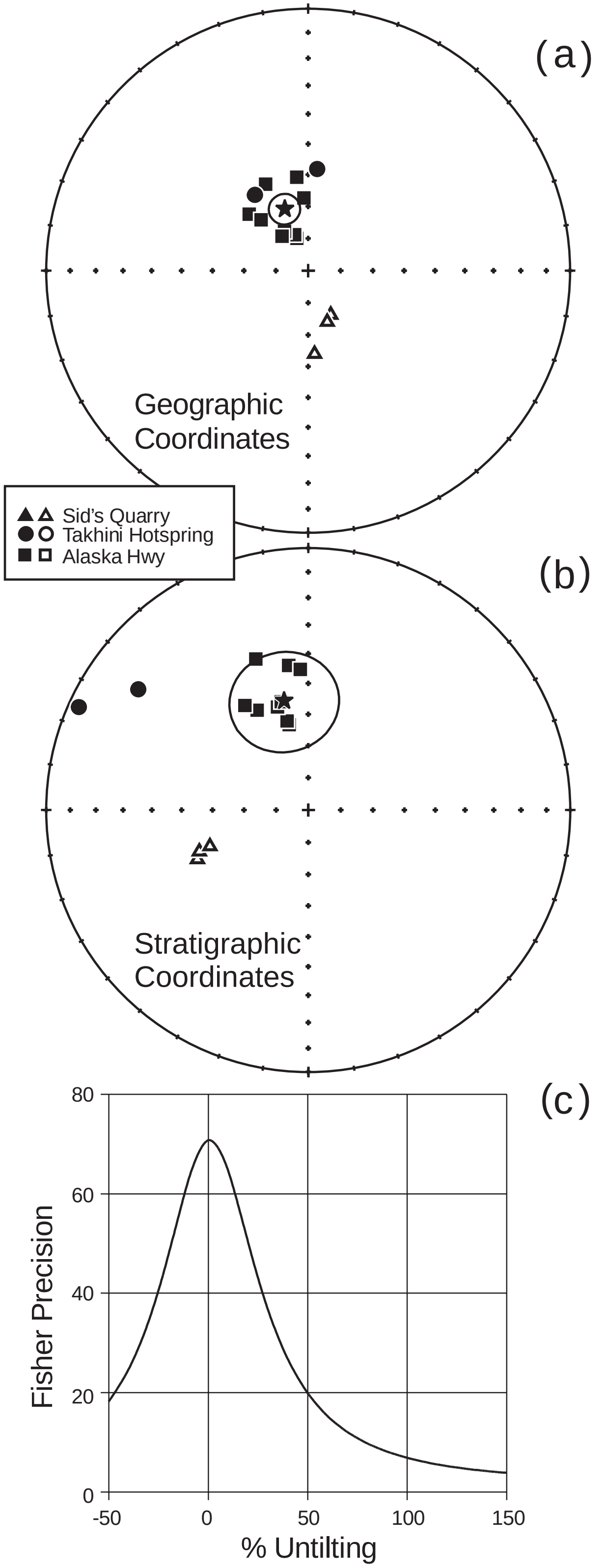


The rocks between a quarter and a half dyke width away (Fig. 6) carry a composite magnetic signature with both normal and reversed components (e.g., Fig. 5, YUT906A).

The maximum unblocking temperature of the reverse component decreases with distance away from the dykes (from 680°C near the contact down to 500°C at one-half dyke width distance). Thus, the reverse magnetization is a thermal overprint produced by the intrusion of the dykes which must have occurred during a reverse geomagnetic polarity chron.

The dykes themselves have completely lost their original remanence. Their normal polarity remanence is soft, with low coercivity (median destructive field less than 10 mT) and low unblocking temperatures (median destructive temperature is about 100°C). The mean direction for the dykes (with respect to present horizontal: $N = 3$ sites, $D = 003.8°$, $I = 66.5°$, $k = 112$, $\alpha_{95} = 11.7°$) is not significantly different ($P = 0.05$) from that of the Present Earth's Field. This locality has preserved a remarkable situation where the dyke itself has retained no primary magnetic memory, but Mandanna rocks in the thermal aureole have recorded the direction of the field at the time the

Fig. 7. Mandanna Member site directions from three localities, and their mean (denoted by ★). The lower and upper hemispheres are marked with solid and open symbols, respectively. (*a*, *b*) Stereographs showing directions before and after tectonic correction. (*c*) Graph showing that maximum concentration of the site mean directions occurs with no tectonic correction (1 ± 5% untilting), indicating a negative fold test.



dyke intruded. Outside the contact zone, Mandanna Member rocks retain a pre-intrusive (>50 Ma) remanence. This constitutes a positive contact test; the magnetization of the Mandanna Member away from dykes predates dyke intrusion.

Conglomerate test

At the locality overlooking the Takhini Hotspring, a polymictic boulder conglomerate of Mandanna Member material was sampled (site T71). Two cores were taken from three different boulders in a single bed. At the 95% confidence level, the remanent directions are too closely clustered to have been chosen at random from a uniform angular distribution ($N = 3$ samples, $R = 2.93 > R_{\mathrm{CRIT}} = 2.71$, where R is the resultant vector and R_{CRIT} is the critical threshold resultant value below which the directons are considered random; Stephens 1964). Furthermore, the mean directions of these boulders is midway between the site mean directions at neighbouring sites T70 and T72. This negative conglomerate test indicates that the Mandanna Member at this location was magnetically overprinted after deposition and lithification.

Site mean directions and reversal and fold tests

The mean directions for each site are listed in Table 1. The formational averages are listed in Table 2. The site mean directions plotted in Fig. 7 show that each locality has a well-defined mean direction, but that they are dispersed after correction for bedding. On the other hand, in present coordinates, they are highly clustered. The degree of unfolding which provides the tightest concentration is at 1 ± 5% (Watson and Enkin 1993), indicating a highly significant negative fold test. The beds were first deformed and then remagnetized.

However, the Alaska Highway (country rock and high-temperature components within the dyke contact zones) and the Takhini Hotspring sites are all normally magnetized, whereas those from Sid's Quarry contain a reverse polarity, indicating that they were not remagnetized at exactly the same time. With respect to present horizontal, the angular difference between the two polarity groups is 3.2 ± 7.1° away from antipodal (95% confidence interval, method of Debiche and Watson 1995), indicating that the sites were remagnetized over a period with no significant apparent polar wander, but long enough (>10 ka) to average out secular variation.

Summary of Mandanna Member paleomagnetism

The positive contact and reversal tests in the Mandanna Member are indicative of stable and ancient (>50 Ma) remanence, and the negative conglomerate and fold tests indicate that the remanent magnetization postdates Middle to Late Jurassic deformation.

The observed inclination is shallow compared with directions predicted from the post-150 Ma North American apparent polar wander path. However, the remanent direction is similar to the distinctive direction isolated from the Carmacks Group (2.6 ± 5.2° difference). This suggests that the Mandanna Member red beds were remagnetized at the same time that Carmacks Group lavas were extruded. Furthermore, these coincident mean directions constitute a large-scale contact test and validate the Carmacks result.

Nordenskiöld Formation

Geology and sampling

The Early Jurassic Nordenskiöld Formation is composed of up to 700 m of crystal-rich dacite tuff and volcanogenic sandstone that accumulated over most of the western Whitehorse Trough (Hart 1997). Its age is constrained by isotopic methods to 184–186 Ma (Hart 1997; Johannson and McNicoll 1997) and biostratigraphically to the Pleinsbachian and Toarcian (Pálfy and Hart 1997; Johannson and McNicoll 1997). The formation is typically coarse grained and consists of subhedral quartz, feldspar, hornblende grains, and clasts of adjacent sedimentary strata or polycrystalline parent tuffaceous material. Grains and clasts are set in a variably altered fine-ash matrix which accounts for <10% of the rock. Attitude is typically well defined by graded beds and intercalations of sandstone or conglomerate.

Paleomagnetism

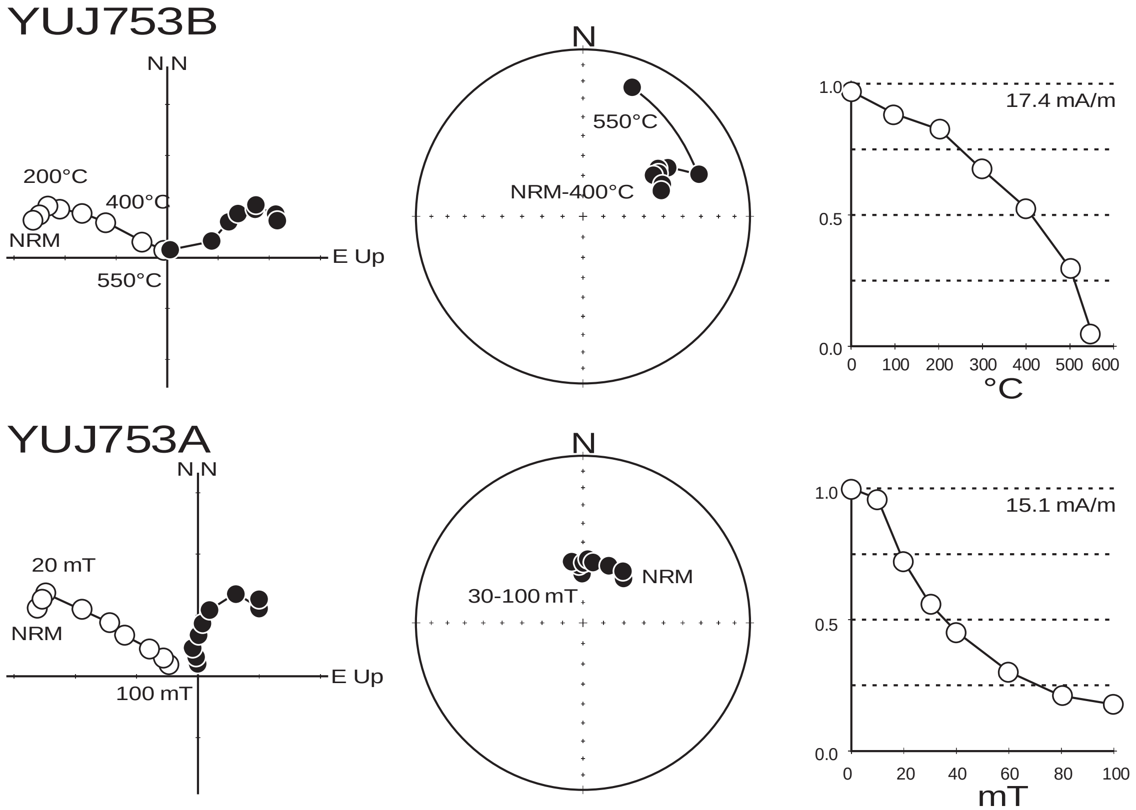
Cores were collected at three localities (Fig. 1). Results from two localities, Cinnamon Bun Row and Atlin Lake, are presented in Table 1. No coherent results were obtained from four sites at the third locality (under the microwave communications tower at 60°55′N, 135°14′W); the magnetization there is characterized by widely scattered NRM directions (clustering does not improve with demagnetization), and soft remanence (median destructive field of 10 mT, median destructive temperature of 100°C). They are poor paleomagnetic recorders and will not be discussed further.

Figure 8 illustrates the typical behaviour of the Nordenskiöld Formation upon demagnetization. A small component, probably due to the present field, is removed at low temperature and alternating fields. The median destructive temperature is around 400°C and the median destructive field between 30 and 40 mT. All directions used in the site averages (Fig. 9; Table 1) were determined using principal component analysis over three to seven treatment steps. The magnetization remaining at high alternating fields is possibly carried by pyrrhotite, since many of the thermal demagnetization curves have a distinct shoulder at 300°C, the unblocking temperature characteristic of pyrrhotite.

The locality mean directions are plotted in Fig. 9 and summarized in Table 2. The fold test is not definitive, since the magnetization directions are not well clustered either before or after tectonic correction. Maximum concentration of site means occurs at the absurd value of –13 ± 4%, indicating that the sites do not come from a single population. With respect to paleohorizontal, the locality means are over 70° apart (Fig. 9*b*); with respect to present horizontal, the two locality means are much closer together (only 22° apart; Fig. 9*a*), suggesting that the magnetization is postdeformational.

Strata at the Atlin Lake locality have been tilted to almost vertical dips. Because of this, correction of the strata back to horizontal produces extreme results. After correction, the site means are subhorizontal, which implies an unreasonable equatorial paleolatitude for the region in the Jurassic. On the other hand, the mean direction in present coordinates is not significantly different (6.6 ± 7.0°) from the mean direction of the Carmacks Group (Fig. 10). The inclination, –68.1°, is shallow compared with expected North America paleolatitudes, but is

Fig. 8. Demagnetization characteristics of Lower Jurassic Nordenskiöld Formation magnetization. See Fig. 3 for symbol conventions. The main magnetic carrier is magnetite.



consistent with the Carmacks Group. It appears, therefore, that, like the Mandanna Member, the Nordenskiöld Formation at this locality was totally overprinted, after tilting, at the time of extrusion of the Carmacks Group.

The interpretation for the Cinnamon Bun Row locality remanence is less straightforward. The mean direction before tectonic correction is nearly vertical, which implies magnetization at the north pole. But after tectonic correction, the direction is shallow even compared with the Carmacks remanence. There are at least three ways this result can be interpreted: (*i*) the remanence could be primary, but it is shallow compared with other Jurassic paleomagnetic data obtained in the southern Intermontane Belt (e.g., Monger and Irving 1980); (*ii*) the remanence could be a predeformational Cretaceous overprint, implying an approximately 60° clockwise vertical axis rotation; and (*iii*) the remanence could be a postdeformational Cretaceous overprint followed by a further tilt of 20° down towards 347°NNW. Tilts of this magnitude have been observed in the Carmacks Formation elsewhere and so it is not unreasonable to invoke a late tilt. This explains the discrepancy between the locality mean direction of Cinnamon Bun Row (tilted after being overprinted during extrusion of the Carmacks Group) and that of Atlin Lake (not tilted after overprinting), and we favour this interpretation.

Discussion

Northward displacement

Our new data confirmed, with added accuracy, the Marquis and Globerman (1988) results for the Carmacks Formation. We now have double the number of sites, an extended areal sampling, and strong positive fold and reversal tests.

The paleomagnetic pole from the Carmacks Formation is at 088.6°E, 78.4°N ($A_{95} = 7.8°$ with $N = 26$ sites) (Fig. 11). To make paleogeographic interpretations, we must compare this pole to the reference pole for cratonic North America. Following a relatively long period with little or no apparent polar wander (130–85 Ma), the Upper Cretaceous is marked by a quick but poorly constrained jump of about 11° in pole position (for discussion see Gunderson and Sheriff 1991; and Diehl 1991). Following Wynne et al. (1992, their Table 3), we average reliable cratonic poles within 10 Ma of 70 Ma. Using 189.9°E, 79.2°N ($A_{95} = 4.2°$, $N = 5$ studies) as the reference 70 Ma pole for cratonic North America, we find (method of Debiche and Watson 1995) a paleolatitude displacement of the Carmacks Group of 17.0 ± 6.5°. The displacement is larger (insignificantly) than that deduced by Marquis and Globerman (1988), due in part to the difference in the reference field calculations and in part to the slightly shallower combined mean inclination.

The 70 Ma paleopole puts the Carmacks Group and associated basement terranes south about 1900 ± 700 km (paleolatitude swath in Fig. 11). Beck et al. (1981) introduced the idea that the oblique subduction of the Kula plate during the Cretaceous and Tertiary could have been the cause of large margin-parallel motions along the North American coast. Recent kinematic models (Johnston et al. 1996; D. Engebretson, unpublished data) indicate that the Kula plate had a margin-parallel displacement of about 2000 km between 70 and 53

Fig. 9. Nordenskiöld Formation site directions from two localities, and their mean (denoted by ★). The lower and upper hemispheres are marked with solid and open symbols, respectively. (*a*, *b*) Stereographs showing directions before and after tectonic correction. (*c*) Graph showing that maximum concentration of the site mean directions occurs at –13 ± 4% untilting. This unrealistic value indicates that the mean directions from the two localities are not sampled from the same population.

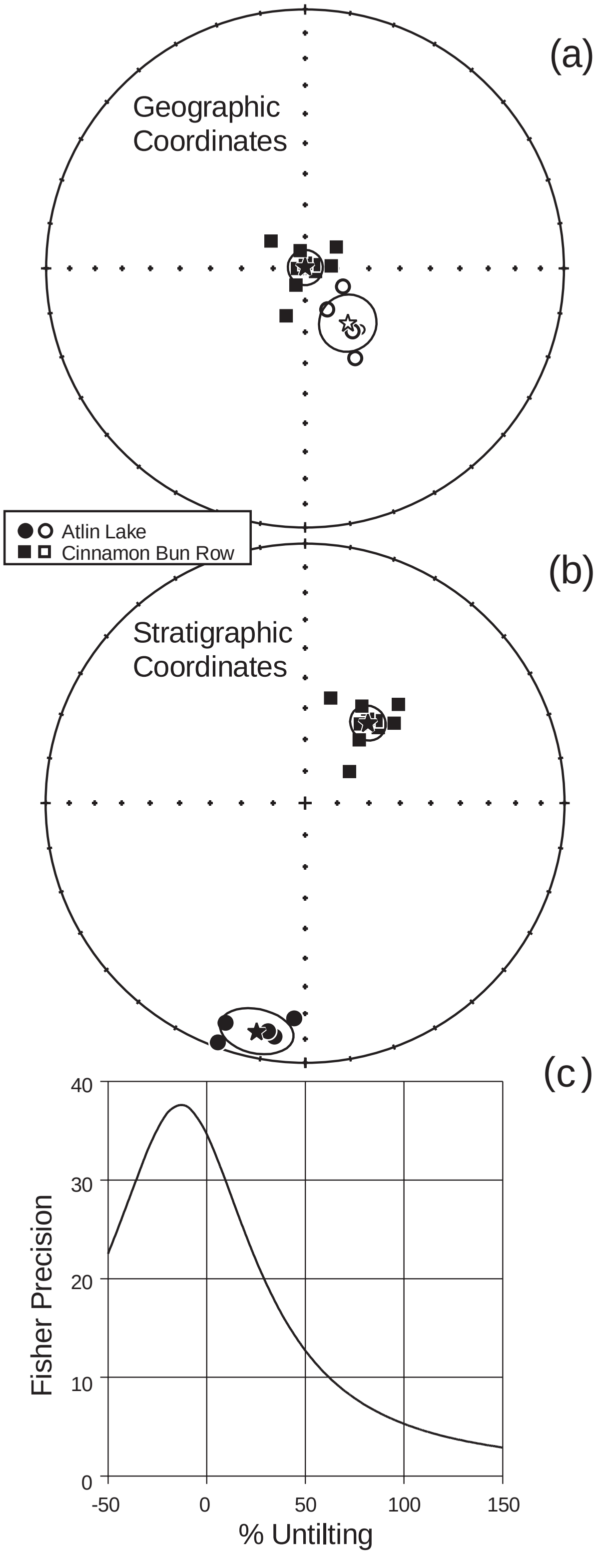
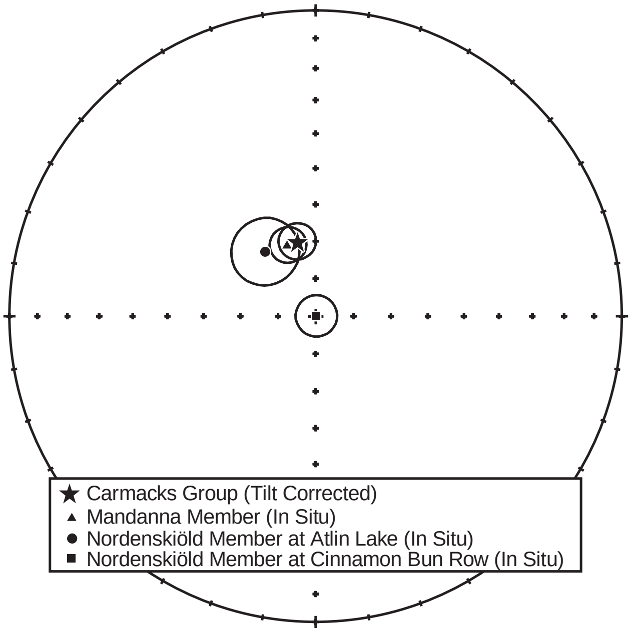


Fig. 10. Comparison of Nordenskiöld Formation and Mandanna Member means (no tectonic correction) with the Carmacks mean after tilt correction. The Mandanna Member from three localities and the Nordenskiöld Formation at Atlin Lake have mean directions which are indistinguishable from the Carmacks Group mean. The Nordenskiöld Formation at Cinnamon Bun Row mean seems to have been tilted after the Late Cretaceous by 20° towards azimuth 347°NNW.



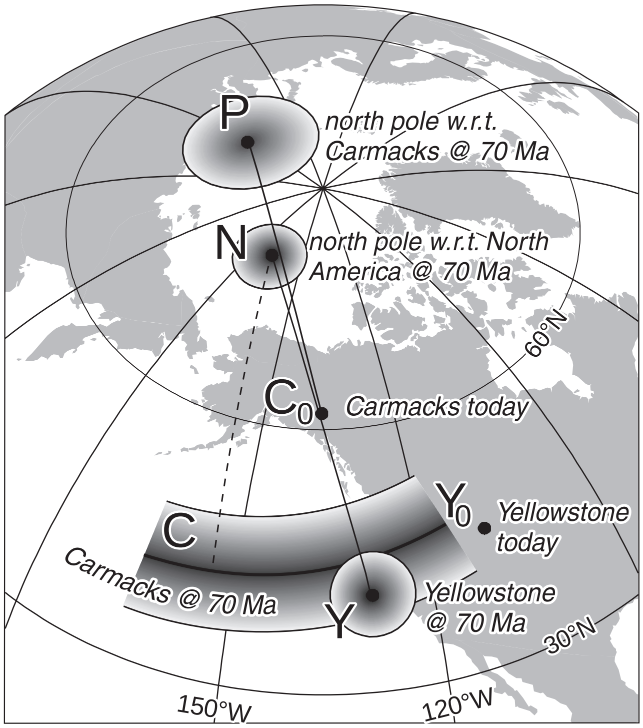
Ma, sufficient to transport the Carmacks Group to its present position. If the northward displacement continued up to 45 Ma, then only 70% coupling is necessary between the margin-parallel component of subducting oceanic plate and the basement terranes carrying the Carmacks Group northward.

The locus of motion between the displaced terranes and cratonic North America continues to be controversial. Although large orogen-parallel faults with significant dextral strike-slip motions are common in the Cordillera, it is difficult to accommodate the >1000 km displacements determined paleomagnetically along the currently recognized faults. Beck (1991) considers several aspects of this problem in relation to the displacement of Baja California. The discrepancy could be caused by errors in the paleomagnetic interpretation or incompleteness of the geological record. The strain could have been distributed among many small and unobserved faults, and displacements along major faults may have been obscured by subsequent events (see, for example, Irving et al. 1996, their Fig. 6). The discrepancy between paleomagnetic and geologically determined displacement serves as a call for further paleomagnetic study and geological mapping.

The big flush

The most surprising result from this study was that the underlying formations have been so thoroughly remagnetized in the distinctive Carmacks direction. Both the Triassic Mandanna Member and Jurassic Nordenskiöld Formation were magnetized after their Jurassic deformation. The positive contact test in the Mandanna Member constrains the remagnetization event to have been before dyke intrusion at 50 Ma. These

Fig. 11. Paleogeographic interpretation of the Carmacks Group paleomagnetism. The paleomagnetic poles (with their 95% confidence intervals) of North America (N) and the Carmacks Group (P) were aligned along the geographic pole at 70 Ma. This implies that central southwest Yukon was displaced to a position within swath C at the time of Carmacks extrusion. The Yellowstone hot spot was at point Y at 70 Ma, which we argue was the source of the Carmacks volcanics and the associated hydrothermal event which remagnetized underlying formations.



formations contain both polarities; however, each locality is uniformly magnetized with a single polarity. Thus, the remagnetization was relatively brief within each locality (polarity chron duration is usually less than 1 Ma during the Upper Cretaceous), but significantly different between localities.

It is possible that the Carmacks volcanism can be causally linked to the remagnetization. Carmacks outcrops appear to be erosional remnants of a widespread sheetlike succession that probably covered much of southwest central Yukon (Tempelman-Kluit 1974). Hydrothermal activity resulting in widespread alteration (Smuk et al. 1997), the resetting of K–Ar systematics, and epithermal and porphyry-style gold mineralization were coeval with Carmacks volcanism (Hart 1995). The lower Carmacks Group is commonly bleached and saussuritized, and contains quartz-chalcedony veins, amygdules, and agates. Older volcanic sequences in west- and south-central Yukon are commonly altered and yield K–Ar ages reset to Late Cretaceous (Hart 1995). We suggest that hydrothermal systems circulated in permeable formations below the flood basalts of the Carmacks Group, recrystallizing iron oxides in the rocks in the ambient field of the Late Cretaceous to produce the postdeformational overprints we observed.

Yellowstone in the Yukon

A hot-spot (mantle plume) origin for the Carmacks Group has been proposed (Johnston et al. 1996). This hot-spot origin may provide an important paleogeographic constraint on the evolution of the Cordillera. The paleomagnetic pole of the formation places the eruption around the position of the Oregon–Washington state boundary coincident with the 70 Ma location of the Yellowstone hot spot. On the basis of geochemistry, this paleomagnetic study, geological mapping, and geochronology, we hypothesized (Johnston et al. 1996) that the Carmacks Group is a displaced segment of the Yellowstone hot-spot track.

Paleomagnetic studies give no information on the paleolongitude of a displaced terrane, since the geomagnetic field is axially symmetric. However, the full paleoposition of a hot spot can be determined from relative plate motion studies and, in the case of the Yellowstone hot spot, provides a paleolongitude for the Carmacks Group. Knowledge of the paleolongitude allows us to estimate 1000 km of post-70 Ma orogen-normal displacement and 2000 km of orogen-parallel displacement. This hypothesis has testable implications, concerning the degree of orogen-normal and orogen-parallel displacement along the entire Cordillera.

Conclusions

The Carmacks Group has an anomalously shallow inclination with respect to North America, confirming the earlier study by Marquis and Globerman (1988). Underlying formations were remagnetized in this same anomalously shallow direction, further supporting the validity of the Carmacks direction. We interpret the regional remagnetization to be the result of extensive hydrothermal alteration coeval with Carmacks magmatism. The Carmacks Group and coeval hydrothermal alteration provide evidence of the passage of central southwest Yukon over the Yellowstone hot spot at 70 Ma.

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