Paleomagnetic and $^{40}Ar/^{39}Ar$ Geochronologic Data from Late Proterozoic Mafic Dikes and Sills, Montana and Wyoming

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1580

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By Stephen S. Harlan, John Wm. Geissman, *and* Lawrence W. Snee

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Paleomagnetic and ^{40}Ar/^{39}Ar results from mafic dikes and sills in northwestern Wyoming and western Montana indicate that they were emplaced during a regional magmatic event at 780 to 770 Ma

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Paleomagnetic and $^{40}Ar/^{39}Ar$ Geochronologic Data from Late Proterozoic Mafic Dikes and Sills, Montana and Wyoming

By Stephen S. Harlan,[1] John Wm. Geissman,[2] *and* Lawrence W. Snee [1]

ABSTRACT

We report paleomagnetic and geochronologic results from two Late Proterozoic mafic dikes exposed in Archean-cored uplifts from northwestern Wyoming and $^{40}Ar/^{39}Ar$ results from a gabbro sill that intrudes lower sedimentary strata of the Belt Supergroup in western Montana. The gabbro sill yields a $^{40}Ar/^{39}Ar$ plateau date of 776 Ma that records the age of sill emplacement during Late Proterozoic time. Paleomagnetic results from the mafic dike at Mount Moran, Teton Range, and the Christmas Lake dike, Beartooth Mountains, indicate magnetizations with similar directions and virtual geomagnetic poles (VGP's), which we interpret to be primary thermoremanent magnetizations acquired during dike emplacement and cooling. A hornblende from the Christmas Lake dike yields a $^{40}Ar/^{39}Ar$ plateau date of 774 Ma, which is statistically identical to that of the gabbro sill from western Montana. The similarity of the dike site-mean directions and VGP's suggest that their magnetizations are of similar age. $^{40}Ar/^{39}Ar$ results from a hornblende-pyroxene concentrate from the Mount Moran dike are discordant and contain excess ^{40}Ar; a precise estimate of the age of this sample is not possible given our data, but the paleomagnetic and geochronologic results suggest that it is of Late Proterozoic age, and not Middle Proterozoic as previously argued. The VGP's from the Mount Moran and Christmas Lake dikes are similar to those of identical age from southwestern Montana and northern and western Canada. These mafic dikes and sills are part of a regional magmatic event that affected the western part of the Laurentian craton at about 780 Ma.

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INTRODUCTION

Swarms of Proterozoic mafic sheets are a common feature of many uplifts of Wyoming and western Montana. In the basement-cored uplifts of the Archean Wyoming province, they are represented by dikes of diverse trend, composition, and apparent age. Reported dike ages from the basement uplifts range from about 2.6 Ga to 0.75 Ga, with apparent age maxima at 2.56 Ga, 2.2–2.0 Ga, 1.45 Ga, 1.3(?) Ga, 1.2 Ga, and 0.75 Ga (Snyder and others, 1989; Baadsgaard and Mueller, 1973; Wooden and others, 1978). In western Montana, mafic intrusions are generally found as sills that intrude sedimentary strata of the Middle Proterozoic Belt Supergroup and have apparent ages of 1.45–1.38 Ga and 0.75 Ga. Despite their wide occurrence and the recognition that mafic dike and sill swarms may be sensitive recorders of fundamental geologic and geodynamic processes (Halls, 1982), correlation of dike and sills of similar age and geochemical compositions between uplifts of western Montana and Wyoming has been limited in scope and is problematic. Although dikes in some individual uplifts have been extensively studied, at present there is little detailed information regarding the regional distribution of sheets of particular age groups or their geochemical characteristics. Hence, the tectonic and geodynamic significance of many swarms is poorly understood.

It has long been recognized that the natural remanent magnetization (NRM) acquired by mafic dikes during cooling can be a reliable recorder of the geomagnetic field and can be geologically stable throughout billions of years. These properties make paleomagnetism an extremely powerful tool for correlating dikes of individual swarms over wide areas (Buchan and Halls, 1990). Recent advances in geochronologic dating methods, including the recognition that mafic dikes can sometimes be dated with great precision by the U-Pb technique and, in some cases, by the $^{40}Ar/^{39}Ar$ method (Hanes, 1988; Krogh and others, 1988; Heaman and

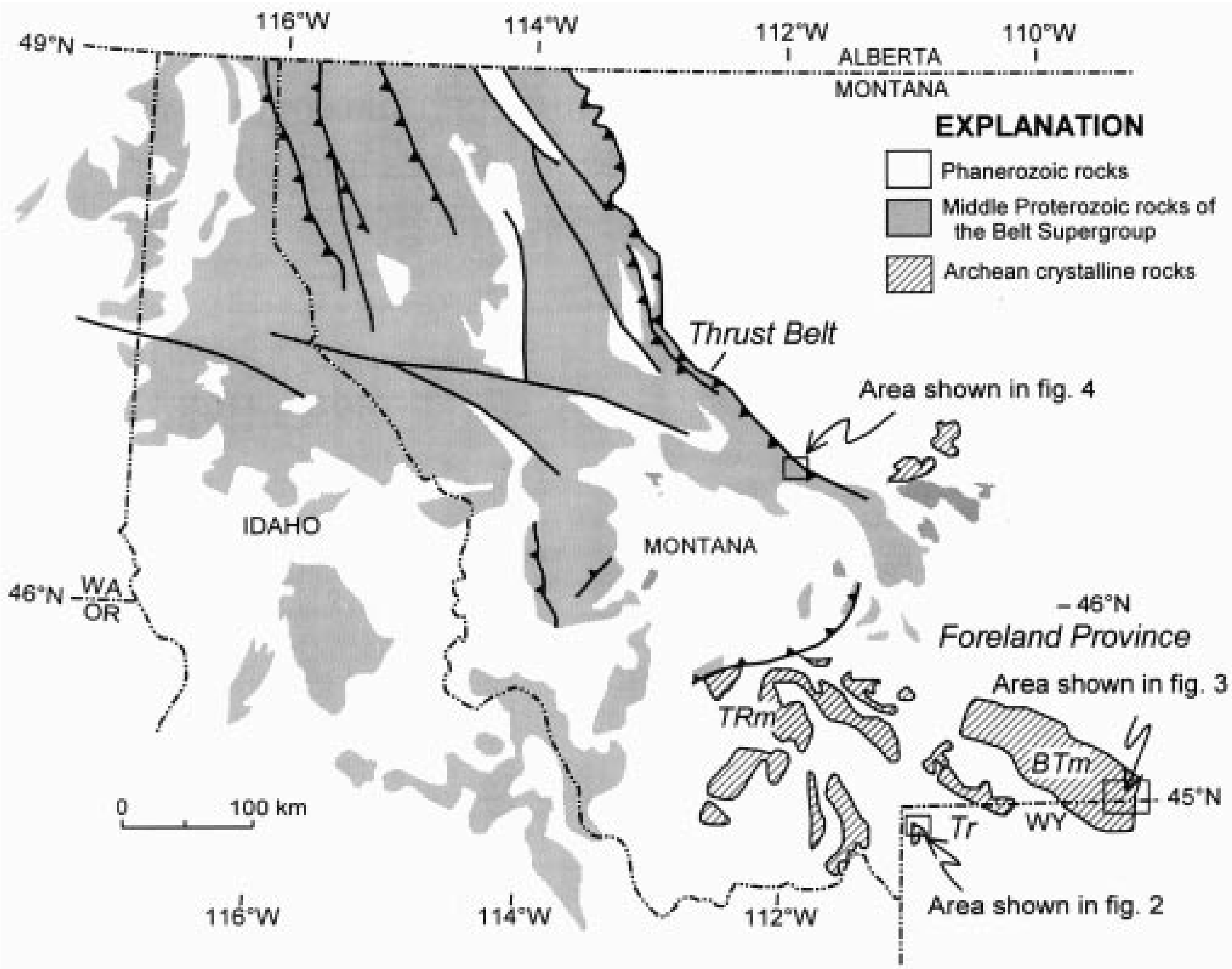


Figure 1. Simplified geologic map of the northern Rocky Mountains showing location of Archean-cored rocks in basement uplifts, distribution of rocks of the Middle Proterozoic Belt Supergroup, and locations of areas described in this report. Tr, Teton Range; BTm, Beartooth Mountains; TRm, Tobacco Root Mountains. Modified from Link and others (1993).

LeCheminant, 1993), have improved understanding of the distribution and mechanisms of mafic dike emplacement (Buchan and others, 1993, 1994). As part of an ongoing study of the paleomagnetism and geochronology of several dike swarms in basement-cored uplifts of Wyoming and Montana, we report paleomagnetic and $^{40}Ar/^{39}Ar$ results from mafic dikes exposed in the Teton Range of northwestern Wyoming and the Beartooth uplift of Montana and Wyoming, and a $^{40}Ar/^{39}Ar$ date from a mafic sill in northwestern Montana (fig. 1). We conclude that these dikes and sills were probably emplaced during a single intrusive episode at about 780–770 Ma. Similarity of our results with paleomagnetic and geochronologic data from other well-dated mafic rocks from the northwestern United States and Canada indicate that 780-Ma mafic magmatism was regional in extent.

GEOLOGIC SETTING AND SAMPLING

TETON RANGE

The Teton Range of northwestern Wyoming (fig. 1) is a fragment of a large, northwest-trending Laramide-age (Late Cretaceous–early Tertiary) structural block that has been modified by Pliocene-Recent movement along a zone of major north-striking normal faults along its eastern margin (fig. 2). Approximately 170 km^2 of Archean crystalline basement is exposed, including complexly deformed gneisses and amphibolite, and discordant plutons. The basement rocks are cut by a swarm of northwest-trending tholeiitic dikes (fig. 2), probably the most spectacular of which is the 30-m-wide

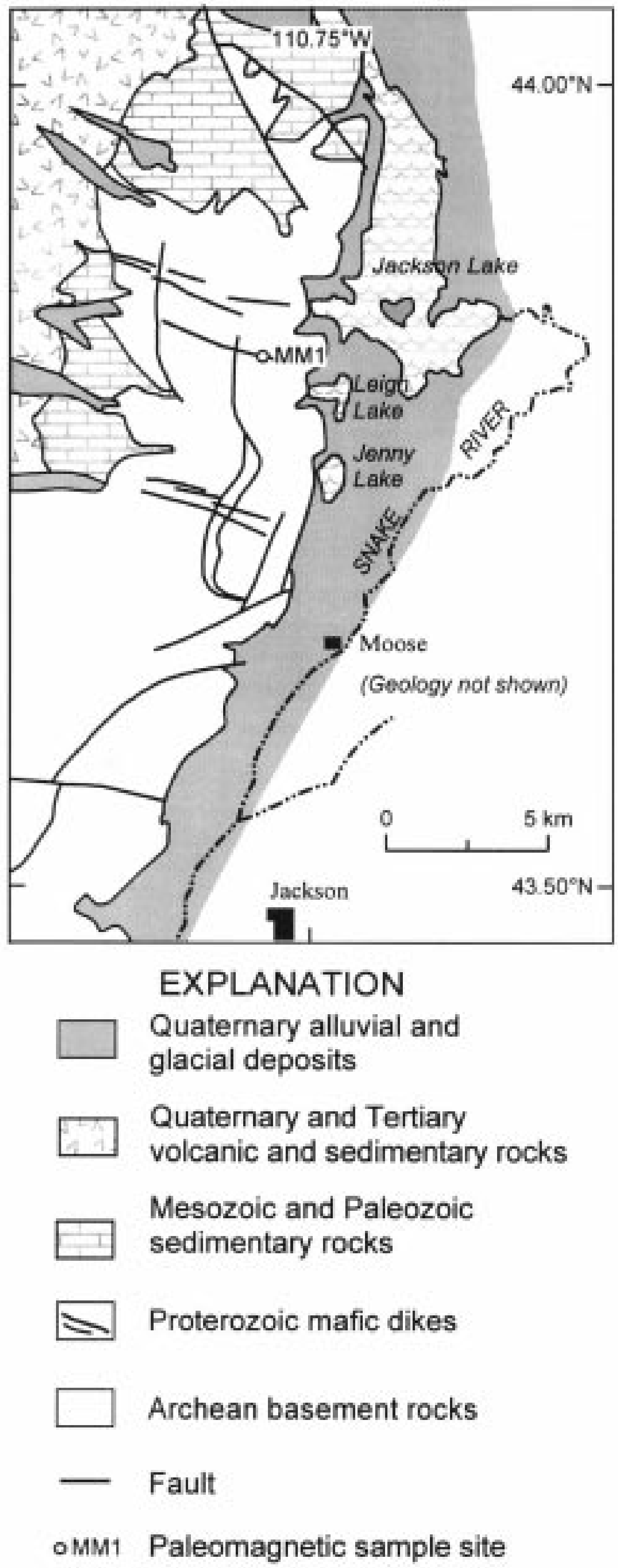


Figure 2. Generalized geologic map of part of the Teton Range, Wyoming, showing location of northwest-trending dikes and paleomagnetic site sampled in this study. Modified from Love and others (1992).

dike at Mount Moran, which has a vertical exposure of more than 1,500 m (Reed and Zartman, 1973; Love and others, 1992). The dikes are medium- to dark-gray or gray-green and consist of fine- to medium-grained diabase. The dikes are undeformed and have well-defined chill margins. The dikes are composed primarily of plagioclase and pyroxene, with minor hornblende and biotite. Tabular phenocrysts of plagioclase are common and show evidence of partial alteration to sericite. Pyroxene is commonly altered to mixtures of blue-green amphibole and chlorite.

K-Ar dates from the Mount Moran dike were reported by Reed and Zartman (1973) and gave apparent ages of 775 Ma for a whole-rock sample from a chilled margin and 583 Ma and 396 Ma for plagioclase from near the dike center. Due to the discordance between the dates and the recognition that K-Ar dates may be spurious due to the loss or gain of ^{40}Ar, Reed and Zartman (1973) dated hornblende and biotite from several basement rocks collected in a traverse perpendicular to the dike contact. Their objective was to date dike emplacement by partial to complete resetting of the host rocks adjacent to the dike contact. They found that hornblendes, regardless of proximity to the dike contact, gave dates of 2,800 to 2,650 Ma, which closely approximates the inferred age of regional metamorphism of the basement rocks. Biotite dates from three samples gave apparent ages of 1,450 to 1,350 Ma regardless of position with respect to the dike. Reed and Zartman (1973) argued that the closest biotite, located 1.5 m from the 30-m-thick dike, should have been elevated to temperatures sufficient to cause partial to complete resetting of its K-Ar age. They concluded that the minimum age for the Moran dike was 1,450 Ma and that younger dates were unreliable.

Paleomagnetic samples for this study were collected from a shoulder east of the main face of Mount Moran at an elevation of about 2,750 m (fig. 2).

BEARTOOTH MOUNTAINS

The Archean crystalline basement of the Beartooth Mountains of south-central Montana and northwestern Wyoming (fig. 1) hosts an extensive array of mafic dikes that trend generally northwest; some north- and northeast-trending dikes are also present (Prinz, 1964) (fig. 3). Using geochemical criteria, Mueller and Rogers (1973) identified at least four geochemical groups, based primarily on variations in TiO_2 content, that have apparent emplacement ages of 2.5 Ga, 1.3 Ga, and 0.75 Ga, based on whole-rock Rb-Sr and K-Ar dating methods (Mueller and Rogers, 1973; Baadsgaard and Mueller, 1973). The youngest group of dikes (group IIIA) is fine- to medium-grained diabase and consists of clinopyroxene, orthopyroxene, and plagioclase, with minor biotite, hornblende, and interstitial granophyre. One of the dikes, the Christmas Lake dike, can be traced for

16 km and has a vertical exposure of 800 m (Prinz, 1964). These dikes gave K-Ar dates that range from 770 to 720 Ma (N = 7 samples), with a composite K-Ar isochron of 740±32 Ma (2σ). A similar date of 780 Ma was obtained by Hanson and Gast (1967) for a dike from this same group.

Paleomagnetic samples for this study were collected where the mafic dike exposed at Christmas Lake crosses U.S. Highway 212 (fig. 3). The sample used for $^{40}Ar/^{39}Ar$ dating was obtained along strike of the dike from an exposure along the shore of Christmas Lake.

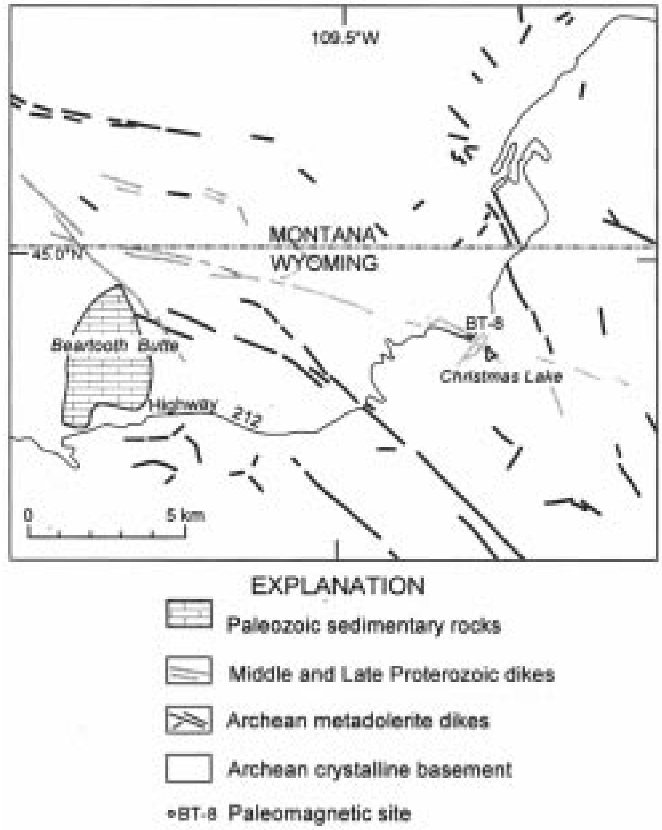


Figure 3. Generalized geologic map of southeastern corner of the Beartooth uplift, Montana and Wyoming, showing location of mafic dikes that cut Archean crystalline basement and location of dike dated in this study. Modified from Prinz (1964) and Mueller and Rogers (1973).

BELT SUPERGROUP

Mafic sills are common in lower sedimentary strata of the Middle Proterozoic Belt Supergroup, a thick (> 15,000 m) sedimentary prism composed of clastic and carbonate rocks deposited along the western margin of North America. They have been called the Purcell sills in the United States and Moyie sills in Canada, with these terms applied to a wide range of rocks including diabase, diorite, quartz diorite, gabbro, metadiorite and metagabbro (Snyder and others, 1989). Sills range in thickness from 1 to 500 m, and in some areas, sills have inflated the Belt stratigraphic section by as much as 30 to 35 percent (Höy, 1989). Typically, sills that intrude the Belt Supergroup are coarse grained and consist primarily of plagioclase and clinopyroxene, although some contain significant hornblende, biotite, and granophyre. Most are extensively altered due to hydrothermal conditions following emplacement (i.e., deuteric alteration) or possibly due to subsequent low-grade regional metamorphism and deformation.

Use of the terms “Purcell” or “Moyie” when describing the sills of the Belt Basin is confusing because no single identifying physical or geochemical characteristic distinguishes a “Purcell” or “Moyie” sill from any other sill and because these terms have been applied to sills that may have been emplaced during more than one intrusive event. Also, the term is sometimes confused with the Middle Proterozoic Purcell lavas (Höy, 1989), which may not be extrusive equivalents of any mafic sills. At least two episodes of sill emplacement (about 1,450–1,420 Ma and 800–780 Ma) in the Belt Basin have been recognized (Zartman and others, 1982; Höy, 1989; Ross and others, 1992), and there may be others (Ross and others, 1992). For these reasons, we suggest that use of “Purcell” should be avoided when referring to any of the numerous mafic sills that intrude sedimentary rocks of the Belt Supergroup.

The gabbro sample dated in this study was collected from a poorly exposed sill along Wolf Creek, approximately 6 km northwest of Wolf Creek, Mont. (fig. 4). The sill is approximately 40 m thick and intrudes undivided sedimentary strata of the Empire and Spokane Formations of the lower part of the Belt Supergroup (Schmidt, 1978). The sill consists primarily of fine- to medium-grained plagioclase and clinopyroxene, with minor biotite, hornblende, and granophyre. Locally, the gabbro is coarse and consists of a highly differentiated granophyre that contains abundant, randomly oriented, dark-brown to black hornblende needles as much as 7 mm long from which a hornblende concentrate was extracted. Samples for paleomagnetic analysis were not collected from this sill because it is located near the frontal margin of the fold and thrust belt, and paleomagnetic analysis of nearby Cretaceous volcanic and sedimentary strata have demonstrated that these rocks have been subjected to local vertical-axis rotations during Late Cretaceous–early Tertiary contractional deformation (Jolly and Sheriff, 1991).

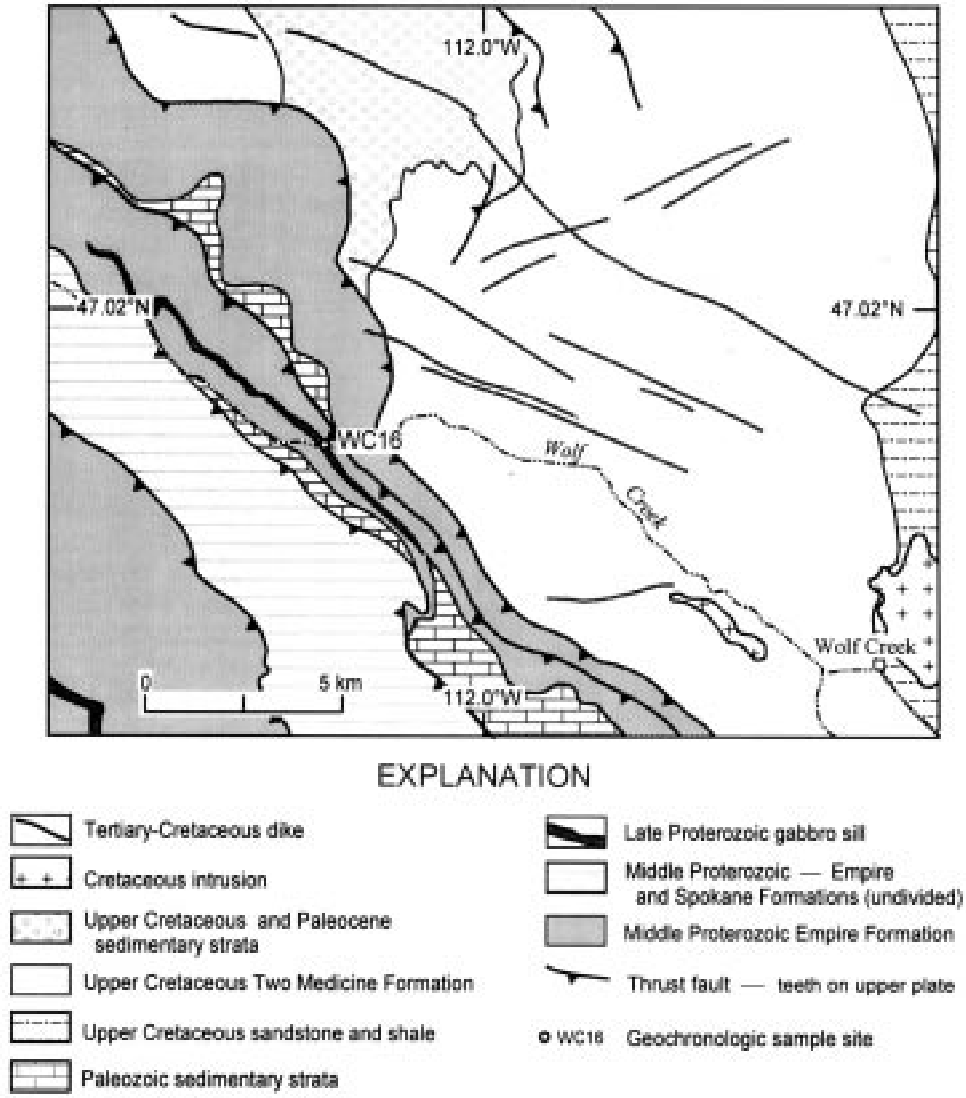


Figure 4. Generalized geologic map of the eastern margin of fold and thrust belt near Wolf Creek, Mont., showing location of the gabbro sill dated in this study. Modified from Schmidt (1978).

ANALYTICAL METHODS

At Mount Moran, we collected seven blocks of the dike, which were oriented using a Brunton compass. In the laboratory, individual samples were obtained from these blocks using a water-cooled diamond drill bit fitted to a drill press. Ten samples from the Christmas Lake dike were obtained with a portable drill; individual samples were oriented using magnetic and solar compasses and a clinometer. An additional five samples were collected at or near the contact of the Christmas Lake dike in order to conduct a baked contact test (Everitt and Clegg, 1962) to determine whether the observed dike remanence was primary, or acquired at some time after dike emplacement.

The natural remanent magnetization (NRM) of each sample was measured using either cryogenic or spinner magnetometers. Detailed alternating field (AF) demagnetization was conducted on all specimens and proved effective in isolating the sample characteristic remanent magnetization (ChRM). Duplicate specimens from a few samples were also thermally demagnetized using a low-magnetic induction furnace. Demagnetization results were examined using vector diagrams, stereographic projections, and normalized intensity decay diagrams. Sample ChRM directions, defined by three or more colinear points on vector diagrams, were calculated using principal components analysis (PCA) (Kirschvink, 1980); all ChRM directions used in this study had maximum angular deviation values less than 7°. Site-mean directions were calculated using statistics from Fisher (1953).

Samples for $^{40}Ar/^{39}Ar$ analysis were crushed, ground, and sieved, and mineral concentrates were produced using standard heavy-liquid and magnetic techniques. Mineral concentrates for the Christmas Lake dike and the Wolf Creek gabbro sill were hand-picked to a purity greater than 99.9 percent. The hornblende concentrate from the Teton dike consists of a mixture of hornblende and pyroxene that could not be purified greater than about 70 percent due to fine grain size and intergrowths.

The $^{40}Ar/^{39}Ar$ samples were irradiated in the U.S. Geological Survey TRIGA reactor for 60 hours. Variations in neutron flux were monitored using hornblende MMhb-1, which has a K-Ar age of 520.4±1.7 Ma (Samson and Alexander, 1987). Corrections for interfering isotopes were made using production ratios derived from potassium and calcium salts irradiated with the samples. Each sample was heated in a double vacuum, low-blank resistance furnace for 20 minutes in a series of 11 to 14 steps to a maximum temperature of 1,300°C. After each heating step, the gas was collected and purified using Zr-Al-Ti getters, and all five naturally occurring isotopes of argon were measured using a mass spectrometer operated in the static mode. Apparent ages for each temperature step and the total gas date were calculated using the decay constants recommended by Steiger and Jäger (1977). A detailed description of analytical procedures similar to those used in this study are given by Tysdal and others (1990).

RESULTS AND INTERPRETATION

PALEOMAGNETISM

NRM intensities from the Mount Moran dike samples ranged from 0.43 A/m to 1.24 A/m, with a geometric mean of 0.84 A/m. Demagnetization results showed that virtually all samples contained two magnetization components (fig. 5). The first component is relatively minor and is characterized by low coercivities and laboratory unblocking temperatures during demagnetization. The resultant direction obtained from this magnetization is commonly of north declination and moderate positive inclination. This component was typically removed by AF demagnetization in fields of 5 to 10 mT, or by temperatures of 100°C to 250°C in thermal demagnetization. The direction and demagnetization characteristics suggest that this is a secondary viscous remanent magnetization that was probably acquired in the present-day field.

At greater demagnetization levels, a well-defined magnetization component of northwest declination and shallow positive to negative inclination that trends toward the origin of demagnetization diagrams was identified (fig. 5). This component was usually isolated by AF fields of 15 to 130 mT and by laboratory unblocking temperatures from 300°C to 590°C. This direction is far from the present-day field and far from expected directions from virtually any time period during the Phanerozoic; hence, we consider this to be the ChRM of the dike and suggest that it is a thermoremanent magnetization (TRM) acquired during cooling following dike emplacement. Isolation of the ChRM by AF demagnetization and complete unblocking by temperatures less than 590°C indicates that the primary carrier of magnetization is low-Ti titanomagnetite.

A site-mean direction calculated from the seven individual samples has an in situ declination of 285.6° and inclination of 11.5° (k = 36, α_{95} = 10.2°) and a virtual geomagnetic pole (VGP) at lat 15.2°N., long 152.6°E. (δp = 5.3°, δm = 10.4°). Application of tilt corrections for the Mount Moran dike are problematic. Although Cambrian Flathead Sandstone nonconformably overlies the dike at the summit of Mount Moran (Love and others, 1992), structural attitudes for these rocks are not available. Overall, the structural geometry of the Teton Range and paleomagnetic evidence suggest that the range has been tilted west at least 10° since Pliocene time along north-trending normal faults that have uplifted the present-day Teton block (Byrd and others, 1994). A tilt correction based on an average strike of N. 10° E. and a 10° west tilt gives a site-mean declination of 285.5° and inclination of 1.5° (fig. 6); the resultant VGP becomes lat 11.6°N., long 148.9°E. Because cooling of a dike such as the dike at Mount Moran occurs in less than a few hundred years, which is short relative to the time required to average geomagnetic secular variation, this result is a spot recording of the geomagnetic field at the time of dike emplacement.

Paleomagnetic results from the Christmas Lake dike are similar to those obtained from the dike at Mount Moran. NRM intensities from the dike samples were fairly uniform, with a range of 0.18 A/m to 0.51 A/m and geometric mean of 0.44 A/m. Demagnetization experiments revealed two well-defined components of magnetization (figs. 7*A* and 7*B*). The first component was of north declination and moderate positive inclination and was removed by AF demagnetization of 10 to 20 mT or by thermal demagnetization of 250°C to 300°C. As with the Christmas Lake dike, the demagnetization characteristics and directions suggest that this is probably a viscous remanent magnetization acquired in the present-day field.

AF demagnetization in fields from 20 to 150 mT and temperatures from 300°C to 590°C reveals a second magnetization of northwest declination and shallow negative inclination, which we consider the ChRM of the dike (figs. 7*A* and 7*B*). AF and thermal demagnetization characteristics indicate that magnetization in these dikes is probably carried by low-Ti titanomagnetite. A site-mean direction calculated from nine of the dike samples gives a declination of 288.3° and inclination of –21.8° (k = 44, α_{95} = 7.9°) and a VGP at lat 4.6°N., long 139.7°E. (δp = 4.4°, δm = 8.3°). The observed ChRM is similar to that reported from two sites, possibly in the same dike, by Larson and others (1973), although these results were based on limited AF demagnetization.

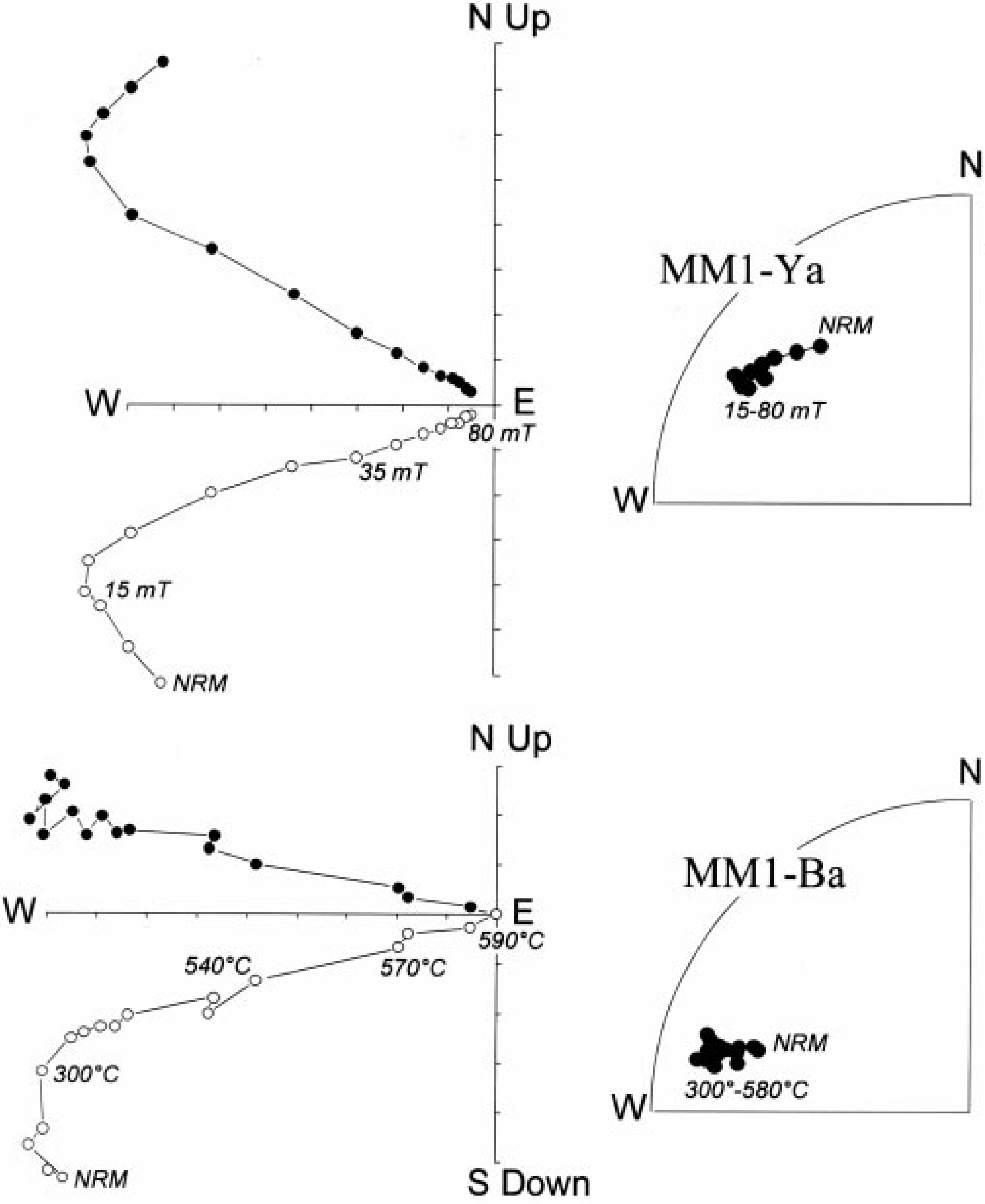


Figure 5. In situ orthogonal vector diagrams and equal-area projections showing behavior of mafic dike samples from dike at Mount Moran during alternating-field and thermal demagnetization. For vector diagrams, open and solid symbols show in situ magnetization components projected onto vertical and horizontal planes, respectively, at each demagnetization step. For equal-area projections, solid circles are projections on lower hemisphere. Demagnetization is in millitesla (mT) and degrees Celsius. For vector diagrams, 1 division = 0.1 A/m.

Because lower Paleozoic sedimentary strata at Beartooth Butte were tilted during Late Cretaceous–early Tertiary uplift of the Beartooth Mountains, we have applied a tilt correction to our data based on a N. 72° W. strike and a southwest dip of 10°. This change has little effect on either the declination or inclination of the magnetization (i.e., tilt corrected declination = 292.3°, tilt corrected inclination = –21.4°; fig. 6) or location of the VGP (lat 7.4°N., long 137.0°E.) because the axis of tilt is similar to the paleomagnetic direction.

Paleomagnetic results from two samples of basement gneiss collected at 1 and 20 cm from the contact with the Christmas Lake dike gave ChRM directions that are essentially identical to those from the dike samples (fig. 7*C*). The remaining three samples collected at distances greater than about 0.8 to 1.2 m from the dike gave erratic directional behavior during AF demagnetization. The similarity of directions from the two gneiss samples from the dike contact zone with ChRM's from the dike (fig. 6) suggest that the contact rocks were thermally remagnetized during dike intrusion. This suggests that the baked contact test is positive and that the dike remanence is a primary TRM. Overall, however, the results of this baked contact test must be considered inconclusive as we cannot demonstrate that this magnetization was superimposed on a preexisting stable remanence. As with the Mount Moran dike, this magnetization is unlike most expected directions of Phanerozoic age. We suggest that the magnetization observed in the dike is probably a TRM acquired during dike emplacement and that the VGP is a spot-reading of the geomagnetic field.

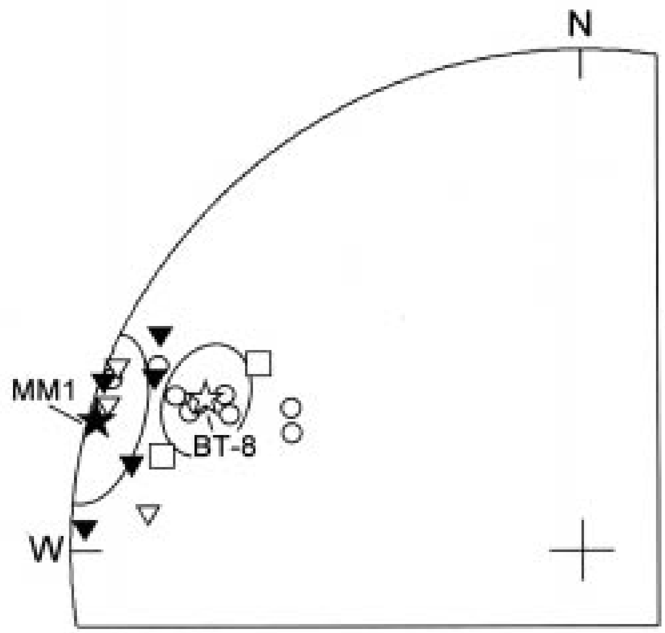


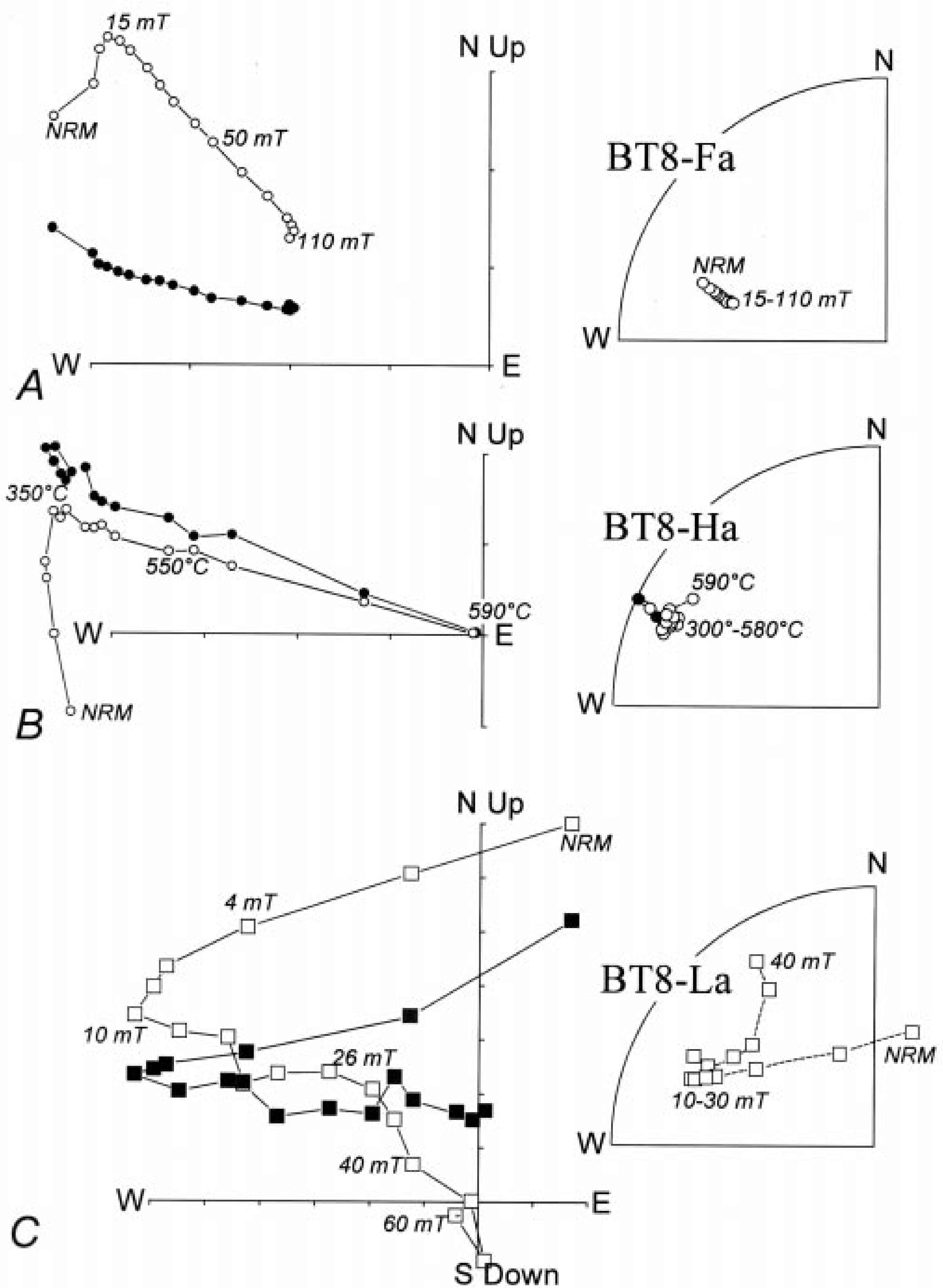
Figure 6. Equal-area projections showing tilt-corrected paleomagnetic results from mafic dike at Mount Moran (Teton Range) and Christmas Lake mafic dike (Beartooth Mountains, Wyoming). Inverted triangles are individual sample ChRM directions from Mount Moran dike; circles are ChRM directions from Christmas Lake dike; and squares are paleomagnetic results from two basement gneiss samples collected adjacent to Christmas Lake dike. Stars are site-mean directions and their α_{95} cones of confidence. Solid symbols are projections on lower hemisphere; open symbols are projections on upper hemisphere.

$^{40}Ar/^{39}Ar$ GEOCHRONOLOGY

$^{40}Ar/^{39}Ar$ results from the hornblende concentrate from the Mount Moran dike yield a total gas date of 881±4 Ma (table 1) but a strongly discordant age spectrum (fig. 8). Initial (700°C to 950°C) and high-temperature (1,075°C to 1,300°C) steps give anomalously old apparent ages that range from 1,340 Ma to 830 Ma, but intermediate-temperature steps record a trough-like pattern with apparent ages of 800 to 765 Ma. Such "U-shaped" age spectra are characteristic of samples that contain excess ^{40}Ar (Lanphere and Dalrymple, 1976). Because excess ^{40}Ar biases the age of individual temperature steps toward older ages, most workers consider the trough of the "U" a maximum estimate for the true age of the sample (Hanes, 1988). The presence of excess ^{40}Ar is a common phenomenon in many plutonic hornblendes, but, in this case, the presence of pyroxene contributes to this problem. In this sample, the 1,025°C and 1,050°C steps overlap in apparent age with a mean of 769±5 Ma (2σ). This date is probably a reasonable estimate of the age of the sample given its similarity with apparent ages from the Christmas Lake dike and the gabbro sill from Wolf Creek, described below. On the basis of these data, we suggest that the dike may be Late Proterozoic in age, and not Middle Proterozoic as proposed by Reed and Zartman (1973). Indeed, paleomagnetic evidence from the dike, discussed below, confirm that the dike was emplaced during Late Proterozoic time.

In contrast to the hornblende-pyroxene concentrate from the Mount Moran dike, $^{40}Ar/^{39}Ar$ results from the hornblende separate from the Christmas Lake dike are relatively straightforward. The sample yields a total gas date of 779±3 Ma (2σ) (table 1) and a relatively flat age spectrum (fig. 8). Low temperature fractions (700°C to 925°C) give apparent ages greater than about 800 Ma, and these correlate with relatively high and variable $^{39}Ar/^{37}Ar$ ratios (i.e., 0.83 to 0.22; table 1), which probably reflect the degassing of either

Figure 7 (following page). In situ orthogonal vector diagrams and equal-area projections showing demagnetization behavior of samples from Christmas Lake dike (*A*, *B*) and basement gneiss collected 1 cm from the dike contact (*C*). The gneiss sample and one collected 20 cm from the dike contact give magnetizations that are essentially identical to those from the dike, suggesting that they acquired a thermoremanent magnetization due to thermal effects associated with dike emplacement. Basement samples collected at greater distances gave erratic and unstable demagnetization behavior. For dike vector diagrams, 1 division = 0. 1 A/m; for gneiss sample, 1 division = 0.0001 A/m. Conventions are the same as those in


15 mT
NRM
50 mT
110 mT
N Up
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B
BT8-Ha
590°C
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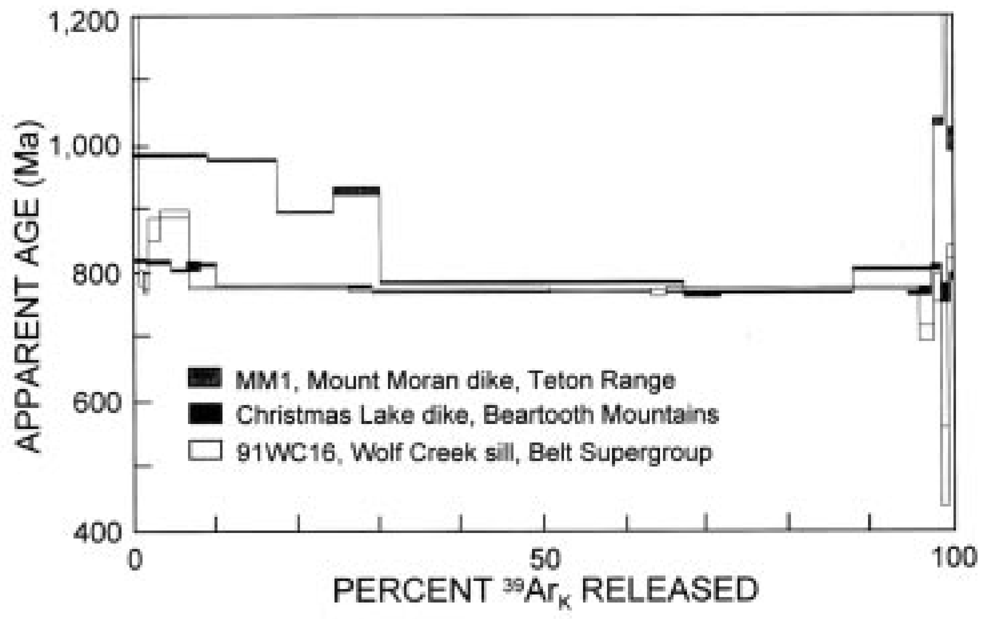

Figure 8. $^{40}Ar/^{39}Ar$ apparent age spectra for dike at Mount Moran, Teton Range; Christmas Lake dike, Beartooth Mountains, Wyoming; and a gabbro sill that intrudes lower Belt Supergroup sedimentary strata near Wolf Creek, Mont. The height of each rectangle represents analytical error in the apparent age of the individual temperature step at ± 1σ.

loosely held excess ^{40}Ar or contamination by relatively high potassium phases. At greater temperatures (950°C to 1,075°C), the age spectrum is essentially flat over greater than 87 percent of the $^{39}Ar_K$ released with individual apparent ages varying by less than 1.02 percent. $^{39}Ar/^{37}Ar$ ratios are relatively uniform, indicating that a single homogeneous mineral phase was degassed over this temperature range. These steps yield a mean plateau age of 774±4 Ma (2σ), which is essentially identical to the total gas date; we consider the plateau date to be a reasonable estimate for the age of emplacement of the Christmas Lake dike. Baddeleyite from this dike gives a U-Pb date of 779 Ma (A.N. LeCheminant, oral commun., 1994), which is statistically indistinguishable from our $^{40}Ar/^{39}Ar$ results.

The hornblende from the gabbro sill near Wolf Creek gives a total gas date of 788±7 Ma (table 1). The low- (600°C to 850°C) and high-temperature (1,100°C to 1,250°C) steps record variable and discordant dates, and the spectrum shows evidence of some excess ^{40}Ar (fig. 8). Intermediate-temperature (900°C to 1,050°C) steps give essentially constant $^{39}Ar/^{37}Ar$ ratios and concordant dates that define a plateau date of 776±5 Ma over about 90 percent of the $^{39}Ar_K$ released (fig. 8). We consider this to be the best age of emplacement of the gabbro sill. We also note that it is statistically identical to the date obtained from the Christmas Lake dike, exposed some 330 km to the southeast, and that it is similar to K-Ar dates from gabbro sills that intrude lower Belt strata elsewhere in western Montana (Schmidt, 1978; Marvin and Dobson, 1979; J.D. Obradovich, oral commun., 1993).

DISCUSSION

Both the Mount Moran dike from the Teton Range and the Christmas Lake dike from Beartooth Mountains give similar paleomagnetic directions and VGP's that plot at low latitudes in the western Pacific Ocean (fig. 9). The concordance of $^{40}Ar/^{39}Ar$ and U-Pb dates from the Christmas Lake dike indicates that it is Late Proterozoic in age and that its geochronologic systems have not been disturbed by subsequent thermal events. The baked contact test from the Christmas Lake dike, although not conclusive, strongly suggests that the observed magnetization is a TRM acquired during cooling following dike emplacement. Because closure temperatures to ^{40}Ar diffusion for hornblende (i.e., 480°C to 540°C) overlap unblocking temperatures for magnetite, we suggest that the 776-Ma age from the hornblende from the Christmas Lake dike probably closely approximates the age of remanence acquisition in the dike. Assuming that the ChRM in the Mount Moran dike is also a TRM acquired during dike emplacement and cooling, the similarity in paleomagnetic directions and VGP's from the Mount Moran and Beartooth dikes strongly suggest that both were emplaced at about the same time.

Table 1. Analytical data for $^{40}Ar/^{39}Ar$ age determinations from mafic dikes and sills, northwestern Wyoming and western Montana.

[$^{40}Ar_R$, abundance of radiogenic ^{40}Ar reported in volts of signal on a Faraday detector; $^{39}Ar_K$, abundance of potassium-derived ^{39}Ar reported in volts of signal; $^{40}Ar/^{39}Ar$, ratio of $^{40}Ar_R$ to $^{39}Ar_K$ after correction for mass discrimination and interfering isotopes; $^{39}Ar/^{37}Ar$, ratio of $^{39}Ar_K$ to $^{37}Ar_{Ca}$ (this value can be converted to the approximate potassium/calcium ratio by multiplying by 0.5); $\%^{40}Ar_R$ is the percentage of total radiogenic ^{40}Ar released in each temperature step; $\%^{39}Ar_K$ is the percentage of total potassium-derived ^{39}Ar released in each temperature step; $^{40}Ar/^{36}Ar_a$, measured atmospheric argon ratio used for mass discrimination at the time of analysis; J value, neutron flux parameter; mg, milligram; 1σ, one standard deviation. Temperature steps in bold type are those used in the calculation of plateau dates discussed in the text]

Temperature (°C)	$^{40}Ar_R$	$^{39}Ar_K$	$^{40}Ar/^{39}Ar$	$^{39}Ar/^{37}Ar$	$\%^{40}Ar_R$	$\%^{39}Ar_K$	Apparent age (Ma at 1σ)
Sample: MM1, Mount Moran dike, hornblende-pyroxene; 45.1 mg; measured $^{40}Ar/^{36}Ar_a$ = 298.9; J value = 0.02743 ± 0.1 percent (1σ)							
700	2.7342	0.10270	26.624	0.64	86.7	8.7	989±2
800	2.6321	0.09992	26.342	0.81	86.5	8.4	981±2
900	1.9619	0.08332	23.546	0.36	92.5	7.0	899±1
950	1.6532	0.06710	24.638	0.28	85.1	5.7	931±6
1,000	8.7542	0.43933	19.926	0.20	97.6	37.0	787±2
1,025	1.0136	0.05261	19.267	0.20	85.0	4.4	765±3
1,050	3.7993	0.19567	19.417	0.13	96.2	16.5	770±2
1,075	2.3665	0.11515	20.551	0.07	96.6	9.7	806±2
1,100	0.53948	0.01901	28.376	0.02	90.9	1.6	1038±6
1,150	0.24334	0.00621	39.196	0.02	79.8	0.5	1317±34
1,300	0.14727	0.00536	27.502	0.02	43.5	0.5	1014±21
Total gas			21.785				845±2
Sample: Christmas Lake, hornblende; 68.8 mg; measured $^{40}Ar/^{36}Ar_a$ = 298.9; J value = 0.02914 ± 0.1 percent (1σ)							
700	0.90667	0.04598	19.719	0.54	57.4	1.5	819±2
800	1.8227	0.09264	19.674	0.83	90.8	3.0	818±2
850	1.1940	0.06193	19.287	0.42	90.9	2.0	805±1
900	0.9725	0.04992	19.481	0.33	89.4	1.6	811±7
925	1.1992	0.06141	19.529	0.22	92.3	2.0	813±2
950	10.697	0.57672	18.548	0.17	98.4	18.8	779±2
975	21.480	1.1736	18.302	0.17	98.8	38.2	771±2
985	3.1296	0.17068	18.335	0.17	98.5	5.6	772±2
1,000	5.8094	0.31654	18.353	0.18	98.6	10.3	773±2
1,050	6.3395	0.34332	18.465	0.16	98.5	11.2	777±2
1,075	1.5739	0.08581	18.341	0.12	93.7	2.8	772±7
1,100	0.76006	0.03905	19.465	0.08	92.0	1.3	811±3
1,150	0.52185	0.02857	18.265	0.07	79.5	0.9	770±14
1,250	0.43426	0.02281	19.034	0.09	68.2	0.7	796±5
Total gas			18.521				779±2
Sample: WC-16, Wolf Creek gabbro sill, hornblende, 61.4 mg; measured $^{40}Ar/^{36}Ar_a$ = 298.9; J value = 0.02895 ± 0.1 percent (1σ)							
600	0.37179	0.00815	45.635	0.19	45.1	0.8	1519±15
700	0.06825	0.00358	19.075	0.12	21.1	0.4	793±12
800	0.13123	0.00710	18.479	0.10	51.2	0.7	773±3
850	0.30724	0.01434	21.423	0.05	78.4	1.5	871±18
900	0.76598	0.03450	22.203	0.07	89.3	3.5	895±6
950	3.5756	0.19175	18.648	0.18	98.8	19.4	779±3
1,000	4.4999	0.24275	18.537	0.20	98.8	24.6	775±1
1,025	2.2928	0.12392	18.501	0.15	96.5	12.6	774±2
1,050	0.2896	0.01572	18.430	0.14	92.1	1.6	771±5
1,075	5.7019	0.30664	18.595	0.16	98.7	31.1	777±3
1,100	0.27804	0.01672	16.631	0.15	81.4	1.7	709±11
1,150	0.17857	0.00958	18.638	0.14	66.2	1.0	778±21
1,200	0.05609	0.0050	11.217	0.13	18.1	0.5	507±76
1,250	0.14586	0.00692	21.080	0.15	40.9	0.7	859±8
Total gas			18.915				788±4

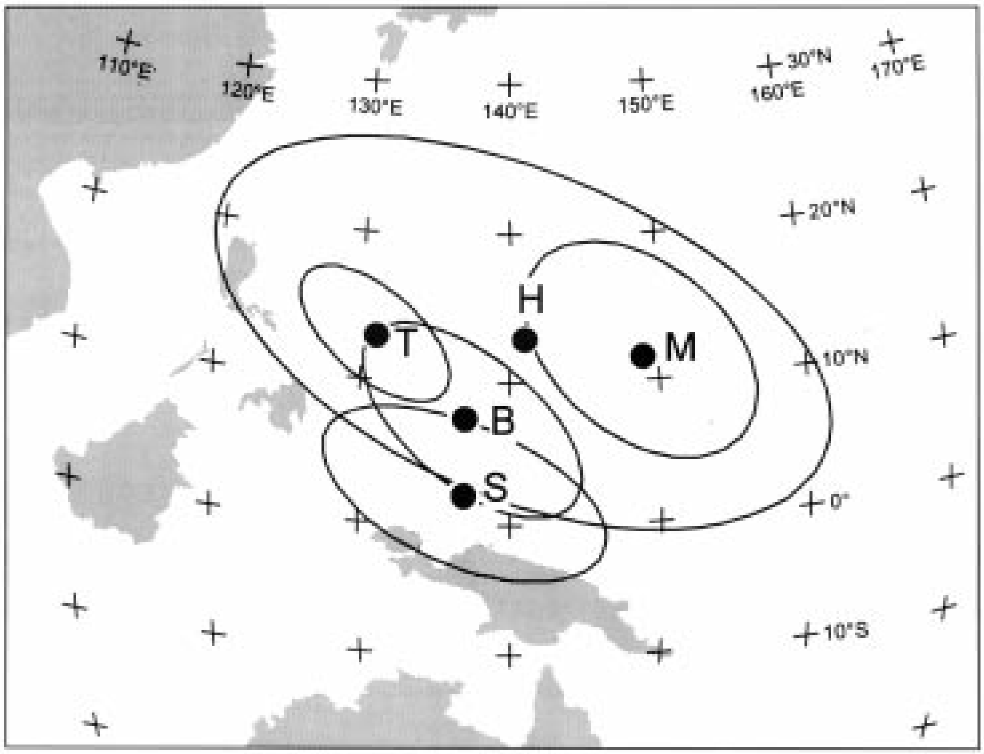

Figure 9. Orthographic global projection centered on lat 20°N., long 135°E., showing location of virtual geomagnetic poles (VGP's) and their 95 percent confidence ellipses from Mount Moran and Christmas Lake dikes (after tilt corrections as described in the text) and location of VGP's of similar age from elsewhere in western North America. Symbols for individual VGP's are given in table 2.

The VGP's from the Mount Moran and Beartooth dikes are distinctly different from most poles from Middle Proterozoic rocks of about 1,400 Ma and 1,200 to 1,100 Ma (Harlan and others, 1994) but are similar to VGP's from northwest-trending mafic dikes exposed in the southern Tobacco Root Mountains of southwest Montana and Late Proterozoic dikes and sills from northern and northwestern Canada (table 2, fig. 9) (Park and others, 1995b). In the southern Tobacco Root Mountains, Harlan (1993) found paleomagnetic and geochronologic evidence for two distinct episodes of dike emplacement in Middle and Late Proterozoic time. Paleomagnetic results from geochemical group-B dikes (Wooden and others, 1978) gave magnetizations of northwest declination and shallow negative inclination, similar to those observed in the Mount Moran and Christmas Lake dikes. $^{40}Ar/^{39}Ar$ dates from hornblende from these dikes give apparent ages of 769±7 Ma (2σ), and biotite from host gneiss immediately adjacent to the contact of a group B dike gave an apparent age of 780 Ma (S.S. Harlan, unpub. data). Preliminary U-Pb data from zircon and baddeleyite from these dikes give similar $^{207}Pb/^{206}Pb$ dates of 782±8 Ma and 785± 8 Ma (S.S. Harlan and W. Premo, unpub. data). VGP's from the Mount Moran, Christmas Lake, and southern Tobacco Root Mountains dikes are similar to those reported from (1) mafic dikes and sills that intrude Late Proterozoic strata in the Mackenzie Mountains of the northern Cordillera in Canada and (2) mafic sills (Hottah sheets) from the northwestern Canadian shield near Great Bear Lake (table 2; fig. 9). Both the dikes and sills from the Mackenzie Mountains and the Hottah sheets of the northwestern Canadian shield give relatively precise U-Pb baddeleyite dates of 779 Ma (LeCheminant and Heaman, 1994) that are essentially identical to the 780- to 770-Ma dates from the Christmas Lake dike, Tobacco Root Mountains dikes, and the gabbro sill exposed near Wolf Creek, Mont. The similarity of the Mount Moran VGP to VGP's from 780- to 770-Ma dikes from elsewhere in Montana and western North America, and the $^{40}Ar/^{39}Ar$ results presented here, suggests that the age of the Mount Moran dike is Late Proterozoic in age, and not Middle Proterozoic as argued by Reed and Zartman (1973). Further isotopic determinations, possibly using U-Pb technique, are needed to more precisely identify the age of dike emplacement.

On a regional scale, the consistency of VGP's and isotopic dates from dikes and sills from northwestern Wyoming to northern Canada demonstrates the coherence of the western margin of the North American craton since Late Proterozoic time and suggests that all the observed

Table 2. Virtual geomagnetic poles from 780-Ma mafic intrusive rocks of western North America.

[*N/n* is the ratio of the number of intrusions to the number of individual paleomagnetic sites used to determine the mean virtual geomagnetic pole direction (VGP); *Plat.* and *Plong.* are the latitude and longitude of the VGP based on the tilt-corrected site-mean directions, as described in the text; δp and δm are the semi-axes of the ellipse of 95 percent confidence about the mean VGP. U, samples dated by the U-Pb method, A, samples dated by the $^{40}Ar/^{39}Ar$ method]

Location	Age (Ma)	Symbol	*N/n*	*Plat.*	*Plong.*	δp	δm	Reference
Teton Range	A ≤770	M	1/1	11.6°N.	148.9°E.	5.3°	10.4°	This study.
Beartooth Mountains	A 774±4	B	1/1	7.4°N.	137.0°E.	4.4°	8.3°	This study.
Tobacco Root Mountains	A 769±7	T	9/18	13°N.	131°E.	3°	6°	Harlan (1993); Harlan and others, unpub. data.
Northern Cordillera	U 779	S	10/17	2°N.	137°E.	5°	10°	Park (1981); Park (1989).
N.W. Canadian Shield	U 779	H	3/6	13°N.	141°E.	11°	22°	Park and others (1995a).

magnetizations are primary in origin (Park and others, 1995b). Mafic magmatism at 780–770 Ma appears approximately synchronous over a broad expanse of western North America that extends from the Canadian Arctic to northwestern Wyoming, a distance greater than 2,400 km. Using high-precision U-Pb dates on baddeleyite from mafic dikes and sills in northern Canada and the Christmas Lake dike in the Beartooth Mountains, Wyoming, A.N. LeCheminant (oral commun., 1994) established a composite age of 781+6/–3 Ma for this event and has tentatively termed it the “gunbarrel igneous event.” Emplacement of a quartz diorite plug dated as 778 Ma (U-Pb, zircon) (Jefferson and Parrish, 1989) and eruption of the coeval Little Dal basalts in the Mackenzie Mountains (Dudás and Lustwerk, 1997) and mafic volcanic rocks of the Windermere Group of northeastern Washington (762±44 Ma, Sm-Nd mineral isochron) (Devlin and others, 1988) may be manifestations of this same event. Identification of 780- to 760-Ma $^{40}Ar/^{39}Ar$ and K-Ar dates on sills from the lower parts of the Belt Supergroup, including the Wolf Creek sill from this study, suggests that they may be more common than previously thought, but detailed geochemical and high-precision geochronologic data are necessary to better understand their distribution. Numerous studies (Link and others, 1993; Harper and Link, 1986; Elston and McKee, 1982; Christie-Blick and Levy, 1989; Stewart, 1972) report the presence of Late Proterozoic mafic intrusive and volcanic rocks to the south, but whether they are part of this event is unclear given the paucity of reliable isotopic dates from this region.

The cause of widespread mafic magmatism at 780 to 770 Ma remains enigmatic. LeCheminant and Heaman (1994) suggest that mafic magmatism was a response to major extension accompanying development of a rift margin along the western margin of the North American craton during Late Proterozoic time. Park and others (1995b) argue that trends from dike subswarms in northwestern Canada and Wyoming define part of a crudely radial pattern that was associated with an ancient mantle plume that produced a giant radiating dike swarm, similar to those of the 1.27-Ga Mackenzie (LeCheminant and Heaman, 1989) and 0.73-Ga Franklin (Heaman and others, 1992) magmatic events. The two hypotheses may not be exclusive, as thermal effects associated with the mantle plume may have been a precursor to, or caused, Late Proterozoic rifting. The proposed location of the plume center is off the present coast of western North America, and Park and others (1995b) argue that the plume center and other parts of the radial swarm were severed from the craton by Late Proterozoic and early Paleozoic rifting and development of a passive continental margin. The rifted continental mass(es) that contain the remnants of the radial dike swarm are unknown but may include parts of east Antarctica and Australia, if parts of these continents lay adjacent to the western margin of the Laurentian craton at about 800 Ma to form part of the supercontinent Rodinia (Dalziel, 1991; Moores, 1991; Hoffman, 1991; Brookfield, 1993; Borg and De Paolo, 1994; Powell and others, 1993). Recently, Park and others (1995b) suggested that the approximately 800-Ma Gairdner dike swarm of western Australia may be part of the radial dike swarm formed at 780–770 Ma. If correct, this interpretation and the hypothesis that western Australia lay adjacent to the North America continent can be tested by comparing high-quality paleomagnetic and geochronologic data from this and other studies of Late Proterozoic dikes and sheets from western North America with those from the Gairdner dike swarm.

CONCLUSIONS

$^{40}Ar/^{39}Ar$ isotopic dates from two mafic dikes and a gabbro sill from northwestern Wyoming and western Montana yield similar Late Proterozoic dates of about 770 Ma. The Mount Moran dike from the Teton Range and the Christmas Lake dike from the Beartooth Mountains yield similar

VGP's that are essentially identical to those from rocks of similar age elsewhere in Montana and Canada. Together, the paleomagnetic and geochronologic data from this and other studies provide evidence for a regional mafic magmatic event at 780–770 Ma that affected a large area of western North America. Mafic magmatism may have been a response to a mafic plume that preceded rifting and breakup of the North American continent during Late Proterozoic and early Paleozoic time. The paleomagnetic and geochronologic data from this and other studies may be useful in testing the validity of Late Proterozoic continental reconstructions.

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REFERENCES CITED

Baadsgaard, H., and Mueller, P.A., 1973, K-Ar and Rb-Sr ages of intrusive Precambrian mafic rocks, southern Beartooth Mountains, Montana and Wyoming: Geological Society of America Bulletin, v. 84, p. 3635–3644.

Borg, S.G., and DePaolo, D., 1994, Crustal structure and tectonics of the Antarctic margin of Gondwana and implications for tectonic development of southeastern Australia: Tectonophysics, v. 196, p. 339–358.

Brookfield, M.E., 1993, Neoproterozoic Laurentia-Australia fit: Geology, v. 21, p. 683–686.

Buchan, K.L., and Halls, H.C., 1990, Paleomagnetism of Proterozoic mafic dyke swarms of the Canadian shield, *in* Parker, A.J., Rickwood, P.C., and Tucker, D.H., eds., Mafic Dike and Emplacement Mechanisms: Rotterdam, Balkeema, p. 209–230.

Buchan, K.L., Mortensen, J.K., and Card, K.D., 1993, Northeast-trending Early Proterozoic dykes of southern Superior province: Multiple episodes of emplacement recognized from integrated paleomagnetism and U-Pb geochronology: Canadian Journal of Earth Sciences, v. 30, p. 1286–1296.

———1994, Integrated paleomagnetic U-Pb geochronologic studies of mafic intrusions in the southern Canadian Shield: Implications for the Early Proterozoic polar wander path: Precambrian Research, v. 69, p. 1–10.

Byrd, J.O.D., Smith, R.B., and Geissman, J.W., 1994, The Teton fault, Wyoming: Topographic signature, neotectonics, and mechanisms of deformation: Tectonics, v. 99, p. 20095–20122.

Christie-Blick, N., and Levy, M., 1989, Stratigraphic and tectonic framework of Upper Proterozoic and Cambrian rocks in the Western United States, *in* Late Proterozoic and Cambrian Tectonics, Sedimentation, and Record of Metazoan Radiation in the Western United States: 28th International Geological Congress, American Geophysical Union Field Trip Guidebook T331, p. 7–21.

Dalziel, I.W.D., 1991, Pacific margins of Laurentia and East Antarctica-Australia as a conjugate rift pair: Evidence and implications for an Eocambrian supercontinent: Geology, v. 19, p. 598–601.

Devlin, W.J., Brueckner, H.K., and Bond, G.C., 1988, New isotopic data and a preliminary age for volcanics near the base of the Windermere Supergroup, northeastern Washington, U.S.A.: Canadian Journal of Earth Sciences, v. 25, p. 1906–1911.

Dudás, F.Ö., and Lustwerk, R.L., 1997, Geochemistry of the Little Dal basalts: Continental tholeiites from the Mackenzie Mountains, Northwest Territories, Canada: Canadian Journal of Earth Sciences, v. 34, p. 50–58.

Elston, D.P., and McKee, E.H., 1982, Age and correlation of the Late Proterozoic Grand Canyon disturbance, northern Arizona: Geological Society of America Bulletin, v. 93, p. 681–699.

Everitt, C.W.F., and Clegg, J.A., 1962, A field test of paleomagnetic stability: Geophysical Journal of the Royal Astronomical Society, v. 6, p. 312–319.

Fisher, R.A., 1953, Dispersion on a sphere: Proceedings of the Royal Society of London, v. A217, p. 295–305.

Halls, H.C., 1982, The importance and potential of mafic dyke swarms in studies of geodynamic processes: Geosicence Canada, v. 9, 145–154.

Hanes, J.A., 1988, Dating of Precambrian mafic dyke swarms by the Rb-Sr, K-Ar and Sm-Nd methods, *in* Halls, H.C., and Fahrig, W.F., eds., Mafic Dyke Swarms: Geological Association of Canada Special Paper 34, p. 137–146.

Hanson, G.N., and Gast, P., 1967, Kinetic studies in contact metamorphic zones: Geochimica et Cosmochimica Acta, v. 31, p. 1119–1153.

Harlan, S.S., 1993, Paleomagnetic and $^{40}Ar/^{39}Ar$ results from Middle and Late Proterozoic intrusive rocks of the central and southern Rocky Mountains [abs.]: Geological Society of America Abstracts with Programs, v. 25, p. 48.

Harlan, S.S., Snee, L.W., Geissman, J.W., and Brearley, A.J., 1994, Paleomagnetism of the Middle Proterozoic Laramie anorthosite complex and Sherman Granite, southern Laramie Range, Wyoming and Colorado: Journal of Geophysical Research, v. 99, p. 17997–18020.

Harper, G.D., and Link, P.K., 1986, Geochemistry of Upper Proterozoic rift-related volcanics, northern Utah and southeastern Idaho: Geology, v. 14, p. 864–867.

Heaman, L.M., and LeCheminant, A.N., 1993, Paragenesis and U-Pb systematics of baddeleyite (ZrO_2): Chemical Geology, v. 110, p. 95–126.

Heaman, L.M., LeCheminant, A.N., and Rainbird, R.H., 1992, Nature and timing of Franklin igneous events, Canada: Implications for a Late Proterozoic mantle plume and the break-up of Laurentia: Earth and Planetary Science Letters, v. 109, p. 117–131.

Hoffman, P.F., 1991, Did the breakout of Laurentia turn Gondwana inside-out?: Science, v. 252, p. 1409–1412.

Höy, T., 1989, The age, chemistry, and tectonic setting of the Middle Proterozoic Moyie sills, Purcell Supergroup, southeastern British Columbia: Canadian Journal of Earth Sciences, v. 26, p. 2305–2317.

Jefferson, C.W., and Parrish, R.R., 1989, Late Proterozoic stratigraphy, U-Pb zircon ages, and rift tectonics, Mackenzie Mountains, northwestern Canada: Canadian Journal of Earth Sciences, v. 26, p. 1784–1801.

Jolly, A.D., and Sheriff, S.D., 1992, Paleomagnetic study of thrust-sheet motion along the Rocky Mountain front in Montana: Geological Society of America Bulletin, v. 104, p. 779–785.

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.

Krogh, T.E., Corfu, F., Davis, D.W., Dunning, G.R., Heaman, L.M., Kamo, S., Machado, N., Greenough, J.D., and Nakamura, E., 1988, Precise U-Pb isotopic ages of diabase dykes and mafic to ultramafic rocks using trace amounts of baddelyite and zircon, *in* Halls, H.C., and Fahrig, W.F., eds., Geological Association of Canada Special Paper 34, 147–152.

Lanphere, M.A., and Dalrymple, G.B., 1976, Identification of excess ^{40}Ar by the $^{40}Ar/^{39}Ar$ age spectrum technique: Earth and Planetary Science Letters, v. 32, p. 141–148.

Larson, E.E., Reynolds, R., and Hoblitt, R., 1973, New virtual and paleomagnetic pole positions from isotopically dated Precambrian rocks in Wyoming, Montana, and Arizona: Their significance in establishing a North American apparent polar wandering path: Geological Society of America Bulletin, v. 84, p. 3231–3248.

LeCheminant, A.N., and Heaman, L.M., 1989, Mackenzie igneous events, Canada: Middle Proterozoic hotspot magmatism associated with ocean opening: Earth and Planetary Science Letters, v. 96, p. 38–48.

———1994, 779-Ma mafic magmatism in the northwestern Canadian Shield and northern Cordillera: A new regional time-marker [abs.], *in* Lanphere, M.A., Dalrymple, G.B., and Turrin, B.D., eds., Abstracts of the Eighth International Conference on Geochronology, Cosmochronology, and Isotope Geology: U.S. Geological Survey Circular 1107.

Link, P.K., Christie-Blick, N., Devlin, W.J., Elston, D.P., Horodyski, R.J., Levy, M., Miller, J.G., Pearson, R.C., Prave, A., Stewart, J.H., Winston, D., Wright, L.A., and Wrucke, C.T., 1993, Middle and Late Proterozoic stratified rocks of the western U.S. Cordillera, Colorado Plateau, and Basin and Range province, *in* Reed, J.C., Jr., Bickford, M.E., Houston, R.S., Link, P.K., Rankin, D.W., Sims, P.K., and Van Schmus, W.R., eds., The Geology of North America, v. C-2, Precambrian, Conterminous U.S.: Boulder, Geological Society of America, p. 463–595.

Love, J.D., Reed, J.C., Jr., and Christiansen, A.C., 1992, Geologic map of Grand Teton National Park, Teton County, Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-2031.

Marvin R.F., and Dobson, S.W., 1979, Radiometric ages: Compilation B, U.S. Geological Survey: Isochron/West, no. 26, p. 3–32.

Moores, E.M., 1991, Southwest U.S.—East Antarctic (SWEAT) connection: A hypothesis: Geology, v. 19, p. 425–428.

Mueller, P.A., and Rogers, J.W., 1973, Secular chemical variation in a series of Precambrian mafic rocks, Montana and Wyoming: Geological Society of America Bulletin, v. 84, p. 3645–3652.

Park, J.K., 1981, Paleomagnetism of the Late Proterozoic sills in the Tsezotene Formation, Mackenzie Mountains, Northwest Territories, Canada: Canadian Journal of Earth Sciences, v. 18, p. 1572–1580.

Park, J.K., Buchan, K.L., and Gandhi, S., 1995, Paleomagnetism of 780 Ma Hottah gabbro sheets of the Wopmay orogen, Northwest Territories, Canada, *in* Current Research, Paper 1995C: Geological Survey of Canada, p. 195–200.

Park, J.K., Buchan, K.L., and Harlan, S.S., 1995, A proposed giant radiating dyke swarm fragmented by the separation of Laurentia and Australia based on paleomagnetism of ca. 780 Ma mafic intrusions in western North America: Earth and Planetary Science Letters, v. 132, p. 129–139.

Park, J.K., Norris, D.K., and Larochelle, A., 1989, Paleomagnetism and the origin of the Mackenzie arc of northwestern Canada: Canadian Journal of Earth Sciences, v. 26, p. 2194–2203.

Powell, C.M.A., Li, Z.X., McElhinny, M.W., Meert, J.G., and Park, J.K., 1993, Paleomagnetic constraints on timing of the Neoproterozoic breakup of Rodinia and the Cambrian formation of Gondwana: Geology, v. 21, p. 889–892.

Prinz, M., 1964, Geologic evolution of the Beartooth Mountains, Montana and Wyoming. Part 5. Mafic dike swarms of the southern Beartooth Mountains: Geological Society of America Bulletin, v. 75, p. 1217–1248.

Reed, J.C., Jr., and Zartman, R.E., 1973, Geochronology of Precambrian rocks of the Teton Range, Wyoming: Geological Society of America Bulletin, v. 84, p. 561–582.

Ross, G.M., Parrish, R.R., and Winston, D., 1992, Provenance and U-Pb geochronology of the Mesoproterozoic Belt Supergroup (Northwestern United States): Implications for age of deposition and pre-Panthalassa plate reconstructions: Earth and Planetary Science Letters, v. 113, p. 57–76.

Samson, S.D., and Alexander, E.J., Jr., 1987, Calibration of the interlaboratory ^{40}Ar-^{39}Ar dating standard, MMhb-1: Chemical Geology, v. 66, p. 27–34.

Schmidt, R.G., 1978, Rocks and mineral resources of the Wolf Creek area, Lewis and Clark and Cascade Counties, Montana: U.S. Geological Survey Bulletin 1441, 91 p.

Snyder, G.L., Hughes, D.J., Hall, R.P., and Ludwig, K.R., 1989, Distribution of Precambrian mafic rocks penetrating some Archean rocks of western North America: U.S. Geological Survey Open-File Report 89-125, 36 p.

Steiger, R.H., and Jäger, E., 1977, Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters, v. 36, p. 359–362.

Stewart, J.H., 1972, Initial deposits in the Cordilleran geosyncline; Evidence of a Late Precambrian (<850 m.y.) continental separation: Geological Society of America Bulletin, v. 83, p. 1345–1360.

Tysdal, R.G., Zimmerman, R.A., Wallace, A.R., and Snee, L.W., 1990, Geologic and fission-track evidence for Late Cretaceous faulting and mineralization, northeastern flank of Blacktail Mountains, southwestern Montana: U.S. Geological Survey Bulletin 1922, 20 p.

Wooden, J.L., Vitaliano, C.J., Koehler, S.W., and Ragland, P.C., 1978, The late Precambrian mafic dikes of the southern Tobacco Root Mountains, Montana: Canadian Journal of Earth Sciences, v. 15, p. 467–479.

Zartman, R.E., Peterman, Z.E., Obradovich, J.D., Gallego, M.D., and Bishop, D.T., 1982, Age of the Crossport C sill near Eastport, Idaho, *in* Society of Economic Geologists Coeur d' Alene Field Conference, Idaho-1977: Idaho Bureau of Mines and Geology Bulletin 24, p. 61–69.

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