Petrology and paleomagnetism of the Long Mountain Granite, Wichita Mountains, Oklahoma

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ABSTRACT

The Long Mountain Granite, a member of the Cambrian Wichita Granite Group, is exposed in the western Wichita Mountains. The rock is red at the surface and grades into a dark gray to green that has been exposed by quarrying operations. The Long Mountain Granite is a granophyric, fluorite-bearing alkali-feldspar granite with hedenbergite as the dominant mafic phase. The red and gray-green granites have similar geochemical signatures. Hematite in the red granite occurs as fracture fill, grain boundary coatings and as elongated crystals along cleavage and exsolution planes in alkali feldspars. The iron in the hematite appears to be sourced from the oxidation of magnetite and ilmenite and the breakdown of mafic minerals.

Anisotropy of magnetic susceptibility analysis shows that the gray-green granite contains a primary magnetic fabric that is consistent with the sill-like emplacement of Wichita Group granites. Paleomagnetic analysis of the gray-green granite yields a magnetization with easterly declinations and steep down inclinations that is interpreted as a primary or early Cambrian thermal remanent magnetization residing in magnetite. The pole (8.8°S, 134.7°E) is consistent with several other paleomagnetic poles of similar age. The red granite has lower magnetic susceptibility and magnetic intensities than the gray-green granite. The magnetization has southeasterly declinations and shallow inclinations with a Permian paleopole and is interpreted as a chemical remanent magnetization (CRM) residing in hematite. The CRM was caused by low-temperature weathering fluids while the granite was exposed near the surface in the late Paleozoic.

INTRODUCTION

Granitoid rocks throughout the world have a wide range of colors, including red. The origin of the hematite, which commonly occurs as inclusions in feldspars, has been the subject of research for decades. Some investigators have proposed a primary magmatic origin for the hematite, although this has usually been dismissed on the grounds that other minerals do not contain hematite (e.g., Ernst, 1960). Others have suggested solid-state exsolution from iron-bearing feldspar minerals, precipitation during deuteric feldspar recrystallization reactions (e.g., Putnis et al., 2007), or general hydrothermal activity (e.g., Wenner and Taylor, 1976) as possible origins of the oxide inclusions. Hematite can hold a magnetic remanence and can be used to constrain the timing of diagenetic events (e.g., Elmore et al., 1998). Paleomagnetic analysis of the hematite in red granites should, therefore, be capable of determining the timing of the alteration of the rock which can help to assess the origin of the coloration.

Long Mountain, a large granite inselberg located in the western Wichita Mountains, Oklahoma (Figure 1), is

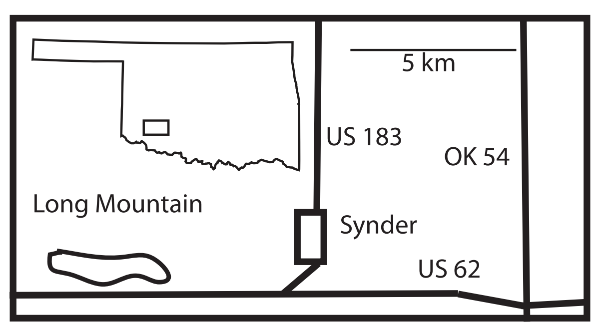

Figure 1. Map showing the location of the Long Mountain Granite west of Snyder, Oklahoma.

an ideal place to test models for the origin of the red color. Surface exposures of the granite are pink to red, and quarrying operations on the west side of the mountain have exposed a sharp transition to gray-green granite (Figure 2). The Wichita Granite Group, of which the Long Mountain Granite is a part, is Cambrian (Ham et al., 1964). The contrasting exposures provide an opportunity to investigate the petrological and magnetic properties of the rock and how they have changed with alteration. Petrological analysis provides information as to the nature of the alteration, and paleomagnetic studies should determine the timing. The Long Mountain Granite also provides an opportunity to obtain a primary Cambrian paleomagnetic pole from the relatively unaltered gray-green Long Mountain Granite.

Figure 2. Martin-Marietta Materials Snyder Quarry with the gray-green granite to the right and the red granite to the left.

GEOLOGIC SETTING

The Long Mountain Granite is part of the Cambrian Southern Oklahoma Aulacogen. The oldest rocks known to be associated with the aulacogen are those of the Glen Mountains Layered Complex, a large layered intrusion that was uplifted, tilted by approximately 15°, and eroded prior to further igneous activity (Powell et al., 1980). Subsequently, a large volume of A-type rhyolites (Carlton Rhyolite Group) were extruded, and a series of sheet-like A-type granite sills, including the Long Mountain Granite, were emplaced at the base of the volcanic pile. Following granite intrusion, a series of rhyolitic and diabasic dikes penetrated the section. The total volume of igneous rocks is estimated at approximately 100,000 km^3 intrusive and over 40,000 km^3 volcanic (Keller and Stephenson, 2007). Once igneous activity ceased, the aucologen quickly began subsiding and accumulated sediments until the Late Mississippian to Early Pennsylvanian, when it began to be re-uplifted by the Ouachita Orogeny (Gilbert, 1982). During the Permian the igneous rocks were re-exposed, only to be covered again by Permian sediments.

All intrusive granitoids in the Wichita Mountains are part of the Wichita Granite Group. Ham et al. (1964) noted that the granites extend across an area of approximately 40,000 km^2 in the subsurface and tend to occur as laterally-extensive sheets approximately 500 m thick. The granites are commonly red and are considered A-type granites (Gilbert and Myers, 1986). All of the Wichita granites have elevated halogen concentrations and are water-undersaturated. The felsic magmas that formed the granites are believed to have been intruded at very high temperatures (900-1000° C) (Gilbert, 1982); this allowed the magmas to intrude nonexplosively into the subvolcanic pile at depths of as little as 1 km. The elevated halogen content (especially fluorine) would have also greatly lowered the viscosity of the magmas, allowing them to spread out over large distances (Hogan et al., 2000). Non-explosive magma intrusion is a critical part of any attempt to model the emplacement conditions of the Wichita granites, as no caldera structures have been found in the region (Ham et al., 1964). Hogan et al. (2000) suggested that the finer-grained granites are earlier, intruded shallowly, and that grain size of the granites increased with the thickness of the volcanic pile and the earlier intruded granitic sills.

Previous studies of the Long Mountain Granite describe it as a reddish, medium-textured granophyric granite predominantly composed of exsolved feldspars and quartz with accessory quantities of magnetite, titanite (sphene), hornblende, zircon, epidote, and calcite (e.g., Hessa, 1964). Hessa (1964) also noted that the granite became gray with depth. Taylor (1915) attributes the red coloration to very fine-grained disseminated hematite, which he hypothesized was produced by the alteration of primary minerals via groundwater.

There have been no previous paleomagnetic studies of the Long Mountain Granite although there have been some studies on the basement rocks in the Wichita Mountains which reported both early and late Paleozoic magnetizations (e.g., Ku et al., 1967; Spall, 1968; Vincenz et al., 1974). Elmore et al. (1998) obtained a presumed primary paleopole from the Cambrian Colbert Rhyolite (likely a part of or at least contemporaneous with the Carlton Rhyolite Group) in the Arbuckle Mountains.

Figure 3. Highly fractured red granite in the quarry.

Figure 4. Fissile, altered diabase dikes in red granite. Dikes are as much as ~30 cm thick. The dike in the center has a maximum thickness of 30 cm.

METHODS

All samples utilized in the present study were obtained in the Martin-Marietta Materials Snyder Quarry located west of the town of Snyder, Oklahoma on the west side of Long Mountain. Cores (2.5-cm diameter) of both gray-green and red granite were collected from in-situ rocks using a portable gasoline-powered water-cooled drill. Specimens were oriented in the field using an inclinometer and Brunton compass. The natural remanent magnetization (NRM) was measured using a 2G-Enterprises cryogenic magnetometer housed in a magnetically shielded room. Specimens were then subjected to low-temperature demagnetization (LTD) in liquid nitrogen to remove the effects of multi-domain magnetic minerals (Dunlop et al., 1997) and the specimens were stepwise thermally demagnetized in an ASC Scientific Thermal Specimen Demagnetizer up to a temperature of 700°C. Demagnetization data were plotted on orthogonal projection diagrams and analyzed using principle component analysis with site statistics after Fisher (1953).

Chips left over from the paleomagnetic cores were prepared into polished thin sections and examined petrographically in order to determine overall mineralogy and texture of the rock as well as to identify magnetic minerals, secondary phases, and alteration textures. Some chips and thin sections were examined using a Cameca SX50 microprobe at the University of Oklahoma Electron Microprobe Laboratory. Phases were distinguished qualitatively on the basis of backscattered electron imaging and EDXA analysis.

RESULTS AND INTERPRETATIONS

Petrology

In the field, the Long Mountain Granite is present in two varieties. One is red, and the other has a gray fresh surface but develops a green coating after exposure. The red granite tends to be more heavily fractured than the gray-green (Figure 3). The granite is intruded in several places by diabase dikes. In the red granite, the dikes tend to be very fissile and almost shale-like (Figure 4). Those penetrating the gray-green granite tend to be more massive, although they are highly fractured in some places.

The Long Mountain Granite is a fine-grained microporphyry with the average size of feldspar and quartz crystals being about 1 to 2 mm. The rock is dominantly (>90 to 95%) composed of quartz and alkali-feldspar intergrowths in a myrmekitic to granophyric texture (Figure 5a). Accessory minerals tend to occur as sub-millimeter crystals in small clusters that may or may not be monomineralic (Figure 5b), giving the rock a cumulophyric to glomerophyric texture in addition to the dominant granophyre. Non-granophyric feldspar and accessory minerals tend to be subhedral.

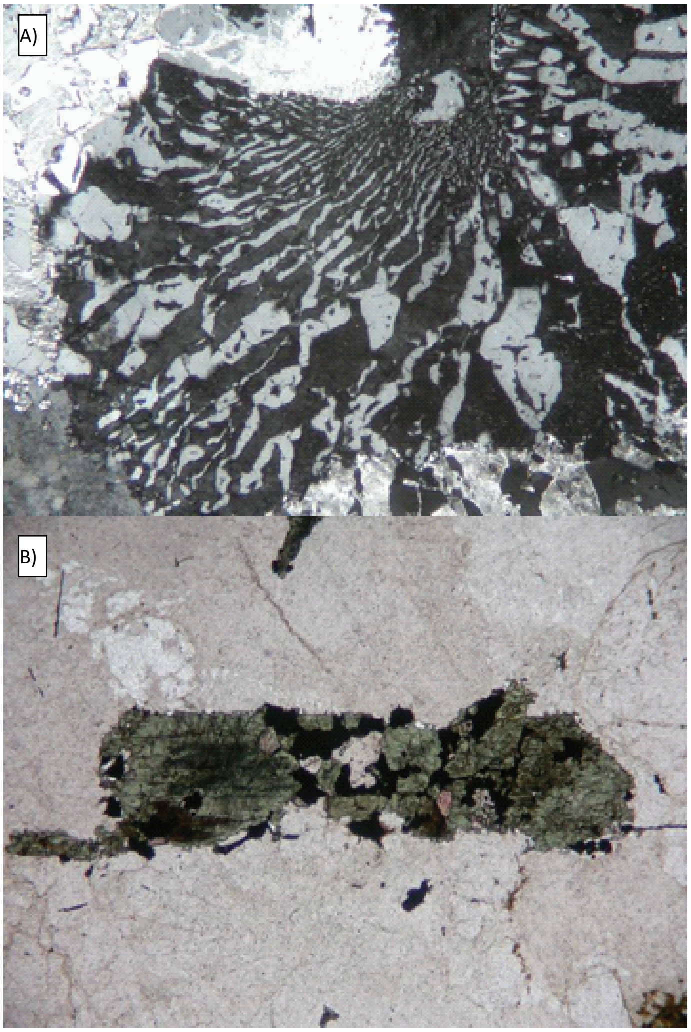

Figure 5. A) Myrmekitic quartz-feldspar intergrowth grading into granophyre. Crossed polarizers, 3.5 mm field of view. B) Cumulophyric cluster of hedenbergite, fluorite, Fe-Ti oxides, and zircon. Plane-polarized light, 3.5 mm field of view.

The dominant mafic phase appears to be a calcic clinopyroxene; electron-microprobe analysis indicates that this phase is essentially end-member hedenbergite ($CaFeSi_2O_6$). Hedenbergite occurs in a variety of shapes from almost euhedral crystals to anhedral blebs. Hornblende, previously reported as the dominant mafic phase (Hessa, 1964), is sparsely present as anhedral masses in some samples but is absent in others. Biotite is also sparse, although a brown phase that has not been conclusively identified appears to be an alteration product of biotite, indicating that it may have once been a more abundant mineral. The alteration product rarely exhibits a very weak pleochroism and a very strong reddish-brown color. It has a micaceous habit, is easily damaged by a steel needle, and contains small rounded grains of biotite. Epidote-group minerals, identified by microprobe as compositionally similar to allanite, are also present.

The most abundant non-mafic accessory minerals in the Long Mountain Granite are iron-titanium oxides. Magnetite and ilmenite are present as exsolved grains. Fluorite is commonly present as small grains, both alone and in association with others. Titanite, which Hessa (1964) reported as a common accessory mineral, was not found in the current study. This is consistent with the presence of fluorite (Price et al., 1999). Other accessory minerals include zircon, monazite, bastnaesite, and chevkinite. Rare grains of apatite have only been found in the cores of monazites or as wholly enclosed inclusions in iron oxides.

The red granite is generally very similar to the gray-green in that it consists mainly of granophyric intergrowths. There are, however, significant differences in the accessory mineral assemblages. The most obvious change in hand sample is, of course, the red coloration. In thin section, the principal difference is that many of the mafic minerals are no longer present. Microprobe analysis indicates that mafic minerals have been altered to a phase that displays what appears to be dessication features and has a chemical composition similar to that of montmorillonite clays (Figure 6). In thin section, these are typically scoured out by the pol-

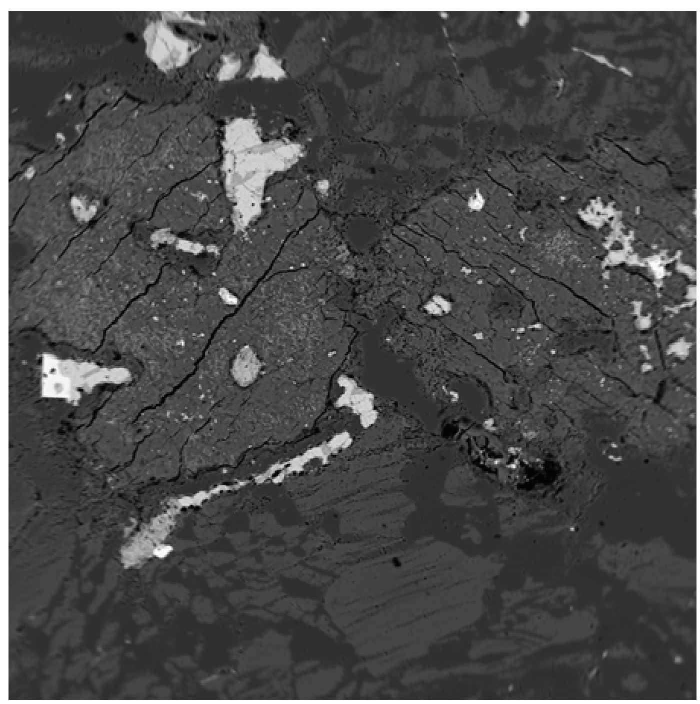

Figure 6. Mafic crystals altered to clays. Backscattered electron image, 1580 µm field of view.

ishing process, leaving behind void spaces. In some cases, the mafic alteration products appear to have been removed from the void spaces prior to sampling or during preparation of the thin sections, and the void spaces contain secondary phases such as epidote-group minerals, calcite, and amorphous silica. The feldspars also exhibit evidence of substantial alteration such as deep hematite staining, sericitization, and evidence of recrystallization associated with fractures (Figure 7). The red granite contains abundant hematite-filled fractures, and strong hematite staining associated with fractures and crystal boundaries is pervasive in much of the rock.

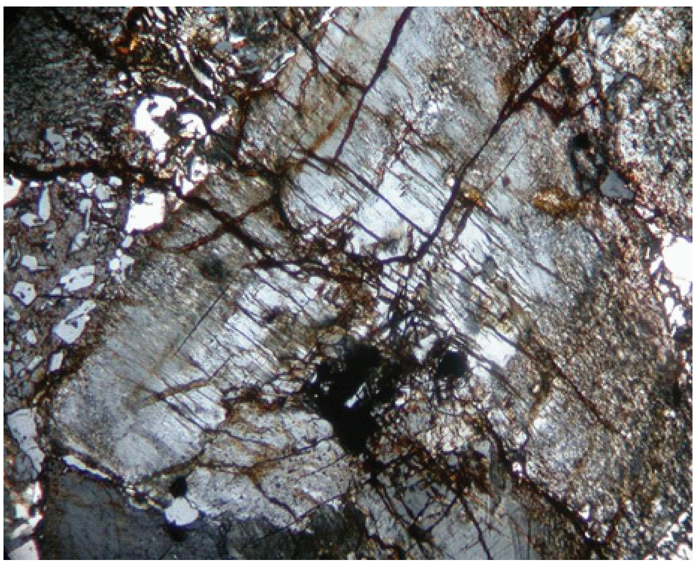

Figure 7. Feldspar crystal showing hematite staining, sericitization, and recrystallization along fractures. Cross-polarized light, 3.5 mm field of view.

The red granite is very similar to the gray-green in terms of minor and trace elements (Hamilton, 2011). The oxidation state of iron (FeO vs. Fe_2O_3) changes with average Fe^{2+}/Fe^{3+} dropping from 1.74 to 0.54; however, the total amount of iron is essentially identical (about 2 wt.%) in the red and gray-green granites (Hamilton, 2011).

In summary, the petrographic results from the gray-green and red granites are similar although most of the mafic minerals in the red granite are absent or have been altered (Hamilton, 2011). The hematite staining in the feldspars in the red granite is largely associated with fractures, although it also occurs as grain-boundary coatings and as crystals along cleavage and exsolution planes in alkali feldspars (Hamilton, 2011). The iron in the hematite appears to be sourced from the oxidation of magnetite and ilmenite and the breakdown of mafic minerals.

Paleomagnetism

Hamilton (2011) reports that anisotropy of magnetic susceptibility (AMS) analysis shows that the gray-green granite contains an oblate fabric interpreted as a primary magnetic fabric that is consistent with the sill-like emplacement of Wichita Group granites. Red granite has approximately two orders of magnitude lower magnetic susceptibility and natural remanent intensity. The degree of magnetic anisotropy is reduced relative to gray-green granite and the AMS fabric is incompatible and is interpreted as an alteration fabric (Hamilton, 2011).

The LTD treatment of the gray-green granite specimens led to a significant drop in magnetic intensity to about an average of 70% of NRM, which indicates the removal of some magnetization in multi-domain magnetite (Dunlop et al., 1997). Thermal demagnetization of gray-green granite specimens removes a characteristic remanent magnetization (ChRM) with approximately east-southeasterly declination and down inclination (Figure 8 and Table 1). This

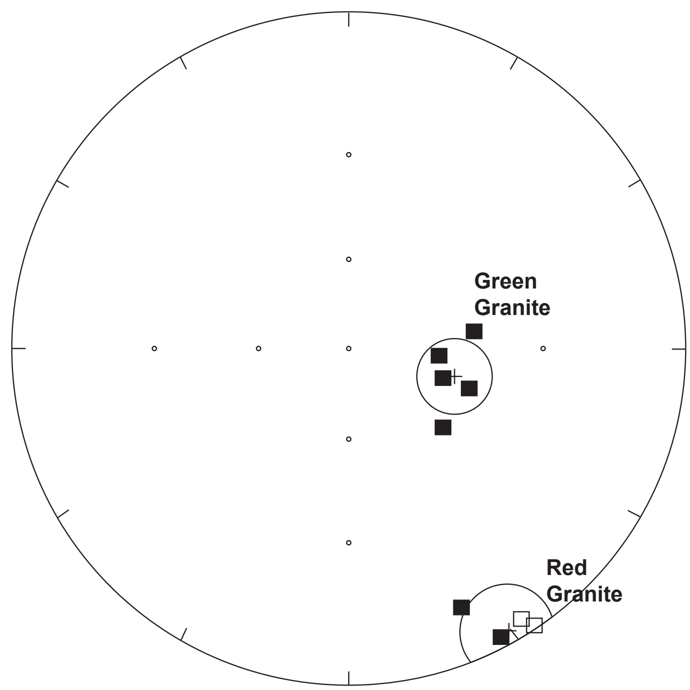

Figure 8. Equal-area projection of ChRM site means from gray-green and red granite. There is no overlap between the two. Open symbols: negative (up) inclinations; solid symbols: positive (down) inclinations.

TABLE 1. SITE STATISTICS AND MEAN DIRECTIONS/ POLES OF CHRMS

Site	N/N_0	Dec	Inc	α_{95}	k	Lat./Long.	dp/dm
Green							
SG 1	5/7	94.1	59.9	8.6	81	-19.1/134.1	9.8/13
SG 2	7/8	108.3	47.8	9.2	43.6	- 3.3/136.7	8/12.1
SG 3a	4/7	129.7	50	19.3	23.6	9.2/123.1	17.2/25.8
SG 5	7/8	82.5	48.7	14.1	19.3	-22/149.5	12.2/18.6
SDH	8/9	107.2	57.4	19.1	9.4	-9.1/130.7	20.4/27.9
Mean	--	104.6	54.1	11.5	45.4	-8.8/134.7	11.3/16.3
Red							
SR 1	11/11	156.5	10	8.6	26.4	44.5/114.9	4.4/8.7
ST 1	3/7	144.4	58.3	11.3	120.1	9.3/108.3	12.4/16.7
SQR 1	8/8	146.3	-0.7	7.9	50.7	43.5/130.9	4/7.9
SQR 2	7/8	147.6	-2.9	6.9	78.11	45.1/130.4	3.5/6.9
Mean	--	150.6	2.1	8.3	123.8	44.9/124.9	4.2/8.3

Note: N/N_0 – Number of specimens with direction vs. number of specimens demagnetized; Dec – Declination; Inc – Inclination; α_{95} – 95% cone of confidence; k – Precision parameter; dp,dm – semiaxes of 95% cone of confidence of pole.

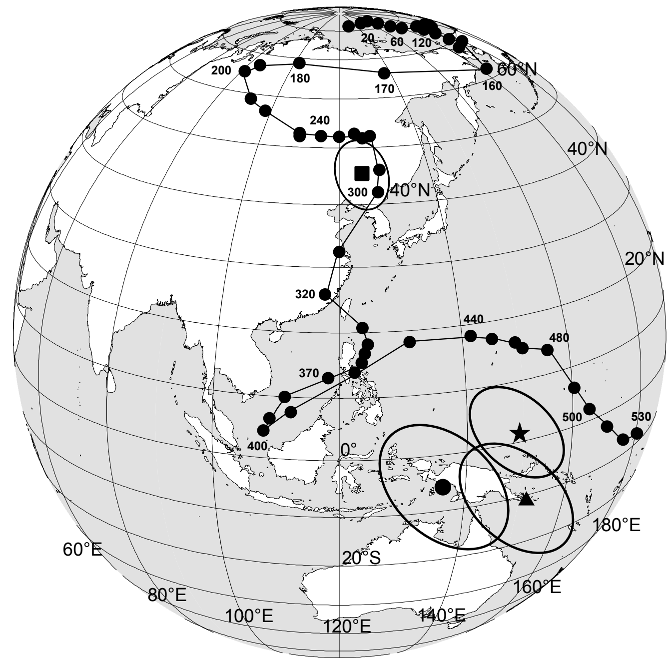

Figure 9. North American Phanerozoic apparent polar wander path (Torsvik et al., 2012) and paleopoles and 95% errors for the green Long Mountain Granite (circle) and the red Long Mountain Granite (square). Triangle is ~530 Ma Colbert Rhyolite pole (Elmore et al., 1998) and the star is from other Wichita granites (Spall, 1968).

component is removed by 540°C and is interpreted to reside in magnetite.

The results of LTD treatment for the red specimens were variable, ranging from 2 to 47% removal of NRM. Thermal demagnetization removes a ChRM with southeasterly declinations and shallow inclinations (Figure 8 and Table 1) to 700°C which indicates that the ChRM resides in hematite.

DISCUSSION AND CONCLUSIONS

The ChRM in gray-green granite appears to be wholly contained within magnetite as evidenced by the demagnetization characteristics and observation of primary magnetite by petrography. The pole (8.8°S, 134.7°E; Figure 9) is consistent with other paleomagnetic data from the Wichita granites (e.g., Spall, 1968; Vincenz et al., 1974) and with some poles of similar age (Kirschvink et al., 1997; Elmore et al., 1998). The ChRM of the gray-green granite is interpreted as a primary thermal remanent magnetization. The AMS fabric is consistent with this interpretation (Hamilton, 2011).

The ChRM in the red granite resides in hematite and has a pole (44.9°N, 124.9°E, Figure 9) that lies on the Permian to Late Carboniferous part of the apparent polar wander path. The granite would have been reburied in the Late Permian after surface exposure during the late Paleozoic (Gilbert, 1982).

The ChRM in the red granite is interpreted as a chemical remanent magnetization (CRM). The CRM is interpreted to have been caused by low-temperature weathering fluids while exposed near the surface in the Permian. The formation of red granite was not associated with significant whole-rock geochemical change.

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