Paleomagnetism of the ~91 Ma Deadman pluton: Post-mid-Cretaceous tectonic motion in central Yukon

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ABSTRACT

The 92 ±1 Ma Deadman pluton is a massive, circular, felsic intrusion of alkalic composition that is part of the Tombstone plutonic suite. It intrudes Neoproterozoic Hyland Group strata within the Dawson thrust sheet in the northernmost Selwyn Basin. Paleomagnetic determinations have isolated a stable characteristic remanent magnetization (ChRM) direction, in magnetite, for 237 specimens from 23 sites. The sites are in three plutonic phases, in three dykes cutting the pluton as well as their contact zones, and in the pluton's contact-zone skarn. The ChRM at all sites is coeval with pluton crystallization. The ChRM directions of all sites form one population with a mean direction of declination = 333.0°, inclination = 76.8° (α_{95} = 2.6°, k = 139, N = 23), giving a paleopole of 144.9°E, 78.5°N (δ_p = 4.5°, δ_m = 4.8°) that is significantly different, at 95% confidence, from the coeval North American cratonic paleopole. This discordance is attributed to post-emplacement, northward displacement of at least several tens of kilometres of the Dawson thrust sheet, possibly along the Dawson thrust fault. The result is the 'beheading' of the Deadman pluton and rotating its 'head' as it was driven up the curved frontal ramp of the thrust fault. This evidence indicates at least local, but significant, post-mid-Cretaceous deformation within rocks underlying northern Selwyn Basin.

RÉSUMÉ

Le pluton de Deadman, datant de 92±1 Ma, est une intrusion felsique massive et circulaire de composition alcaline qui fait partie du cortège plutonique de Tombstone. Il pénètre les strates du Groupe de Hyland, datant du Néoprotérozoïque, à l'intérieur de la nappe de charriage de Dawson, dans la partie la plus septentrionale du bassin de Selwyn. Les analyses paléomagnétiques ont permis d'isoler une direction stable d'aimantation rémanente caractéristique (ChRM), dans la magnétite, pour 237 spécimens prélevés en 23 sites. Les sites se répartissent en trois phases plutoniques : à l'intérieur de trois dykes recoupant le pluton ainsi que leurs zones de contact, et dans le skarn de la zone de contact du pluton. Dans tous les sites, la ChRM est contemporaine de la cristallisation du pluton. Les directions de la ChRM appartiennent à une même population statistique avec une direction moyenne de déclinaison = 333,0°, une inclinaison = 76,8° α_{95} = 2,6°, k = 139, N = 23), indiquant une position du paléopôle par 144,9° E. et 78,5° N. (δ_p = 4,5°, δ_m = 4,8°), ce qui représente un écart significatif, à un niveau de confiance de 95 %, par rapport au paléopôle du craton nord-américain d'âge identique. Cet écart est attribuable au déplacement vers le nord de la nappe de charriage de Dawson, après la mise en place, sur au moins plusieurs dizaines de kilomètres le long de la faille de chevauchement de Dawson. Ainsi, le pluton de Deadman's Gulch a été « étêté », sa « tête » subissant une rotation tandis qu'elle était poussée vers le haut contre la rampe frontale incurvée de la faille de chevauchement. Ces constatations indiquent que les roches du protocontinent nord-américain, en général et le long de la faille de Dawson en particulier, ont subi une déformation importante, à tout le moins par endroits, ultérieure au Crétacé.

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INTRODUCTION

Previous paleomagnetic studies of Mesozoic rocks in the northern Canadian Cordillera have indicated significant displacements and rotations of those more outboard tectonic elements (i.e., terranes) in the western and central Cordillera (e.g., Irving and Wynne, 1992). In order to provide a local mid-Cretaceous paleopole, the Deadman pluton was chosen to provide a paleopole for the North American craton close to the large, transcurrent Tintina Fault, which represents the craton's edge and boundary with the allochthonous accreted terranes, including Yukon-Tanana Terrane (YTT) (Figs. 1, 2). This aim was based on the geologic rationale that the rocks of the Selwyn Basin that host the Deadman pluton had been a stable entity since the middle Cretaceous. However, since the study began and samples were taken in 2000, several lines of geophysical evidence have emerged to support the opposite hypothesis — that the basin has been involved in active orogenesis since the pluton's emplacement (Symons *et al.*, 2005). This paper provides a test of conflicting hypotheses regarding the participation, mobility and timing of deformation in the miogeoclinal strata above the cratonic basement.

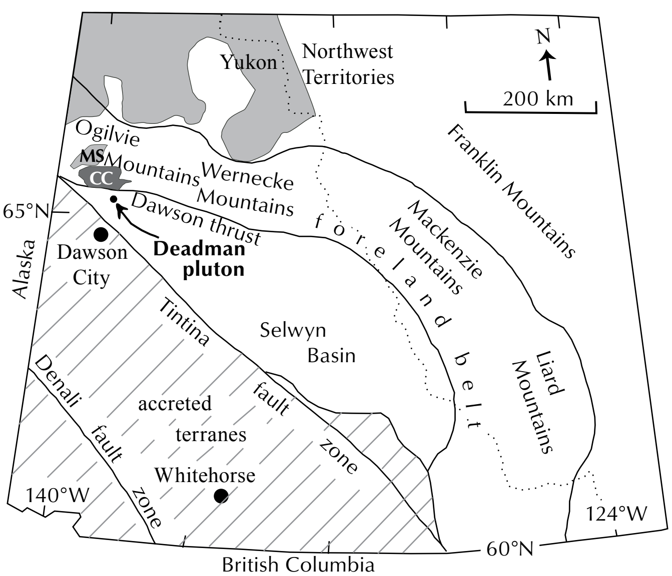

Figure 1. *Location map for Deadman pluton, and assorted tectonic elements of Yukon (modified after Gordey and Makepeace, 2003). Accreted terranes are shown with diagonal hatching; the ancient North American cratonic margin in white; dark shade is the Proterozoic Coal Creek (CC) inlier; light shade is Cretaceous basins, including the Monster synclinorium (MS).*

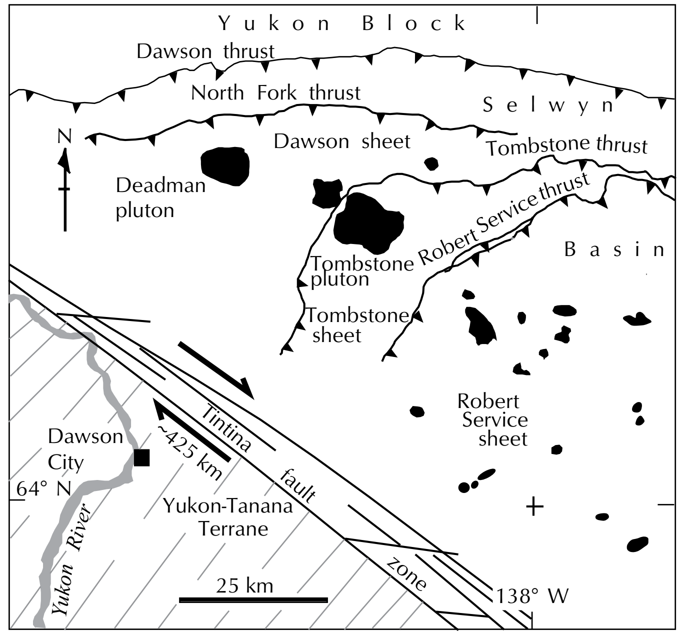

Figure 2. *Regional geology after Gordey and Makepeace (2003) showing the northwestern end of the Tombstone plutonic suite and major faults. The plutons are represented by the solid black polygons. The barbs on the thrust faults indicate the downdip direction, and the Tintina Fault has a right-lateral displacement of ~425 km. The accreted Yukon-Tanana Terrane has diagonal hatching.*

Within the framework of Lithoprobe, Canada's National Geoscience Project (Clowes *et al.*, 1999), the Slave-Northern Cordillera Lithospheric Evolution (SNORCLE) transect provided support for multidisciplinary studies aimed at examining the complex relationships within and between terranes in northwestern Canada. This study of the Deadman pluton in Yukon is one of a series of paleomagnetic studies begun under SNORCLE's aegis (Symons *et al.*, 2005).

GEOLOGY

The Deadman pluton is located about 55 km north of Dawson City, Yukon (Fig. 2). The stock is the most northerly member of a northwest-trending string of five mid-Cretaceous plutons and numerous assorted stocks, dykes and sills that parallel the Tintina Fault, which is ~35 km to the south-southwest (Anderson, 1987; Hart *et al.*, 2004). The plutons comprise the Tombstone plutonic suite, which are essentially defined by their alkalic compositions (Hart *et al.*, 2005). The plutons intrude deformed but weakly metamorphosed strata of the Selwyn Basin that represent the most outboard components of the western North American miogeocline. Selwyn Basin assemblages at this location includes Neoproterozoic coarse clastic Hyland Group; lower Paleozoic Road River Group black shales and chert; Mississippian quartzite; Permian shale and chert; Triassic quartzite, calcareous siltstone, limestone and gabbro; and Jurassic black shale. These Selwyn Basin rocks are juxtaposed across the Dawson Fault against the Yukon Block (Abbott, 1997) where Proterozoic assemblages of the Coal Creek inlier are exposed beneath Lower Paleozoic dolostone and shale. The Coal Creek inlier includes three dominantly sedimentary assemblages: the Paleoproterozoic Wernecke Supergroup (Gillespie Lake and Quartet groups), Mesoproterozoic Pinguicula/Fifteen-Mile Group and Neoproterozoic Mt. Harper Group volcanic strata (Thompson *et al.*, 1992; Abbott, 1997). Paleozoic rocks include Ordovician to Devonian dolostone of the Bouvette Formation and time-equivalent black shale and chert of the Road River Group, and Devono-Mississippian black shale, chert and siliciclastic rocks of the Earn Group. North of the Coal Creek inlier, the Earn Group is overlain by a succession of Carboniferous, Permian and Triassic shale, limey shale and limestone. Triassic strata are unconformably overlain by Cretaceous siliciclastic rocks of the Monster Formation in the Monster synclinorium (Ricketts, 1988).

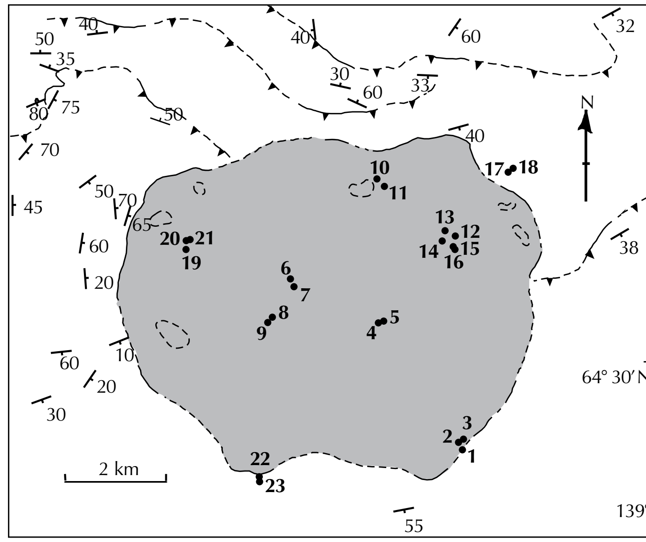

Figure 3. *Location of sampling sites (solid circles) in, and adjacent to, the Deadman pluton (shaded). The surrounding host rocks belong to the Precambrian Hyland Group (clear) but have been hornfelsed within the pluton's contact aureole. Strikes and dips are shown for these strata, as are subsidiary thrust faults of the Dawson thrust with barbs pointing downdip. Modified from Thompson et al., (1992).*

Plutons of the Tombstone plutonic suite intrude the Selwyn Basin strata. The Deadman pluton is circular, about 7 km in diameter and has steep sides (Fig. 3). It is a concentrically zoned multiphase alkalic pluton composed mostly of medium- to coarse-grained alkali-feldspar syenite and biotite-hornblende monzonite, with lesser amounts of quartz monzonite and pseudoleucite-phyric tinguaite (Anderson, 1987). Vein, skarn and disseminated uranium-thorium-fluorine, antimony-arsenic-gold, tin-silver and gold-copper-bismuth mineralization occur within and adjacent to the Tombstone suite plutons (Hart *et al.*, 2005). In the Deadman pluton, uranium-thorium mineralization is associated with the tinguaite, a silica-undersaturated, highly potassic leucite porphyry. The stock is dated at 91 ± 1 Ma by the U-Pb SHRIMP method on zircons that are large and mostly unzoned (C. Hart, unpublished). This date is similar to determinations from other plutons in the suite, and similar K-Ar dates from the adjacent Tombstone pluton (Fig. 2) indicate that the plutons cooled rapidly within a few million years (Anderson, 1987; Hart *et al.*, 2005). Based on petrography and slightly elevated aeromagnetic responses and magnetic susceptibility values, Hart *et al.*, (2004) deem the Tombstone suite to be magnetite-series granitoids (Ishihara, 1981). They correlate the suite with the Livengood suite in east-central Alaska to form the Livengood-Tombstone plutonic belt, which requires ~425 km of post-emplacement dextral displacement on the Tintina fault zone.

Folds with west- to northwest-trending fold axes and related thrust faults deform the Selwyn Basin assemblages (Thompson, 1995; Murphy, 1997), and to a lesser degree those of the Yukon Block. The Dawson, Tombstone and Robert Service faults are thought to be low-angle thrust faults (Fig. 2) and account for most of the northward displacement (Tempelman-Kluit, 1982; Thompson *et al.*, 1992; Murphy, 1997; Mair *et al.*, in press). Regional metamorphism is at sub-greenschist levels. Deformation is dated at pre-Late Jurassic by macrofossils from deformed Jurassic rocks in the footwall of the Tombstone thrust fault (Poulton and Tempelman-Kluit, 1982), and at pre-105 Ma by Ar-Ar dates on metamorphic micas in deformed Hyland Group in the Robert Service thrust sheet (Mair *et al.*, in press). Deformation in Selwyn Basin, at surface, predates emplacement of the Tombstone suite plutons based on the massive non-foliated character of the plutons (Anderson, 1987) and their mapped cross-cutting relationships with folds and thrust faults (Tempelman-Kluit, 1970; Thompson *et al.*, 1992; Murphy, 1997). For example, undeformed Tombstone suite plutons cut both the Tombstone and Robert Service thrust faults. The Deadman pluton intrudes thrust-faulted Hyland Group strata in the Dawson thrust sheet and presumably cuts the south-dipping Dawson thrust fault at depth (Fig. 2).

EXPERIMENTAL METHODS

SAMPLING

The Deadman pluton forms an isolated rugged 2000 m mountain peak rising about 1000 m above the adjacent valley floors. Outcrops are accessible by helicopter, and most are exposed in cirques. Six or seven 2.54-cm diameter cores were drilled, oriented by sun compass or by magnetic compass in a few cases, and collected from each of twenty-three sites (Fig. 3). Of these sites, 8 were located in monzonite, 5 in syenite, 1 in tinguaite, 3 in felsic dykes cutting the pluton, 2 in dyke contact zones, and 4 in skarns of in the Precambrian host rocks around the pluton. From 8 to 13 standard paleomagnetic specimens with a 2.20-cm length were sliced from the cores to represent each site (Table 1). The specimens were stored in a magnetically shielded room with an ambient field of about 0.2% of the Earth's magnetic field intensity for about three months before measurement to allow their unwanted viscous remanent magnetization (VRM) components to substantially decay. VRM are unstable easily changed magnetization components in a specimen that are produced by the Earth's ambient magnetic field in the field or laboratory.

NATURAL REMANENT MAGNETIZATIONS

The natural remanent magnetizations (NRM) of the specimens were measured on a Canadian Thin Films DRM-420 cryogenic magnetometer with a sensitivity of ~10^{-6} A/m. The median (M) NRM intensities by rock type were monzonite, M = 2.2 x 10^{-1} A/m, N = 100 specimens; syenite, M = 1.2 x 10^{-1} A/m, N = 49; tinguaite, M = 4.4 x 10^{-1} A/m, N = 13; felsic dykes, M = 0.46 x 10^{-1} A/m, N = 37; dyke contact zones, M = 1.5 x 10^{-1} A/m, N = 15; and, host rock skarns, M = 2.3 x 10^{-1} A/m. Excluding the skarn specimens, the overall NRM intensity for the pluton is M = 1.6 x 10^{-1} A/m with first and third quartile values of Q_1 = 0.65 x 10^{-1} A/m and Q_3 = 3.2 x 10^{-1} A/m.

Table 1. *Site mean remanence directions.*

Site	Rock unit	N m, e	D °	I °	α_{95} °	k
1	Pm	10, 8	332.8	72.1	3.1	323
2	Pc	11, 11	348.2	74.4	11.1	18.0
3	df	11, 11	329.4	72.2	5.9	60.5
4	Pm	13, 13	354.9	71.6	3.8	119
5	Pm	12, 10	295.5	67.3	7.7	40.2
6	Pm	8, 8	8.7	67.9	6.9	65.9
7	Ps	8, 8	322.7	76.4	2.0	745
8	Ps	8, 8	320.0	74.0	4.5	154
9	Ps	8, 8	342.0	83.5	5.1	119
10	Pt	9, 9	304.3	75.2	2.4	465
11	Pm	10, 10	311.1	82.1	6.8	51.0
12	Pm	11, 10	306.0	80.3	6.6	55.2
13	Pm	12, 12	324.7	75.7	7.5	34.1
14	Pm	13, 13	338.5	75.5	3.6	130
15	Pc	14, 14	313.9	75.5	4.8	69.7
16	df	9, 8	325.4	77.1	4.8	137
17	H	8, 8	318.8	78.9	19.4	9.14
18	H	8, 8	321.0	83.9	10.9	26.8
19	Ps	12, 12	26.6	76.7	6.4	51.8
20	Ps	10, 10	337.1	79.5	2.9	271
21	df	11, 10	344.8	78.0	5.0	93.5
22	H	11, 11	346.4	72.9	2.6	310
23	H	10, 9	347.2	72.9	2.5	438

Rock unit abbreviations: c = contact zone, d = dyke, f = felsic, H = host rock, m = monzonite, P = pluton, s = syenite, t = tinguaite. Number (N) of specimens measured (m) and used endpoint directions (e). Mean Declination (D), Inclination (I) and Radius of Cone of 95% Confidence (α_{95}) in degrees (°) and precision parameter (k) of Fisher (1953).

STEP DEMAGNETIZATION

Two specimens with typical NRM intensities and directions were selected from each site and subjected to thermal demagnetization in 12 steps up to 600°C using a Magnetic Measurements MMTD-80 thermal demagnetizer. The NRM is the vector sum of the remanent magnetization components present in a specimen when it is first measured. The steps were preferentially concentrated in the 260 to 330°C and 500 to 600°C temperature ranges that are diagnostic for thermally demagnetizing pyrrhotite and magnetite, respectively. A further two typical specimens from each site were alternating field (AF) demagnetized in 12 steps up to 130 mT using a Sapphire Instruments SI-4 AF demagnetizer. Based on the results from these four specimens per site, the remaining specimens from each site were step demagnetized using one of three regimens. Specimens from two baked contact zones of dykes (sites 2 and 15) were thermally demagnetized following the 12-step pattern used for the initial two specimens. Specimens from five sites (12, 13, 14, 19 and 22) were thermally demagnetized in 10 steps between 390 and 600°C, and those from the remaining 16 sites were AF-demagnetized in 6 steps between 20 mT and 70 to 110 mT.

The characteristic remanent magnetization (ChRM) directions of the 237 specimens were determined using visual inspection of vector component plots (Zijderveld, 1967) and calculated using the least-squares fitting method (Kirschvink, 1980). The ChRM component is the stable remanence of geologic interest that is preserved by a specimen. As evident from the 97% of specimens yielding endpoint ChRM directions that were used (Table 1), nearly all of the specimens gave normal directions with maximum angular deviation values of ≤10° over several steps. Examples of specimens from the various petrologic phases of the pluton that show this reliable paleomagnetic behaviour on thermal and AF step demagnetization are given in Figures 4 and 5, respectively. The steep decrease in intensity on thermal demagnetization above 500°C shows that the ChRM resides mostly in magnetite or very low-titanium titanomagnetite.

Host rock sites 22 and 23 are within ~200 m of the observed contact with the Deadman pluton and sites 17

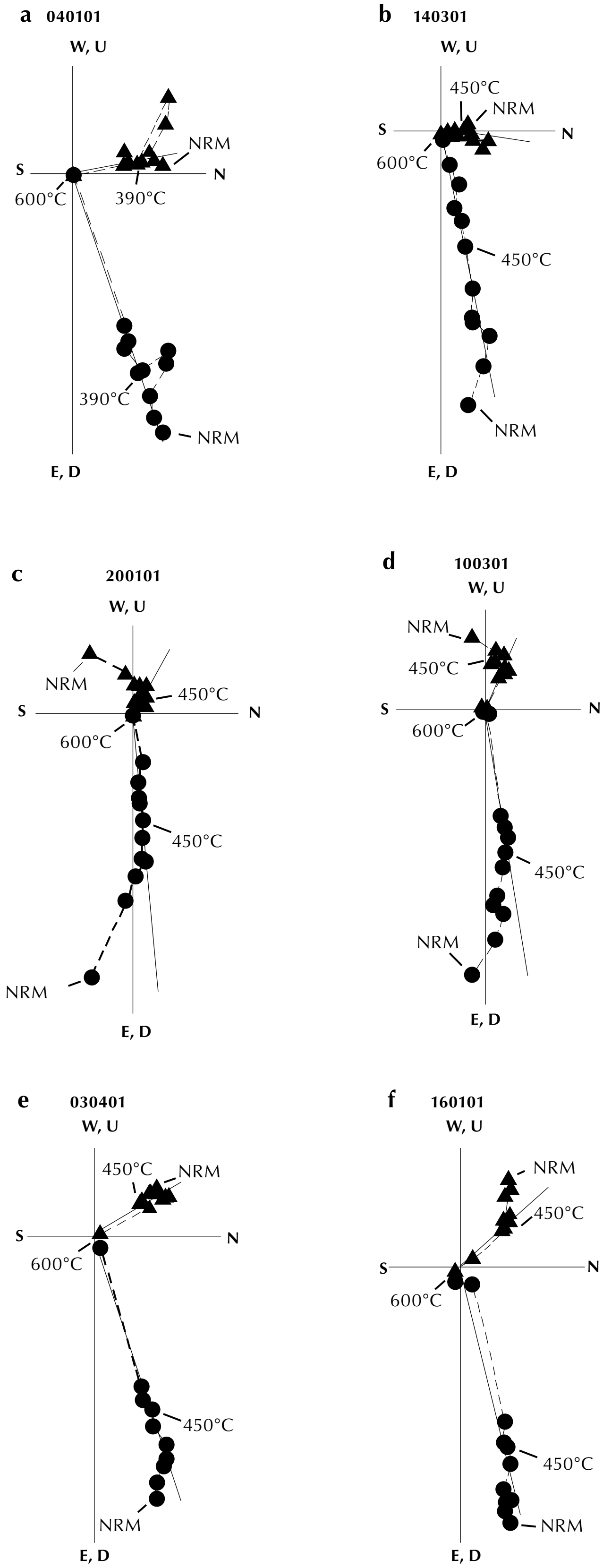

Figure 4. *Thermal step demagnetization of example specimens from phases of the Deadman pluton: **(a)** monzonite, site 4; **(b)** monzonite, site 14; **(c)** syenite, site 20; **(d)** tinguaite, site 10, **(e)** felsic dyke, site 3; and **(f)** felsic dyke, site 16. The characteristic remanent magnetization (ChRM) vector is projected onto the horizontal plane (triangles; north (N), east (E), south (S), and west (W) axes) and vertical plane (circles; up (U), north (N), down (D), and south (S) axes). The axial values are the ratio of the measured ChRM intensity (J) to the initial natural remanent magnetization (NRM) intensity (J_0), and the J_0 values in 10^{-1} A/m are: **(a)** 0.548; **(b)** 1.29; **(c)** 3.03; **(d)** 4.29; **(e)** 0.206; and **(f)** 0.166. The temperatures of some demagnetizing steps are given in °C.*

and 18 are about 300 to 400 m from the contact, but all four sites are in skarn within the pluton's contact aureole. Most of the specimens gave normal steeply downward northwesterly ChRM directions (Fig. 6a,b). Thermal step demagnetization shows that the ChRM resides in magnetite in most cases (Fig. 6c), except for some specimens from the skarn at site 17, in which it resides in pyrrhotite (Fig. 6d).

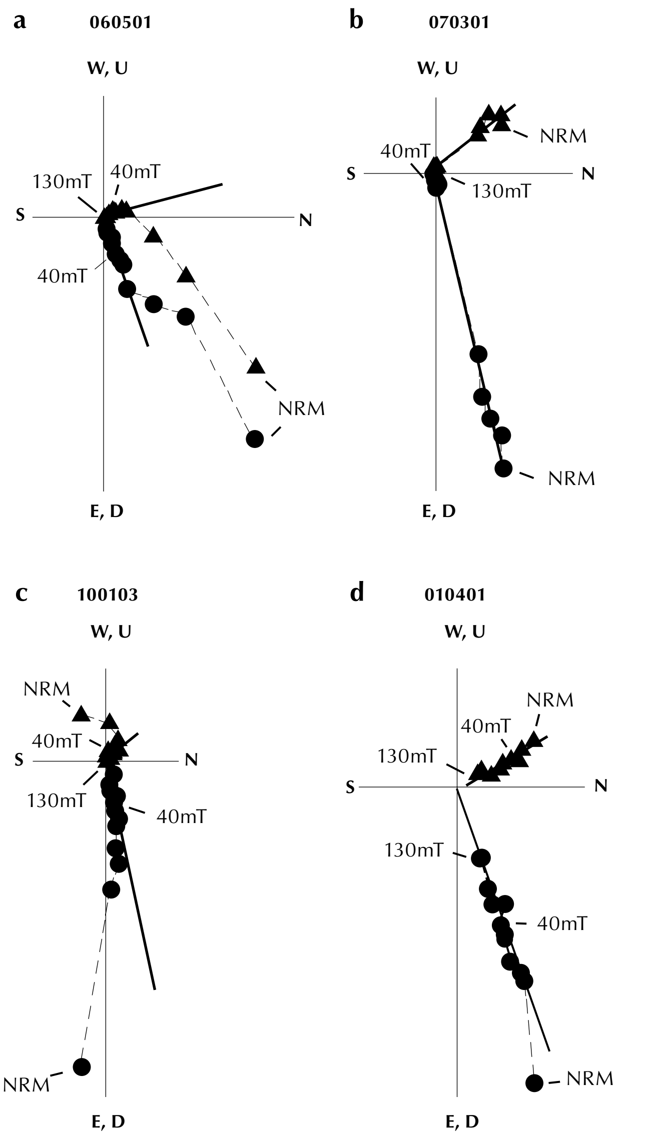

Figure 5. *Alternating-field (AF) step demagnetization of example specimens from phases of Deadman pluton: **(a)** monzonite, site 6; **(b)** syenite, site 7; **(c)** tinguaite, site 10; and **(d)** felsic dyke, site 1. Conventions as in Figure 3. The J_0 values in 10^{-1} A/m are: **(a)** 6.42; **(b)** 0.281; **(c)** 3.38; and **(d)** 2.79. The intensity of some demagnetizing steps are given in mT.*

SATURATION REMANENCE

Saturation isothermal remanent magnetization (SIRM) testing was done on 12 specimens to better characterize the magnetic minerals in the various rock types. A given magnetic mineral, such as pyrrhotite, reaches magnetic saturation in a distinctive range of applied direct-field intensities, and the rates of SIRM acquisition and demagnetization are indicative of the dominant domain sizes present in the mineral. The specimens were pulse magnetized in 12 steps up to 900 mT using a Sapphire

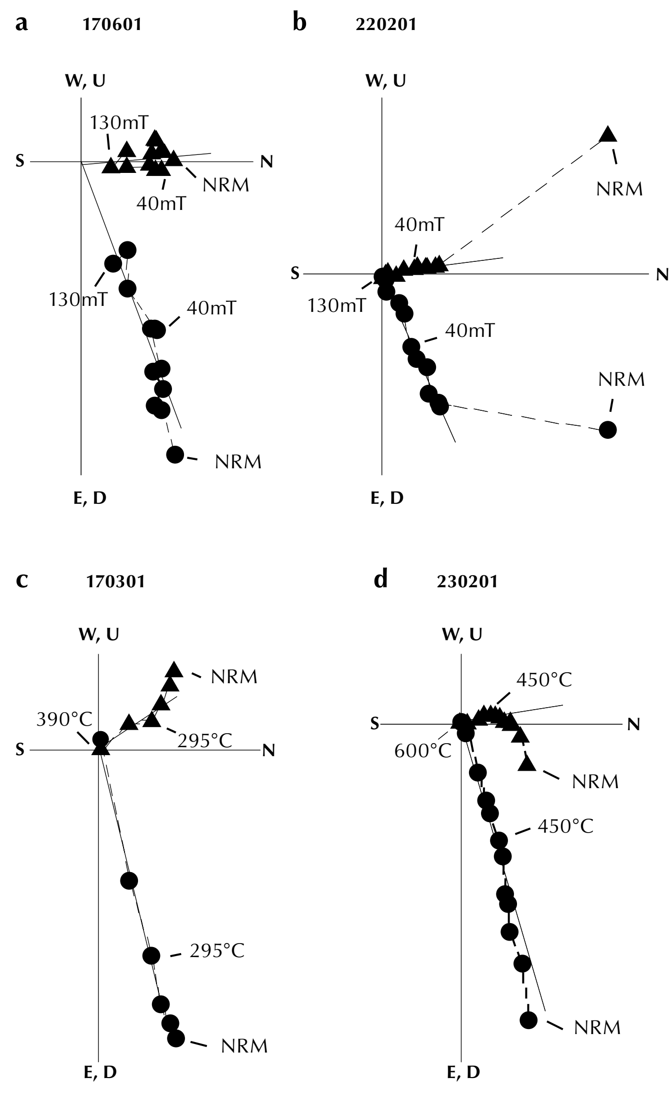

Figure 6. *Alternating-field and thermal step demagnetization of example specimens from the host rock skarn of the Deadman pluton from: **(a)** site 17; **(b)** site 22; **(c)** site 17; and **(d)** site 23. Conventions as in Figure 3 and 4. The J_0 values in 10^{-1} A/m are: **(a)** 0.591; **(b)** 0.253; **(c)** 4.01; and **(d)** 5.50.*

Instruments SI-6 direct-field pulse magnetizer to define their SIRM acquisition. In all cases, the specimens saturated by ~250 mT, indicating that their remanence is carried mainly by magnetite (Fig. 7a). The specimens were then AF demagnetized in 12 steps to 150 mT. The decay rates of their SIRM intensities, when plotted against type curves for magnetite, indicate that the ChRM is carried mostly by single and pseudosingle domain magnetite (Fig. 7b). In general, single or pseudosingle domain magnetite is carried by inclusions in the major minerals of an igneous rock and, therefore, is the most likely remanence component to retain a stable primary ChRM. Also, when the axial values for the crossover points are compared to type curves for magnetite (Fig. 7c) (Symons and Cioppa, 2000), the lithologies all give comparable intensity ratio values (J/J_{900}) of 0.32 ± 0.04 (pluton, 0.33 ± 0.04; dykes, 0.30 ± 0.04; skarn, 0.31). These values all indicate considerable interaction between the magnetic fields of the individual magnetite crystals in the specimens, thereby decreasing the values from a non-interacting ideal value of 0.50. Finally, the crossover points yield a mean value of 22 ± 12 mT for the magnetizing and demagnetizing fields in the nine pluton specimens, indicating that they carry mostly pseudosingle domain magnetite, with lesser amounts of single and multidomain magnetite. Similarly, the two dyke specimens and the skarn specimen give values of 23 ± 3 mT and 32 mT, respectively, indicating that their magnetization is carried mostly by pseudosingle domain magnetite.

SITE/UNIT MEAN CHRM DIRECTIONS

The site mean ChRM directions were calculated from the 229 accepted specimen directions using methods described by Fisher (1953). Only 8 specimens, or 3%, gave an aberrant ChRM direction or failed to give a reliable direction. Nearly all sites had well clustered specimen directions, giving a median value for the radii of their cones at 95% confidence (α_{95}) of 5.0° and for their precision parameters (k) of 93.5. Site 17 in the host rock skarn was the sole exception and gave loosely clustered directions with α_{95} = 19.4° and k = 9.14. This is the site in which the ChRM resided in both pyrrhotite and magnetite, suggesting that the two minerals acquired their remanence at different times and that either apparent polar wander or tectonic tilt occurred during the intervening time.

Plotted on a stereonet (Fig. 8), the site mean ChRM directions form a coherent cluster. Therefore, the test of McFadden and Lowes (1981) was used sequentially to

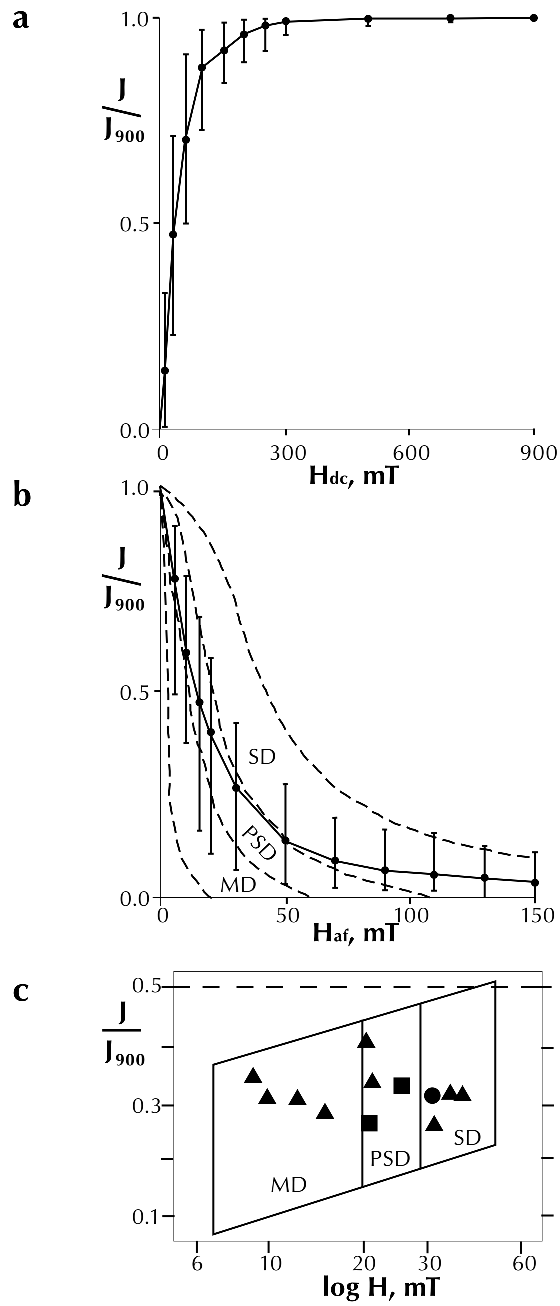

Figure 7. *Saturation isothermal remanent magnetization (SIRM) data for example specimens of various lithologies:* ***(a)*** *SIRM acquisition;* ***(b)*** *AF demagnetization of SIRM; and* ***(c)*** *crossover points for the acquisition and decay curves. The magnetizing H_{dc} and demagnetizing H_{af} field axes are labeled in mT and the y-axis is the ratio of the measured intensity (J) to the saturation intensity at 900 mT (J_{900}). The reference curves are for magnetite: SD = single domain, PSD = pseudosingle domain, and MD = multidomain. The symbols denote specimens from the ▲ pluton, ■ dykes, and ● host rock skarn.*

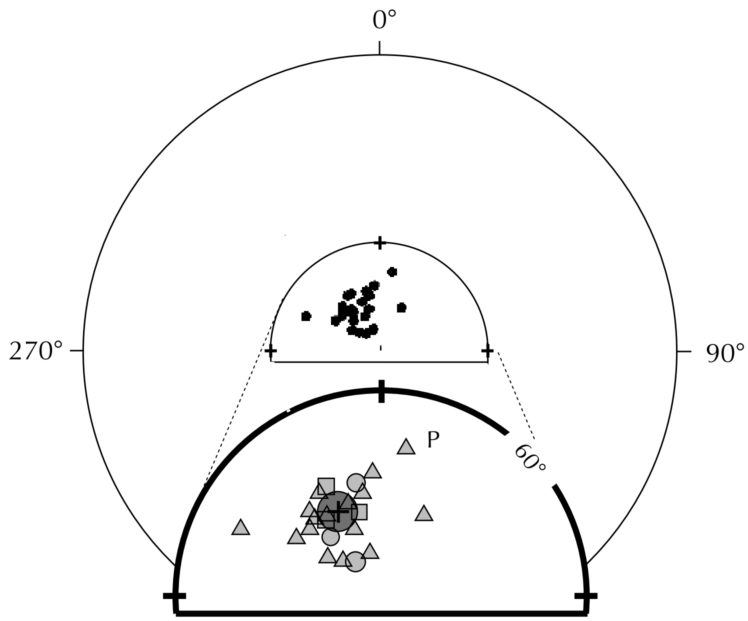

Figure 8. *Equal-area stereonet showing the site mean directions for the Deadman pluton collection. Site symbols: ▲ pluton, ■ dykes, ● host rock skarn. The inset shows the central portion of the stereonet at inclinations of >60° for added clarity, along with the population mean (+) and its cone of 95% (2σ) confidence. The present Earth's magnetic field direction is shown by a "P".*

compare the mean directions for the various lithologies, to see if they represented statistically different populations at >95% confidence. The test showed that: a) the pluton's 8 monzonite site mean directions are indistinguishable from the 5 syenite site mean directions, that is, they may share a common mean and thus the two populations may be combined; b) the tinguaite site's direction is indistinguishable from the 13 monzonite and syenite sites' population and can thus be added to it; c) the 3 dyke sites form a directional population that is indistinguishable from the 14 site population from the pluton; d) similarly, the 2 sites from the contact zones of two of the dykes have directions that are indistinguishable from both the 14 site population of the pluton and the 3 site population from the dykes; thus all 19 sites may be combined to form a single population; and e) the directions from the 4 sites in the host rock skarns form a population that is indistinguishable from the 19 site population within the pluton. This sequential analysis shows that the mean directions for all 23 sites may be combined to form a single population to represent the Deadman pluton. The pluton yields a unit mean ChRM direction of declination D = 333.0° and inclination I = 76.8° with a cone radius of 95% confidence α_{95} = 2.6°, precision parameter of Fisher (1953) k = 139, and number of sites N = 23.

There is no evidence to suggest that the Deadman pluton has been remagnetized since emplacement, therefore, it is deemed to have retained a primary thermoremanent magnetization (TRM) in magnetite. The associated dykes intruded and cooled with a primary TRM, and likely remagnetized their baked contact zones with a partial TRM. The host rocks of the Hyland Group were altered to skarn and calc-silicate within the pluton's contact zone and underwent thermochemical remagnetization, all within a few million years, and probably very much less, as the dykes are likely simply a late phase of the pluton. All of these magnetizations have a normal polarity, consistent with their acquisition during the Cretaceous normal polarity superchron from 119 to 84 Ma (Opdyke and Channell, 1996).

DISCUSSION

POLE POSITION

Using a mean location for the 23 sites of 220.88°E, 64.51°N, the unit mean ChRM direction for the Deadman pluton gives a pole position of 144.9°E, 78.5°N, dp = 4.5°, dm = 4.8° (longitude, latitude, semi-axes of the oval of 95% confidence along and perpendicular to the site-pole great circle) (Fig. 9). If the Deadman pluton has not moved since being emplaced into a "stable" North American craton, then the pluton should give a paleopole that is concordant with the craton's paleopole at 91 Ma. From the recently computed apparent polar wander path (APWP) of Besse and Courtillot (2002) for the North American craton, the expected paleopole would be located at 205.0°E, 75.7°N (A_{95} = 5.4°), where A_{95} is the radius of the cone of 95% confidence about the expected paleopole. Clearly, the determined and expected paleopoles for the pluton are significantly different at >>95% confidence (Fig. 9). Several hypotheses merit consideration to explain the discordance between the paleopoles. These are considered in turn in the following sections.

RAPID COOLING OF THE PLUTON

One possibility is that the Deadman pluton cooled sufficiently fast that secular variation in the Earth's magnetic field was not sufficiently averaged out, as happens in a lava flow. In general, it is deemed that a

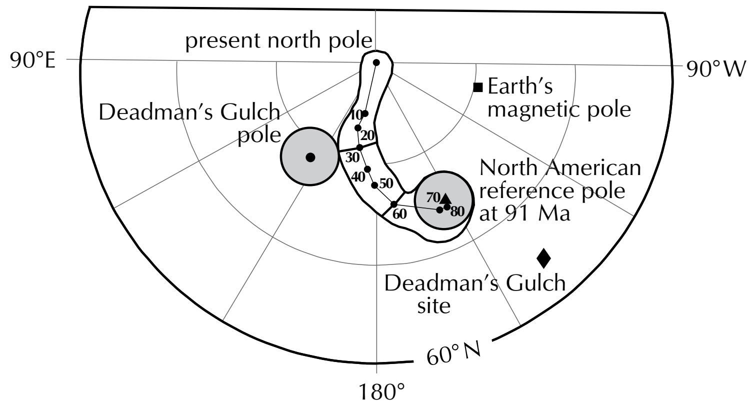

Figure 9. *North polar projection showing the Apparent Polar Wander Path for the North American craton of Besse and Courtillot (2002) after 91 Ma, the 91 Ma reference paleopole (▲), and the Deadman pluton's paleopole (●) with their 1σ confidence limits. To a close approximation, if the 1σ bounds of two populations do not cross, then the two populations are significantly different with >95% confidence. The diamond (♦) is the pluton's location, and square (■) the Earth's present magnetic pole.*

paleopole should represent a time period in excess of a few thousand years (i.e., 10^3-10^4 years) to average out the biasing effects of secular variation (Merrill and McElhinny, 1983). The pluton's sites were located between the perimeter and core of the pluton (Fig. 3). Following Carslaw and Jaeger (1959) and Jaeger (1964), the magnetic minerals in rocks from the perimeter sites would cool through the ~600°C to ~400°C blocking temperature range of magnetite in less than a year. In contrast, using a vertical cylinder model and assuming a minimal ambient host rock temperature of ~ 100°C or depth to top of the pluton of ~ 3 km, the rock in the core sites of this 7-km-diameter pluton would pass through the same blocking temperature range about 10^5 years later. Thus, it appears that rapid cooling of the pluton is an improbable explanation for the pluton's deviant paleopole.

POST-EMPLACEMENT REMAGNETIZATION

Remagnetization of the Deadman pluton to give its discordant paleopole is an unlikely explanation for two fundamental reasons. First, the rocks show no petrologic evidence of post-emplacement alteration by either metamorphism to generate a partial thermal remagnetization overprint or hydrothermal fluid flow to generate a partial chemical overprint. Second, in the absence of any subsequent tectonic activity, a remagnetization should give a pole position on the apparent polar wander path at some time after 91 Ma. In contrast, the ChRM of the Deadman pluton gives a pole position that is significantly off the 91 Ma to Recent path for North America (Fig. 9).

ALLOCHTHONOUS TERRANE TECTONICS

Another way to bring the Deadman pluton and 91 Ma North America reference paleopoles into concordancy would be to translate the terrane hosting the pluton northward (i.e., poleward) to its present North American location. This would require that the pluton's host terrane originated 12.8° ± 5.7° or 1420 ± 600 km to the south-southeast along North America's western margin in present-day southern British Columbia (BC). If the host terrane was part of what is known as the allochthonous Baja BC terranes (Irving, 1985; Irving *et al.*, 1996), it could have been translated northward, coupled with the Kula plate between 91 Ma and 52 Ma with the rest of Baja BC. This explanation is improbable for two reasons. First, the host rocks of the Hyland Group correlate well with miogeoclinal strata that extend far into the adjacent craton and there is no geological evidence, such as faults, that would permit this solution. Second, although the translation distance agrees closely with the value of 8.3° ± 7.0° calculated in a recent analysis of paleomagnetic data for Baja BC by Symons *et al.*, (2005), the 9° ± 23° vertical-axis counterclockwise rotation estimate since mid Cretaceous for the Deadman pluton conflicts significantly from the 51° ± 14° clockwise rotation found in most Intermontane regions of Baja BC.

TECTONIC TILT

Another possibility is that the Deadman pluton was tilted after cooling. This requires correction for a tilt of 7.1° down to the southeast about a horizontal axis striking at N55.6°E to bring the pluton's paleopole into agreement with the North American reference paleopole. The required correction is significant at >>95% confidence as the pluton's ChRM vector direction is significantly different from the vector direction of D = 341.6°, I = 83.8°, α_{95} = 2.7° that is required at the sampling site to give the reference paleopole. The obvious question is whether or not this post-emplacement tilt is geologically reasonable.

The Deadman pluton intrudes the Dawson thrust sheet (Fig. 2). Strata north of the Dawson thrust fault strike at about N80°E (Fig. 2), and strata in the overlying

Tombstone thrust sheet to the southeast strike at about N30°E. The pluton is located about half-way between these two thrust faults in a complex structural zone that may reflect interference between these structural trends. A horizontal tilt axis about half-way between these two trends, or about N55°E, is possible. Further, it should be noted that there are numerous intervening subsidiary thrust faults, such as the larger North Fork Thrust (Fig. 2), as well as several others that are crosscut by the pluton (Fig. 3). Cross-sections and map patterns of the thrust faults indicate moderate to shallow dips to the south and southeast (Tempelman-Kluit, 1970; Thompson *et al.*, 1992) (Fig. 3), which favour a downward tilt to the south and east.

DISPLACEMENT

If the Deadman pluton has been tilted southeasterly by tilting of the Dawson thrust sheet, it is important to consider the nature of that displacement. Three constraints are important. First, the pluton crosscuts several thrust faults without evident displacement of its contacts. This suggests that the thrust faulting predates emplacement of the pluton but requires that tilting occurred as the result of reactivation of the Dawson thrust fault, or movement of the Dawson sheet along another structure, but without substantial disruption of the internal part of the Dawson thrust sheet during motion. The second constraint is that the pluton is ~7 km in diameter, which means that its entire exposed area, along with the surrounding area of host rock contact aureole and skarn, had to be tilted by 7.1° to give the determined result. The third constraint is the typical geometry of regional thrust faults and the paleomagnetic imperative of rotation about a horizontal axis. Simple linear displacement of a thrust sheet along a shallowly dipping thrust fault will not cause a pluton's ChRM vector to rotate (Fig. 10a). For example, displacement of 111 km on a flat-lying sole fault of a pluton towards the Earth's pole position, as is the case here, is required to cause the pluton's paleopole to deviate by an insignificant 1° from the corresponding reference paleopole. What is required is that the thrust sheet hosting the pluton be pushed up the curving frontal ramp of a thrust fault so that the thrust sheet's dip is increased by 7.1° throughout the entire sampled area on average (Fig. 10b).

The geometry of the Dawson thrust is not well constrained. This is an old, extensional structure that controlled facies variations throughout the Proterozoic, and which marked the limit between basinal and platformal deposition through Neoproterozoic and early Paleozoic time (Roots and Thompson, 1992; Abbott, 1997). Abbott (1997) considers the structure to have been a moderately steep south-dipping normal fault originally. However, Mesozoic inversion of Selwyn Basin reactivated the normal fault as a reverse fault over much of its length. Maps of the Dawson Thrust show dips ranging from flat to moderately steep (60°) and the cross-sections of Abbott (1997), from 100 km to the east, indicate a southerly shallowing of dip angles. The Dawson thrust sheet is composed mostly of strata of the 4000-m-thick Upper Proterozoic Hyland Group and emerges about 15 km

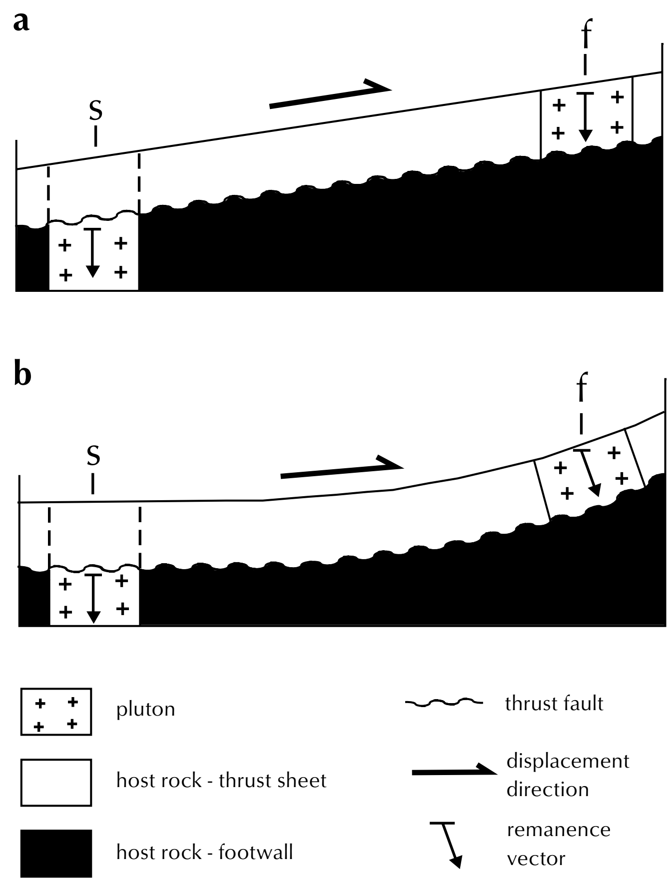

Figure 10. *Schematic depiction, not to scale, of the head of a beheaded pluton being pushed up a thrust fault ramp that is:* ***(a)*** *linear; and,* ***(b)*** *curved. Note in* ***a*** *that the ChRM vector in the head and its host rocks in the thrust sheet are unchanged in inclination from the start (s) of displacement to its final (f) position, whereas in* ***b*** *that the vector's inclination shallows as the curved ramp's inclination steepens and the sheet moves towards the paleopole. Deadman pluton likely endured various amounts of both types of displacement before reaching its current location.*

north of Deadman pluton (Fig. 2), suggesting that much of the fault beneath the pluton is flat-lying. These observations imply that the Deadman pluton would have had to be displaced by tens of kilometres northward on the Dawson Thrust after 91 Ma to achieve the required 7.1° tilt rotation. Furthermore they also imply that the pluton is now the head of a beheaded pluton.

There is, however, little evidence for significant post-Cretaceous displacement on the Dawson fault. Displacement of the Dawson thrust sheet, and associated tilting above thrust ramps, could otherwise have occurred along a master detachment that continued northward into the Yukon Block. This fault cut the Proterozoic Coal Creek inlier at depth, and migrated progressively north and east during later stages of Late Cretaceous deformation into the interior. As an example, deformation of the Monster synclinorium strata, north of the Coal Creek inlier, post-dates Monster Formation deposition (Ricketts, 1988), such that rocks as young as Cenomanian (99-93 Ma, Gradstein *et al*., 2004) are folded, requiring some uncertain amount of deformation and potential tilting after the intrusion of the Deadman pluton.

TECTONIC STABILITY AFTER 91 MA?

The post-mid-Cretaceous tectonic history of the Selwyn Basin and adjacent Ogilvie-Wernecke-Mackenzie foreland belt (Fig. 1) is based on very limited geologic data. First, the youngest deformed strata observed in the foreland belt is Late Cretaceous (Yorath, 1992; McMechan *et al*., 1992). Second, intrusions of the mid-Cretaceous Selwyn plutonic suites are massive and show little sign of post-emplacement deformation. Most deformation is deemed to be Early Cretaceous or earlier (McMechan *et al*., 1992; Tempelman-Kluit *et al*., 1992; Murphy, 1997), partly because of the lack of strata that is younger than 91 Ma in the Selwyn Basin to be deformed. The Cenomanian Monster Formation and Paleocene-Eocene strata in the northern Ogilvie, Wernecke and Franklin ranges are folded, which indicates that deformation continued into the Tertiary. The dearth of strata younger than 91 Ma south of the Dawson thrust indicates that they were either never deposited or since eroded, implying continual uplift and erosion since ~91 Ma. In the absence of post-91 Ma strata in the immediate study area, but indications of inboard deformation of Late Cretaceous strata, we speculate that horizontal motion occurred on sole faults or other horizontal detachment zones after 91 Ma in the Selwyn Basin and the adjacent foreland belt.

ACTIVE TECTONISM AFTER 91 MA

Curiously, there is considerable geophysical evidence to support the existence of post-91 Ma motion. Current global positioning system (GPS) data show that Whitehorse, located on the accreted terranes (Fig. 1) of the Intermontane Belt (IMB), is moving east-northeastwards (ENE) towards Yellowknife on the craton at 5.2 ± 2.2 mm/a (Fletcher and Freymueller, 1999). Combining GPS and earthquake seismology data, Mazzotti and Hyndman (2002) calculated a northeasterly maximum rate of 4.5 ± 2.5 mm/a through Whitehorse, and that changes to ENE through Yellowknife and north through the Ogilvie Mountains. They argued that the shortening was caused by the impact of the Yakutat plate on the Alaskan coastline and was being accommodated by crustal detatchments exposed as thrust faults in the Mackenzie Mountains. Further, Lewis *et al*., (2002) found from analysis of heat flow data in the northern Cordillera that the upper crust is sufficiently cool and rigid to be pushed ENE over top of the hot, and more fluid, lower crust on detachment zones. Additionally, continued ENE thrust-fault motion provides an explanation for the much higher rate of earthquake energy release in the northern foreland belt when compared to the southern foreland belt (Sweeney *et al*., 1992). It also provides an explanation for the highly negative -80 to -120 mgal Bouguer gravity values found in the Mackenzie Mountains (Lowe *et al*., 1994; Cook *et al*., 2001), which are consistent with relatively rapid long-term uplift. Furthermore, the Lithoprobe SNORCLE seismic profiles across the northern Cordillera show the presence of well defined near-horizontal discontinuities that indicate that strata of the IMB terranes overlie a westward-thinning ramp of cratonic Proterozoic strata (Snyder *et al*., 2002; Cook *et al*., 2004). These profiles are thought to record thin-skin tectonics with the IMB strata having moved ENE over and up the marginal ramp. Such motion may also explain geological features such as: 1) the arcuate shape of the Mackenzie Arch, assuming maximum ENE displacement occurred on a vector about through Whitehorse; 2) the relative dearth of post-91 Ma intrusive and extrusive rocks in the northern Cordillera compared to the southern IMB because of continuing compression and uplift that records substantial extension (Souther and Yorath, 1992); and 3) the inboard offset from their probable mantle source regions of alkaline basalts of the northern Cordillera, as suggested by geochemical and isotopic signatures of mantle xenoliths (Abraham *et al*., 2001).

Since the first suggestion that Eocene and younger paleomagnetic pole positions from the IMB could be recording thin-skin tectonics of the IMB rotating clockwise over the craton on sole faults (Symons *et al.*, 2000), the evidence has been accumulating and its paleomagnetic analysis has evolved (Symons *et al.*, 2003, 2005). In summary, the paleomagnetic data now indicate that the northern IMB rotated 16° ± 6° (2σ), or at 0.29 ± 0.11°/Ma, clockwise on top of the cratonic ramp during the past 54 Ma, with insignificant 2° ± 4° (220 ± 440 km) northward translation (Symons *et al.*, 2005). Using a pivot point near the Peace River arch in north-central British Columbia, where extension in the southern IMB appears to change to compression in the northern IMB, leads to a calculated compressional ENE shortening of 305 ± 125 km. If the two GPS estimates for the current ENE compression of 5.2 ± 2.2 and 4.5 ± 2.5 mm/a are valid for the past 54 Ma, then they give comparable ENE shortening estimates of 280 ± 120 km and 240 ± 135 km, respectively. Further, the paleopoles for the IMB show that it was rotated an additional 35° ± 14° clockwise and translated 8.3° ± 7.0° (2σ) (915 ± 775 km) northward during the time interval from 102 ± 14 and 54 Ma. The northward motion suggests that the IMB terranes were being carried on the Kula plate, and the rotation suggests that they were being driven against and onto the cratonic ramp, thereby being the driving force for the Laramide orogeny from earliest Cretaceous to Early Eocene time. How much compressive shortening occurred prior to, or post, 91 Ma is uncertain given the presently available paleomagnetic data base. It is likely, however, that substantial ENE shortening continued after 91 Ma because the Kula plate was still active.

The obvious question then is "why are abundant Late Cretaceous and Tertiary rock units of the IMB terranes not found in the Selwyn Basin or Mackenzie Arch?" The answer could be that these areas northeast of the Tintina fault zone have undergone more rapid uplift than those on the southwest side because of continuing ENE compression against, and thrust faulting in, the more competent carbonate plateau strata of the Mackenzie Mountains. Thus, the Late Cretaceous and Tertiary strata of the IMB that likely overrode the proto-Tintina fault zone to cover a large area on its northeastern side have since been eroded except for the wedge of accreted terranes in southeastern Yukon that presumably overlies cratonic strata of the Selwyn Basin (Fig. 1).

Within this scenario, the Deadman pluton paleomagnetic result provides an additional line of evidence. It supports a post-91 Ma transport direction to the north as Mazzotti and Hyndman (2002) observed in the GPS and earthquake seismicity data. It further suggests that the pluton moved at least several tens of kilometres, and perhaps much further, within the Dawson thrust sheet and possibly along the Dawson fault. This is consistent with existing geological estimates of at least 20 km of shortening in the Dawson sheet, at least 100 km of structural overlap in the Tombstone and Robert Service thrust sheets, and perhaps much more shortening overall (Tempelman-Kluit *et al.*, 1992). Also consistent with these estimates of substantial post-91 Ma northward motion is the displacement found on the adjacent Tintina fault zone. It shows a dextral displacement of about 425 km, of which about 125 km is thought to be post-Eocene (Gabrielse, 1985; Murphy and Mortensen, 2003). Accepting the transmission of transtensional stress across the Tintina fault zone, both the northward displacement of the thrust sheets, and of the southwest side of the Tintina Fault, could well be part of the same long-term Late Cretaceous-to-present tectonic process.

CONCLUSIONS

This paleomagnetic study shows that the Deadman pluton, crosscutting dykes, and adjacent host-rock skarn retain a ChRM that resides in magnetite and has a direction of D = 333.0°, I = 76.8° (α_{95} = 2.6°, k = 139, N = 23). The ChRM is considered to be a primary TRM in the plutonic phases, including the late phase dykes, and a secondary thermochemical remagnetization in the skarn that were all acquired at 91 ± 1 Ma. The pluton's paleopole of 144.9°E, 78.5°N (δ_p = 4.5°, δ_m = 4.8°) is significantly different at >>95% confidence from the expected coeval paleopole for the North American craton. The difference is interpreted to reflect tilting of the pluton and surrounding host rocks of the Dawson thrust sheet as they were driven northward and up a curved frontal ramp of a thrust fault, likely the Dawson fault. Geometrical considerations suggest that the northward displacement amounts to a few tens of kilometres at least and perhaps much more. This requires the Deadman pluton to be the head of a beheaded pluton that is far removed from its source. Tilting likely occurred as deformation moved progressively inboard during Late Cretaceous, but a growing body of evidence increasingly supports active tectonism in Yukon from mid-Cretaceous to the present.

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