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## PALEOMAGNETISM OF THE MOUNT STUART BATHOLITH REVISITED AGAIN: WHAT HAS BEEN LEARNED SINCE 1972?

B. A. HOUSEN, M. E. BECK, JR., R. F. BURMESTER, T. FAWCETT, G. PETRO,  
R. SARGENT, K. ADDIS, K. CURTIS, J. LADD, N. LINER, B. MOLITOR,  
T. MONTGOMERY, I. MYNATT, B. PALMER, D. TUCKER, and I. WHITE

Geology Department, Western Washington University, 516 High Street,  
Bellingham, Washington 98225-9080

**ABSTRACT.** We have collected 20 new paleomagnetic sites from the Mount Stuart batholith and the adjacent Beckler Peak stock. Using thermal and low-temperature demagnetization, and rock-magnetic tests, we have found that the remanence in most of the batholith is carried by single-domain magnetite. The mean of the new Mount Stuart batholith sites is  $D = 354.2^\circ$ ,  $I = 46.2^\circ$ ,  $k = 87.2$ ,  $\alpha_{95} = 4.6^\circ$ ,  $N = 11$ , and is similar to those of the Beck and Noson (1972) and Beck and others (1981) studies. Examination of Ar geochronology of hornblende and biotite from the Mount Stuart batholith finds that the southern part of the batholith cooled through the blocking temperature of magnetite at 91 Ma. The northern part cooled through the blocking temperature of magnetite at 86 Ma, and of pyrrhotite at 83 Ma. From these combined results, we conclude that the paleomagnetic directions from the southern part of the batholith were acquired within 0.5 to 1.0 Ma of the time at which the AH barometers cooled below their closure temperature. Use of the AH barometry to establish paleohorizontal for these rocks is thus well justified. Correcting the Mount Stuart direction for the tilt indicated by the Aluminum-in-hornblende (AH) barometry, the mean becomes  $D = 355.9^\circ$ ,  $I = 50.6^\circ$ . This result places the Mount Stuart batholith at a latitude of  $31.3^\circ +3.8^\circ / -3.4^\circ$  N at 91 Ma. By identifying the carrier of remanence in the Mount Stuart batholith as being single domain (SD) magnetite, we have removed the major remaining uncertainty in interpreting the paleomagnetism of these rocks. The characteristic magnetization repeatedly found in the Mount Stuart rocks clearly supports the microplate tectonic model of Beck and Noson (1972), presently manifest as the Baja British Columbia (Baja-BC) hypothesis.

### INTRODUCTION

Thirty years ago the initial study of the paleomagnetism of the Cretaceous Mount Stuart batholith (Beck and Noson, 1972) was published. It was among the first to report highly discordant paleomagnetic directions from Cretaceous rocks of the North America Cordillera, spawning the continued debate over what is now known as the "Baja British Columbia" (Baja-BC) hypothesis (Irving, 1985; Umhoefer, 1987). The central tenet of the Baja-BC hypothesis is that a set of large terranes (mainly the Insular superterrane) was 3000 kilometers south of their present locations at 90 to 85 Ma, and moved northward along the continental margin between 85 and 55 Ma. Housen and Beck (1999) provide a recent summary of paleomagnetic evidence on which the Baja-BC hypothesis is based; see Cowan and others (1997) for a more complete summary of the geologic implications of the Baja-BC hypothesis. Many geologists have strong objections to the Baja-BC hypothesis and prefer tectonic reconstructions that involve little or no displacement of these terranes; see Butler and others (2001) for the latest summary of these objections and alternate tectonic models. Although logically crucial tests of the Baja-BC hypothesis based on certain geological evidence have been

proposed (Cowan and others, 1997) and conducted (Mahoney and others, 1999; Housen and Beck, 1999), the basis for the hypothesis rests largely upon paleomagnetic data from the relevant terranes. The paleomagnetic data also provide other crucial tests of the hypothesis, in that additional paleolatitudes obtained from rocks associated with these terranes will serve to either disprove the Baja-BC hypothesis, or its minimal-displacement alternatives. During the 30<sup>th</sup> anniversary year of the Beck and Noson paper, students in a senior level paleomagnetism course conducted a new paleomagnetic study and review of the role that the Mount Stuart batholith has played in the Baja-BC controversy. We report these results here, offer some new conclusions regarding the paleomagnetism of this pluton, and discuss the tectonic implications of these results.

### *Regional Geology and Tectonics*

The western part of North America is composed of an array of tectonostratigraphic terranes whose origin with respect to the stable craton is "suspect" (Coney and others, 1980). Within the geologic record contained in these terranes lies a greater than 200 Ma history of interactions between the convergent margin of a large continental plate and its adjacent oceanic neighbors. One of the important pieces of information contained in these terranes is the history of kinematic interaction between continental and oceanic plates. Comparing the direction and magnitude of terrane motion with motion of North America can, for example, place constraints on the motion of offshore oceanic plates. Kinematic information can be found by examination of structures indicative of slip direction, shear sense, or vergence. North-South motion of terranes can be indicated by changes in paleolatitude determined by paleomagnetism and paleoclimatic zonation, and lateral (longitudinal) motion can be inferred in some terranes by methods such as sediment provenance. Because the western margin of North America has been oriented roughly north-south for the past 250 Ma, detection of large latitudinal (> 500 km) displacement of terranes along the North American margin by paleomagnetism is optimized (Mahoney and others, 2000).

The rocks involved in the Baja-BC controversy come from the Insular superterrane (fig. 1) (Wrangellia and Alexander terranes, Coast Plutonic Complex, North Cascades); for a more detailed review of the relevant geology see Cowan and others (1997). Accretion of the Insular superterrane to the margin of North America may be middle-late Jurassic (for example, McClelland and others, 1992), to perhaps mid-Cretaceous (for example, Moores, 1998). Post accretion translation of the Insular superterrane (regardless of the magnitude of this translation) was accomplished by motion along margin-parallel transform faults (Beck, 1976; Price and Charmichael, 1986; Hollister and Andronicos, 1997; McClelland and others, 2000; Umhoefer, 2000), driven by highly N-oblique (Kula plate) or slightly N-oblique (Farallon plate) convergence of offshore oceanic plates with the North American margin (see Debiche and others, 1987).

The Mount Stuart batholith intruded the Nason terrane in the North Cascades of Washington State. The intrusion has an early mafic phase (Big Jim Complex), and main phase of tonalite, diorite, and granodiorite. The large (~20 × 40 km) batholith was emplaced at shallow depths (4-10 km) at 93 Ma, based on Al-in-hornblende barometry and U-Pb dates of zircon, as summarized in Paterson and others (1994), and Ague and Brandon (1996). Depths of crystallization of rocks currently exposed at the surface increase from 4 kilometers in the southeast to 10 kilometers in the northwest (Ague and Brandon, 1996). Recent work (Evans and Davidson, 1999) suggests that post-emplacement metamorphism in the region is simple enough to evaluate its effects on the batholith. Using terminology from Evans and Davidson (1999), contact metamorphism of rocks surrounding the Mount Stuart batholith (Chiwaukum Schist and Ingalls ophiolite complex) by its intrusion is designated as M2. A regional,

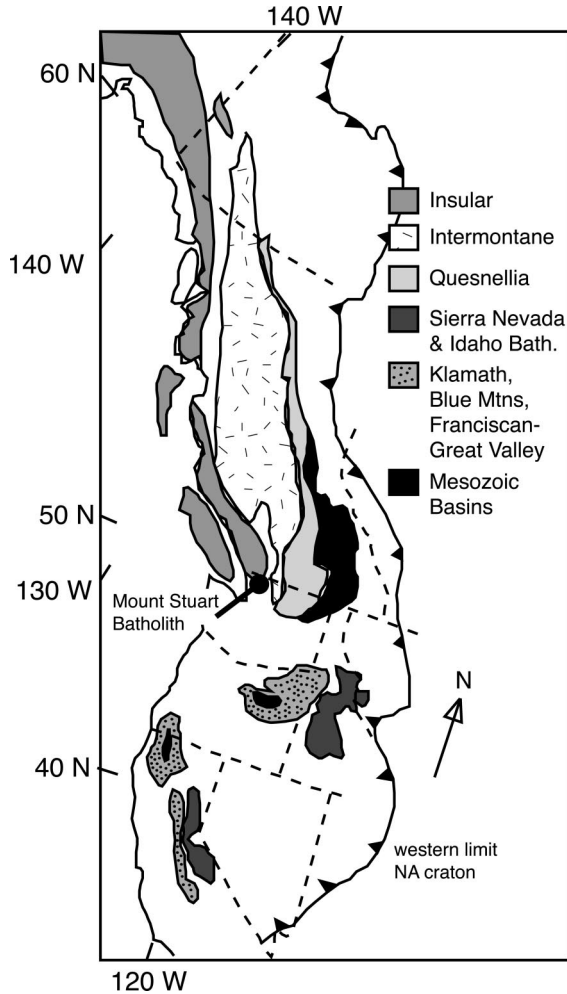


Fig. 1. Map of large-scale Cordilleran terranes, showing location of the Insular, Intermontane, and other large superterrane. Modified from McClelland and others, 2000.

Barrovian metamorphism, M3, followed very shortly after emplacement. M3 records increasing pressures and temperatures in the NW part of the Nason terrane driven by magma loading by intrusion of higher-level plutons (Brown and Walker, 1993), or to thrust loading (McGroder, 1991). Study of metamorphic textures and mineral assemblages, and geochronology (K-Ar,  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  on amphiboles and mica, and Sm-Nd on M3 garnets) relevant to the timing of M2 and M3 indicate that M3 in the vicinity of the Mount Stuart batholith was essentially synchronous with cooling of the batholith and its metamorphic (M2) aureole (Evans and Davidson, 1999). According to Evans and Davidson (1999), peak temperatures during M3 (attained at about 90-92 Ma) did not exceed temperatures reached during post-emplacement cooling in the vicinity of the Mount Stuart batholith. This means that minerals such as hornblende retained their igneous compositions, so those barometers (Al-in-hornblende) used to constrain crystallization depths (Ague and Brandon, 1996) were not reset during M3. The primary effect of M3 on the batholith was a slight (2-4 kbar) increase in pressure (Evans

and Davidson, 1999). Cooling ages inferred from  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  and K-Ar dates of biotite and amphibole, are oldest (88-93 Ma) in the southeast and youngest (83-95 Ma) in the northwest part of the batholith and its adjacent wall rocks (Ague and Brandon, 1996; Evans and Davidson, 1999). Late Cretaceous to Eocene (71-57 Ma) apatite fission track ages from the Mount Stuart batholith indicates it was exhumed and cooled by Eocene time (Ague and Brandon, 1996). The relevance of the thermobarometric data described above for interpretation of paleomagnetic results from the Mount Stuart batholith will be discussed in a later section.

#### *Prior Paleomagnetic Studies*

Tectonic applications of paleomagnetism rest upon certain assumptions, and require certain information about the rocks studied and the nature of their remanent magnetization to be known. The first assumption is that the geomagnetic field can be treated as having a geocentric axial dipole (GAD) field geometry (see Butler, 1992). To meet the requirements of this hypothesis, the samples from which paleomagnetic directions are obtained must have averaged at least 10,000 years of geomagnetic field variation. Information on the age and thermal history of rocks to be studied using paleomagnetism is needed to constrain the age of their magnetization. The other key piece of information is paleohorizontal, which is needed to relate an ancient paleomagnetic direction to the location of the ancient spin axis via the GAD hypothesis. For an evaluation of possible displacement, tilt, or rotation of a displaced or deformed unit (such as a terrane) with some other reference unit (such as a stable craton), a reliable set of paleomagnetic results from rocks with similar ages from both units is needed (see Beck, 1989).

Beck and Noson (1972), Beck and others (1981), and Paterson and others (1994) each reported paleomagnetic results for the Mount Stuart batholith. The results of these studies are summarized below. Dissenting interpretations of these results will be discussed later.

Beck and Noson's (1972) study was based on 47 samples from 5 sites. Two of the sites were collected from the Beckler Peak stock, a small 92 Ma intrusive body immediately west of the Mount Stuart batholith (fig. 2). Remanence was measured with a Schonstedt SSM-1 spinner magnetometer. Samples were subjected to step-wise alternating field demagnetization using a 4-axis tumbling-specimen alternating field (a.f.) demagnetizer constructed by Major Lillard. Remanence stability was evaluated by decay of remanence intensity, and whether or not directions reached a stable end-point on a stereographic projection. Directions for each site were determined from results demagnetized to an "optimum level" of 15, 20, or 50 mT (table 1). Two sites were excluded from further analysis on the basis of unstable remanence (Site C) or directional scatter with an  $\alpha_{95}$  of  $>45^\circ$  (Site B). The three accepted sites (29 samples), all with normal polarity remanence, yielded a mean direction of  $D = 2.3^\circ$ ,  $I = 53.2^\circ$ ,  $k = 122.5$ ,  $\alpha_{95} = 11.2^\circ$  (fig. 3A). As Beck and Noson noted, this direction was significantly different from the Cretaceous direction (or pole position) obtained from the craton. The primary feature of this difference was the paleolatitude predicted for the sample location if it were part of North America (56.5 N), and the paleolatitude that can be calculated from the inclination of the mean direction (33.8 N). After exploring the possibility of non-averaged secular variation, a  $25^\circ$  up-to-north tilt of the batholith, or effects of non-dipole fields, Beck and Noson favored a plate tectonic explanation calling for the Mount Stuart batholith to be on a separate plate from North America in pre-Tertiary time. In their model, translation would have occurred along either a transform or a convergent plate boundary, perhaps driven by motion of the Kula plate.

Beck and others (1981) reported the results from 20 new sites (200 samples) collected from a more extensive area of the batholith (fig. 2). Three of these sites were

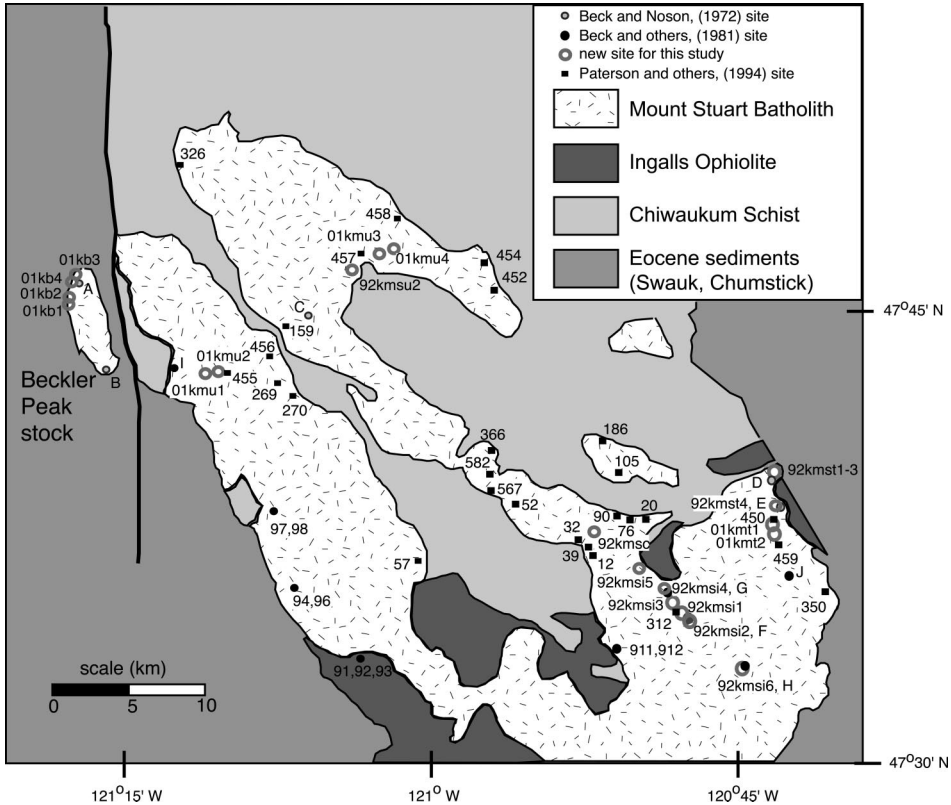


Fig. 2. Map of the Mount Stuart batholith region, after Tabor and others (1987, 1993). The sample sites from the Beck and Noson (1972); Beck and others (1981); Paterson and others (1994); and from this study, are indicated.

contact-metamorphosed peridotite of the Ingalls ophiolite from the southwest margin of the batholith. Laboratory instruments were similar to those used in the Beck and Noson, (1972) study, with the exception being that a Schonstedt GSD-5 three-axis tumbling-specimen a.f. demagnetizer was used. For this study, two specimens from each site were step-wise demagnetized using alternating fields ranging from 5 to 100 mT. Directional dispersion and attainment of stable end-point directions were examined to determine an optimum demagnetization treatment for each site. Directions measured after treatment with alternating fields of 10 to 30 mT were used to determine each site mean direction. All samples had normal magnetic polarity. Six of the new sites had  $\alpha_{95} > 15^\circ$ ; these were rejected from further analysis. The 14 new sites with  $\alpha_{95} < 15^\circ$  were used in the calculation of the new mean direction (table 1). These new sites plus the three sites reported by Beck and Noson (1972), yielded a mean of  $D = 10.0^\circ$ ,  $I = 45.4^\circ$ ,  $k = 53.1$ ,  $\alpha_{95} = 4.9^\circ$  (fig. 3B). This newer study confirmed the result of Beck and Noson (1972), namely that the Mount Stuart batholith has a stable paleomagnetic direction, and that this direction is very discordant with respect to a direction expected for its present location in North America for late Cretaceous (90 Ma) time. Armed with a larger paleomagnetic data set for other Cordilleran terranes, and a plate tectonic model (Beck, 1976) to explain them, Beck and others (1981) were able to make more detailed interpretations of their data. They explored possible large tilts ( $34.5^\circ$  to the SW, about a horizontal axis of  $301^\circ$ ) of the batholith to explain the

TABLE 1  
*Prior paleomagnetic results*

study	unit	Site	N	D°	I°	k	$\alpha_{95}^{\circ}$	Treat.	Lat °N	Lon °W
BN72	Bps	A	15	353.5	46.5	63.3	4.8	15 mT	47.72	121.28
BN72	Bps	B	8	348	43	5.4	>45	50 mT	47.71	121.28
BN72	Msb	D	5	350.5	51	57.5	10.2	20 mT	47.65	121.70
BN72	Msb	E	9	16.5	52	57.6	6.8	20 mT	47.63	120.72
B81	Msb	F	11	358.5	43.5	34.3	7.9	25 mT	47.58	120.79
B81	Msb	G	10	350.5	42.5	41.6	7.6	25 mT	47.59	120.80
B81	Msb	H	9	10.5	41.5	46.8	7.1	30 mT	47.54	120.75
B81	Msb	I	8	8.5	32.0	63.8	7.0	20 mT	47.72	121.21
B81	Msb	J	6	346.0	51.5	156.7	5.4	10 mT	47.79	120.72
B81	Msb	94	17	21.0	42.5	44.5	5.1	15 mT	47.58	121.10
B81	Msb	96	8	16.5	41.0	76.4	5.7	15 mT	47.58	121.10
B81	Msb	97	12	22.5	39.0	82.6	4.3	20 mT	47.63	121.13
B81	Msb	98	14	30.5	44.5	51.0	5.2	10 mT	47.63	121.13
B81	Msb	911	13	12.0	45.5	38.7	6.2	20 mT	47.54	120.82
B81	Msb	912	12	12.0	48.5	50.6	5.9	25 mT	47.54	120.82
B81	Io	91	9	358.5	50.0	11.0	14.1	15 mT	47.54	121.05
B81	Io	92	8	26.5	46.5	21.8	10.6	20 mT	47.54	121.04
B81	Io	93	9	27.5	43.5	25.0	9.3	20 mT	47.54	121.04
P94	Msb	C-I	5	7.2	41.9	nr	17.2	Therm.	var	var

Rocks: Bps = Beekler Peak Stock, Msb = Mount Stuart batholith, Io = Ingalls Ophiolite.

Studies: BN72 = Beck and Noson (1972); B81 = Beck and others (1981); P94 = Paterson and others (1994). N = number of specimens; D, I = site mean declination and inclination, k = Fisher (1953) precision parameter;  $\alpha_{95}$  = radius of 95% confidence circle for mean direction; lat, lon = site latitude, longitude. Treatment is optimum level of peak field for a.f. demagnetization. Note that for the P94 result, N represents the number of Class-I sites with  $\alpha_{95} < 15^{\circ}$  used to calculate the reported mean direction.

discordance. Although acknowledging that ruling out tilt of this sort is difficult, Beck and others (1981) considered tilt unlikely because no evidence of metamorphism that would result from 10 to 12 kilometers of differential burial of the southwest part of the region exists. Their preferred model to explain the data was based on Beck (1976), invoking a combination of 3500 kilometers of northward translation and  $39.5^{\circ}$  of clockwise vertical-axis rotation of the Mount Stuart batholith produced by motion of its

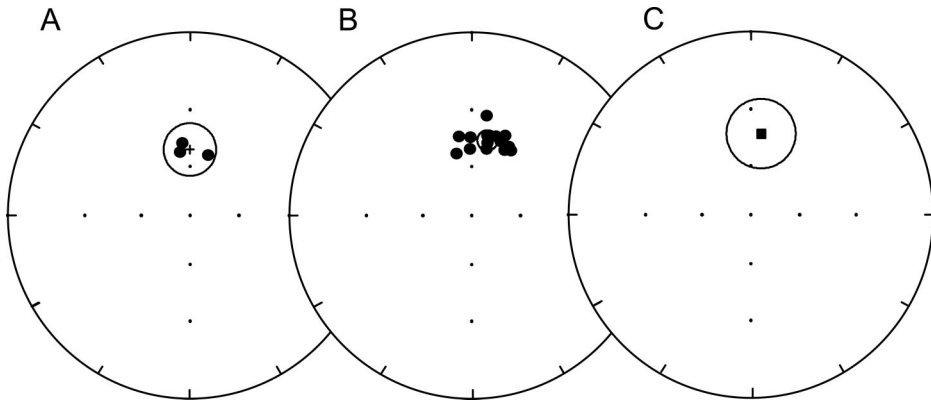


Fig. 3. Site mean directions from prior paleomagnetic studies of the Mount Stuart batholith. (A) Beck and Noson, 1972. (B) Beck and others, 1981. (C) Paterson and others, 1994 (this result is the mean of 5 sites whose individual directions were not reported).

“microplate” along the North America margin. As before, oblique convergence of the Kula plate was the proposed driving mechanism for motion of their microplate.

Paterson and others (1994) reported data from 27 sites collected in various parts of the Mount Stuart batholith (fig. 3). Their methods differ from those of Beck and Noson (1972), and Beck and others (1981) in that they employed step-wise thermal as well as alternating-field demagnetization. The paleomagnetic data of Paterson and others (1994) are not tabulated, so a complete discussion of their results is not possible. They measured directions from 4 core specimens drilled from oriented block samples collected at each site. The number of independently oriented block samples collected at each site was not provided in their paper. Of their 27 sites, 22 had results that were sufficiently consistent to determine magnetic mineralogy via thermal unblocking temperature, and 5 sites had directions well enough defined to include in calculations of a mean direction. Of the 22 sites with reported results, 17 have directions for which the unblocking temperature was less than 400°C. Several of these sites also displayed little loss of NRM during alternating field demagnetization between 20 and 100 mT. Citing similarities with a paleomagnetic study of the Porteau and Spuzzum plutons by Irving and others (1985), Paterson and others (1994) attribute these low unblocking temperatures and relatively high coercivities to pyrrhotite. For 13 of the reported 22 sites, the polarity of remanence reported by Paterson and others (1994) was reverse. Four of the reverse polarity sites have high unblocking temperatures indicative of magnetite. Remanence in the remaining 9 reverse polarity sites is carried by pyrrhotite. All the reverse polarity sites come from the northern part of the batholith. Paterson and others (1994) attributed the difference in magnetic polarity to a difference in thermal history between the more deeply buried northern part of the batholith, and the shallowly buried southern part. The N-R polarity transition was interpreted by them to represent the end of the Cretaceous long-normal superchron (83.5 Ma). The data from 5 sites with  $\alpha_{95} < 15^\circ$  have a mean direction of  $D = 7.2^\circ$ ,  $I = 41.9^\circ$ ,  $\alpha_{95} = 17.2^\circ$  (fig. 3C). Directional data from the remainder (17) of the 22 reported sites were not reported. Paterson and others (1994) conclude that most of the paleomagnetic directions obtained by Beck and Noson (1972) and Beck and others (1981) are carried by pyrrhotite, and that this Fe-sulfide is the primary igneous magnetic mineral in the batholith. To interpret the paleomagnetic data, they favored a complex combination of tilt and internal deformation of the Mount Stuart batholith.

#### SAMPLING AND METHODS

For this study 20 new sites (180 samples) were sampled (fig. 2). Of these sites, 4 were located within the Beckler Peak stock. The remaining sites were all within the Mount Stuart batholith proper. Several of the sites in the northern portion of the batholith (including two of the Beckler Peak sites) contained fine-grained dikes, which were sampled as well. Most samples were collected using a gas-powered drill, and were oriented in the field using a magnetic compass, supplemented with sun compass orientations when conditions permitted. All of the sun compass declinations were within a degree of the magnetic compass declinations. Some of the samples were collected as oriented blocks, with 2 cores drilled from each block sample. All of the cores were cut into 2.2 centimeter specimens.

Remanent magnetization was measured within a field-free room (internal field  $\sim 350$  nT), using a 2-G 755 DC-SQUID magnetometer. Demagnetization was done with either a D-Tech alternating field demagnetizer (200 mT peak field), or an ASC TD-48 thermal demagnetizer. One or two specimens from each site were step-wise demagnetized using alternating fields of 2.5 to 200 mT. The remaining samples were subjected to step-wise thermal demagnetization, using steps of 5° to 50°C from room temperature to 650°C. Principal component analysis (PCA, Kirschvink, 1980) was employed to

determine the remanence components, and statistical methods of Fisher (1953) were used to calculate and evaluate the mean directions obtained from these components.

Prior to thermal demagnetization, an additional treatment was employed to minimize the contribution by remanence of large, multi-domain (MD) magnetite to our results. Intermediate to felsic plutons, such as the Mount Stuart batholith, commonly contain coarse grained magnetic phases that grow during slow cooling of the pluton. Large MD grains are prone to acquisition of magnetic overprints by thermoviscous mechanisms (see Dunlop and Özdemir, 1997, for a complete treatment of this topic). Dunlop and Xu (1994) found that thermoviscous magnetization carried by MD magnetite, even if acquired at relatively low temperatures, can have laboratory unblocking temperatures as high as the Curie temperature of magnetite (580°C). This thermal stability would, at worst, allow a younger Thermo-viscous remanent magnetization (TVRM) to be mistaken for a truly primary Thermoremanent magnetization (TRM). The presence of a high thermal unblocking temperature overprint can also serve to mask or contaminate a primary TRM direction. In order to avoid this complication, low temperature demagnetization (LTD) was employed for this study. Approximately 60 percent of our specimens were treated to the following cycle. First, immersion in liquid nitrogen ( $T = 77$  K) for 15 to 30 minutes cools the specimens. They are then extracted from the non-magnetic dewar, and placed in the ultra-low field environment of our thermal demagnetizer (at room temperature), and allowed to warm to room temperature. After warming, the magnetization of each specimen is measured. Specimens were treated to this LTD cycle either once or twice, depending on how much the natural remanent magnetization (NRM) changed after the first cycle.

The physical basis for LTD is as follows. At a temperature of 120 K, magnetite undergoes a phase transition, becoming monoclinic below this temperature. A magnetic isotropic point, at which the magnetocrystalline anisotropy factor becomes zero, also occurs when magnetite reaches a temperature near 120 K. The changes in magnetic and electrical properties of magnetite at this temperature are referred to as the Verwey transition (Verwey, 1939). The effect of thermal cycling from room temperature to the Verwey temperature and back on natural remanence of magnetite is different for MD and SD grains. Single domain grains retain a perfect memory of their original room temperature remanence after cycling to below 120 K and back. For the larger MD magnetite, such cycling erases a significant portion of their room temperature remanence. Whether related to the 120 K phase change or the magnetic isotropic point, MD magnetite is most likely demagnetized through unpinning of domain walls from internal crystal defects during low temperature cycling (Dunlop and Özdemir, 1997). For a sample with a mixture of SD and MD magnetite, LTD cycling will preferentially demagnetize the MD grains while leaving the magnetization of the SD grains unaffected. The LTD method has been used previously in paleomagnetic studies of rocks that have been subjected to post-magnetization thermal events. Dunlop and others (1997) employed LTD to define and isolate overprint directions carried by MD magnetite that were acquired during burial metamorphism of the Sydney Basin. Warnock and others (2000) employed LTD in their paleomagnetic study of regionally metamorphosed rocks of the Grenville province (Ontario). Both studies documented that LTD treatment greatly improved the resolution of the primary remanence obtained during step-wise thermal demagnetization. The site mean directions they obtained were significantly different than the results of non-LTD treated samples. In addition to obtaining directions that are better determined and have less likelihood of being contaminated by younger overprint directions, LTD-treated rocks have thermal demagnetization characteristics that can be evaluated using classic theories of SD magnetization. This fact allows the thermal unblocking temperatures

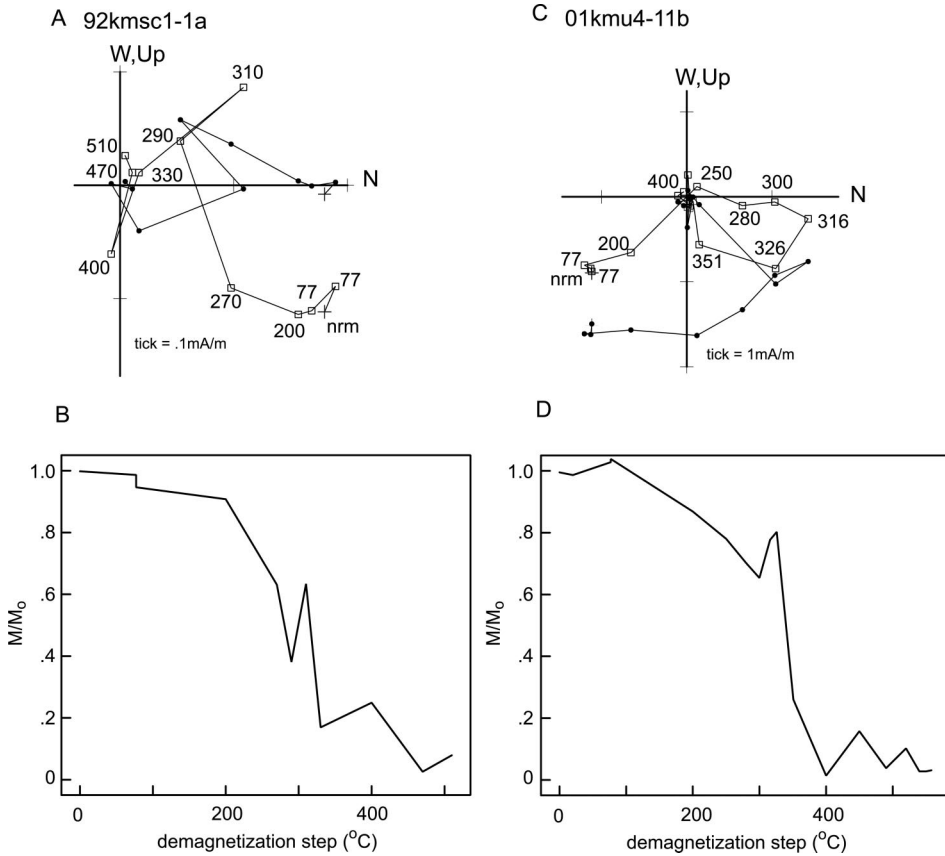


Fig. 4. Results of thermal demagnetization of Mount Stuart batholith samples that show evidence for pyrrhotite, but have poorly-defined directions. (A, and C) are orthogonal vector plots, with closed symbols denoting projection of the vector on a horizontal plane, and open symbols denoting projection of the vector on a vertical plane. Temperature steps in  $^{\circ}\text{C}$  for each demagnetization step are noted. The 77 step denotes LTD treatment. (B, and D) are normalized remanence intensity plots, showing the decay of remanence intensity following each thermal demagnetization step. For these samples, the sharp decay of remanence intensity would be consistent with pyrrhotite.

obtained by thermal demagnetization of our samples to be evaluated in terms of TRM acquisition temperature and acquisition time (Pullaiah and others, 1975). This procedure was done by Dunlop and others (1997), who found that the unblocking temperatures of directions acquired during the burial metamorphic event by SD magnetite matched the unblocking temperatures predicted by the Pullaiah and others (1975) model.

An additional test was used to determine the magnetic mineralogy of the Mount Stuart samples, in light of the conclusions by Paterson and others (1994) that pyrrhotite is the primary carrier of remanence in these rocks. Lowrie (1990) describes a technique for thermal demagnetization of a multi-component isothermal remanent magnetization (mIRM) in order to distinguish between magnetite, pyrrhotite, and hematite bearing rocks. For these experiments, we used an ASC pulse magnetizer to impart orthogonal IRMs with a 2.5 T field along the specimen Z-axis, a 0.4 T field along the Y-axis, and a 0.1 T field along the X-axis. Hematite has both high coercivity ( $>1$  T) and high Néel temperature ( $\sim 670^{\circ}\text{C}$ ). Single-domain pyrrhotite has intermediate

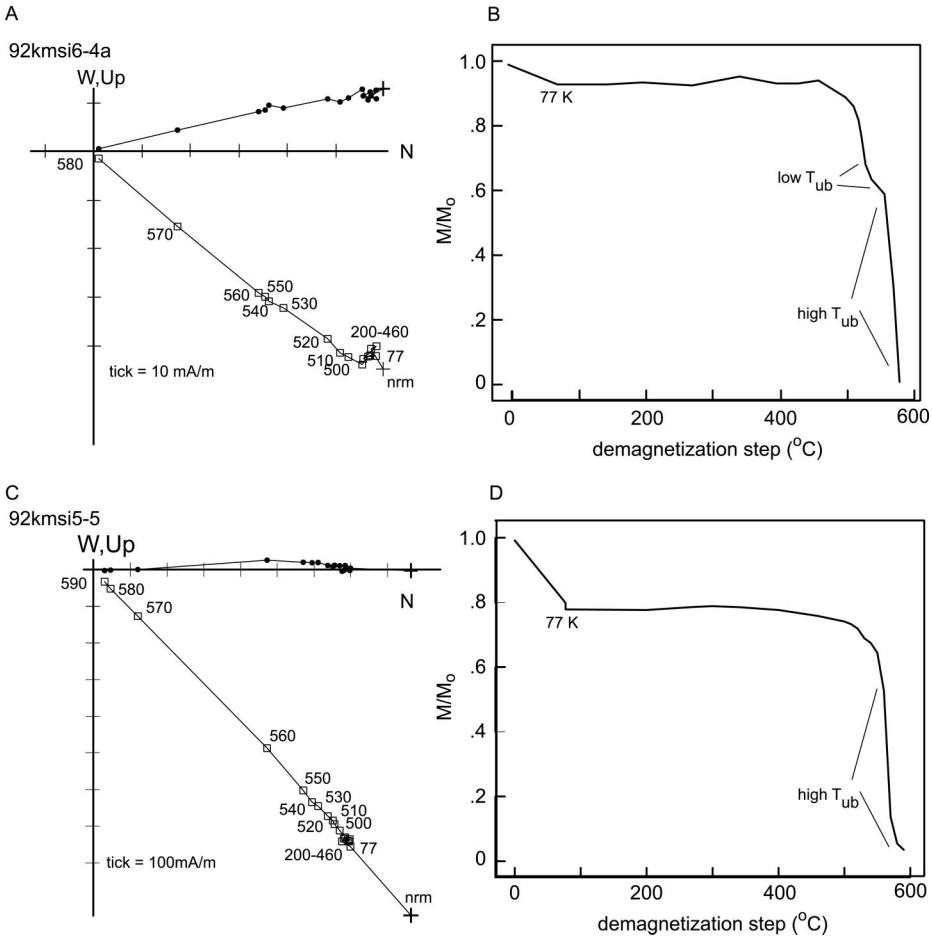


Fig. 5. Results of thermal demagnetization of specimens from the Mount Stuart batholith that have well-defined directions. (A, C, E, and G) are orthogonal vector plots and (B, D, F, and H) are normalized remanence intensity plots as in figure 4. Loss of remanence after the 77 K LTD treatments, and the range of well-defined laboratory unblocking temperatures are denoted on the normalized intensity plots.

coercivity (between 0.4 and 1.0 T) and a Curie temperature of  $320^{\circ}\text{C}$ . Larger pyrrhotite and magnetite has lower ( $< 0.3$  T) coercivity, with magnetite's Curie temperature being  $580^{\circ}\text{C}$  (Dunlop and Özdemir, 1997). The thermal unblocking temperatures of these differing mIRM components are thus diagnostic of these minerals (Lowrie, 1990). The mIRM experiments were performed on specimens remaining from 9 of the Beck and others (1981) sites.

#### PALEOMAGNETIC RESULTS

Stepwise thermal and alternating field demagnetization of the new collection of Mount Stuart rocks revealed well-defined and interpretable behavior for most specimens. After removal of a very slight overprint (less than  $200^{\circ}\text{C}$ ), most specimens had well-defined demagnetization paths that trended to the origin (stable end-point behavior). Exceptions to this behavior were exhibited by all specimens from five sites scattered within the Mount Stuart batholith and one site from the Beckler Peak stock.

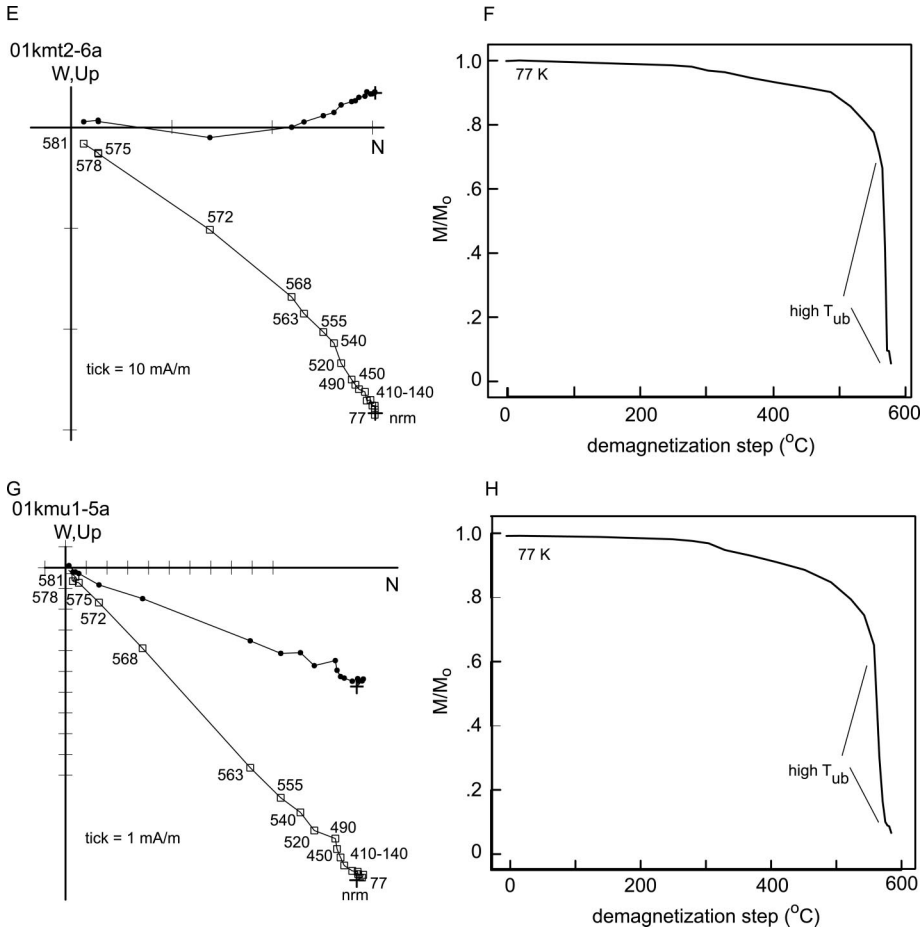


Fig. 5 (continued)

For these rejected sites both alternating field and thermal demagnetization paths were erratic, with remanence completely unblocked by 350°C (fig. 4). A few of these specimens had well defined unblocking temperatures between 270° and 320°C, which is consistent with pyrrhotite as a remanence carrier. These low laboratory unblocking temperature magnetizations have either normal or reverse polarity (fig. 4), but we were unable to define any components using PCA with acceptable confidence maximum angular deviation (MAD angles < 15°).

All specimens from the Mount Stuart batholith that have acceptable thermal and alternating field demagnetization behavior have normal polarity magnetizations. Laboratory unblocking temperatures were well defined in most of the specimens, by very abrupt decreases in remanence intensity between 560° and 580°C (fig. 5). Several specimens also have a small part of remanence lost over a lower, but clear, laboratory unblocking temperature range (520° to 560°C) (fig. 5A). Some specimens had small (10%) decreases in NRM intensity following LTD treatment, while others had no noticeable change in magnetization (fig. 5). The magnetizations isolated during demagnetization all have northerly declinations, and moderate (down) inclinations (fig. 5). We did not find any definable reverse-polarity directions in any Mount Stuart

TABLE 2  
New paleomagnetic results

Site	unit	old	No/N	D°	I°	k	$\alpha_{95}^{\circ}$	Lat N	Lon W
01kb1	Bpsc		7/7	356.8	71.1	100.5	6.1	47°44'	121°23'
01kb2	Bpsc		8/8	353.4	70.4	51.5	7.8	47°44'	121°23'
01kb1,2	dikes		13/13	359.8	66.3	36.0	7.0	47°44'	121°23'
01kb4	Bps	A	7/6	27.8	33.3	75.9	7.7	47°44'	121°23'
01kmu1	Msb		7/5	23.1	45.2	149.9	6.3	47°44'	121°08'
01kmu2	Msb		5/4	356.8	51.1	46.7	13.6	47°44'	121°08'
01kmt1	Msb		7/7	356.7	51.5	38.1	9.9	47°37'	120°44'
01kmt2	Msb		7/5	1.3	43.7	18.2	18.4	47°37'	120°44'
92kmsi1	Msb		4/4	345.6	46.7	1747	2.2	47°34'	120°48'
92kmsi2	Msb	F	12/12	343.2	44.5	81.8	4.8	47°34'	120°48'
92kmsi3	Msb		11/11	351.5	40.5	237.2	3.0	47°35'	120°48'
92kmsi4	Msb	G	17/17	347.3	41.4	62.6	4.5	47°35'	120°48'
92kmsi5	Msb		7/7	354.0	49.5	126.2	5.4	47°36'	120°49'
92kmsi6	Msb	H	10/10	343.2	44.0	80.0	5.4	47°33'	120°45'
92kmst4	Msb		20/16	356.2	44.0	19.3	8.6	47°38'	120°43'
Means:	part	coord	N	D°	I°	k	$\alpha_{95}^{\circ}$		
Msb	all	IS	11	354.2	46.2	87.2	4.6		
Msb	south	IS	9	350.9	45.3	193.7	3.7		
Msb	south	TC	9	355.9	50.6	193.7	3.7		

Rocks: Bpsc = contact metamorphosed Beckler Peak stock, dikes = fine grained dikes, Bps = Beckler Peak Stock, Msb = Mount Stuart batholith.

Old refers to site from BN72 or B81 that was resampled for this study. No = number of samples measured, N = number of samples with MAD < 15° used for mean; D, I = site mean declination and inclination, k = Fisher (1953) precision parameter;  $\alpha_{95}$  = radius of 95% confidence circle for mean direction; lat, lon = site latitude, longitude. For mean directions, part refers to sub-set of Msb data used to calculate the mean, coord is the spatial coordinate system; IS = in-situ and TC = tilt-corrected using the AH barometry surface.

specimen, nor did we isolate any magnetization with laboratory unblocking temperatures (with or without LTD) that were below 500°C. For all but one of the 11 sites from which we were able to define specimen-level directions, site mean  $\alpha_{95}$  errors were less than 15° (table 2). Site means are well grouped (fig. 6); the combined mean of these new Mount Stuart batholith sites is D = 354.2°, I = 46.2°, k = 87.2,  $\alpha_{95}$  = 4.6°, N = 11.

Two of the new sites within the Beckler Peak stock were in granodiorite with no nearby fine-grained dikes. Only one of these sites yielded an acceptable result. The magnetization of this Beckler Peak site is all normal polarity, with high (550° to 580°C) laboratory unblocking temperatures (fig. 7). The mean direction of this site is similar to those from the Mount Stuart batholith proper (table 2).

The other two Beckler Peak pluton-related sites were mainly fine-grained dikes, or small parts of contact-metamorphosed plutonic rock between dikes. Such dikes were also sampled at two of the sites within the northern part of the Mount Stuart batholith proper. All plutonic specimens from the two Beckler Peak sites have normal-polarity magnetizations with steep inclinations, and laboratory unblocking temperatures between 400° and 560°C (fig. 8). Specimens from the dikes at these two sites have two-component remanence. The first-removed component is unblocked between 200° and 525°C, has normal polarity in some dikes and reverse in others. All of the first-removed components are poorly defined with MAD values above 10° in most cases (fig. 9). The second-removed component in all of the dike samples is unblocked between 330° and 575°C, and has normal-polarity (fig. 9). This component was well defined for the dikes from Beckler Peak, and poorly defined for the dikes from Mount Stuart. The mean directions of the second-removed component from the dikes is D = 359.8°, I = 66.3°, k = 36,  $\alpha_{95}$  = 7.0° (table 2). The dike magnetization is very similar to

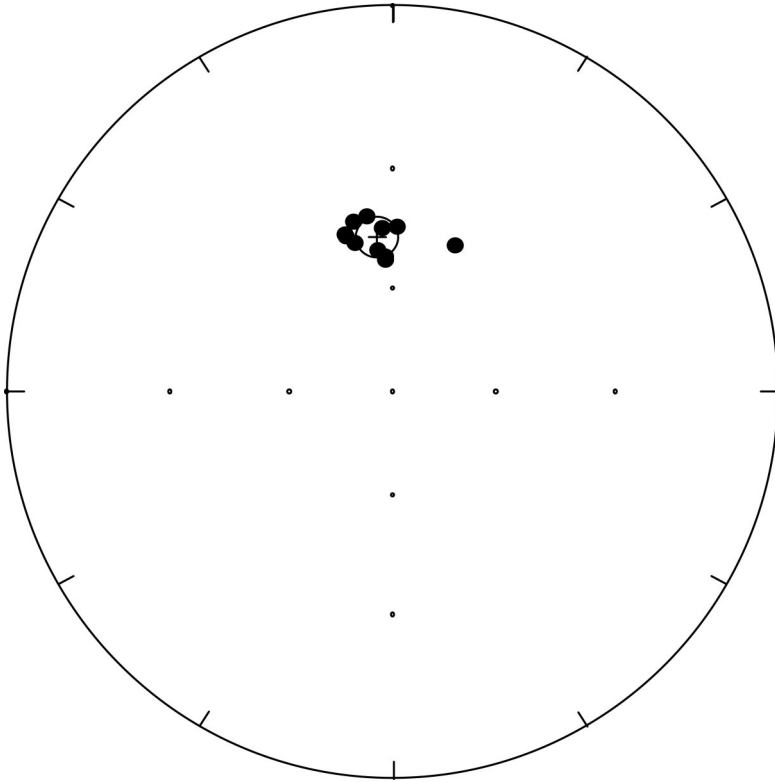


Fig. 6. Equal angle projection, showing the site-mean directions of the 11 new sites from the Mount Stuart Batholith. The overall mean of these directions, and its  $\alpha 95$  circle of confidence is also shown.

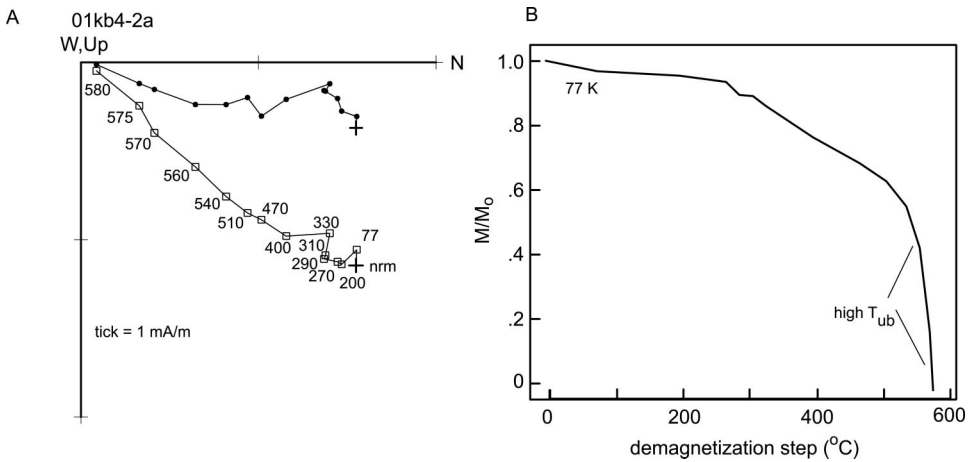


Fig. 7. Results of thermal demagnetization of a typical specimen from the Beckler Peak stock. (A) is an orthogonal vector plot, (B) is a normalized intensity plot, as in figure 4 and figure 5.

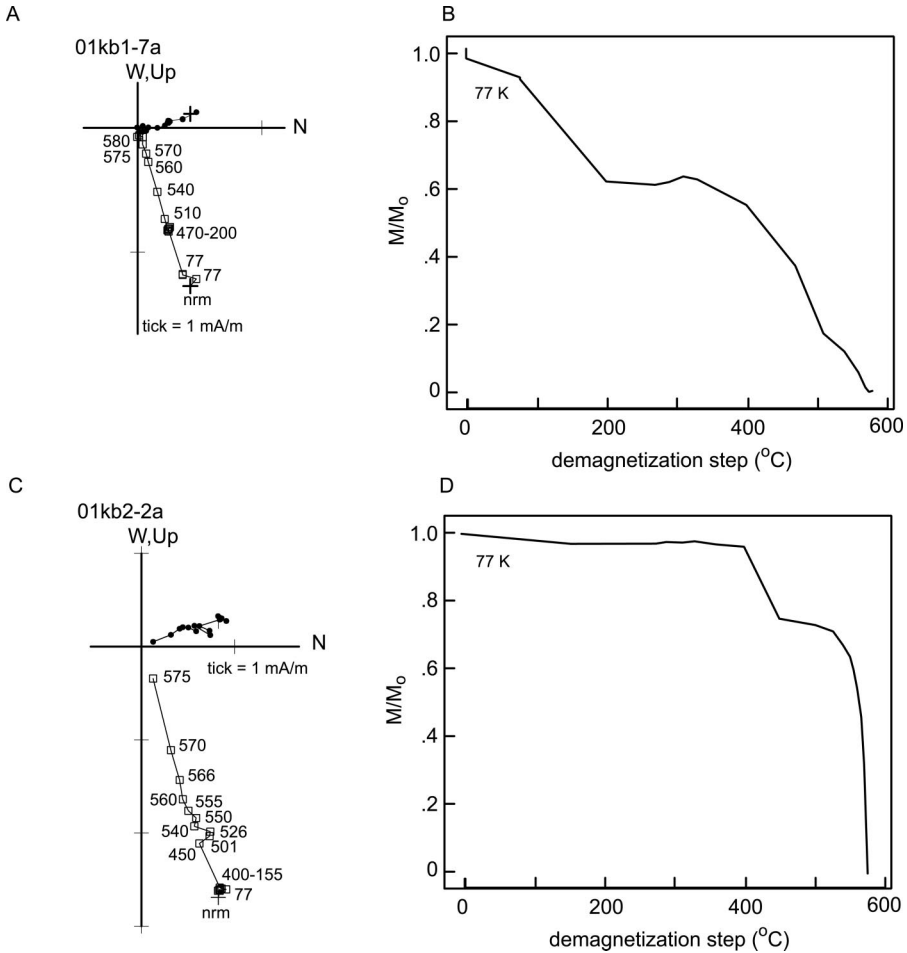


Fig. 8. Results of thermal demagnetization of typical specimens from fine grained dikes. (A, and C) are orthogonal vector plots; (B, and D) are normalized intensity plots, as in figure 4 and figure 5.

that found in the contact metamorphosed plutonic samples from the Beckler Peak stock. These magnetizations are similar in direction to an expected direction for Eocene and younger rocks at this location. We note that these results constitute a positive baked contact test for the Beckler Peak stock. The dikes and their associated contact metamorphosed plutonic rocks have well-defined magnetizations that are identical, whereas the sites within the Beckler Peak stock that were not intruded by these dikes have well-defined magnetizations that are statistically distinguishable.

#### ROCK MAGNETIC RESULTS

The results of thermal demagnetization of isothermal remanent magnetization (IRM) and multi-component IRM (mIRM) (Lowrie, 1990) allow elucidation of the magnetic mineralogy of Mount Stuart batholith specimens from the Beck and others (1981) study. Results of these experiments revealed three types of mIRM demagnetization, indicative of three magnetic mineral assemblages. The most common mIRM type has most of the magnetization carried by the low coercivity ( $H < 0.1$  T) component,

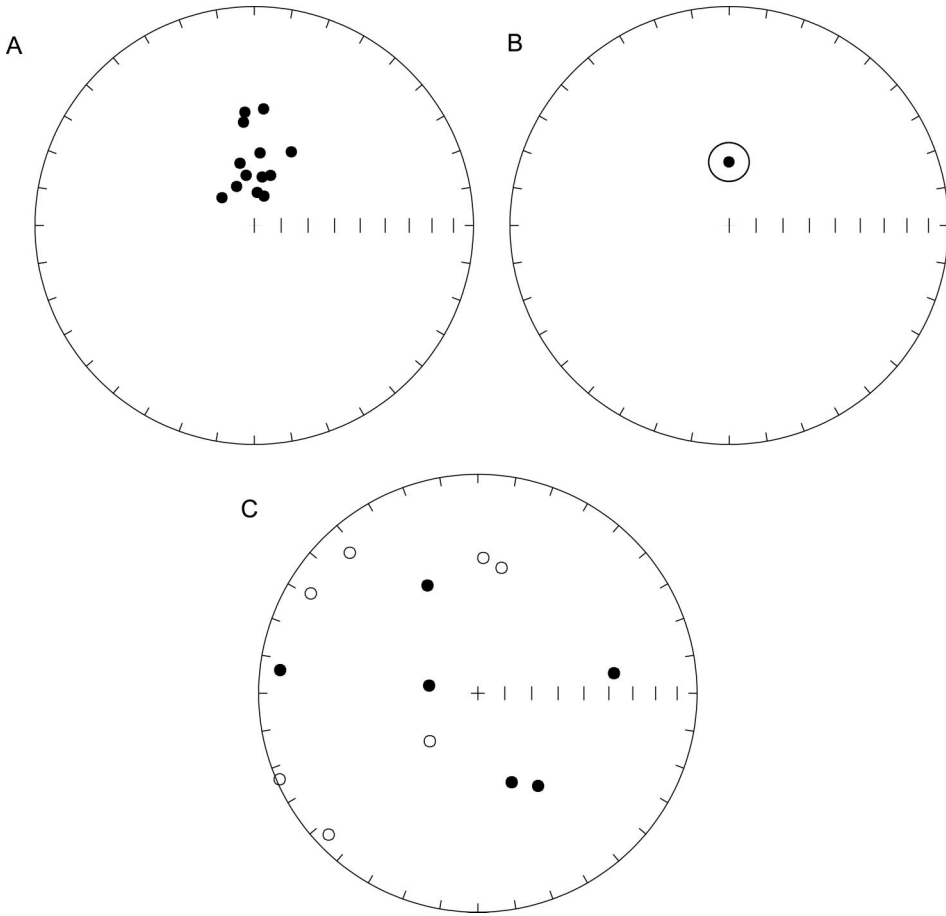


Fig. 9. Equal-area plots of directions obtained from fine-grained dikes. (A) specimens with high unblocking-temperature magnetizations and directions with best-fit lines having  $MAD < 10^\circ$ . (B) The mean direction of these specimens, with its  $\alpha_{95}$  circle of confidence. (C) specimens with low unblocking-temperature magnetizations.

which unblocks between  $540^\circ$  and  $580^\circ\text{C}$  (fig. 10A and B). This combination of coercivity and mIRM unblocking temperature is indicative of magnetite; we refer to this behavior as magnetite-type. Magnetite type mIRM results were obtained in most of the Mount Stuart batholith sites (table 3). The next most common behavior has a high proportion of the mIRM carried by the highest coercivity ( $H > 0.4$  T) component. The thermal unblocking temperature of this component was not reached (fig. 10C), as these specimens disintegrated between  $480^\circ$  and  $540^\circ\text{C}$ . Because this component has high coercivity, and did not unblock at all in the range of  $250^\circ$  to  $450^\circ\text{C}$ , hematite or hemoilmenite is the mineral most consistent with this type of mIRM result. Hematite type mIRMs were found in three sites (table 3). The least common type of mIRM behavior has mIRMs carried mainly by the low and intermediate coercivity ( $H < 0.4$  T) components. The unblocking temperature of these components is between  $280^\circ$  and  $340^\circ\text{C}$  (fig. 10D, E, and F). One specimen from site 911 within the Mount Stuart batholith had two unblocking temperatures for the low coercivity component; one between  $280^\circ$  and  $340^\circ\text{C}$ , and the other between  $540^\circ$  and  $580^\circ\text{C}$  (fig. 10D). This

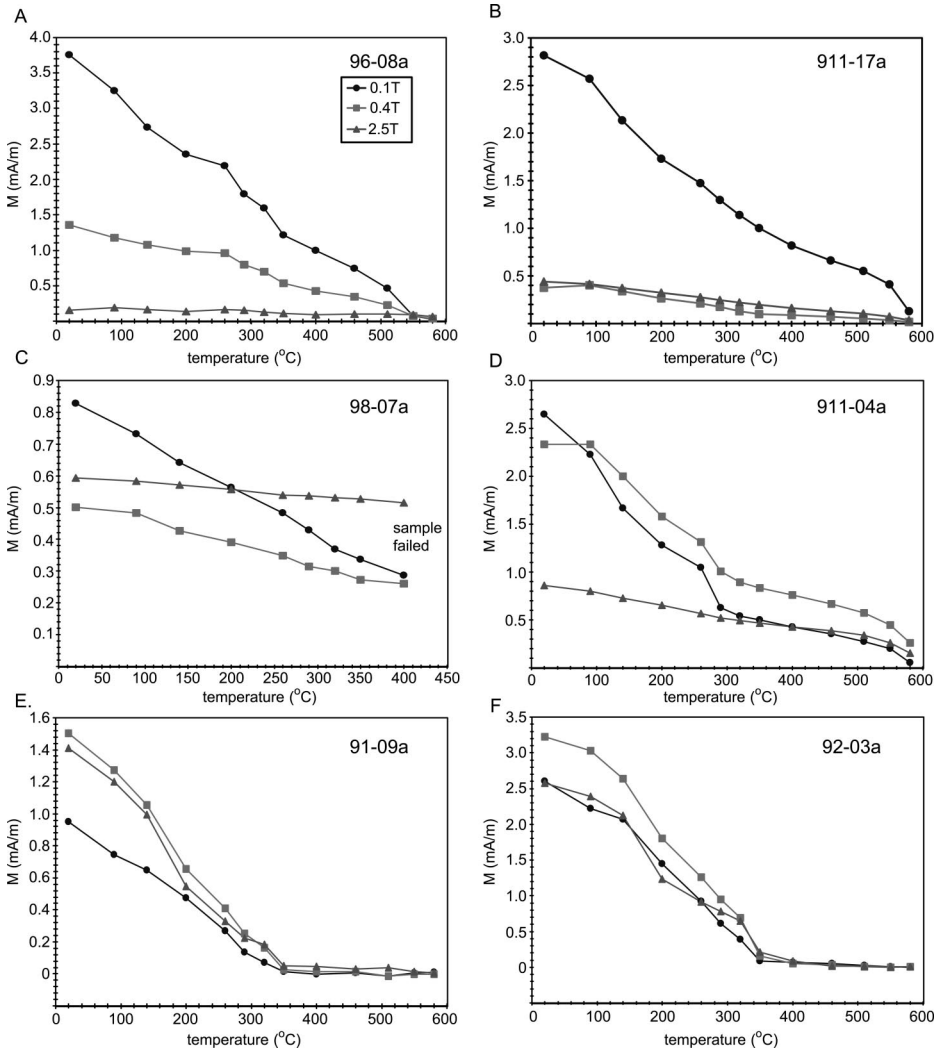


Fig. 10. Thermal demagnetization of multi-component IRM (Lowrie, 1990), for samples from the Beck and others, 1981 study. In all plots, the vertical axes are remanence intensities, the horizontal axes are temperatures used during thermal demagnetization of the mIRM. The hard (2.5 T) component is denoted by a triangle, the intermediate (0.4 T) component by a square, and the soft component (0.1 T) by a circle. (A, and B) are results indicative of magnetite. (C) result indicative of hematite (note that the sample failed by disintegration after the 400°C step). (D) result indicative of a sample with both magnetite and pyrrhotite. (E, and F) results from peridotite of the Ingalls ophiolite, indicative of only pyrrhotite.

combination of coercivity and thermal unblocking temperature is consistent with both pyrrhotite and magnetite as magnetic phases. These pyrrhotite-type mIRMs typify one of the Mount Stuart batholith sites, and two of the sites collected in the Ingalls Ophiolite and reported by Beck and others (1981) (table 3).

#### DISCUSSION

The paleomagnetic results obtained from the Mount Stuart batholith over the past 30 plus years are, for the most part, mutually consistent. The mean directions

TABLE 3  
*Magnetic mineralogy*

Site	unit	remanence carriers	method	Remanence $T_{ub}$
01kb1	Bpsc	mgt	TD	500-580
01kb2	Bpsc	mgt	TD	500-580
01kb1,2	dikes	mgt	TD	520-580
01kb4	Bps	mgt	TD	560-575
01kmu1	Msb	mgt	TD	560-575
01kmu2	Msb	mgt	TD	570-580
01kmt1	Msb	mgt	TD	565-575
01kmt2	Msb	mgt	TD	570-580
92kmsi1	Msb	mgt,hem	TD, L	>500*
92kmsi2,F	Msb	mgt	TD	560-580
92kmsi3	Msb	mgt	TD	530-560, 560-580
92kmsi4,G	Msb	mgt	TD	550-580
92kmsi5	Msb	mgt	TD	560-580
92kmsi6,H	Msb	mgt	TD	520-530, 560-580
92kmst4	Msb	mgt	TD	560-580
01kmu3	Msb	po?	TD	290-330
01kmu4	Msb	po?	TD	290-330
92kmsc	Msb	po?	TD	280-330
92kmu2	Msb	po?	TD	270-330
94	Msb	mgt	L	
96	Msb	mgt	L	
97	Msb	mgt,hem	L	
98	Msb	mgt,hem	L	
911	Msb	mgt,po	L	
912	Msb	mgt	L	
91	Io	po	L	
92	Io	po	L	
93	Io	mgt	L	

Rocks: Bpsc = contact metamorphosed Beckler Peak stock, dikes = fine grained dikes, Bps = Beckler Peak Stock, Msb = Mount Stuart batholith, Io = Ingalls ophiolite.

Magnetic minerals: mgt = magnetite, hem = hematite, po = pyrrhõite.

Method: TD = thermal demagnetization of NRM; L = thermal demagnetization of mIRM after Lowrie, 1990. Remanence  $T_{ub}$  refers to the temperature range over which significant loss of NRM intensity was observed during thermal demagnetization (see figure 5). \* = specimens failed during heating.

obtained by Beck and Noson (1972), Beck and others (1981), Paterson and others (1994), and this study (fig. 11) are all, within error, similar to each other. The magnetization characteristics of the Mount Stuart batholith were thus successfully isolated even with the small number of sites and simple laboratory techniques used by Beck and Noson (1972). The next step, in order to understand the possible tectonic importance of this magnetization, is to understand the timing of remanence acquisition relative to the post-emplacement thermal history of the Mount Stuart batholith. With this understanding, the effects of possible post-magnetization tilt, rotation, or internal deformation can be examined.

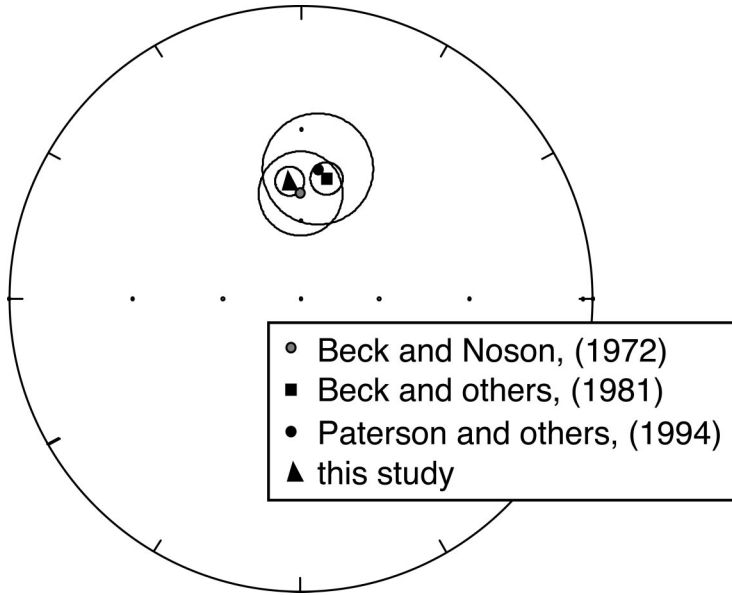


Fig. 11. Equal-angle projection, showing site mean directions and their circles of 95% confidence for each of the four paleomagnetic studies of the Mount Stuart batholith.

#### *Origin of Mount Stuart Batholith Remanence*

Magnetic mineralogy is the most important factor in determining the origin of a rock's magnetization. From our thermal demagnetization results of both natural and artificial magnetizations, we can conclude that the well-grouped and well-behaved magnetizations successfully isolated from all of our new sites ( $N = 11$ ), and 10 of 11 of the sites within the Mount Stuart batholith reported by Beck and others (1981), are carried solely by magnetite. Because LTD had only minor effect on sites to which it was applied, these magnetizations can all therefore be interpreted as carried by single domain magnetite.

*Pyrrhotite-dominated remanence.*—One of the Beck and others (1981) Mount Stuart sites (site 911) has both magnetite and pyrrhotite, and two of their sites in contact metamorphosed peridotite of the Ingalls Ophiolite complex have only pyrrhotite as an important remanence carrier. Other than that, the only evidence for pyrrhotite that we found came from poorly defined demagnetization behavior with low unblocking temperatures, in several sites from within the Mount Stuart batholith, and from dikes sampled at four sites. Our thermal demagnetization and mIRM results have implications for two observations reported by Paterson and others (1994); that of widespread pyrrhotite as the primary remanence carrier, and that of stable reverse-polarity results from the northern sector of the batholith. Two of our new sites (01Kmu1, 2) with well-defined, normal polarity magnetization carried by magnetite come from the northwest part of the batholith. These two sites are very near a set of four sites where a reverse-polarity magnetization carried by either magnetite or pyrrhotite was reported by Paterson and others, 1994. The only definable low unblocking temperature magnetizations we found in this part of the Mount Stuart batholith were low-temperature components carried by dikes, and these were all very scattered (see fig. 9). Four of our sites (92kmsc, 92kmsu2, 01Kmu3, 4) were collected close to the locations of several sites for which reverse polarity magnetizations carried by pyrrhotite were reported. We

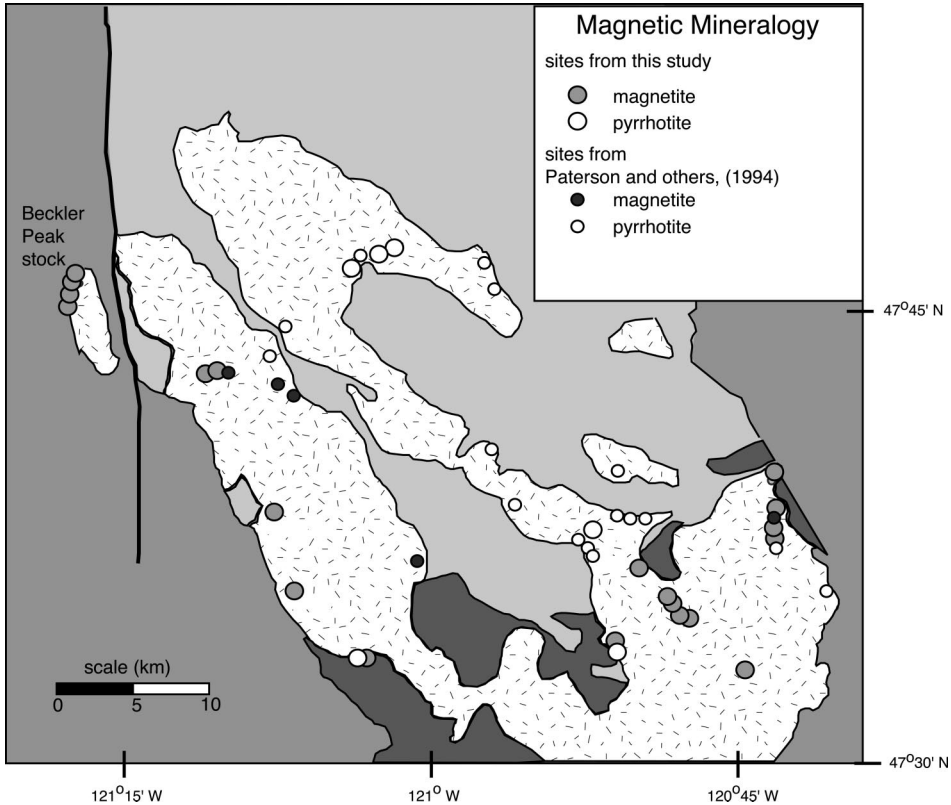


Fig. 12. Map of the Mount Stuart batholith region, showing locations where the principal magnetic mineralogy has been determined by either thermal demagnetization of NRM or of mIRM. Data are from this study, and figure 22 in Paterson and others (1994). Note that pyrrhotite appears to be confined to the hook-shaped part of the batholith, and near the batholith margins. Geology as in figure 2.

found evidence for low-unblocking temperatures from these sites, some of which had reverse polarity magnetizations. We could not define these magnetization components on the specimen level with acceptable confidence. Another set of sites (92kms1-6, 92kmst4, 01kmt1, 2) all with normal polarity magnetization carried exclusively by magnetite are near locations (sites 312, 459) reported by Paterson and others (1994) to have normal polarity magnetization carried by pyrrhotite. From our thermal demagnetization and mIRM experiments, we conclude that magnetite is widespread within the Mount Stuart batholith, and that pyrrhotite is probably restricted to the fish-hook shaped part of the batholith (fig. 12). It is also possible that pyrrhotite may be entirely restricted to the margins of the batholith. Fifteen of the 17 Paterson and others (1994) sites with reported pyrrhotite, and 6 of 6 sites in this study with pyrrhotite indicated by mIRM or thermal demagnetization are within 1 kilometer of the batholith margin.

Lacking specific details of Paterson and others' published data, or having information regarding which 5 of their 27 original sites have magnetization that was well-enough defined to be suitable for calculation of site means, it is difficult to evaluate the paleomagnetic data published by Paterson and others (1994). Based on their methodology and our rock-magnetic results, we can offer an explanation for some of the discrepancies between their data and ours. First of all, they defined the occurrence of pyrrhotite on the basis of laboratory unblocking temperatures of natural remanence

that were below 400°C, and high-coercivity for a.f. demagnetization. The latter observation, following our mIRM experiments, can safely be attributed to the presence of hematite in two of the Mount Stuart sites. Thus it is likely that at least some of their reported pyrrhotite-bearing sites (notably 312, but perhaps many others) may in fact have significant hematite instead. As for the occurrences of pyrrhotite defined by their < 400°C unblocking temperature, this definition is somewhat questionable due to the fact that pyrrhotite has a Curie temperature of 320°C (Dunlop and Özdemir, 1997). For example, our mIRM data show that specimens from the Ingalls Ophiolite (fig. 10D) lose nearly all of their remanence between the 320° and 350°C demagnetization step. If the unblocking temperatures reported by Paterson and others (1994) were significantly above this temperature, pyrrhotite could actually be ruled out as a remanence carrier. In this light, we would suggest that many of the pyrrhotite occurrences reported by Paterson and others (1994) might be considered suspect until detailed rock magnetic studies on those samples are performed. In addition, any petrographic identification of pyrrhotite would need to confirm that the pyrrhotite is in its monoclinic phase (compositions in the range of  $\text{Fe}_7\text{S}_8$  to  $\text{Fe}_{11}\text{S}_{12}$ ), as hexagonal phase pyrrhotite does not exhibit stable ferrimagnetic behavior.

*Magnetic mineral petrogenesis.*—Petrographically, characterizing the magnetic mineral assemblage in any rock can be daunting, due to the size (between 30 nm and 0.1  $\mu\text{m}$ ) and low concentration (1% to several p.p.b.) of the fine-grained magnetized particles that are most likely to carry a stable remanent magnetization. Although large Fe-oxides and Fe-sulfides are readily observable in plutonic or metamorphic rocks, these large grains are of multi-domain character and seldom carry an ancient paleomagnetic signal (see Dunlop and Özdemir, 1997). Thus, although Paterson and others (1994) reported microprobe observations of pyrrhotite, and reported that they could not detect any magnetite, it is clear from our rock magnetic work that SD magnetite is (paleomagnetically) abundant in the Mount Stuart batholith. In reviewing the paleomagnetism of felsic and intermediate plutonic rocks, Dunlop and Özdemir (1997) noted that ancient and well-defined remanence was typically carried by small inclusions of SD magnetite produced by exsolution within feldspars or Fe-silicates. Such exsolution almost always occurs at high temperatures, and thus we consider it very likely that magnetite in the Mount Stuart batholith is primary, in that it dates from the earliest post-crystallization cooling history of these rocks. The pyrrhotite reported by Paterson and others (1994) could be primary as well. The origin of hematite we identified via rock magnetic experiments could be from early exsolution of a primary Fe-Ti oxide phase to hematite + ilmenite. Hematite could be due to alteration, as it was invariably associated with disintegration of our samples due to mineral expansion during heating experiments (the critical laboratory temperature for this disintegration process appears to be about 540°C).

*Temperature of remanence acquisition.*—In the following discussion, it will be clear that any tectonic interpretation of the paleomagnetic results from the Mount Stuart batholith is strongly influenced by the temperature at which the remanence in these rocks was acquired. In this case, we have a population of data for which both magnetic mineralogy and domain state of its mineralogical carrier are known. At the very least, rocks from a total of 17 sites clearly have magnetite as their remanence carrier (tables 2 and 3). The magnetic mineralogy is demonstrated by the mIRM experiments and thermal demagnetization response. We also conclude that the magnetizations isolated by thermal demagnetization of specimens from 11 of these sites are carried by single domain magnetite because low-temperature demagnetization effectively removes any remanence carried by MD grains, and the normalized remanence plots show sharp, square-shouldered unblocking spectra indicative of demagnetization of SD phases. Because our magnetizations as isolated by thermal demagnetization are carried by SD

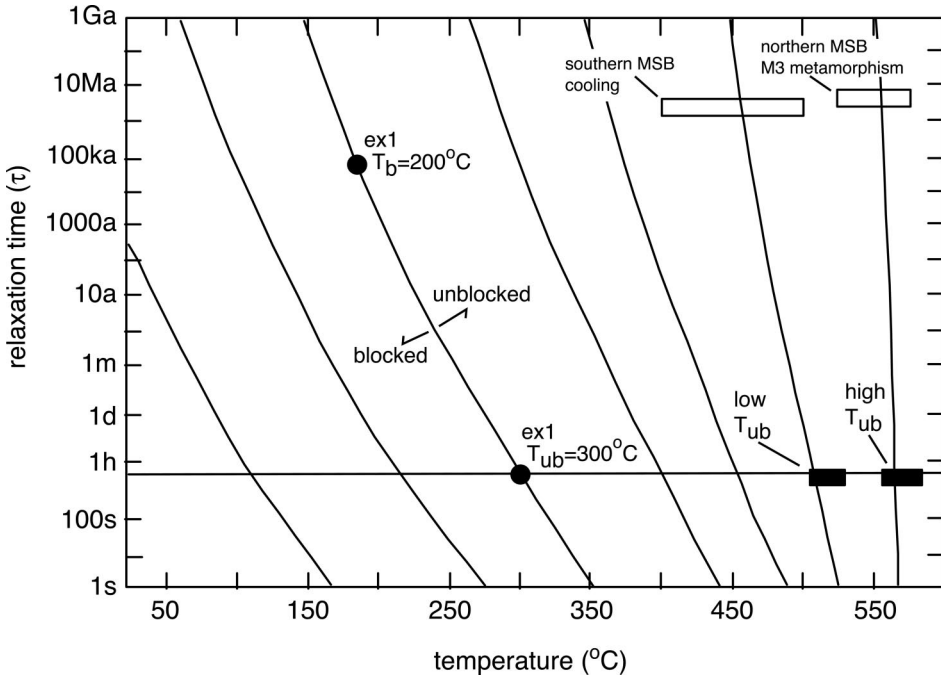


Fig. 13. Pullaiah and others (1975) plot of magnetic relaxation time ( $\tau$ ), versus temperature, modified from Dunlop and others, 1997. The curves on the plot denote effect that combinations of temperature and duration time spent at a given temperature have on remanence carried by single-domain magnetite. An example (ex1) is plotted to describe how to interpret this plot. In this case, a TRM is acquired in a rock during a 200°C thermal event that lasts 100 ka. In the laboratory, this TRM will be unblocked by heating the sample to 300°C in an oven for 30 minutes. The laboratory unblocking temperatures obtained during demagnetization of NRM after LTD treatment can be used to constrain the thermal history that could be responsible for their TRMs, and can also be used to determine if a known thermal event has produced a TRM. The black squares denote ranges of unblocking temperatures found in magnetite-bearing rocks from the Mount Stuart batholith (from table 3). Open rectangles denote the temperature and duration of two important thermal events, cooling of the southern portion of the Mount Stuart batholith between the Ar closure temperatures of hornblende and biotite, and the peak temperature and duration of the M3 metamorphic event (Evans and Davidson, 1999) that affected the northern part of the Mount Stuart batholith.

magnetite, the relationships between laboratory thermal unblocking of TRM and acquisition of TRM during cooling (Pullaiah and others, 1975) can be exploited to obtain the temperature of remanence acquisition. The laboratory unblocking temperatures and heating times used to obtain them are plotted on the theoretical curves of Pullaiah and others (1975). The high unblocking temperature magnetizations were acquired at temperatures  $> 560^\circ\text{C}$  (fig. 13). The low-intensity, lower unblocking temperature magnetization in a sub-set of the Mount Stuart rocks could have been acquired over longer periods of time at temperatures as low as  $450^\circ\text{C}$  (fig. 13).

The temperature of remanence acquisition for the pyrrhotite-bearing rocks cannot be defined with this precision, as the domain state of the pyrrhotite is not as clearly known. We can conclude that, based on the reported Curie temperature of pyrrhotite ( $320^\circ\text{C}$ ), the remanence in rocks carried by pyrrhotite would be acquired below  $320^\circ\text{C}$ .

*Timing of remanence acquisition.*—Comparison of the temperature of remanence acquisition with the time-temperature evolution of the Mount Stuart batholith, based on existing geochronology, places constraints on the timing of remanence acquisition.

TABLE 4  
*Geochronologic data*

Unit	mineral	method	Age (Ma)	± (Ma)	Loc. lat	Loc. lon	reference
Bps	Bio	K-Ar	93.2	2.8	47°42.9'N	121°16.3'W	2
Bps	Bio	K-Ar	82.3	5.0	47°42.9'N	121°17.2'W	3
Bps	Bio	K-Ar	92.1	2.7	47°43.3'N	121°16.7'W	3
Bps	Hbl	K-Ar	92.1	2.7	47°43.3'N	121°16.7'W	3
Cs	Hbl	<sup>40</sup> Ar- <sup>39</sup> Ar	86.7	1.5	47°46'N	120°56'W	4
Cs	Bio	<sup>40</sup> Ar- <sup>39</sup> Ar	83.7	0.3	47°46'N	120°56'W	4
Cs	Bio	<sup>40</sup> Ar- <sup>39</sup> Ar	86.3	1.1	47°46'N	120°56'W	4
Cs	Bio	K-Ar	84.6	2.5	47°42.6'N	121°00.1'W	2
Io	Hbl	K-Ar	82.4	2.0	47°45.5'N	121°10.3'W	1
Io	Hbl	K-Ar	85.5	3.7	47°42.6'N	121°00.1'W	2
Msb	Bio	K-Ar	90.0	2.6	47°32.7'N	120°44.3'W	2
Msb	Bio	K-Ar	82.3	2.4	47°46.5'N	121°04.5'W	3
Msb	Bio	K-Ar	82.4	1.3	47°45.5'N	121°10.3'W	1
Msb	Bio	K-Ar	87.7	2.6	47°32.8'N	120°41.8'W	2
Msb	Bio	K-Ar	87.7	0.2	47°34.2'N	121°01.8'W	1
Msb	Bio	K-Ar	85.3	1.4	47°36.2'N	120°53'W	5
Msb	Bio	K-Ar	87.7	2.6	47°33.7'N	120°46.6'W	2
Msb	Bio	<sup>40</sup> Ar- <sup>39</sup> Ar	87.6	2.0	47°32'N	120°53'W	4
Msb	Hbl	K-Ar	95.0	3.3	47°46.5'N	121°04.5'W	3
Msb	Hbl	K-Ar	90.0	2.7	47°32.7'N	120°44.3'W	2
Msb	Hbl	K-Ar	90.0	2.9	47°32.8'N	120°41.8'W	2
Msb	Hbl	K-Ar	87.5	3.0	47°34.2'N	121°01.8'W	1
Msb	Hbl	K-Ar	93.2	3.1	47°33.7'N	120°46.6'W	2
Msb	Hbl	<sup>40</sup> Ar- <sup>39</sup> Ar	89.3	0.5	47°32'N	120°53'W	4

Geological units: Bps = Beckler Peak stock, Cs = Chiwaukum schist, Io = Ingalls Ophiolite, Msb = Mount Stuart batholith. Errors as stated in original publication.

References: 1) Tabor and others (1993), 2) Engels and Crowder (1971), 3) Yeats and Engels (1971), 4) Evans and Davidson (1999), 5) Tabor and others (1987).

For our purposes, the most relevant data are K-Ar and <sup>40</sup>Ar-<sup>39</sup>Ar geochronology of amphibole and biotite (summarized by Paterson and others, 1994; Ague and Brandon, 1996; and Evans and Davidson, 1999). The nominal closure temperature for significant diffusion of Ar in hornblende is 530° ± 50°C, and the nominal Ar closure temperature for biotite is 350° ± 50°C (McDougall and Harrison, 1999). The dates obtained by Ar geochronology of these phases represents the interpreted age at which the rocks cooled below these closure temperatures. For comparison with the paleomagnetic data, the dates obtained from the amphiboles place a minimum age constraint for remanence acquisition by magnetite-bearing rocks. The nominal Ar closure temperature is slightly (45°C) below their remanence acquisition temperature. The biotite Ar closure temperature is slightly above the Curie temperature of pyrrhotite, so the Ar dates of these rocks is interpreted to be the maximum possible age of the remanence carried by pyrrhotite.

Twenty-four Ar dates of amphibole or biotite from the Mount Stuart batholith proper or from country rocks within 5 kilometers of the batholith margin are available (table 4, fig. 14). With the exception of one 82 Ma K-Ar age from the northwest part of the batholith, all of the amphibole dates are older than 85 Ma. Many (6 of 10) of the amphibole Ar dates are 88 Ma or older, including one of the <sup>40</sup>Ar-<sup>39</sup>Ar plateau ages reported by Evans and Davidson (1999). All but one of these dates is from the southeast half of the Mount Stuart batholith. The youngest amphibole Ar dates are from the extreme northwest quadrant of the batholith (fig. 14), but not all dates in the northwest part are equally young. Dates there include a 95 Ma K-Ar result, and a result from Evans and Davidson (1999) with a <sup>40</sup>Ar-<sup>39</sup>Ar plateau age of 86.7 ± 1.5 Ma.

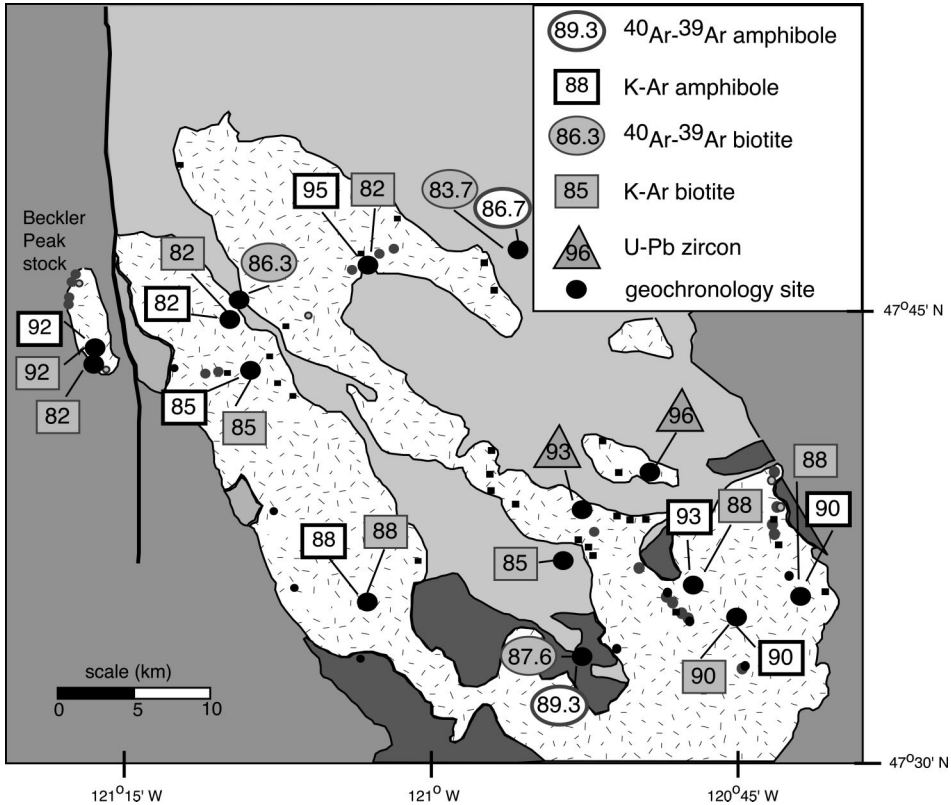


Fig. 14. Map of the Mount Stuart batholith region, showing the locations and dates obtained by geochronology studies. K-Ar and  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  results and locations are provided in table 4. Geology as in figure 2.

Collectively, the Ar geochronology indicates that the batholith cooled below the Ar closure temperature of amphibole by 85 Ma. All magnetite-bearing rocks come from parts of the Mount Stuart batholith with Ar amphibole dates that are older than 85 Ma, with all but two sites located within 5 kilometers of a location with an Ar amphibole date of 90 Ma or more. It is clear that the batholith had cooled below  $530 \pm 50^\circ\text{C}$  within 2 to 3 Ma of its 93 Ma U-Pb zircon crystallization age, and that the magnetizations carried by SD magnetite from 9 of our 11 new paleomagnetic sites were acquired by 90 Ma.

The Ar dates of biotites from either the Mount Stuart batholith or nearby country rocks are more variable (table 4). Biotite dates that are identical (within error) to the amphibole Ar dates, ranging from 87.6 to 90 Ma, are found in rocks from the southeast part of the batholith (fig. 14). Younger biotite Ar dates (82-86 Ma) are found in samples from the central and northwest portions of the batholith (fig. 14). Two of these results from the northwest are from  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  step-heating experiments, which yield plateau ages of  $83.7 \pm 0.3$  Ma and  $86.3 \pm 1.1$  Ma (Evans and Davidson, 1999). From these dates, we can conclude that the batholith cooled below the nominal Ar closure temperature of biotite ( $350 \pm 50^\circ\text{C}$ ) at about 88 Ma in the southwest part and at about 84 Ma in the northwest part. Acquisition of remanence carried by pyrrhotite occurred during this time.

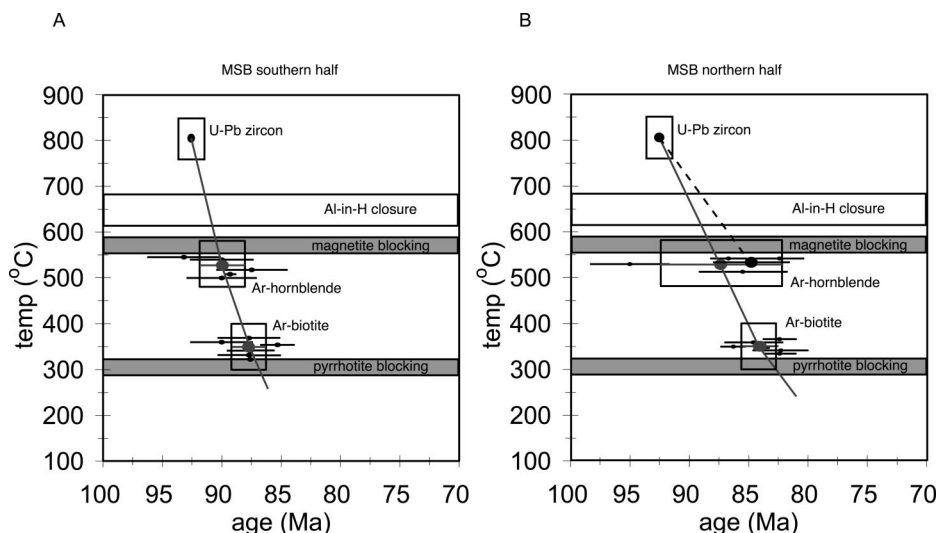


Fig. 15. Temperature-time plots showing the cooling history of the Mount Stuart batholith, obtained from the geochronology data (table 4), and using nominal Ar closure temperatures of  $530^{\circ} \pm 50^{\circ}\text{C}$  for hornblende, and  $350^{\circ} \pm 50^{\circ}\text{C}$  for biotite. (A) southern part of the batholith. (B) northern part of the batholith. K-Ar and  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  hornblende and biotite dates and their errors are plotted (the offset of the temperatures for the individual data are done to facilitate viewing the data, and are not intended to represent actual temperature variations). Squares surrounding the average age estimate for each mineral set are scaled to show the standard deviation of each mean age, and the range in nominal Ar closure temperatures for that mineral. For (B), dashed line leads to the mean of the hornblende dates that excludes the 95 Ma K-Ar date that is a probable outlier. Temperatures of TRM blocking for magnetite and pyrrhotite are indicated.

The range in dates described above, together with patterns of metamorphic mineral assemblages and associated metamorphic barometry and thermometry data, clearly indicate that the thermal history of the northern and southern parts of the Mount Stuart batholith may be different (Paterson and others, 1994; Ague and Brandon, 1996; Evans and Davidson, 1999). The difference in thermal history of the northern and southern parts of the batholith is attributed to post-emplacement regional M3 metamorphism. To better evaluate the effect of post-emplacement thermal events on the timing of remanence acquisition, the available Ar geochronology results are divided into northern and southern subsets. Based on dates in table 4, the U-Pb zircon date of 93 Ma for crystallization of the Mount Stuart batholith, and the nominal closure temperatures for Ar in hornblende and biotite we can construct separate temperature-time plots for the northern and southern parts of the batholith. In the southern half, the mean of the Ar dates from hornblende is  $90.0 \pm 2.1$  Ma and the mean of the Ar dates from biotites is  $87.6 \pm 1.5$  Ma. (Errors associated with these mean dates are at 95% confidence). The temperature-time plot (fig. 15A) for this area indicates that the rocks cooled through the blocking temperature range for magnetite between 91 and 90.5 Ma, and through the blocking temperature range for pyrrhotite between 87 and 86 Ma. In the northern part of the batholith, the mean of all the Ar dates from hornblende is  $87.4 \pm 5.4$  Ma. One date (a 95 Ma K-Ar result) appears to be an outlier; if this date is excluded, the mean Ar date of the hornblende is  $84.9 \pm 2.2$  Ma. The mean of the Ar dates from biotite in the northern half of the batholith is  $83.9 \pm 1.5$  Ma. The resulting temperature-time plot for the northern part of the Mount Stuart batholith (fig. 15B) indicates that the rocks here cooled through the blocking temperature range for magnetite between 86 and 85 Ma, and through the blocking

temperature range of pyrrhotite between 83 and 82 Ma. Remanence acquisition by either magnetite or pyrrhotite thus appears to be delayed by about 5 Ma in the northern half of the batholith. Notably, pyrrhotite in the northern part of the batholith is likely to carry a reverse polarity primary remanence because chron 34n, the Cretaceous normal superchron, ended at about 83.5 Ma (Gradstein and others, 1994).

Understanding the thermal history of the Mount Stuart batholith improves the application of the Pullaiah and others (1975) model to our unblocking temperature data. Two important thermal events affected the batholith; cooling of the southern half through the Ar closure temperatures of hornblende and biotite, and the M3 metamorphic event that affected the northern half of the batholith (fig. 13). The M3 event was of sufficient temperature and duration to produce a post-emplacement TRM carried by SD magnetite that would have laboratory unblocking temperatures  $> 560^{\circ}\text{C}$ , such as we found in sites from the northern part of the batholith such as 01Kmu1, 2. The temperature range and duration of cooling in the southern half of the Mount Stuart batholith falls on the Pullaiah and others (1975) curve intersecting the lower laboratory unblocking temperature results from the sub-set of specimens from the southern part of the batholith (for example, fig. 5A). Those specimens have thus had a small portion of their remanence blocked in during cooling between  $530^{\circ}$  and  $350^{\circ}\text{C}$  over a period of about 3 Ma. This fact serves to confirm the use of the Pullaiah and others (1975) curves to evaluate unblocking temperatures of LTD-treated rocks in terms of thermal events (as was done by Dunlop and others, 1997). In addition, according to the Pullaiah and others (1975) model, the high laboratory unblocking temperatures for remanence carried by SD magnetite from rocks of the southern part of the batholith could not have been thermally reset during post-emplacement cooling.

The timing of remanence acquisition of the fine-grained dikes and their contact-metamorphosed hosts is not well known because the dikes in this area have not been dated directly. Significant thermal events have not affected the region, based on the apatite fission-track dates summarized in Ague and Brandon (1996), and more recent U-Th-He dates from apatite and zircon from the Mount Stuart batholith (Reiners and others, 2002). The closest volcanic rocks are the Eocene Barlow Pass Volcanics, which are locally abundant near the Beckler Peak stock (Tabor and others, 1993). We tentatively assume the fine-grained dikes and contact metamorphism of adjacent plutonic rocks are of this age. The texture of these dikes suggests rapid cooling, so the remanence recorded by the dikes and contact metamorphosed plutons would have been acquired shortly after their crystallization. The magnetization we isolated from the Beckler Peak stock is consistent with an age older than these dikes. An interpretation of the directions from the dikes in the Mount Stuart batholith in terms of a baked contact test is less definitive. We can conclude that the samples from the batholith are magnetically more stable than the dikes we sampled.

The reverse-polarity magnetizations reported by Paterson and others (1994), carried mainly by pyrrhotite, could be as old as 83 Ma. An alternative, based on our paleomagnetic data from the northern part of the Mount Stuart batholith, assumes that magnetization may be in part associated with younger igneous activity. Here, the only evidence for reverse polarity magnetizations carried by pyrrhotite came from samples of Eocene dikes. Beck and others (1981), and Beck and Noson (1972) reported that many sites from the northern portion of the batholith had poorly-defined paleomagnetic results. The results from Paterson and others (1994) are obviously very scattered, given that only 5 of 27 sites have mean directions with  $\alpha_{95} < 15^{\circ}$ . Ague and Brandon (1996) also reported that minerals such as amphibole were most-altered in the northern part of the batholith. It is distinctly possible that the occurrences of pyrrhotite and the reverse-polarity magnetizations reported by Pater-

son and others (1994) reflect alteration of rocks in the northern part of the Mount Stuart batholith caused by fluids associated with the Eocene dikes.

#### *Establishing Paleohorizontal*

Assessing the present-day attitude of paleohorizontal in a plutonic rock is difficult (Beck and others, 1981) and solutions obtained are often non-unique. An important advance in the tectonic application of paleomagnetism was the use of igneous barometry to approximate a paleohorizontal surface in large plutons (Ague and Brandon, 1992). Barometry in such rocks is most commonly done using the Al-in-hornblende (AH) method. The AH method has been improved upon and applied to many other plutonic bodies where paleomagnetic data have been obtained (Ague, 1997; Harris and others, 1997, 1999; Symons and others, 2000; Butler and others, 2002). The application of the AH technique is by no means simple, and has engendered some controversy. Paterson and others (1994) criticized the Ague and Brandon (1992) application of AH barometry data to the Mount Stuart batholith. A subsequent study of the Mount Stuart batholith (Ague and Brandon, 1996) with a larger set of AH data confirmed their earlier result. This in turn resulted in a set of comments and replies by Anderson (1997), and Ague and Brandon (1997). For those readers who wish a complete and in-depth discussion of the AH data sets, methods, and various criticisms we refer you to those articles.

As summarized by Paterson and others (1994), Ague and Brandon (1996), Anderson (1997), Ague and Brandon (1997), Ague (1997), and Evans and Davidson (1999), discussions of AH barometry in these rocks largely revolves around differences in data selection criteria. The most inclusive criteria for selecting data were used by Paterson and others (1994), and Anderson (1997). They have a larger set of data because they included AH results from rocks that contained most, but not all, of the mineral assemblage called for in the papers that document the basis for the AH barometer. Using their larger, but less selective, data set, Paterson and others (1994) find evidence in the barometry for a slight doming of the Mount Stuart batholith, with very high ( $>10$  kbar) pressures from rocks of the central part of the pluton. Ague and Brandon (1996) used AH barometry only in those rocks for which they could document the existence of the entire mineral assemblage and proper lithology called for by barometer's calibration studies. Ague and Brandon (1997), and Ague (1997) emphasized that careful selection of rocks whose mineralogy meets the requirements for use of the barometer is important to insure that anomalous results from non-equilibrium assemblages are avoided. Using their smaller (but still extensive with  $>40$  sites) set of barometry data, Ague and Brandon (1996) found that the spatial distribution of crystallization depths in the batholith was fit best by a simple plane. Other geometric fits to their data were explored, and possible differential tilting of parts of the batholith relative to one another was also evaluated. More complicated structural variations were not found to improve fit to their data. Their best-fit paleohorizontal surface has a strike of  $43.2^\circ \pm 30.4^\circ$  and a dip of  $7.0^\circ \pm 2.0^\circ$  towards  $133.2^\circ$  (Ague and Brandon, 1996). Evans and Davidson (1999) found these results to be consistent with the pattern of kinetically (thermally) activated M3 metamorphic reactions found in the aureole around the northwest part of the batholith, and with the progression of Ar dates from oldest in the southeast to youngest in the northwest in the area. A relatively uniform and small amount of tilt is also consistent with the fact that an andalusite (or relict andalusite) contact metamorphic aureole surrounds the entire batholith. We agree that the results of Ague and Brandon (1996) define a planar paleohorizontal surface within the Mount Stuart batholith.

Thermometry data indicate that the AH assemblages equilibrated at about  $650^\circ\text{C}$  under sub-solidus conditions in the Mount Stuart rocks, and was not reset by post-emplacement M3 metamorphism (Ague and Brandon, 1996; Evans and Davidson,

1999). This information is important, in that one uncertainty to mention in using AH barometry to establish paleohorizontal for paleomagnetic data is the potential for a significant time lag between closure of the AH barometer assemblage and remanence acquisition during cooling. For our magnetizations carried by SD magnetite, the time lag between the AH and paleomagnetic information would be the time it took for the batholith to cool from about 650° to below the blocking temperature range for the magnetite. From the temperature-time paths (fig. 15), we estimate the closure temperature for the AH barometer was reached at ~91.5 Ma. In the southern half of the Mount Stuart batholith the difference in AH closure age and the time during which the magnetite-carried remanence was blocking in is 0.5 to 1.0 Ma (fig. 15A). In the northern portion, a time lag of 5.5 to 6.5 Ma between the time the AH barometer closed and the directions carried by SD magnetite were acquired is indicated by the thermochronology data (fig. 15B). Any stable magnetization carried by pyrrhotite would be subject to a longer delay between AH closure and remanence acquisition time. In the southern part of the batholith this difference would be 4.5 to 5.5 Ma. In the northern part of the batholith the difference would be 8.5 to 9.5 Ma.

Given the correspondence between the time at which the Mount Stuart batholith cooled below the AH closure temperature and the acquisition temperature of the remanence carried by SD magnetite, use of the paleohorizontal surface established by AH barometry in these rocks for correction of the paleomagnetic directions is well justified for the southern part of the batholith. Using the mean magnetization directions defined solely by SD magnetite-dominated sites ( $N = 9$ ) within this part, and the paleohorizontal surface of Ague and Brandon (1996), we obtain a tilt-corrected direction of  $D = 355.9^\circ \pm 10^\circ$ ,  $I = 50.6^\circ \pm 4^\circ$ ,  $N = 9$ , using the bootstrap statistical technique of Ague and Brandon (1992). This result places the Mount Stuart batholith at a latitude of  $31.3^\circ \text{ }^{+3.8^\circ} / \text{ }_{-3.4^\circ} N$  at 91 Ma.

Because a considerable period of time elapsed between AH closure and remanence acquisition by pyrrhotite in all parts of the pluton, or by magnetite in the northern half of the pluton, use of AH barometry as a structural correction for those magnetizations entails greater uncertainty. Given that post-emplacment tilt of at least the northern part of the batholith occurred during the circa 5 Ma lag time between AH closure and remanence acquisition in the northern part of the batholith (Evans and Davidson, 1999), it is likely that the AH-defined paleohorizontal surface was not horizontal when the northern part of the batholith was magnetized.

#### *North America Reference Poles*

To compare the paleolatitude of the Mount Stuart batholith with that of cratonic North America for purposes of evaluating paleogeographic models, there also needs to be a reliable set of paleomagnetic data from the undisturbed craton of North America. We will not exhaustively review the paleomagnetic data for North America. A review of this paleomagnetic data was done by Van Fossen and Kent (1992), and by Tarduno and Smirnov (2001). For the time frame of 125 to 85 Ma, a set of high quality paleomagnetic data from seven different rock units from different settings provide paleomagnetic reference poles for North America. Of these, six are from intrusive rocks (dikes or plutons), and one is from a sedimentary sequence (table 5). Traditionally, the mean direction of each study is used to calculate its reference pole, and then each reference pole is given unit weight in a calculation of a grand-mean pole to be used as a reference point on the APW path. This approach is perfectly valid if the amount of time averaged by each study is similar. The Newfoundland dikes pole (Lapointe, 1979) is based on sites collected from just three dikes, likely represents a geologically short time period, and should be best treated as a single virtual geomagnetic pole (VGP). Given that many of the other results are from dikes or small intrusive bodies, we divided the seven studies into 19 VGPs (table 5). A plot of these poles (fig. 16) shows that they are well

TABLE 5  
Cretaceous poles for North America

pole	unit	Pole lat	Pole lon	Ref.
1	Mt. Megantic	68	171	1
2	Niobrara, Pueblo loc	66	187	2
3	Niobrara, Trego loc	65	194	2
4	Niobrara, Kemmerer loc	62	178	2
5	Montergian Int., Oka loc	74.3	186.2	3
6	MI., Ste. Dorothee loc	63.9	185.7	3
7	MI., Brilund loc	68.3	224.0	3
8	MI., Carillon loc	80.7	242.2	3
9	Newfoundland dikes	68.6	206.6	4
10	Arkansas Int., Magnet Cove loc	72.5	189.5	5
11	Al., Little Rock loc	72.3	174.9	5
12	Al., Potash Sulfur Spring loc	70.0	185.1	5
13	White Mtns. Int., Mt. Ascotney loc	68.5	186.6	6
14	WMI, Mt. Tripyramid loc	70.2	185.7	6
15	WMI, Mt. Pawtuckaway loc	76.9	191.2	6
16	Maine Intrusions, Tatnic loc	65.9	209.5	7
17	Mal, Alfred loc	73.8	211.4	7
18	Mal, Lebanon diorite loc	70.8	197.8	7
19	Mal, Cape Neddeck loc	74.6	179.5	7
Mean:	Plat = 70.1°N, Plon = 191.2°E, k = 164.8, A95 = 2.7°, N = 18			

References: 1) Larochelle (1961), 2) Shive & Frerichs (1974), 3) Foster and Symons (1979), 4) Lapointe (1979), 5) Globerman and Irving (1988), 6) Van Fossen and Kent (1992), 7) McEnroe (1996)

clustered with the exception of one result; pole 8, Carillon locality of the Montergian Intrusions. The mean of all 19 poles has an angular standard deviation of  $\delta = 7.1^\circ$ ; Pole 8 is  $> 2\delta$  ( $14.9^\circ$ ) away from the mean direction, and is discarded. The well-grouped poles from this distribution indicate that the geomagnetic north pole was stationary relative to North America between 125 and 85 Ma (fig. 16). This interval of little or no apparent polar wander is referred to as the Cretaceous still-stand. Much of this interval (118–83.5 Ma) also corresponds to the Cretaceous long-normal superchron, during which time the geomagnetic field maintained a normal magnetic polarity (compare Gradstein and others, 1994). By all respects, this set of poles provides one of the best-defined time segments of the entire North America apparent polar wander (APW) path. Using the Cretaceous still-stand pole, the expected direction for the present location of the Mount Stuart batholith is  $D = 334.6^\circ$  ( $\Delta D = 4.7^\circ$ ),  $I = 73.1^\circ$  ( $\Delta I = 1.7^\circ$ ) (fig. 17). Compared with the reference direction, the tilt-corrected direction from the Mount Stuart batholith is significantly shallower and has a declination that is clockwise of the expected direction (fig. 17). The Mount Stuart batholith has a characteristic magnetization with an inclination flattened by  $22.5^\circ \pm 5.7^\circ$  and declination rotated clockwise by  $21.3^\circ \pm 14.7^\circ$ . Based on a paleohorizontal surface approximated by AH barometry, our results indicate that the Mount Stuart batholith was  $3040 \pm 630$  kilometers south of its present location at 91 Ma, and that  $\sim 20^\circ$  of clockwise vertical axis rotation affected these rocks since 91 Ma.

#### *Alternatives and Uncertainties*

Now we explore some of the alternative explanations that have been proposed for the metamorphic and structural history of the Mount Stuart batholith, possible

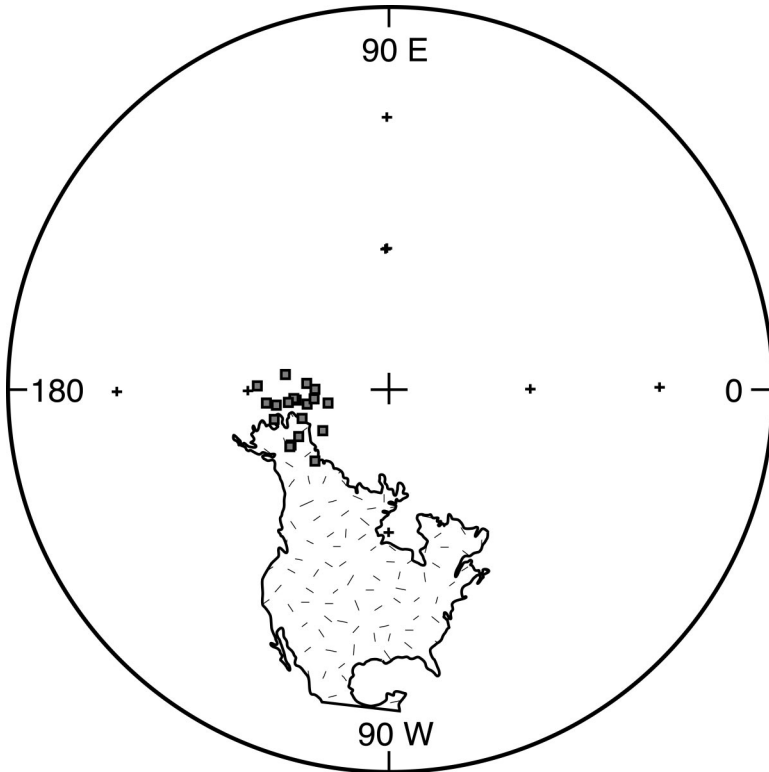


Fig. 16. Plot of virtual geomagnetic poles (VGPs) for the 18 Cretaceous reference poles for North America, given in table 5, but excluding pole 8.

interpretations of additional paleomagnetic data, and outline some of the uncertainties associated with our interpretation.

*Deformation and tilt of the Mount Stuart batholith.*—There is abundant evidence for deformation of the Mount Stuart batholith during its emplacement, as recorded by magmatic fabrics, solid-state fabrics, and anisotropy of magnetic susceptibility (AMS) (Miller and Paterson, 1994; Benn and others, 2001). This deformation occurred above both the closure temperature of the AH barometers and the acquisition temperature of the characteristic remanence, and so does not pose a complication to either set of data.

Based on extensive field observations, and a more liberal interpretation of the barometry and paleomagnetic data Paterson and others (1994) proposed a more complicated post-emplacement deformation history with a different interpretation of the paleomagnetic data. The key differences include doming of the batholith, differential NE-side down tilting of the northeast and central parts of the batholith, and significant (about 20°) of differential vertical axis rotation between the northeast and southwest parts of the batholith. Butler and others (1989) also proposed a larger-magnitude post-magnetization tilting event.

Evidence for doming of the batholith, as proposed by Paterson and others (1994), is based on the use of AH barometry data from mineral assemblages that do not include all of the phases needed to establish equilibrium conditions consistent with the calibrations of the AH barometer. If this more inclusive set of barometry data is in fact

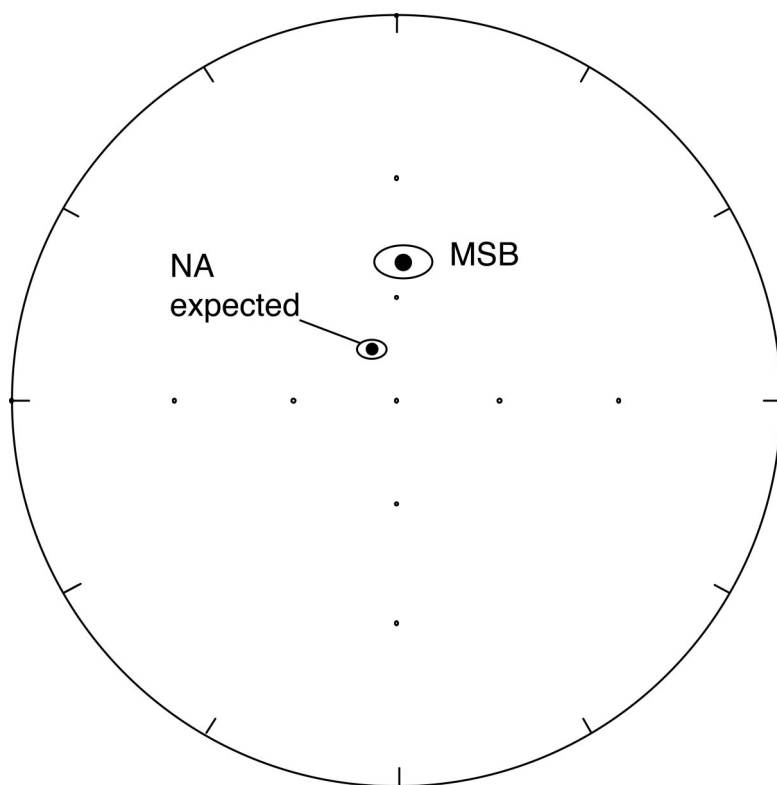


Fig. 17. Equal-angle projection of the direction expected for the Mount Stuart batholith's location if it were part of North America (based on the mean of the poles in table 5), and the mean of 9 sites from the southern part of the Mount Stuart batholith whose remanence is carried by SD magnetite. The mean Mount Stuart direction is corrected for tilt of the batholith using the AH barometry of Ague and Brandon (1996).

the best one to use in these rocks, then the relatively uniform paleohorizontal surface proposed by Ague and Brandon (1996) should be questioned (as in Anderson, 1997). We note, however, that use of a more robust thermodynamically calibrated AH barometry technique (Ague, 1997) also duplicates the results of Ague and Brandon (1996), further bolstering the reliability of their data set.

The inferred NE-side down tilting of the batholith is a manifestation of the post-emplacment M3 metamorphic event, which affected the northern part of the batholith (see also Brown and Walker, 1993; and Evans and Davidson, 1999). Metamorphic temperatures may have exceeded 600°C in the extreme northwest part of the Mount Stuart batholith during the M3 metamorphism (Brown and Walker, 1993; Paterson and others, 1994; Evans and Davidson, 1999). Notably, none of our paleomagnetic sites are from this area. Although it is clear that the northwest part of the batholith experienced higher T and P conditions during the M3 metamorphism, evidence for differential tilt of the northwest, northeast, and southeast parts of this batholith, as called for by Paterson and others (1994) is equivocal. In fact, Evans and Davidson (1999) concluded that patterns of M3 metamorphic assemblages in and near Mount Stuart reflected the progression of post-emplacment cooling of the batholith as supported by the AH barometry of Ague and Brandon (1996). If the M3 conditions cited by Paterson and others (1994) were in fact kinetically controlled, as Evans and

Davidson (1999) suggest, loading of the batholith during the M3 event could have been uniform over a large portion of its area.

Butler and others (1989), following up on discussion of possible tilt of the Mount Stuart batholith in Beck and others (1981), proposed a large ( $\sim 30^\circ$ ) SW-side down tilt to explain the discordance between the magnetization of Mount Stuart and the expected magnetization direction from North America. The main evidence for tilt of this sense and magnitude is based on bedding attitudes of Eocene Swauk Formation strata, which crop out to the south and south-west of the batholith. Swauk Formation bedding attitudes at occurrences near the batholith (see Tabor and others, 1987) have a high degree of structural variability, arguing against simple tilt of these strata. The Swauk-Mount Stuart batholith contact is also complex, leading Miller and others (1990) to question the use of Swauk strata as an Eocene paleohorizontal datum for the Mount Stuart batholith. The large structural relief (or series of smaller faults within the batholith to allow for domino-style tilting of parts of the batholith) that the Butler and others (1989) tilt model would require is not compatible with the available thermochronology, metamorphic petrology, or geologic mapping of the area (Paterson and others, 1994; Ague and Brandon, 1996). In fact recently reported U-Th-He geochronology of apatite and zircon yield dates as old as 60 Ma in the southeast part of the Mount Stuart batholith (Reiners and others, 2002), which argues against any significant variation in structural relief since the Paleocene.

Based on our paleomagnetic and rock-magnetic data, and analysis of thermochronology data, any possible tilt that would invalidate our interpretation of the combined paleomagnetic and AH barometry data would have to have occurred between the time that the Mount Stuart batholith cooled from  $650^\circ$  to  $580^\circ\text{C}$ . Tilting concurrent with cooling the batholith from  $580^\circ$  to about  $550^\circ\text{C}$  would result in a streaking of the paleomagnetic directions (Beck, 1992), which we see no evidence for in our data. Tilting after the batholith cooled below  $550^\circ\text{C}$  would have occurred after both the AH barometers closed to diffusion and remanence was blocked in, and so would be reflected in the AH paleohorizontal surface. As noted by Beck and others (1981) and Butler and others (1989), the tilt required to remove the inclination-anomaly evident in the Mount Stuart paleomagnetic data is  $20^\circ$  to  $30^\circ$ , down to the southwest. The following, albeit complex, series of events is permitted by our data. After closure of the AH barometers, the batholith is tilted  $20^\circ$  to  $30^\circ$  down toward the southwest between 92 and 91 Ma. This tilting event fully stops, and the remanence carried by magnetite is blocked in at about 91 Ma. Sometime after remanence carried by magnetite in the northern part of the batholith, and remanence carried by pyrrhotite from all parts of the batholith, was blocked in (after about 83 Ma), the batholith is tilted approximately  $30^\circ$  top-down to the northeast in order to restore the AH paleohorizontal surface to its present dip of  $7^\circ$  towards the southeast. We feel that this scenario is unlikely. A tilt of greater than  $20^\circ$  to the southwest while the rocks were at high temperatures within a span of 1 Ma should be evident in the geologic record of the area. Although there is evidence for some northeast side down tilt (see above), it almost certainly occurred between circa 90 and 85 Ma.

The only other viable alternative to the above scenario would be tilting of small fault-bounded blocks of the batholith in a domino fashion. In an extreme case, one can imagine that fault-bound blocks on the scale of the paleomagnetic sites might exist in the batholith. If such block tilt had occurred, it must have been very uniform in order to produce the well-clustered magnetization directions we have found in these rocks. Block tilting of this type would be difficult to detect using any barometric technique, but we would presume that such fault zones could be clearly mapped. No such faults were noted in our fieldwork, or in any previous mapping work in the area as discussed by Paterson and others (1994), and Ague and Brandon (1996).

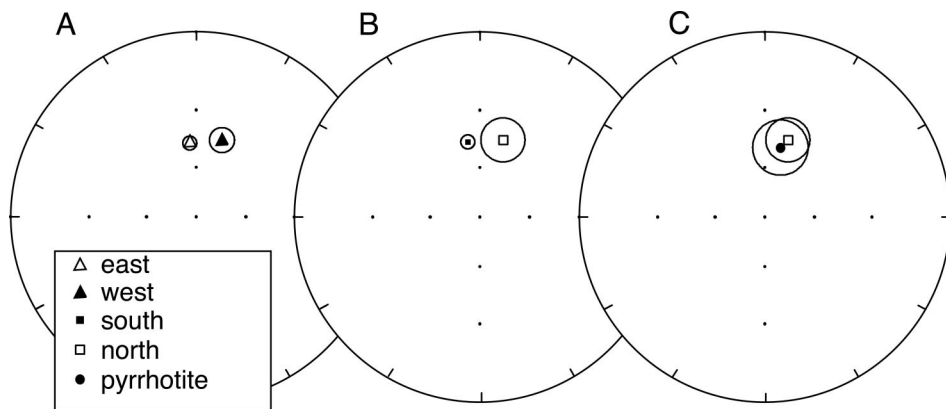


Fig. 18. Equal-angle projections showing site mean directions from different sets of Mount Stuart sites. (A) sites from the east and the west parts of the batholith (after Beck and others, 1981). (B) sites from the north and south parts of the batholith. (C) northern sites compared to the mean of all sites whose remanence is carried by pyrrhotite (sites 91, 92, 911).

The only evidence cited by Paterson and others (1994) to support differential, vertical axis rotations of parts of the Mount Stuart batholith are the two clusters of paleomagnetic directions reported by Beck and others (1981). Sites from the eastern half of the batholith have a mean direction that is more westerly than the mean direction of the sites from the western half (fig. 18A). Geographically, 9 of our 11 new sites are from the eastern half of the batholith; their mean direction is identical to that of the eastern sub-group of Beck and others (1981). With our new data the group means of the two geographical subgroups are far less statistically distinct. Beck and others (1981) discussed a number of possible explanations for the difference between the two sub-group directions. The simplest explanation is the two groups represent paleosecular variation of the geomagnetic field recorded during cooling. Another is that there was some differential rotation of the two areas. Beck and others (1981) endorsed possible horizontal-axis rotation ( $17^\circ$  about an axis trending towards  $355^\circ$ ), while Paterson and others (1994) attribute this difference to about  $20^\circ$  of vertical axis rotation. Other rotations about inclined rotation axes are permissible. Because the difference in these sets of directions can be explained by geomagnetic field variations, using the slight statistical discordance between the eastern and western subgroups to invoke internal deformation of the Mount Stuart batholith should be viewed as permissible, but not required, by the paleomagnetic data.

To interpret the difference between the remanence directions from the eastern and western parts of the Mount Stuart batholith in terms of internal deformation of the batholith presumes that magnetization in all parts of the batholith was acquired at approximately the same time. The thermochronologic and rock-magnetic data make it clear that parts of the Mount Stuart batholith may have magnetization ages that differ by 5 Ma or longer. This difference, however, is greatest between the 91 Ma magnetization carried by magnetite in the southern part of the batholith and the magnetization carried by magnetite in the northern portion of the batholith, rather than eastern versus western portions. Comparison of magnetite-carried remanences from the southern and northern parts of the batholith shows that the difference between remanence directions between north and south parts is greater than the difference between east and west parts. This is consistent with different ages of magnetization south to north (fig. 18B). An additional comparison can be made by including the three sites from the Beck and others, 1981 study that have rock-magnetic evidence for

remanence carried by pyrrhotite. The mean of these sites is identical to that of the northern sub-set of sites (fig. 18C). We thus conclude that the most reasonable explanation for the different sub-sets of paleomagnetic directions is that the magnetization age of the northern part, and magnetization carried by pyrrhotite, is about 5 Ma younger than the magnetization age of magnetite in the southern part of the batholith. The difference in magnetization directions in the north and south parts of the batholith may reflect a combination of tilt during the intervening time, translation/rotation during transport, or polar wander.

#### *Tectonic Implications*

Butler and others (2001) evaluated the discordant paleomagnetic data from the 15 published studies of Cretaceous rocks in Cordilleran terranes that are part of the proposed Baja-BC model and argued that the discordance should be explained away in terms of remagnetization, sediment compaction, and deformation and tilt of crustal panels. They proposed an ad hoc displacement of 1000 kilometers of the Insular and Intermontane superterranes south of their current locations relative to North America at 90 Ma, to achieve a simple, linear, quasi-continuous, Andean-type arc complex along the Cordilleran margin for this time. For plutonic rocks in these terranes, the effects of possible deformation and tilt on their early-acquired magnetizations are examined using a combination of metamorphic and igneous thermobarometry, geochronology, and structural studies. As a model for this approach, Butler and others (2002) proposed that the discordant directions of the 90 Ma Ecstall pluton, in southwest British Columbia, are best explained in terms of post-magnetization folding of the pluton. Given that the paleomagnetic directions for this pluton are strung out along an arc of nearly 80° along a well-fit small circle, and that local structures as indicated by Butler and others (2002) might be compatible with deformation of the pluton in this fashion, it is clear that deformation in the vicinity of the Prince Rupert shear zone has significantly affected the paleomagnetism of the Ecstall pluton. In terms of the Butler and others (2001) tectonic model, the key question to ask is: "Does such deformation adequately explain the paleomagnetic results of other locations, such as Mount Stuart?" We have found that the remanence from the Mount Stuart batholith is well defined, with mean directions that are tightly clustered. By combining rock magnetic techniques such as low-temperature demagnetization (LTD) to isolate the direction carried by SD magnetite with Ar thermochronology results we can constrain timing of remanence acquisition in the southern half of the batholith to within 3 Ma of crystallization. More crucially, the remanence carried by SD magnetite dates to within 0.5 to 1.0 Ma of the time at which the AH barometers equilibrated, validating the use of the paleohorizontal surface defined by the AH barometry to correct the paleomagnetic data for the slight tilt this method detected. Additional metamorphic petrology, thermochronology, and structural data support our conclusion that post-emplacement thermal effects have not altered our paleomagnetic results (from the southern portion of the batholith). These data can also rule out the large tilt of the Mount Stuart batholith's crustal panel that would be required to fit the Butler and others (2001) model. Furthermore, in the northern part of the batholith where post-emplacement metamorphism is evident from local and regional geology, we along with Paterson and others (1994) find that the paleomagnetic directions from those rocks are significantly different from the directions carried by SD magnetite in the southern part of the batholith. This difference can be viewed as a regional "metamorphic contact test", and clearly indicates that the magnetizations from the southern part of the Mount Stuart batholith predate the post-emplacement M3 metamorphic event.

Although appealing in its simplicity, the Butler and others (2001) Andean-inspired tectonic model for the North American Cordillera is inconsistent with the actual paleomagnetic results from Cretaceous plutonic rocks from the Andes. All

paleomagnetic results from Andean arc plutons have inclinations that are uniformly concordant with those expected for their present locations with respect to Cretaceous South America (Beck and others, 1994; Somoza and others, 1996; Beck, 1998). The internal deformation and tilting, if real, that apparently plagues the North American Cordillera is utterly lacking in the Andes of South America.

The Mount Stuart batholith data, corrected to Cretaceous paleohorizontal, agree remarkably well with the 88 Ma result of the Mount Tatlow syncline (Wynne and others, 1995). The rocks from Mount Tatlow include both volcanic flows and interbedded sedimentary rocks, thus providing well-defined paleohorizontal control. A fold test of the paleomagnetic data established a 100 percent pre-folding age for the remanence in these rocks. We see no reason to discard such data, and suggest that the available paleomagnetic results of Cretaceous rocks from the North America Cordillera are best integrated into a model, such as Baja-BC, in which the Insular superterrane is placed 3000 kilometers south of its present location at 90 Ma, and moved northward between this time and 55 Ma, when all available evidence suggests differential motion between these terranes and North America ceased (see Housen and Beck, 1999). New paleomagnetic data from 80 Ma rocks at McColl Ridge (Stamatatos and others, 2001), and paleolatitude estimates based on fossil assemblages in about 75 Ma rocks of the Nanaimo Group (Kodama and Ward, 2001), both yield amounts of displacement for Wrangellia that are approximately 1000 kilometers less than displacements obtained for 90 Ma rocks of the Insular superterrane such as Mount Tatlow and Mount Stuart. These newer results most likely reflect a change in latitude as Baja-BC moved north, driven by the Kula plate (Beck, 1976; Debiche and others, 1987).

#### CONCLUSIONS

In the 30 years since the initial results from the Mount Stuart batholith were available, dramatic improvements in paleomagnetic approaches allow more thorough investigation of remanence carriers and more exact determination of components of magnetization, as well as better understanding of magnetization stability through time. Similar advances in paleobarometry and paleothermometry of both metamorphic and igneous rocks, and geochronology, permit the history of a rock body, and by extension its magnetic remanence, to be quantified far better than was imagined then. Improved plate tectonic models for motion of offshore oceanic plates (Engelbreton and others, 1985) and application of these models to test terrane transport scenarios (Debiche and others, 1987) allow paleogeographic implications of paleomagnetic results to be tested in terms of possible driving mechanisms. It is with these tools that we were able to revisit magnetization of the Mount Stuart batholith in hopes of resolving some of the controversy that large-scale transport interpreted from its shallow inclination spawned. Our new work has made some contributions to understanding when and how the magnetization of Mount Stuart was acquired. Our new data simply enforce the fact that the Mount Stuart batholith's magnetization is shallower than and clockwise of the direction expected if it were magnetized near its present location. As proved true for pioneering efforts to test continental drift using paleomagnetism (Dubois and others, 1957; Creer and others, 1958; Collinson and Runcorn, 1960), subsequent work on the Mount Stuart batholith has only refined the answer provided 30 years ago. These new results leave unchanged the increasingly inescapable picture that major parts of the Pacific Northwest Cordillera have undergone substantial northward transport in the late Cretaceous.

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## REFERENCES

- Ague, J. J., 1997, Thermodynamic calculation of emplacement pressures for batholithic rocks, California: Implications for the aluminum-in-hornblende barometer: *Geology*, v. 25, p. 563–566.
- Ague, J. J., and Brandon, M. T., 1992, Tilt and northward offset of Cordilleran batholiths resolved using igneous barometry: *Nature*, v. 360, p. 146–149.
- 1996, Regional tilt of the Mt. Stuart batholith, Washington, determined using aluminum-in-hornblende barometry: Implications for northward translation of Baja British Columbia: *Geological Society of America Bulletin*, v. 108, p. 471–488.
- 1997, Regional tilt of the Mount Stuart batholith, Washington, determined using aluminum-in-hornblende barometry: Implications for northward translation of Baja British Columbia: Discussion: *Geological Society of America Bulletin*, v. 109, p. 1225–1227.
- Anderson, J. L., 1997, Regional tilt of the Mount Stuart batholith, Washington, determined using aluminum-in-hornblende barometry: Implications for northward translation of Baja British Columbia: Discussion: *Geological Society of America Bulletin*, v. 109, p. 1223–1225.
- Beck, M. E., Jr., 1976, Discordant paleomagnetic pole positions as evidence of regional shear in the western Cordillera of North America: *American Journal of Science*, v. 276, p. 695–712.
- 1989, Paleomagnetism of continental North America: Implications for displacement of crustal blocks within the Western Cordillera, Baja California to British Columbia, *in* Pakiser, L., and Mooney, W., editors, *Geophysical framework of continental United States*: Geological Society of America Memoir 172, p. 471–492.
- 1992, Some thermal and paleomagnetic consequences of tilting a batholith: *Tectonics*, v. 11, p. 297–302.
- 1998, On the mechanism of crustal block rotations in the central Andes: *Tectonophysics*, v. 299, p. 75–92.
- Beck, M. E., Jr., and Noson, L., 1972, Anomalous paleolatitudes in Cretaceous granitic rocks: *Nature, Physical Science*, v. 235, p. 11–13.
- Beck, M. E., Jr., Burmester, R. F., and Schoonover, R., 1981, Paleomagnetism and tectonics of the Cretaceous Mt. Stuart batholith of Washington: Translation or tilt?: *Earth and Planetary Science Letters*, v. 56, p. 336–342.
- Beck, M. E., Jr., Burmester, R. F., Drake, R. E., and Riley, P. D., 1994, A tale of two continents: Some tectonic contrasts between the central Andes and the North America Cordillera, as illustrated by their paleomagnetic signatures: *Tectonics*, v. 13, p. 215–224.
- Benn, K., Paterson, S. R., Lund, S. P., Pignotta, G. S., and Kruse, S., 2001, Magmatic fabrics in batholiths as markers of regional strains and plate kinematics: Example of the Cretaceous Mt. Stuart batholith: *Physics and Chemistry of the Earth (A)*, v. 26, p. 343–354.
- Brown, E. H., and Walker, N. W., 1993, A magma-loading model for Barrovian metamorphism in the southeast coast plutonic complex, British Columbia and Washington: *Geological Society of America Bulletin*, v. 105, p. 479–500.
- Butler, R. F., 1992, *Paleomagnetism: Magnetic domains to geologic terranes*: Boston, Blackwell Scientific Publications, 319 p.
- Butler, R. F., Gehrels, G. E., McClelland, W., May, S., and Klepacki, D., 1989, Discordant paleomagnetic poles from the Canadian Coast Plutonic Complex: Regional tilt rather than large scale displacement?: *Geology*, v. 17, p. 691–694.
- Butler, R. F., Gehrels, G. E., and Kodama, K. P., 2001, A moderate translation alternative to the Baja British Columbia hypothesis: *GSA Today*, v. 11, p. 4–10.
- Butler, R. F., Gehrels, G. E., Baldwin, S. L., and Davidson, C., 2002, Paleomagnetism and geochronology of the Ecstall pluton in the Coast Mountains of British Columbia: Evidence for local deformation rather than large-scale transport: *Journal of Geophysical Research*, v. 107 (B1), p. 3-1–3-13.
- Collinson, D. W., Runcorn, S. K., 1960, Polar wandering and continental drift: evidence of paleomagnetic observations in the United States: *Geological Society of America Bulletin*, v. 71, p. 915–958.
- Coney, P. J., Jones, D. L., and Monger, J. W. H., 1980, Cordilleran suspect terranes: *Nature*, v. 288, p. 329–333.
- Cowan, D., Brandon, M., and Garver, J., 1997, Geologic tests of hypotheses for large coastwise displacements - A critique illustrated by the Baja British Columbia controversy: *American Journal of Science*, v. 297, p. 117–173.
- Creer, K. M., Irving, E., Nairn, A. E. M., and Runcorn, S. K., 1958, Palaeomagnetic results from different continents and their relation to the problem of continental drift: *Annales de Géophysique*, v. 14, p. 492–501.
- Debiche, M. G., Cox, A., and Engebretson, D., 1987, The motion of allochthonous terranes across the North Pacific basin: *Geological Society of America Special Paper* 207, 49 p.
- Du Bois, P. M., Irving, E., Opdyke, N. D., Runcorn, S. K., Banks, M. R., 1957, The geomagnetic field in Upper Triassic times in the United States: *Nature*, v. 180, p. 1186–1187.
- Dunlop, D. J., and Özdemir, Ö., 1997, *Rock magnetism: fundamentals and frontiers*: Cambridge, Cambridge University Press, 573 p.

- Dunlop, D. J., and Xu, S., 1994, Theory of partial thermoremanent magnetization in multidomain grains, 1. Repeated identical barriers to wall motion (single microcoercivity): *Journal of Geophysical Research*, B, Solid Earth and Planets, 99, p. 9005–9023.
- Dunlop, D. J., Özdemir, Ö., and Schmidt, P. W., 1997, Paleomagnetism and paleothermometry of the Sydney Basin; 2. Origin of anomalously high unblocking temperatures: *Journal of Geophysical Research*, B, Solid Earth and Planets, 102, 12, p. 27,285–27,295.
- Engelbreton, D. S., Cox, A., and Gordon, R. G., 1985, Relative motions between oceanic and continental plates in the Pacific basin: *Geological Society of America Special Paper* 206, 59 p.
- Engels, J. C., and Crowder, D. F., 1971, Late Cretaceous fission-track and potassium-argon ages of the Mount Stuart granodiorite and Beckler Peak stock, North Cascades, Washington, in *Geological Survey research* 1971: U. S. Geological Survey Professional Paper 750-D, D39-D43.
- Evans, B. W., and Davidson, G. F., 1999, Kinetic control of metamorphic imprint during synplutonic loading of batholiths: An example from Mount Stuart, Washington; *Geology*, v. 27, p. 415–418.
- Fisher, R., 1953, Dispersion on a sphere: *Proceedings of the Royal Society of London*, A, v. 217, p. 295–305.
- Foster, J., and Symons, D. T. A., 1979, Defining a paleomagnetic polarity pattern in the Montereian intrusives: *Canadian Journal of Earth Sciences*, v. 16, p. 1716–1725.
- Globerman, B. R., and Irving, E., 1988, Mid-Cretaceous reference field for North America: Restudy of 100 Ma intrusive rocks from Arkansas: *Journal of Geophysical Research*, v. 93, p. 11,721–11,733.
- Gradstein, F., Agterberg, F., Ogg, J., Hardenbol, J., van Veen, P., Thierry, J., and Huang, Z., 1994, A Mesozoic time scale: *Journal of Geophysical Research*, v. 99, p. 24,051–24,074.
- Harris, M. J., Symons, D. T. A., Blackburn, W. H., Hart, C. J. R., 1997, Paleomagnetic and geobarometric study of the mid Cretaceous Whitehorse pluton, Yukon Territory: *Canadian Journal of Earth Sciences*, v. 34, p. 1379–1391.
- 1999, Paleomagnetic and geobarometric study of the Late Cretaceous Mount Lorne Stock, southern Yukon Territory: *Canadian Journal of Earth Sciences*, v. 36, p. 905–915.
- Hollister, L., and Andronicos, C., 1997, A candidate for the Baja British Columbia fault system in the Coast Plutonic Complex: *GSA Today*, v. 7, p. 1–7.
- Housen, B. A., and Beck, M. E., Jr., 1999, Testing Terrane Transport: An inclusive approach to the “Baja-BC” controversy: *Geology*, v. 27, p. 1143–1146.
- Irving, E., 1985, Whence British Columbia?: *Nature*, v. 314, p. 673–674.
- Irving, E., Woodsworth, W., Wynne, P., and Morrison, A., 1985, Paleomagnetic evidence for displacement from the south of the Coast Plutonic Complex: *Canadian Journal of Earth Sciences*, v. 22, p. 584–598.
- Kirschvink, J. L., 1980, The least-squares line and plane and the analysis of paleomagnetic data: *Geophysical Journal of the Royal Astronomical Society*, v. 62, p. 699–718.
- Kodama, K. P., and Ward, P. D., 2001, Compaction-corrected paleomagnetic paleolatitudes for Late Cretaceous rudists along the Cretaceous California margin: Evidence for less than 1500 km of post-Late Cretaceous offset for Baja British Columbia: *Geological Society of America Bulletin*, v. 113, p. 1171–1178.
- Lapointe, P. L., 1979, Paleomagnetism of the Notre Dame Bay lamprophyre dikes, Newfoundland, and the opening of the North Atlantic Ocean: *Canadian Journal of Earth Sciences*, v. 16, p. 1823–1831.
- Larochelle, A., 1961, Application of palaeomagnetism to geological correlation: *Nature*, v. 192, p. 37–39.
- Lowrie, W., 1990, Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties: *Geophysical Research Letters*, v. 17, p. 159–162.
- Mahoney, J. B., Mustard, P. S., Haggart, J. W., Friedman, R. M., Fanning, C. M., and McNicoll, V. J., 1999, Archean zircons in Cretaceous strata of the western Canadian Cordillera: The “Baja B.C.” hypothesis fails a “crucial test”: *Geology*, v. 27, p. 195–198.
- Mahoney, J. B., Tikoff, B., Maxson, J., and Haugerud, R. A., 2000, Terrane accretion along the western Cordilleran margin: Constraints on timing and displacement: *GSA Today*, v.10, no. 2, p. 11–13.
- McClelland, W. C., Gehrels, G. E., and Saleeby, J. B., 1992, Upper Jurassic-Lower Cretaceous Basin Strata along the Cordilleran Margin: implications for Accretionary History of the Alexander-Wrangellia-Peninsular Terrane: *Tectonics*, v. 11, p. 823–835.
- McClelland, W. C., Tikoff, B., and Manduca, C. A., 2000, Two-phase evolution of accretionary margins: Examples from the North American Cordillera: *Tectonophysics*, v. 326, p. 37–55.
- McDougall, I., and Harrison, T. M., 1999, *Geochronology and thermochronology by the <sup>40</sup>Ar/<sup>39</sup>Ar method*, 2<sup>nd</sup> edition: New York, Oxford University Press, 269 p.
- McEnroe, S. A., 1996, A Barremian-Aptian (Early Cretaceous) North American paleomagnetic reference pole: *Journal of Geophysical Research*, v. 101, p. 15,819–15,836.
- McGroder, M. F., 1991, Reconciliation of two-sided thrusting, burial metamorphism, and diachronous uplift in the Cascades of Washington and British Columbia: *Geological Society of America Bulletin* 103, p. 189–209.
- Miller, R. B., and Paterson, S. R., 1994, The transition from magmatic to high-temperature solid-state deformation: Implications from the Mount Stuart batholith, Washington: *Journal of Structural Geology*, v. 16, p. 853–865.
- Miller, R. B., Johnson, S. Y., and McDougall, J. W., 1990, Discordant paleomagnetic poles from the Canadian Coast Plutonic Complex: Regional tilt rather than large displacement?: *Comment: Geology*, v. 18, p. 1164–1165.
- Moore, E. M., 1998, Ophiolites, the Sierra Nevada, “Cordillera,” and orogeny along the Pacific and Caribbean margins of North and South America: *International Geology Review*, v. 40, p. 40–54.
- Paterson, S. R., Miller, R. B., Anderson, J. L., Lund, S., Bendixson, J., Taylor, N., and Fink, T., 1994, Emplacement and evolution of the Mount Stuart batholith, in Swanson, D. A., and Haugerud, R. A., editors, *Geologic field trips in the Pacific Northwest, Volume 2*: Seattle, University of Washington, Department of Geological Sciences, and the Geological Society of America, p. 2F1–2F47.

- Price, R. A., and Charmichael, D. M., 1986, Geometric test for Late Cretaceous - Paleogene intracontinental transform faulting in the Canadian Cordillera: *Geology*, v. 14, p. 468–471.
- Pulliaiah, G., Irving, E., Buchan, K. L., and Dunlop, D. J., 1975, Magnetization changes caused by burial and uplift: *Earth and Planetary Science Letters*, v. 28, p. 133–143.
- Reiners, P. W., Ehlers, T. A., Garver, J. I., Mitchell, S. G., Montgomery, D. R., Vance, J. A., and Nicolescu, S., 2002, Late Miocene exhumation and uplift of the Washington Cascade Range: *Geology*, v. 30, p. 767–770.
- Shive, P. N., Frerichs, W. E., 1974, Paleomagnetism of the Niobrara Formation in Wyoming, Colorado and Kansas: *Journal of Geophysical Research*, v. 79, p. 3001–3007.
- Somoza, R., Singer, S., and Coira, B., 1996, Paleomagnetism of upper Miocene ignimbrites at the Puna: An analysis of vertical-axis rotations in the central Andes: *Journal of Geophysical Research*, v. 101, p. 11,389–11,400.
- Stamatatos, J. A., Trop, J. M., and Ridgway, K. D., 2001, Late Cretaceous paleogeography of Wrangellia: Paleomagnetism of the MacColl Ridge Formation, southern Alaska, revisited: *Geology*, v. 29, p. 947–950.
- Symons, D. T. A., Williams, P. R., McCausland, P. J. A., Harris, M. J., Hart, C. J. R., Blackburn, W. H., 2000, Paleomagnetism and geobarometry of the Big Creek Batholith suggests that the Yukon–Tanana Terrane has been a parautochthon since Early Jurassic: *Tectonophysics*, v. 326, p. 57–72.
- Tabor, R. W., Frizzell, V. A., Jr., Whetten, J. T., Waitt, R. B., Swanson, D. A., Byerly, G. R., Booth, D. B., Hetherington, M. J., and Zartman, R. E., 1987, Geologic map of the Chelan 30-minute by 60-minute quadrangle, Washington: United States Geological Survey Map I-1661.
- Tabor, R. W., Frizzell, V. A., Jr., Booth, D. B., Waitt, R. B., Whetten, J. T., and Zartman, R. E., 1993, Geologic map of the Skykomish River Chelan 30-minute by 60-minute quadrangle, Washington: United States Geological Survey Map I-1963.
- Tarduno, J. A., and Smirnov, A. V., 2001, Stability of the Earth with respect to the spin axis for the last 130 million years: *Earth and Planetary Science Letters*, v. 184, p. 549–553.
- Umhoefer, P. J., 1987, Northward translation of “Baja British Columbia” along the Late Cretaceous to Paleocene margin of western North America: *Tectonics*, v. 6, p. 377–394.
- 2000, Where are the missing faults in translated terranes?: *Tectonophysics*, v. 326, p. 23–36.
- Van Fossen, M., and Kent, D., 1992, Paleomagnetism of 122 Ma plutons in New England and mid-Cretaceous paleomagnetic field for North America: True polar wander or large-scale differential motion: *Journal of Geophysical Research*, v. 97, p. 19,651–19,662.
- Verwey, E. J., 1939, Electronic conduction of magnetite ( $\text{Fe}_3\text{O}_4$ ) and its transition point at low temperature: *Nature*, v. 144, p. 327–328.
- Warnock, A. C., Kodama, K. P., and Zeitler, P. K., 2000, Using thermochronometry and low-temperature demagnetization to accurately date Precambrian paleomagnetic poles: *Journal of Geophysical Research*, v. 105, p. 19,435–19,453.
- Wynne, P. J., Irving, E., Maxson, J., and Kleinspehn, K., 1995, Paleomagnetism of the Upper Cretaceous strata of Mount Tatlow: Evidence for 3000 km of northward displacement of the eastern Coast Belt, British Columbia: *Journal of Geophysical Research*, v. 100, p. 6,073–6,092.
- Yeats, R. S., and Engels, J. C., 1971, Potassium-argon ages of plutons in the Skykomish-Stillaguamish areas, North Cascades, Washington, in *Geological Survey research 1971: United States Geological Survey Professional Paper 750-D, D34–D38*.