TESTING THERMAL VISCOUS REMANENT MAGNETIZATION (TVRM) AS A TOOL TO DATE GEOMORPHIC EVENTS

Danika Globokar

A thesis submitted in partial fulfillment of

the requirements for the degree of

Master of Science

University of Washington

2014

Committee:

Juliet Crider

Terry Swanson

Program Authorized To Offer Degree:

Department of Earth and Space Sciences

University of Washington

ABSTRACT

Testing thermal viscous remanent magnetization (tvrm) as a tool to date geomorphic events

Danika Globokar

Chair of the Supervisory Committee:
Assistant Professor Juliet Crider
Earth and Space Sciences

When a rock forms, it acquires a thermal remanent magnetization (TRM) aligned with Earth's magnetic field. If the rock becomes misaligned with the magnetic field (by e.g. rockfall or glacial plucking and deposition), it may acquire a thermal viscous remanent magnetization (TVRM) which partially overprints the TRM. The strength of the TVRM is dependent on the exposure time and temperature (Neel, 1949). Given the temperature and duration of heating required to remove the TVRM, along with estimates of the environmental temperature, one can determine the exposure time required to produce it, thereby dating displacement. I evaluate the potential for TVRM dating using a suite of cosmogenically-dated, granodiorite moraines in the Icicle Creek drainage of the North Cascades, Washington, with ages ranging 13-112 ka.

About 40% of boulders and 25% of samples contained both a TVRM and TRM component. A subset of these were identified as "qualifying samples", whose TVRM components were in the direction of magnetic north. This is a critical distinction to make, as it indicates that the TVRM was more likely acquired since moraine emplacement. The temperature at which a TVRM is removed from a sample is the unblocking temperature (T_u), or turning point temperature.

I used nomographs published by Pullaiah et al. (1975) and Middleton and Schmidt (1982) to translate T_u to a displacement age and compared output ages from both methods. The Middleton

and Schmidt equation yielded moraine ages within about an order of magnitude of cosmogenic ages, while the equation of Pullaiah et al. yielded ages that differed by multiple orders of magnitude. This difference suggests that pseudo-single-domain magnetite is the remanence carrier in the moraine boulders. Error inherent in the dating method includes mis-identification of the turning point due to a diffuse TVRM/TRM relationship, correcting for oven temperature gradients, and relying on assumptions for field acquisition conditions, all of which have the potential to introduce large variation into an age. At present, TVRM is a useful relative dating method to confirm geomorphic interpretations, and may provide approximate age constrains where no other methods are applicable.

ACKNOWLEDGEMENTS

First and foremost I offer my sincerest gratitude to my advisor, Professor Juliet Crider, for her constant, unwavering support throughout my entire tenure at the University of Washington. Her patience and dedication to my research, particularly when "the going got tough", helped guide me through developing and writing my thesis. It's difficult to find words to express my gratitude for the countless hours of guidance and encouragement provided over the past three years, so I leave it as a simple and heartfelt, "Thank you." I could not have done it without you, Juliet.

Russell Burmester, Research Associate at Western Washington University, was also instrumental in my paleomagnetism research. I fondly call him "the paleomag guru" when I explain my thesis to friends and colleagues and I attribute much of my understanding of paleomagnetism to his teachings. During my laboratory work, Russ was right beside me studying the results. His promptings and questions forced me to evaluate my samples more thoroughly and seek answers through more in-depth analysis. My research spans two disciplines, and he provided a strong support pillar for one of those.

My other committee member, Terry Swanson, furthered my understanding of the Icicle Creek basin's glacial history. Not many professors would spend an entire day playing "show and tell" in the field for a single graduate student.

I also would like to thank the Geological Society of America and the University of Washington's Department of Earth and Space Sciences for the funding they were able to provide to me in order to make this thesis possible. Additionally, the Pacific Northwest Paleomagnetic Laboratory at Western Washington University provided the equipment needed to analyze my samples. My peers Brandon Miller and Karl Lang provided much-needed hands in the field in freezing snow and scorching summer heat, respectively. Thanks guys!

Finally, I thank my family. To my sister, "thanks" for teaching me how to edit my figures. To my husband, "thanks" for the steady supply of encouraging words and for pushing me to keep inching towards that light at the end of the tunnel. I wouldn't have made it without you.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (CONTINUED)

LIST OF TABLES

TABLE OF CONTENTS (CONTINUED)

Page

LIST OF FIGURES

1.0 INTRODUCTION

Can thermal viscous remanent magnetization (TVRM) be used to date geomorphic events such as rock fall and moraine deposition? Unlike other dating methods commonly used by geomorphologists, the TVRM dating method doesn't depend on surface exposure, quartz content, or organic matter. It has the potential to cover a wide range of ages (several decades to 100ka+), date various rock types, and is relatively inexpensive. Potential applications include dating rock fall, moraine deposition, and archeological masonry. I first review common geomorphic dating tools and their shortcomings. Then I will introduce the TVRM dating method and how it was used in the context of this study.

1.1 Geomorphic Events and Motivation

Geology, tectonic geomorphology, and archeology are only some of the numerous disciplines that require time controls on landscapes to answer a wide array of scientific questions. Ages of rock fall, moraine deposition, fault propagation, and anthropogenic displacement of rocks serve to increase hazard awareness, elucidate historic climate shifts, and give insight into human occupation in an area. The variety in types of dateable events, combined with differences in the question being asked, precision needed, material being dated, and environmental and physical constraints has led to the development of a wide arsenal of dating techniques for geomorphology.

1.2 Other Dating Techniques

A fundamental division of dating techniques is the distinction between relative and absolute dating methods. Relative dating yields only relational information (moraine X is older than moraine Y), whereas absolute dating allows us to assign a numerical age to a surface, without reference to another surface. Additionally, geomorphologists classify some dating methods as "pseudo-quantitative", in that they are relative dating techniques, but can be used to obtain absolute ages if calibrated to a locally known event or boulder age.

1.2.1 Relative Dating Methods

Some commonly used relative dating techniques, their range of ages, as well as materials needed to date the surface or event are summarized in Table 1.

Clast seismic velocity is more commonly known as "clink vs thud". Geomorphologists have used this technique for years by hitting the boulder to be dated with a hammer. Younger, less weathered boulders produce a sharp "clink" sound, whereas older boulders produce a dull "thud". Although this method was quantified by Crook (1986), it is still limited as the user is forced to calibrate the technique against locally-known surfaces of the same rock-type (Gillespie, 1982).

The weathering rind dating method relies on the basic assumption that minerals near the surface of a boulder will experience chemical and mechanical weathering, thereby creating a rind of altered minerals. The thickness of the rind is related to length of time the boulder has been emplaced. Though geomorphologists have sought to quantify this technique, it remains, at best, a pseudo-quantitative method as different lithologies, local climate, and vegetation all introduce age uncertainty and calibration to a known local surface age is required (Colman and Pierce, 1986).

In addition to the aforementioned relative dating tools, we can also obtain relative ages for moraines by comparing where one moraine is in relation to another: the oldest moraine is the moraine furthest down-valley, whereas the youngest moraine is the furthest up-valley. Intermediate-aged moraines would fall between the two. This dating method is valid as long as the moraines themselves are still present and not completely degraded (300 ka+).

1.2.2 Absolute Dating Methods

Common absolute dating methods include, among others, radioisotopic dating (for organic material such as wood, shells, and coral), thermoluminescence dating (quartz and feldspar sands), paleomagnetic secular variations (fine sediment), tephrochronology (volcanic ash),

dendrochronology (tree rings), sclerochronology (coral), and cosmogenic nuclide surface exposure dating.

Cosmogenic nuclide dating, used to date the length of time a rock surface has been exposed to the Sun's cosmic rays, is currently one of the most commonly used dating techniques in geomorphology (Heyman et al.. 2011; Putkonen and Swanson, 2003). This method measures the amount of cosmogenic nuclides that have accumulated in a sample sitting at Earth's surface, the amount of which can be equated to age, because the nuclides are produced at a known rate. Numerous isotopes can be used depending on the mineralogy of the rock to be dated (10Be, 26Al, He, Ne, 36Cl), and the technique can be used to date surface exposures from 0 – 4 Ma (Phillips et al. 1986).

Under certain conditions this method has very high precision, but there are shortcomings to cosmogenic dating which can introduce significant uncertainty. A rock can have more or fewer nuclides than expected if it was previously at the surface, slowly exhumed over time, covered with snow for part of the year, eroded, resting at an unexpected angle (angle of incidence), or shielded by a nearby cliff. In an analysis of published cosmogenic exposure ages for moraine boulders, Putkonen and Swanson (2003) calculated an average range of 38% between the oldest and youngest boulders from each moraine. Though one of the more precise dating tools, cosmogenic nuclide dating is also one of the most expensive, costing up to $2,000 or more per sample (Purdue Rare Isotope Measurement Laboratory, 2014).

Although there are many relative and absolute dating methods, each with different strengths and weaknesses, they are not always appropriate or applicable in all situations. TVRM offers a complementary tool for dating geomorphic events. TVRM directly dates the length of time a rock has been displaced, rather than simply surface exposure. TVRM acquisition occurs even if the sample is buried, and it does not require quartz or organic matter. This technique has the potential to date a variety of rock types, a range of ages, and is relatively inexpensive, especially compared to some dating techniques currently being used.

1.3 Basic Paleomagnetism

Magnetite, hematite and pyrrhotite are the most common minerals that retain a magnetization. When these minerals grow large enough or cool in an igneous rock, through their blocking temperature, they can acquire a remanent magnetization in the direction of the ambient magnetic field. Size and composition control when during growth or cooling a grain is magnetized, or acquires its thermal remanent magnetization (TRM). This magnetization is in line with Earth's magnetic field at the time and location of cooling. Mineral size and composition, along with grain shape, are the main controls of stability of the magnetization. Stable magnetizations are used to obtain paleomagnetic directions, paleopole locations, and thereby reconstruct plate and continental movement (Butler, 1992; Tauxe, 2010). Magnetizations that are less stable allow changes in a rock's magnetization with time, which can be used for other purposes, such as TVRM dating.

1.4 TVRM

If a rock topples or is displaced so that it is no longer in-situ, such as in a rock fall or moraine plucking and deposition, it will likely be deposited such that its TRM is no longer in alignment with Earth's magnetic field. This misalignment causes some of the weak moments in the magnetic carriers to "jump" and align with the external magnetic field. This introduces a second component of magnetization, a thermal viscous remanent magnetization (TVRM), which partially overprints the TRM (Tauxe, 2010). The strength of the TVRM is dependent on exposure time and temperature (Neel, 1949). Thus, assuming constant temperature, the larger the TVRM component, the longer a rock has been displaced from its original orientation in the magnetic field. The sum of these two components is the natural remanent magnetization (NRM) An example TVRM/TRM demagnetization plot is shown in Figure 1.

In principle, a rock's TVRM can be removed by thermally demagnetizing the sample at a time-temperature combination that is equivalent to that at which the TVRM was acquired (Neel, 1949). The temperature at which the TVRM component is completely erased is termed its unblocking temperature (Tub). For single-domain magnetite, Neel (1949) describes the

theoretical relationship between TVRM acquisition conditions and unblocking conditions which Taxue (2010) simplifies to:

$$T_{field}\frac{lnC\tau_{field}}{M_s^2(T_{field})} = T_{lab}\frac{lnC\tau_{lab}}{M_s^2(T_{lab})}$$

where C is the characteristic frequency of thermal fluctuation (~ 10^{10} Hz; Neel, 1949; Pullaiah, 1975), $M_s(T)$ is magnetic susceptibility as a function of Temperature, T is temperature in either the lab or field, and τ is the relaxation time, a measure of the probability of a mineral to change or flip its remanence. Relaxation time varies greatly depending on grain size, grain shape and temperature. As magnetite grain size increases, relaxation time logarithmically increases from seconds (unstable remanence) to over one billion years (Tauxe, 2010). Furthermore, increasing the temperature to which a mineral is exposed decreases relaxation times. The TVRM dating method exploits the time-temperature relationship described by Neel (1949). We can directly measure unblocking time and temperature in the laboratory and make an educated estimate of the paleotemperature of the rock at Earth's surface. With the values of M_s and C being constant and known, the only undefined variable is τ_{field}. This, the relaxation time in field conditions, is the length of time the rock has been acquiring a TVRM in its new orientation to Earth's magnetic field.

Sets of nomographs of equivalent time-temperature combinations for single domain magnetite have been published by Pullaiah et al. (1975) and Middleton and Schmidt (1982), though the two are quite different from one another. Both sets of authors initially derive their nomographs from the single domain theory of Neel (1949). Pullaiah et al. supplement their calculations with laboratory results using experiments on single-domain magnetite grains. Middleton and Schmidt supplement their work with field observations and found their results to be more closely in accord with Walton's (1980) calculations which assume a log-normal grain-size distribution of magnetite in natural settings. This deviates from the purely single-domain theory of Neel (1949), in that it accounts for a larger grain-size distribution of magnetite and applies to pseudo-single domain magnetite. Walton (1980) modifies Neel's equation to:

$$T_{field}\frac{\ln^2 2C\tau_{field}}{M_s^2(T_{field})} = T_{lab}\frac{\ln^2 2C\tau_{lab}}{M_s^2(T_{lab})}$$

which assumes a log-normal grain size distribution of magnetite grains in a sample. Sets of nomographs following Walton's (1980) above equation been published by Middleton and Schmidt (1982). These nomographs, and those of Pullaiah (1975) are two of the more commonly used nomographs in the paleomagnetism community.

1.4.1 "Jumping" magnetic moments

Ferromagnetic mineral grains seek to minimize their total energy by changing their magnetic configurations (Tauxe, 2010). Within a single magnetic crystal, certain directions are at a lower energy than others, and the magnetic moment can switch from one "easy" direction to another. Doing so, however, requires overcoming the energy barriers that hold the direction of magnetic remanence in place.

When a mineral's moment is misaligned with an external magnetic field, the moment has additional energy, similar to the potential energy a mass has when placed in a gravitational field. The forces keeping the magnetic moment in place are the magnetocrystalline and shape anisotropy energies (Butler, 1992). If the external magnetic energy overcomes the resistant anisotropy energies, the moment will "jump" across the barrier, and align itself in a new, "easy" direction. The likelihood of this happening is defined by a minerals' relaxation time (tau), which is a measure of the probability that a grain will have sufficient thermal energy to overcome the anisotropy energies and switch its moment. Two ways to overcome the anisotropy energies are by applying a sufficiently large external field, or increasing the temperature of the mineral (Tauxe, 2010; Butler, 1992).

1.4.2 Multi-domain magnetite

TVRM as described by Neel (1949) theory applies to single-domain (SD) magnetite. Single domain particles have relatively low self-energies and are uniformly magnetized in one direction.

As magnetite crystal size increases past 80nm, the internal self-energy increases and a single direction of magnetization is no longer the lowest energy state. To reduce self-energy, large magnetite grains separate their magnetization into multiple magnetic domains in which several antiparallel moments are separated by domain walls (Figure 2). It is common for magnetite in rock to vary in grain size from nanometers, through ~80nm (pseudo-single domain, PSD), and greater than 200nm (multi-domain, MD) (Tauxe, 2010).

Due to multiple directions of magnetization in a crystal, as well as domain walls which accommodate some of the crystal's self energy, MD magnetite does not strictly behave within the confines of SD theory. Unblocking temperatures obtained from thermal demagnetization of MD magnetite are higher than SD magnetite theory predicts, making the TVRM acquisition period seem longer than it truly is (Dunlop et al., 1997). For this reason, rocks with remanence carried by MD magnetite are not optimal candidates for the TVRM dating method.

1.5 Testing the TVRM technique in granodiorite moraines

The TVRM dating technique has been used successfully to date basalt landslides (Smith and Verosub, 1994; Crider et al., 2010), emplacement of limestone blocks in archeological sites (Borrodaile and Almqvist, 2006), and regionally acquired TVRM in limestone (Kent, 1985). These studies obtained ages within an order of magnitude accuracy, with increased accuracy when calibrated to another event of known age. With the exception of Kent (1985), each study dated events younger than 20ka. In my study, I evaluate the application of TVRM dating to granodiorite boulders in events of ages 12ka -105ka, with the eventual goal of expanding applications further.

2.0 GEOLOGIC SETTING

The study area is in the Icicle Creek drainage basin, along the Eastern margin of the Cascade Mountain Range in central Washington State (Figure 3). The basin has experienced multiple pulses of glaciation in the past 200,000+ years. Glaciation has left its mark upon the landscape in the form of the classic "U-shaped" valley, as well as the deposition of till, outwash, and moraines. The moraines are comprised almost solely of granodiorite boulders from the southeast region of the Mount Stuart Batholith (MSB).

2.1 Moraine Sequence and Nomenclature

The glacial-geologic history of the basin has been studied since the early 1900's, with the first description of the moraines published by Page (1939). In his study, Page identified three distinct moraines that provided evidence for three successive Pleistocene glaciations, each of which was less extensive than the previous. In order from most to least extensive, he named the glacial deposits Peshastin, Leavenworth, and Mount Stuart. He described the Peshastin deposit as notably decayed, with till boulders representing less than 5% of the ground surface. Though mostly composed of granodiorite boulders, other rock types, such as schist, gneiss, serpentine, conglomerate, sandstone, and shale, were present in small amounts. He notes that some of the average-sized granodiorite boulders, 3 or 4 feet in diameter, are weathered to the core, and that all boulders show weathering to a depth of 3-8 inches below the surface. The Leavenworth deposit is identified as a well-preserved lateral moraine that runs several miles along Boundary Butte Ridge. It is 400 to 600 feet high, and Page describes the moraine as resembling "a railroad embankment of gigantic proportions." Boulders in this moraine usually cover 5-75% of the ground, and are much less weathered than Peshastin boulders. The youngest moraine Page identified was what he named the Stuart moraine. Moraines from this glaciation exist solely in the higher parts of the region, and one of the moraines at the mouth of Rat Creek is described as a "perfect horseshoe". Page reports that boulder composition and count are similar to Leavenworth deposits down valley.

A subsequent study by Porter (1969) renamed the three deposits previously identified by Page, and also recognized a fourth, older moraine in the region that he designated as Peshastin. Porter also subdivided the Leavenworth deposits into four separate substages, with Page's Rat Creek "Stuart" glaciation representing the youngest Leavenworth advance. Waitt (1977) proposed additional nomenclature changes of the two older moraines to Mountain Home and Boundary Butte, and further subdivided the Leavenworth deposits into five stages. See Table 2 for nomenclature history.

In Porter and Swanson's recent work (2008), eight distinct moraines were identified, and nomenclature was revised. The five Leavenworth stages proposed by Waitt were separated into two stages of Rat Creek moraines (previously Page's Stuart deposits) and two stages of Leavenworth moraines. Porter and Swanson revert back to the Peshastin nomenclature Page used for the prominent, yet highly weathered moraine, and retain Waitt's designation of Boundary Butte for the oldest moraine that lies upslope from it. They also identified two previously unrecognized lateral moraines between the Leavenworth and Peshastin deposits. One deposit can be traced discontinuously for 5km and nearly parallels the local Mountain Home Road; this has been designated the Mountain Home moraine. The second moraine has limited exposure, consisting of only two short lateral moraine segments that lie outside the Mountain Home moraine. Porter and Swanson propose that it could potentially be Peshastin-aged, but designate it as pre-Mountain Home.

2.2 Moraine Ages

Page (1939) and Porter (1969) compared Icicle Creek moraine deposition to global glaciations, and both speculated that Leavenworth deposits were late-Wisconsin in age. Porter further inferred that the Peshastin moraine was pre-Wisconsin, and that the intermediate deposit was early Wisconsin in age. Waitt (1977) estimated that the Leavenworth moraines are 11,500 to 18,000 years old, the Mountain Home moraine (Peshastin) is 130,000 to 140,000 years old, and the Boundary Butte moraine is 700,000 to 850,000 years old based on theoretical weathering rates of boulders. Waitt et al.. (1982) trace the Galcier Peak tephra layer (Porter, 1978) to the outer edge of cirque glaciers above the Rat Creek moraines. This implies that the Rat Creek

advance must be older than 11,000 to 11,300 14C years, which is the age of the tephra (Foit et al., 1993), and Wait et al. (1982) conclude the Rat Creek advance took place between 11,000 and 13,000 years ago.

Perhaps the greatest step forward in establishing numerical ages for the local pulses of glaciation was work by Porter and Swanson (2008) which utilized ^{36}Cl cosmogenic nuclide dating to calculate surface exposure ages for the moraines. Chlorine-36 is produced in rocks in the top meter of the lithosphere through cosmic-ray-induced reactions with natural ^{35}Cl, ^{39}K, and ^{40}Ca present in the rocks. These reactions and the subsequent accumulation occur at a known rate but vary based on latitude, elevation, angle of incidence to the sun, and snow cover (Zreda et al., 1991). By calibrating Icicle Creek isotope production rates with samples from the Puget Sound region at the same latitude (Swanson and Caffee, 2001), Porter and Swanson (2008) were able to date the Icicle Creek moraines quantitatively using the cosmogenic dating method as applied to ^{36}Cl.

Though average surface exposure ages were calculated for each moraine, Porter and Swanson concluded that the true age of an individual Icicle Creek moraine is more likely represented by the age of the oldest boulder that is not a statistical outlier (Putkonen and Swanson, 2003). As the moraine weathers, boulders are gradually exhumed and start accumulating cosmogenic isotopes at different times. Hence, excluding statistical outliers, the oldest cosmogenic age would belong to a boulder that did not have prior inheritance and was near the top of the moraine crest. Both mean cosmogenic ages and oldest cosmogenic age from the Porter and Swanson study are summarized in Table 3.

2.3 Moraine recognition and testing conventions for this study

For this study I accept the oldest moraine ages provided by Porter and Swanson to be most accurate and adopt the nomenclature from their 2008 study. I test the TVRM dating technique by comparing our age results to those published ages. Because of the close ages of Rat Creek I to Rat Creek II, as well as Leavenworth I to Leavenworth II, I do not expect to distinguish between those pairs of ages. I also did not sample pre-Mountain Home deposits because of their close

age-accordance with the Peshastin deposits. Porter and Swanson had difficulty dating the Boundary Butte deposits because of extreme weathering and boulder degradation. In the field, I was unable to locate any boulders competent enough from which to obtain samples, and therefore excluded the Boundary Butte age from this study. By combining or not testing certain moraines, I limit this study to test four distinct ages: Rat Creek II (13.5ka), Leavenworth II (17ka), Mountain Home (72.2ka), and Peshastin (112.8ka).

3.0 PALEOMAGNETISM STUDIES OF THE MOUNT STUART BATHOLITH

The bedrock of this area, from which the moraine boulders are derived, is the Mount Stuart Batholith (MSB). A granodioritic pluton of Cretaceous age, the origins of the batholith remain controversial. Two primary competing hypotheses exist that attempt to explain its history over the last 90Ma. Beck and Noson (1972) were among the first to study the paleomagnetic properties of the MSB, and they reported highly discordant paleomagnetic directions from current magnetic North in batholith rocks and other Cretaceous rocks of the North American Cordillera. These results gave rise the "Baja British Columbia" (Baja-BC) hypothesis (Irving, 1985; Umfoeher, 1987; Cowan et al., 1997; Housen and Beck, 1999) which proposes that the Insular Superterrane (including the MSB) formed 90 to 95Ma at a location 3000km south of its present location. Subsequent northward translation along the continental margin between 85 and 55Ma resulted in the terrane's present location and discordant paleomagnetic direction. Some workers reject the possibility of thousands of kilometers of translation, and instead prefer tectonic reconstructions that limit latitudinal displacement of these terranes (Mahoney et al., 1999). Recent sedimentary studies both support (Krijgsman and Tauxe, 2006), and disagree (Kim and Kodama, 2004) with the Baja-BC hypothesis.

Though the Baja-BC hypothesis has been subjected to logically crucial tests (Cowan et al., 1997; Mahoney et al., 1999; Housen and Beck, 1999) to evaluate geologic possibility, the basis for the hypothesis relies largely on paleomagnetic evidence from the terranes. Because of heavy reliance on the paleomagnetic data, Housen et al.. (2003) compiled existing paleomagnetic data and collected additional data from new sites in order to review the part that the Mount Stuart batholith played in the Baja BC controversy. Their reevaluation of the MSB confirms prior paleomagnetic findings in that paleomagnetic directions are highly discordant, and also supports the Baja BC hypothesis.

Central to finding these paleomagnetic directions is understanding how magnetic remanence is carried and recorded in the host rock, with different minerals showing different characteristics during demagnetization. Initial paleomagnetism work in the MSB by Beck and Noson (1972), and Beck et al. (1981) used alternating field (AF) demagnetization to show that magnetite is the

magnetic carrier of remanence in much of the batholith. Conversely, Paterson et al. (1994) concluded that the remanence of the batholith was carried by pyrrhotite, since 23 of their 27 sites showed low unblocking temperatures (<400^{o}C) and relatively high coercivities. Despite this claim, they concede that in all of their pyrrhotite-dominated samples, there is evidence in blocking temperatures and coercivity to suggest small amounts of magnetite and hematite. Their remaining four sites carry a strong, stable, remanent magnetization in magnetite.

In light of these findings, Housen et al. (2003) employed an additional test described by Lowrie (1990) using multi-component isothermal remanent magnetization (mIRM) to determine the magnetic mineralogy of the MSB samples. The primary difference between the minerals is their thermal unblocking temperatures and coercivities. Single domain (SD) pyrrhotite has an unblocking temperature of 320^{o}C and moderate coercivities (between 0.4 and 1.0 T), while SD magnetite has an unblocking temperature of 580^{o}C and relatively low (<0.3 T) coercivities. Hematite has unblocking temperatures of 670^{o}C and high (>1.0 T) coercivities.

Housen et al. (2003) performed mIRM analysis on both their newly collected samples, and 9 other samples from Beck et al. (1981). Results from the experiments revealed that all three magnetic carriers were present in different rocks of the MSB. Most of the sites showing well-grouped, well-behaved magnetizations showed that remanence was carried by a low coercivity (H < 0.1 T) mineral which unblocked between 540 and 580. These properties are diagnostic of single-domain magnetite. Spatially, this is the dominant remanence carrier in the Southern part of the batholith. Figure 4 shows the mapped extents of the batholith, as well as nearby geology. Also plotted are sample locations from previous studies and information on the magnetic carriers (pyrrhotite or magnetite) of those samples. Hematite was found in three sites, where it displayed high coercivities (H > 0.4 T) and did not reach its unblocking temperatures when thermally demagnetized. Only one site distinctly shows low (270-320) unblocking temperatures, which indicates the presence of pyrrhotite. Other sites from the Housen et al. (2003) study show poorly defined demagnetization behaviors with low unblocking temperatures, again indicating pyrrhotite as the remanence carrier. This carrier was found to be spatially restricted to dikes and areas within 1km of the edge of the batholith. Housen et al. (2003) conclude that the remanence of the majority of their MSB sites, along with 10 of 11 of the MSB sites from Beck et al. (1981),

are carried solely by magnetite. From the results of their laboratory tests, they further classify the magnetic carrier as single-domain magnetite.

Housen et al. (2003) explain the discordance between their results and Paterson et al.'s (1994) as a result of several possible factors. First, Paterson et al. define the presence of pyrrhotite based on laboratory unblocking temperatures of <400^{o}C and high coercivities when subjected to A.F. demagnetization. However, pyrrhotite's unblocking temperature is between 320^{o}C and 350^{o}C, and all of Housen et al.'s pyrrhotite-bearing rocks showed demagnetization between those temperatures. If a remanence persisted until 400^{o}C, there was likely another remanence carrier present, such as hematite or magnetite, which altered the samples' overall unblocking temperature. Paterson et al. admit to the possibility in their published work. Additionally, Paterson et al. performed electron microprobe analysis of their samples and reported seeing pyrrhotite, but no magnetite. On the contrary, Housen et al. find abundant amounts of SD magnetite via paleomagnetic means. They further note that in felsic and intermediate plutonic rocks, original and well-defined remanence is typically carried by very small, nanometer-scale inclusions of SD magnetite within feldspars and Fe-silicates (Dunlop and Ozdemir; 1997). These points lead Housen et al. to believe that the reported pyrrhotite occurrences by Paterson et al. (1994) are suspect.

I am inclined to believe Housen et al.'s (2003) conclusion that the primary magnetic remanence carrier in the batholith is SD magnetite. Their detailed mIRM, AF demagnetization, and thermal demagnetization work all support that their samples, in addition to previously collected samples, have abundant magnetite that is recording the original thermal remanence the batholith acquired upon cooling. Although Housen et al. do identify pyrrhotite as the remanence carrier for some samples in the batholith, these sites are restricted to the northern end of the batholith, as well as sites within 1km of the batholiths' edges. Conversely, remanence in the southern part of the batholith is carried almost solely by SD magnetite. As this is the source region for boulders comprising the Icicle Creek moraines, I infer that SD magnetite is the remanence carrier in the moraine boulders in our study.

4.0 METHODS

4.1 Field Sampling

Boulders from four moraines - Rat Creek, Leavenworth I, Mountain Home, and Peshastin- were sampled in order to determine if the TVRM dating method could succeed in obtaining accurate and distinguishable ages in events over a range of 100ka. Large boulders (2m-10m diameter) along moraine crests are the least likely to be displaced after initial deposition, as the energy required to displace them is much higher than for smaller boulders. Therefore, these boulders should have the most distinct turning point upon demagnetization. I sampled 3-10 boulders along the crest of each of the four moraines; moraine crest locations are shown in Figure 5A. Sample locations along moraine crests are shown in Figure 5B and 5C. In about 50% of these boulders I drilled two or more cores. Of these cores, some were sufficiently long for subdivision into multiple specimens. Table 4 summarizes the number of boulders, cores, and specimens per moraine.

No boulders competent enough to sample were found in the Boundary Butte moraine. The next oldest moraine, Peshastin, was marked by 3-meter or larger diameter boulders every 5-20 meters. A quarter of the boulders investigated produced cores which crumbled upon sampling. Mountain Home boulders had a similar rate of core deterioration, though boulders were much less common than in the Peshastin moraine, with one every 20-30 meters. Both Leavenworth and Rat Creek moraines were comprised of continuous, competent boulders. For these moraines, I predominately sampled the largest boulders nearest the moraine crest that were somewhat embedded in the moraine soil. Ease of access also determined which boulders were sampled.

Multiple boulders were sampled per moraine in order to assess variability due to NRM direction and rock texture. Sampling numerous boulders also allowed us to dismiss samples not showing both TVRM and TRM components. A boulder may not show both components upon demagnetization if it has been remagnetized by lightning strike, or if its NRM was aligned with magnetic north when emplaced in the moraine. Another concern in this study was that different sides of a boulder could experience different temperatures due to different solar incident angles. This could potentially cause sides to register different unblocking temperatures and therefore

record multiple ages within the same boulder. To address this, I collected multiple cores from different sides of the same boulder for 50% of the boulders. All cores were cut into 2.2cm specimens, with some cores long enough to divide into 2 subspecimens. Testing multiple specimens from the same core allows evaluation of the precision and repeatability of the technique. Sampling locations, obtained from GPS waypoints, are plotted in Figure 6.

I used a gas-powered core drill to obtain samples and oriented them in the field using a magnetic compass. For strongly magnetic rocks it is sometimes customary to use a sun compass to verify magnetic compass readings. Housen et al. (2003) found that all sun compass declinations in the Mount Stuart Batholith were within a degree of the magnetic compass declinations. I therefore opted not to use a sun compass in this study. Samples were stored in a cool, dark place to minimize acquisition of a new TVRM component until they were ready for lab preparation. No more than two weeks were allowed to pass before sample processing. A rock saw was used to cut samples into 2.2cm specimens, and subsamples were created from any core longer than 4.4cm. After sample preparation, the cores were stored in a room-temperature, field-free room for the remainder of the study.

4.2 Laboratory Methods

I first measured the magnetic anisotropy of each sample with a Kappa Bridge susceptometer to determine if boulder remanence is influenced by the crystalline fabric of a rock. A strong fabric could potentially cause large anisotropic energy barriers within the rock, therefore requiring an inordinate amount of thermal energy to overcome the barriers for the moment to "jump." This could dampen the TVRM signal, or prevent TVRM acquisition entirely. Initial remanent magnetization of all samples was measured within a field-free room at room temperature (20^{o}C) using a cryogenic magnetometer, a machine capable of measuring very small magnetic variations in rocks by using supercooled liquid helium. The majority of samples were then treated with liquid nitrogen in low temperature demagnetization (LTD) cycles (Dunlop et al., 1997; Housen et al. 2003) until no significant changes were observed in the measured remanence.

The samples were thermally demagnetized in discrete temperature steps of 5°C to 20°C from 50°C to 250°C. From 250°C to 450°C, I used larger and varied gaps between discrete steps. At each step, oven temperature was held constant for 30 minutes. After cooling for 10-15 minutes, remanent magnetization was measured in a 2-G 755 DC-SQUID magnetometer. At higher temperatures (>330°C), some samples started to crumble and show signs of internal fracturing. To prevent granular disintegration, select samples were immersed in a clear, non-magnetic, ceramic hardener for two to five minutes. Oven temperature over the course of heating was monitored and logged to increase accuracy. Although there is digital display of oven temperature, accuracy of these monitors was confirmed by the use of non-reversible temperature labels. These labels are a one-time usage indication that a specified temperature has been exceeded, and are useful in a situation where an operator does not have access to the label during a test. These labels retain the record of temperature reached even after heating is over. The temperature labels were placed on samples in different zones of the oven (far left, center, far right) to measure the temperature gradient within the oven and to observe discrepancies between the temperature at the surface of the rock samples and oven sensor temperatures.

With the exception of the LTD treatment, the above steps are standard paleomagnetism techniques in thermal demagnetization (Neel, 1949; Butler, 1992, Housen, 2003). In this study, I additionally employed LTD to reduce the contributions of multi-domain (MD) magnetite grains to our results. Intermediate to felsic plutons, like the Mount Stuart Batholith, are commonly coarse grained, and thus likely contain large, MD magnetite grains (> 200 nm). Dunlop et al. (1997) observed anomalously high unblocking temperatures distributed over a wide range (>250°C) in rocks containing MD magnetite. Both the average and maximum unblocking temperatures in this range were much higher than expected when compared to single-domain Neel (1949) theory. These high unblocking temperatures resulted in the TVRM acquisition event to appear older than it actually was. Additionally, the TVRM recorded by MD grains, even if acquired at low temperatures, can have laboratory unblocking temperatures of up to the Curie temperature of magnetite (580°C) (Dunlop and Xu, 1994).

Although Housen et al. (2003) determined SD magnetite to be the primary carrier of remanence in the Southern end of the MSB, I cannot assume that MD grains are absent from the samples

due to the nature of the bedrock being a coarse-grained, felsic pluton. Because the TVRM dating technique relies on identifying the precise unblocking temperature of the TVRM component, the large range of unblocking temperatures resulting from the presence of MD magnetite could reduce precision and accuracy of ages obtained using this method. Misidentification of the unblocking temperature by even 5^{o}C results in a 20-40% error in age. If MD magnetite is found to dominate the samples, the Middleton and Schmidt (1982) nomographs should be used rather than nomographs generated by Pullaiah et al. (1975).

To reduce the contribution and overprint of MD magnetite to a sample's "true" remanence, I employed low temperature demagnetization (LTD) so as to erase MD remanence and isolate SD remanence. After I measured initial remanent magnetization at room temperature, I immersed approximately 90% of the samples in liquid nitrogen (T = 77K) in a non-magnetic container. After 20 minutes of immersion, the samples were extracted and allowed to rewarm to room temperature in a field-free room for 10-20 minutes. Magnetization of each sample was measured again. Samples that experienced a great change in magnetic moment after LTD treatment were treated in liquid nitrogen again until remanence changed by less than 5% between subsequent measurements.

The physical basis for the LTD treatment is described at length by Dunlop and Ozdemir (1997) and Housen et al. (2003). At a temperature of 120K, magnetite undergoes a phase transition from cubic structure to monoclinic structure. The changes in magnetite's magnetic and electrical properties as it passes through this temperature are referred to as the Verwey transition (Verwey, 1939). Thermally cycling a rock between the Verwey temperature and room temperature in a field-free room has a different effect on the remanence carried by single- versus multi-domain magnetite. While single domain grains retain a near perfect memory of their original room temperature remanence, larger, multi-domain grains lose a significant portion of their remanence. The MD magnetite is thought to demagnetize by unpinning domain walls, caused by internal crystal defects, within an individual grain (Dunlop and Ozdemir, 1997; Tauxe, 2010). For a sample containing both single- and multi-domain magnetite grains, LTD cycling will preferentially erase the remanence carried by MD grains and leave SD grains' remanence unaffected (Dunlop et al., 1997; Housen et al., 2003). The LTD treatment has been used in past

studies (Housen et al., 2003; Warnock et al., 2000; Borrodaile and Almqvist, 2006) to isolate and erase the remanence carried by MD magnetite, and leave the more stable, SD remanent magnetization intact to be measured. In particular, Dunlop et al. (1997) found that pretreating their MD-containing samples with the LTD treatment resulted in unblocking temperatures that matched the temperatures predicted by Pullaiah et al.'s model (1975). It is worth noting that remanence carried by MD magnetite could possibly be stabilized by unknown mechanisms unaffected by the LTD treatment.

The 2-G 755 DC-SQUID magnetometer measures and records a sample's magnetism at each temperature step. The output of these measurements is a set of x, y, z, coordinates that can be translated into polar coordinates of inclination and declination. All of the temperature step measurements from a single sample were then plotted on the same Zijderveld diagram to observe changes in magnetic direction and intensity with progressive thermal demagnetization (Figure 1).

I utilized further tests to determine magnetic mineralogy of my samples. I placed rocks chips from unheated subsamples in a Vibrating Sample Magnetometer (VSM) to obtain hysteresis curves, isothermal remanent magnetization (IRM) curves, and direct current demagnetization (DCD) measurements. Some samples' signals were overshadowed by the paramagnetic behavior of biotite. To remove this signal from the samples, I crushed four samples, each displaying a different hysteresis behavior, and separated the quartz and plagioclase from the biotite. The crushed felsics (particles <1 mm) were placed in gel capsules, packed with non-magnetic baking soda to reduce movement, and then measured in the VSM. From both whole chips and crushed samples I obtained the following magnetic properties: saturation remanence (Mr), saturation magnetization (Ms), coercivity of remanence (Hcr), and coercivity (Hc). Each samples' parameters were plotted on Day plots to distinguish between single, pseudo-single, and multi domain magnetite.

5.0 RESULTS

Less than half of the samples subjected to thermal demagnetization showed a TVRM component, and instead, several other behaviors became apparent. In this section I will first discuss sample petrologic characteristics and the demagnetization behaviors prevalent in the samples. The homogeneity of demagnetization behavior between samples from the same boulder and moraine will also be discussed.

Also critical in this study is choosing a turning point temperature from the Zijderveld plot. I will comment on how I chose turning points for the samples and how turning points from different moraines compare to one another.

5.1 Petrologic Characteristics

Visually, boulder petrologic properties varied between two end member appearances. Samples on one end of the visual spectrum consisted of ~40% mafics, had a grain size of 2mm, and minerals were aligned in a noticeable fabric (texture A). Samples from the other end of the spectrum had ~20% mafics, 4mm grain diameters, and no preferential alignment (texture B) (Figure 6). Texture A dominated boulders from the Rat Creek moraine, with approximately 60%-70% of boulders having this texture. The remaining 30%-40% of boulders displayed properties that varied between the two end member textures. Few boulders from the Leavenworth moraine displayed either end member texture, and most boulders were instead composed of an intermediate texture; ~30% mafics, 3mm grain size, and a slight to no noticeable mineral alignment. The Mountain Home boulders all consisted of texture B. A single Peshastin boulder showed texture A, while the other four boulders from the same moraine showed texture B.

Another noticeable characteristic of boulders was the degree of surficial weathering each had experienced. The amount of weathering varied not only between different moraines, but also between boulders within the same moraine. I use the weathering classification proposed by

Brown (1981; Table 5) to categorize the amount of weathering seen in each boulder. Each of the two younger moraines, Rat Creek and Leavenworth, had approximately 50% of their boulders fall into Class I (Fresh rock; no visible signs of weathering) and 50% into Class II (Slightly weathered rock; discoloration). Boulders from the two older moraines varied between half in Class II and the other half in Class III (Moderately weathered rock; rock material decomposing). The oldest moraine in the Icicle Creek region, Boundary Butte, consisted of Class V material, or completely weathered rock, in which all rock material is decomposed to soil. For this reason I was unable to obtain competent samples from this moraine. Boulder petrologic characteristics and weathering amounts are summarized in Table 6.

5.2 Characteristic Demagnetization Behaviors

Single-domain magnetite theory predicts thermal demagnetization to produce demagnetization plots in which a sample's TVRM and TRM are two distinct components distinguishable by a change of direction. This change of direction theoretically occurs at a specific numerical temperature which can then be correlated to age, thereby dating time since displacement.

In my study, however, less than half of the specimens displayed this expected sharp turning point. Plotting of specimen's magnetization on Zjiderveld diagrams yielded several characteristic demagnetization trends. I assign the following classification nomenclature to these behaviors, examples of which are shown in Figure 7. A summary of demagnetization behaviors by moraine is in Table 7.

Approximately 26% of samples show the expected TRM and TVRM turning point relationship. I designate this behavior as "two-component". It is characterized by two vector components in either (or both) the inclination or declination demagnetization paths on the Zjiderveld diagrams. Excluding the low-temperature liquid nitrogen treatment points (all steps below 80^{o}C), the TVRM consists of several points making up a line that increase away from the origin. At some temperature, there is an abrupt change and the points begin marching towards the origin. This component is assumed to be the TRM. The temperature that divides these two behaviors is the turning point that we can equate to the rock's time since displacement.

Another 44% of samples were given the designation of "cluster". When subjected to thermal demagnetization, there was no appreciable change in magnitude, declination, or inclination of the magnetic moment with progressive thermal heating. Most of these specimens showed a constant moment from room temperature measurements up to as high as 480^{o}C. Immersion in liquid nitrogen seemed to have little effect on preventing this behavior, as there were both treated and non-treated samples that displayed clustering behavior.

Two samples displayed the behavior called "fluctuating". Samples exhibiting this behavior appeared to demagnetize with progressive heating, but at some higher temperature, usually greater than 250^{o}C, the demagnetization paths begin fluctuating wildly in both magnitude and direction. This behavior only occurred in samples with very small magnetic moments (< 1 μemu).

Samples with "linear" behavior display a single vector component decaying linearly towards the origin. Loss in moment magnitude is loosely proportional to temperature, with the sample losing an equal percentage of moment between equally spaced temperature steps. Approximately 26% display "linear" behavior.

The last defined behavior is the "curving" turning point behavior, exhibited by 2 samples. This behavior is characterized by two vector components separated by a diffuse turning point. The initial component is usually demagnetizing in a direction away from the origin, suggesting that this component is the TVRM. Upon turning, the second component appears to be demagnetizing towards the origin, implying that this is the TRM. Unlike the desired "two-component" behavior, the diffuse turning relationship between the two components in this example obscures my ability to definitively select a precise turning point temperature. At best, I can constrain the turning point in the samples to occurring somewhere within the curve; between 225^{o}C and 275^{o}C for both samples.

5.3 Specimen, Core, Boulder Homogeneity

Though only nine or fewer boulders were sampled from each moraine, three times that number of specimens were tested by collecting multiple cores per boulder and subdividing some cores into multiple specimens. Multiple boulders were sampled per moraine in order to assess variability due to NRM direction and rock texture. For some boulders, several cores per boulder were collected to determine if different sides of the same boulder behaved differently or registered different turning point temperatures. Multiple specimens from the same core were tested to evaluate the precision and repeatability of the technique.

Specimens from the same core: In general, specimens from the same core do display similar thermal demagnetization behaviors. If one specimen from a core displays clustering behavior, there is a strong likelihood of the other specimen from the same core showing clustering behavior as well. In the case that the second specimen doesn't show what is classified as "clustering" behavior, there is almost always still a component of clustering, but an additional, stronger appearance of linear or two-component behavior. Two specimens from the same core tend to have similar magnetization vector directions, and moment strengths within an order of magnitude of one another.

Cores from the same boulder: Compared to specimens within the same core, there is increased variability in the type of remanent magnetization behavior between cores of the same boulder. Of boulders from which multiple cores were collected, approximately 40% have multiple cores that exhibit similar behaviors. Another 40% of boulders' cores have distinct similarities to each other, but vary enough to be sorted into different behavior classifications. Approximately 20% of the boulders have multiple cores displaying significant variance.

Boulders from the same moraine: In general, there are no major demagnetization trends/similarities between boulders within the same moraine. All of the moraines have a mix of demagnetization behaviors present in their specimens: there is no single dominant behavior in any specific moraine. There are perhaps slight trends present: Rat Creek and Leavenworth have more clustering samples than the older two moraines. These two moraines also have no

fluctuating or curving specimens. The Mountain Home and Peshastin moraines, while still containing specimens that cluster, have proportionally fewer clustering specimens, and the fluctuating and curving behaviors appear.

5.4 Choosing a Turning Point Temperature

Turning points were identified by visual inspection of the Zijderveld plots. To check the objectivity of turning-point selection, plots were also reviewed by an unbiased observer not connected to this study.

Some of the specimens that display two components of magnetization, a supposed TVRM and TRM, have "distinct" turning points, where there are two visible vector components in either the inclination or declination plots. There is an obvious temperature point at which these two components meet. The demagnetization path of the specimen shows an abrupt and clear change in direction, indicative of the ideal TVRM/TRM behavior that single domain magnetite theory predicts.

The other populations of specimens that display two- components have less obvious turning points. Rather than a demagnetization trail with a sharp change in direction over a short temperature interval, most specimens show an initial vector (the TVRM) gaining in moment magnitude away from the origin. At some temperature, the demagnetization plot begins to cluster, with subsequent temperature steps remaining nearly constant in both magnitude and direction. At some higher temperature, the demagnetization plot "breaks free" from the cluster and begins losing its moment magnitude in the direction of the origin. This indicates the TRM component, which theoretically would reach the origin, or zero moment, once the NRM is totally erased. Though it is apparent that there are two magnetic directions in these specimens, it is difficult at first glance to pinpoint an "exact" temperature at which the TVRM is erased and the TRM starts.

There are a few possible ways to retrieve turning point data from these specimens. One method is to identify either the last temperature before the clustering behavior begins or the last

temperature point of the cluster as the turning point temperature. This approach results in discordant turning point temperatures between samples with "distinct" turning points and samples with "cluster" turning points. For example, a specimen in the Leavenworth moraine shows a distinct turning point at 230°C. Most other specimens in the moraine show clustering turning points over the temperature range 160°C - 230°C.

An alternate approach to identifying the turning point temperature is to choose the median temperature within the cluster as the turning point. I decided to pick turning point temperatures using this approach. For a group of specimens in the same moraine, choosing the temperature point at the middle of the cluster results in lower standard deviations and fewer outliers than picking the temperature of either the start or end of the cluster. To determine the cluster's middle point, an unbiased outsider to this research was asked to view the demagnetization plots for all the specimens. The outsider toggled the temperature step points on and off within the CT Analysis software, allowing him to view specific points and, without external influence, to pinpoint where clustering began and ended for each specimen. After the cluster's beginning and end point temperatures were identified, the outsider selected a measured temperature point closest to the middle of the cluster range. For example, a specimen shows a cluster turning point with the cluster end points at 160°C and 230°C. The middle of this range is 195°C, but without a measurement on that precise temperature step I chose the next closest, measured point. For this sample, that is 197°C.

In addition to being statistically preferable, choosing the middle of the cluster also makes some intuitive sense. While the "distinct" turning point samples display a sharp transition between TVRM and TRM, the clustering turning point samples could be thought of as undergoing a more gradual transition from TVRM to TRM. The rate of change in moment direction from TVRM to TRM may slow as the specimen approaches the turning point, much like a sine curve approaching a local maximum. Another possible interpretation is that the two components of magnetization are retained by separate populations of minerals within the sample that have distinct, non-overlapping unblocking temperatures.

A few samples showed two turning points, indicating more than one TVRM component. This could occur if the boulder was displaced recently relative to when it was originally emplaced in the moraine. By moving post-depositionally, a rock's minerals are once again misaligned with magnetic north and weak moments begin flipping to align themselves. For specimen with two turning point temperatures to choose from, I chose the highest temperature, as that most likely represents the initial displacement, and therefore moraine emplacement.

5.5 Oven Temperature Gradient

Digital displays showed oven temperatures in the outer oven, as well as inside the oven at both the outer end and in the middle of the sample zone. To determine the accuracy of the displays and to confirm the possibility of a temperature gradient within the oven I placed irreversible, self-adhesive temperature stickers on select samples. The stickers consist of five to ten heat-sensitive indicators sealed under transparent, heat-resistant windows. The centers of the indicator circles turn black at the temperature ratings shown on the label. The change to black is irreversible and registers the temperature history of the sample in the oven.

Each sample "boat" contained between 10 and 20 core samples, spread over its length of about 18 inches. For most boats, temperature indicator stickers were placed on the far left and right samples, as well as the centermost sample. Sample locations in the boats were kept constant throughout the entire demagnetization process so that temperature correction factors could be applied, if deemed necessary.

At lower temperatures, $< 200^{o}C$, I measured a temperature gradient within the oven of about 10 to $20^{o}C$. Figure 8B shows over temperature gradients across the oven for three separate boats over three different temperatures. The boat showing a digital display of $160^{o}C$ resulted in a measured temperature of $166^{o}C$ at the left end, $160^{o}C$ in the middle of the boat, and $154^{o}C$ at the right end. As temperature increases with subsequent steps, the measured temperature increases past the digital read-out, and the variation in temperature across the boat also increases.

At higher temperatures, above 200°C, I noticed that the gradient across the boat was becoming large, in excess of 20°C. To more accurately account for the gradient, I placed up to six temperature indicator stickers on samples in certain boats, and continued placing three in other boats. Figure 8A shows temperature gradients within the oven for three additional boats at temperature steps above 200°C. In each case, there is a steep gradient from the left end of the boat to the middle, and a shallower gradient from the middle to the right end of the boat. This trend might have been apparent at lower temperatures too if more than three stickers had been placed in each boat. It is obvious that turning point temperatures from samples on the far left must be corrected prior to using in analysis. Samples near the middle of the boat likely experienced the "true" digital display temperature, and samples near the right end of the boat appear to have registered lower temperatures than the display.

5.5.1 Correcting Turning Point Temperatures Due to Oven Gradient

Temperature gradients within the oven are quite large, in excess of 30°C, at temperature steps above 200°C. To achieve a reliable TVRM age, it is necessary to adjust the turning point temperatures to account for the oven temperature gradient. To do this, I observed the temperature stickers and thus the temperature gradient within each boat for a given temperature step. For most samples with a turning point I had some record of the actual oven temperatures, and was thus able to add or subtract between 5 and 20 degrees for each sample based on its position within the boat and the oven gradient for that particular temperature step. For samples without a measured gradient, I used observed gradients from similar temperature steps to apply a correction. Typically, adjustments for samples near the right side of the boat were small, and I increased the turning point temperature by 5°C. Samples on the far left end of the boat were reduced by 20°C to 10°C, depending on the temperature step.

5.6 Turning Point Temperature Statistics

For each moraine's set of turning point temperatures, I calculated and graphed a suite of statistics that includes the mean, standard deviations and maximum/minimum turning point temperatures.

Results are summarized in Table 8. Data sets for moraines were limited to approximately 5 or 6 turning point values.

In general, the raw, unfiltered results match what is predicted by TVRM theory: older moraines tend to have higher turning point temperatures. Though the youngest moraine, Rat Creek, has higher turning point temperatures than the Leavenworth moraines, the Leavenworth, Mountain Home, and Peshastin moraine sequence follows the expected trend of older moraines having higher temperatures. Rat Creek also has lower turning point temperatures than the two oldest moraines. Additional discussion of turning point temperature results will be presented in Section 6, Analysis.

5.7 Hysteresis Loops

One method of determining the mineral carrying the magnetic remanence within a rock specimen is to obtain the specimen's magnetic parameters from hystereis loop data. The ratio of these parameters to each other (Hcr/Hr vs. Mr/Mr) can provide insight into the magnetic remanence carrier.

Hysteresis loops are obtained by subjecting a specimen to an increasing magnetic field and are the sum of all the contributing magnetic particles in a rock specimen. For an ideal specimen dominated by single-domain magnetite, an increasing field will gradually flip the single domain grains into the direction of the applied field. If the flipping condition is not met (external energy < internal crystal lattice energy), then the magnetization will return to its original direction when the external field is removed. If the flipping condition is met (external energy > internal crystal lattice energy), the magnetization will be in the opposite direction upon removal of the magnetic field. Loops are generated by subjecting a specimen first to a very strong positive field, and then gradually decreasing th field until it is very strong in the opposite direction. The process is then repeated, changing the field from negative to positive.

Different minerals, such as hematite, biotite, and magnetite SD/MD react differently to the alternating external fields. The differences are primarily caused by the mineral's ability to hold

remanent magnetization, or their memory of the field that has been applied to them in the past. Thus, some minerals have characteristic/unique hysteresis loop shapes. By visually observing hysteresis loops from the Icicle Creek moraines, as well as graphing the ratio of their resulting magnetic parameters, I can gain insight into the magnetic carriers within my samples.

The characteristic hysteresis loops found in this study are shown in Figure 9. A straight diagonal line with a slope of 1 (Figure 9A) is indicative of a specimen dominated by paramagnetic behavior. A paramagnetic mineral, like biotite, hold no remanence. Thus, it only holds a magnetization in the presence of an external field, and when the field is removed, the specimen loses its magnetization. The strength of the remanence carried is proportional to the external field (stronger field, stronger apparent mineral magnetization).

Many samples' hysteresis loops show this behavior, which is not surprising given that biotite is visually abundant in the MSB granodiorite. The slight "jog" in the hysteresis loop near the origin is evidence of another magnetic carrier (one that actually holds remanence) in the sample. Biotite itself does not hold a true remanence: it merely overpowers the signal of the actual remanence carrier.

To gain insight into the true magnetic remanence carrier in the rocks, I crushed the specimens and manually separated the felsic minerals (plagioclase and quartz), from the biotite. It is assumed that the microscopic magnetite minerals are inclusions within the felsics (Dunop and Ozdemir, 1997). I then placed the powdered felsic minerals in a gel capsule, and ran the specimen on the vibrating sample magnetometer to generate its hysteresis loop. Adjustments were made in order to correct for grain vibration in the gel capsule, as well as to account for the background magnetization of the capsule itself. The hysteresis loops for a crushed Leavenworth sample and crushed Rat Creek sample are shown in Figure 9B and 9C, respectively.

The Leavenworth loop is characteristic of a specimen whose remanence carrier is single-domain magnetite with uniaxial anisotropy, indicating that SD magnetite could be the magnetic carrier within this particular specimen. Although the Rat Creek hysteresis loop appears to have a similar shape to the Leavenworth sample, the narrower curve (the result of a lower M_r/M_s ratio)

is indicative of lower magnetic stability. This hysteresis behavior is indicative of pseudo-single domain magnetite. Both Rat Creek specimens for which I ran hysteresis experiments showed this PSD behavior, as did the two Peshastin specimen. Leavenworth specimens, on which I performed the most tests, showed a mixture of PSD and SD behavior. I did not perform hysteresis experiments on any Mountain Home specimens.

5.8 Day Plot Results

While hysteresis loops can shed light into the remanence carrier and/or domain state, they provide additional useful information by way of the parameters M_r, M_s, and H_{cr}. These parameters, combined with the parameter, H_c, obtained from additional magnetic tests, allow us to plot the ratios of saturation remanence to saturation magnetization (M_r/M_s) against the ratio of coercivity of remanence to coercivity (H_{cr}/H_c), on Day Plots, sometimes referred to as Day diagrams.

A graph of these ratios was proposed by Day et al. (1977), and further developed by Parry (1982), as a method of identifying magnetite domain state (single-domain, SD; pseudo-single-domain, PSD; multidomain, MD), and, by implication, grain size. Theoretical calculations and actual results allowed Day to place quasi-theoretical boundaries on the Mr/Ms vs Hcr/Hc plot, thereby allowing us to plot the ratio of these parameters for any specimen and, at a glimpse, determine the domain state of the magnetite within a specimen. The Day plot is one of the principal ways paleomagnetists determine domain state and grain size (Tauxe, 2010; Butler, 1992). The Day diagram is divided nominally into regions of SD, PSD, and MD magnetite. It is generally accepted that any specimen with a Mr/Ms value of >0.5 contains SD magnetite, and <0.05 contains MD magnetite. Pseudo-single domain magnetite lies between these two regions and in practice, most geologic materials plot in this zone (Day et al., 1977; Dunlop, 2002).

Using hysteresis loops and other magnetic tests, I obtained the magnetic ratio parameters for numerous specimens and plotted them on a Day plot (Figure 10). Specimens are plotted by both moraine and specimen type (bulk or powdered). Most of the tests were performed on bulk specimens of the Leavenworth moraine. Two tests each were run on powdered specimens from

the Leavenworth, Rat Creek, and Peshastin moraines. Most specimens plotted in the PSD magnetite zone, though there were a small handful that plotted in the MD zone. In general, the powdered specimens had higher Mr/Ms ratios, indicating a stronger similarity to SD magnetite properties. The sample LW09B2A in particular has a Mr/Ms ratio of almost 0.5. Its hysteresis loop is plotted in Figure 9B, and shows characteristic SD behavior.

The results of our hysteresis loop and Day plot analysis strongly indicate that although some samples contain SD-like magnetite, the majority of our samples contain PSD magnetite as their magnetic remanence carrier.

6.0 ANALYSIS

In this section I discuss what the results of the hysteresis data indicate regarding the samples' magnetic carrier, selecting qualifying samples from all those with two demagnetization components, and the turning point temperatures for those qualifying samples. I then discuss converting turning point temperatures to ages using both the Pullaiah et al. (1975) and Middleton and Schmidt (1982) nomographs, and the error inherent in the TVRM dating method as the result of misidentifying the turning point temperature, spread within a single moraine, and assuming different acquisition temperatures. The number of samples needed to make this dating method work is also discussed.

6.1 Day Plots, Hysteresis and VSM

I did not observe any significant correlation between demagnetization behavior type and hysteresis loop shape. Samples with demagnetization behaviors linear, clustering, and two-component had both narrow (PSD and MD magnetite) and fuller (SD-like) loops.

Of the 10 samples which were tested with the vibrating sample magnetometer, only three of the characteristic behaviors were represented: clustering, 2-component, and linear. Seven of the ten samples came from the Leavenworth moraines, two from the Rat Creek moraine, and one from the Peshastin. Results are somewhat skewed because I tested some samples multiple times to test repeatability under varying test conditions. For example, I tested different chunks from the same sample, some containing more or less biotite, to observe the influence of mineral composition on results. I also changed the machine's data collection technique, such as induced magnetic field, collection time, and averaging interval. When I powdered samples, I ran tests with the mineral grains packed with baking soda and/or alumina (the contributions of which were later subtracted out) to observe which method yielded less noisy data. Though there are many points on the Day Plots, in reality I tested only 10 unique samples.

All samples plot it the pseudo-single domain (PSD) magnetite zone. Even with variable testing procedures, test results from the same sample generally have similar result and plot in similar

locations on the Day Plot. I am skeptical of the 2012 LW analyses being more single-domain-like, as those two points are two tests from the same sample. In general, although powdered samples tend to yield more SD-like results, all of the samples tested show evidence that their magnetic carrier is pseudo-single domain magnetite. This was unexpected given Housen et al.'s (2003) conclusion that the magnetic carrier of the Mount Stuart Batholith was single domain magnetite. The results from the Day Plot prompt us to rethink using Pullaiah's single domain time-temperature relationship theory and instead consider using the methods of Walton (1980).

6.2 Stereonet Data: yields "Qualifying Samples"

For our samples categorized as having "two-component" behavior, I used the CT analysis software to measure declination and inclination for both the TVRM and TRM components. The directions for the magnetic components are measured as a declination and inclination, which are translated to trend and plunge when plotted on a stereonet. I plotted all 26 of the TVRM directions on a stereonet. There was a very obvious relationship, in that about half of the TVRM components were grouped within 30 steradians of current magnetic north in the Leavenworth area (16^o declination, 70^o inclination). A number of additional specimens show directions within about 40 steradians of magnetic north.

Eight TVRM components fell outside this radius, I interpret them as not being acquired as a viscous remanent component due to the sample's emplacement in the moraine. The secondary magnetic component in these samples is likely the result of post-depositional magnetization/heating event, such as a fire, lightning strike, or displacement after an initial period of TVRM gain. I removed these eight from consideration, as they cannot accurately tell us the length of time since moraine emplacement which is ultimately our goal. I also looked to sample's petrologic characteristics to identify any similarities shared by the discarded samples. For each sample I tabulated amount of weathering experienced by the boulder, the presence of an elongated mineral fabric, and an estimation of the amount of biotite in the sample (Table 6). Though there is no obvious trend in weathering amount or presence of a fabric, discarded samples as a group tended to have more biotite than the qualifying samples.

This leaves 18 samples within about 40 steradians of current magnetic north. Those are shown on Figure 11A, with different moraines plotted as different symbols/colors. I retain samples within a large radius from current magnetic north in order to account for paleosecular variation of the magnetic field over the last 100,000 years (Constable, 2007; Tauxe, 2010). Of this short-list of samples, the average declination is 26^{o} and the average inclination is 72^{o}: similar to current magnetic north. The wide variability in TVRM direction could possibly be attributed to measurement error in the field, or slight rotation of the boulder as it was exhumed from the moraine.

These 18 samples, hereafter identified as "qualifying samples", are the most likely recorders of an actual TVRM acquired while sitting in a moraine. For these qualifying samples, I plotted their TRM directions on a separate stereonet plot (Figure 11B). These points appear randomly-oriented and widely scattered, which is what is expected for the TRM components of a moraine deposit. The difference in steradians between the qualifying sample's TVRM and TRM direction was as little as 17^{o} and as much as 101^{o}. The average difference between two components was 52^{o}. All sample's turning point temperatures are recorded in Table 9.

6.3 Samples and Averages are in Chronological Order

When turning point temperatures for the qualifying samples are plotted on a simple line chart, it becomes clear that there is a trend of increasing turning point temperature with moraine age (Figure 12). There is some temperature overlap between the different moraines however. Rat Creek turning point temperatures fall between 160 and 195, while Leavenworth, the next youngest moraine, has turning point temperatures between 175 and 220. Calculating the average turning point temperatures by moraines also shows a trend of increasing temperatures with increasing moraine age (Table 10). Rat Creek, which previously appeared slightly older than Leavenworth upon first glance at turning point temperatures, now appears more in line with all of the other moraines when we focus only on the qualifying samples. This suggests the possibility that some of the boulders incorporated into the Rat Creek moraine suffered from prior inheritance, or significantly hotter temperatures since emplacement.

There is a lack of data from the Peshastin moraine. Though four samples from the moraine were classified as two-component, only two of the four are qualifying samples. These two samples vary by 60°C, and although their average falls in line with the other three moraines, this moraine is highly suspect. Being the oldest, very few competent boulders remained as part of the moraine. Many had grusified, and others crumbled during drilling or during the demagnetization process before reaching unblocking temperatures. I continue the analysis using Peshastin's average turning point temperature, though the validity of my results for this particular moraine would increase if additional qualifying samples were obtained.

6.4 Converting Turning Point Temperatures to Ages

6.4.1 Middleton & Schmidt vs. Pullaiah Nomographs

Having gathered actual turning point temperature values, we can begin to evaluate these temperatures and obtain corresponding ages using both the Pullaiah et al. (1975) method and the Walton (1980) method as adapted by Middleton and Schmidt (1982). Both methods use the same numerical values for C, gamma, and M_c (0°C). The same inputs for laboratory time and temperature ($\tau 1$ and T1, directly measured from our laboratory work) and acquisition temperature (T2, an educated assumption of paleotemperature) were also used when comparing results from the two methods.

In Figure 13 I plot the average turning point temperatures for the Rat Creek and Mountain Home moraines on nomographs from both Pullaiah et al. and Middleton and Schmidt. Cosmogenic ages for the moraines are also plotted, assuming an acquisition temperature of 10°C. A solid blue line connects the two points of each moraine. If a nomograph is correct, this connection line should parallel the time-temperature curves. From the figure, we clearly see that both moraines adhere more closely to the Middleton and Schmidt nomographs, while using the Pullaiah nomographs requires crossing several time-temperature equivalence lines in order to connect the two points.

Our results thus support the Walton method, similar to conclusions reached by Kent (1985), Middleton and Schmidt (1982), Jackson and Van der Voo (1986), Williams and Walton (1988),

Dunlop and Argyle (1991), Dunlop and Özdemir (1993), and Borrodaile and Almqvist (2006). These studies support the conclusion made by Walton (1980): that most assemblages of magnetite consist of a lognormal grain-size distribution. While Pullaiah et al.'s equation (n=1) is valid for single-domain (SD) magnetite assemblages, pseudo-single domain (PSD) to multi-domain (MD) assemblages require higher demagnetization temperatures to remove an equivalent TVRM and follow Walton's equation (n= 2). From our Day Plot and VSM analysis our samples are mostly comprised of PSD magnetite.

In a similar study by Smith and Verosub (1994), the nomographs of Pullaiah et al. (1975) were deemed more accurate. However, it is likely that single-domain magnetite was the magnetic carrier in the basalt columns studied.

6.4.2 Field Acquisition Temperature Assumptions

Calculating an acquisition time using the TVRM dating method relies heavily on making an educated estimate of paleotemperature. This is not a straightforward issue. Many studies assume acquisition temperatures of about 20^{o}C without further explanation (Smith and Verosub, 1994; Borrodaile and Almqvist, 2006). This is not unreasonable assuming an average daytime temperature during the Holocene. As we attempt to date older rocks, such as glacially deposited boulders from the Pleistocene, it is more difficult to assume an accurate average paleotemperature. The fundamental mechanics of "how" a TVRM is acquired is called into question. Is a more accurate age obtained from averaging the paleotemperature during the entire acquisition time, or would brief periods of warmer temperatures have a stronger weighted effect on TVRM acquisition? Though the average acquisition temperature would likely be around 0^{o}C, it seems plausible that a higher temperature could be used. I evaluated the likelihood of the range of acquisition temperatures in Figure 14. Laboratory time and turning point temperatures for the Mountain Home moraine (A) and Rat Creek moraine (B) are plotted with the Middleton and Schmidt nomographs. I obtained TVRM acquisition times for a range of acquisition temperatures from 0^{o}C to 30^{o}C with results summarized in Table 11. Though all acquisition temperatures under-predict the age for Rat Creek, a reasonable age for Mountain Home is obtained assuming an acquisition temperature between 0^{o}C and 5^{o}C. These results lead me to

believe that assuming an acquisition temperature of 5°C is appropriate for the Icicle Creek moraines.

6.4.3: 5°C Turning Point Identification Error

Choosing a precise turning point temperature is not an exact science. As discussed previously, the TVRM method involves picking the obvious turning point, when present, or the mid-point of a cluster. The cluster-method in particular required some subjectivity. An additional source of error was that I demagnetized some of the samples at coarse intervals between steps. Figure 15 shows the error induced into a moraine's age if a turning point is identified by ± 5 °C. For the average turning point temperature of the Mountain Home moraine (224°C), the age predicted by Middleton and Schmidt (1982) for an acquisition temperature of 5°C is 35,000 years old. For a range of temperatures between 219°C and 229°C, the predicted age for the moraine ranges between 15,000 and 80,000 years, over half and double the initial age, respectively. This amount of error is similar for the other moraines as well, regardless of age. Accounting for this uncertainty, the TVRM dating method can predict ages within an order of 2, and definitely within an order of magnitude.

6.4.4 Age Variation Within Single Moraine

Although the TVRM dating method shows realistic results for the Mountain Home, it is worth noting that the age obtained, 35ka, results from using the average turning point temperature from the four qualifying specimens in the moraine. The spread of turning points ranges from 212°C to 250°C which results in a very wide range of acquisition times as shown in Figure 16. Though three of the specimens produce ages that are within an order of magnitude from each other, the outlying temperature of 250°C produced an age of almost 1Ma if plotted with an acquisition temperature of 5°C. In future studies, I would discard outliers that stand out this much

6.4.5 Moraine Age Predictions using TVRM Dating Method

Average turning point temperatures for the four moraines are shown in Table 10. The laboratory acquisition time and temperature, along with the Middleton and Schmidt nomographs, are plotted for each moraine in Figure 17. Assuming an acquisition temperature of 5^{o}C, we obtain numerical ages of 300 years for Rat Creek, 1 ka for Leavenworth, 35 ka for Mountain Home, and 160 ka for Peshastin. These ages and the moraine's cosmogenic ages from Porter and Swanson (2008) are summarized in Table 12. Also included are the moraine ages if we assume +/- 5^{o}C, and the error between TVRM and cosmogenic ages. The two younger moraines, Rat Creek and Leavenworth, are significantly and unrealistically younger than cosmogenics predict. Mountain Home and Peshastin, meanwhile, are within a factor of two of the cosmogenic ages.

6.5 Qualifying Samples – boulders, cores, samples needed

Ultimately, I demagnetized 95 specimens, from 62 core samples, from 34 boulders, from 4 moraines. Of these, 18 specimens were "qualifying samples" and had both a TVRM and TRM component of magnetization, with the TVRM in the direction of magnetic north. These 18 qualifying samples come from 16 unique cores, 15 unique boulders, and from the four unique moraines in this study. Since samples from the same core usually share demagnetization patterns, obtaining multiple samples per core is not necessary. Different cores from the same boulder are also usually similar to each other, but there is a higher likelihood of different demagnetization behaviors than with samples from the same core. Thus, I would not discount the benefit of occasionally obtaining multiple cores per boulder.

I expected cores from the same boulder to display similar demagnetization patterns, rather than the differences observed. Possible explanations for these variations include boulder mineralogy heterogeneity, and lighting strikes or forest fires preferentially "resetting" the magnetic moments on different sides of the boulder. The differences could also be caused by experimental error, such as overheating a core by the drill bit during drilling.

If I were to repeat this experiment with the Icicle Creek moraines, I would recommend sampling 10 boulders per moraine, to obtain enough qualifying sample to analyze. In general, there was a noticeable pattern shared between all the moraines, in that about 4 of every 10 boulders yielded a qualifying sample, assuming multiple cores for about half of the boulders. Sampling 3 boulders from Mountain Home yielded 4 qualifying samples from 2 boulders, and sampling 5 boulders from Peshastin yielded 2 qualifying samples from 2 boulders. I obtained 8 qualifying samples from 19 Leavenworth boulders, and 4 qualifying samples (from 3 unique boulders) from 7 total Rat Creek boulders.

Unlike cores from the same boulder, I expected there would be differences in demagnetization behavior in boulders from the same moraine. Mineralogy heterogeneity, lighting strikes, and forest fires could cause the differences seen, as could post-depositional movement of the boulder, exposure temperature of different boulders, or emplacement of the boulder into the moraine such that its moments are already in line with magnetic north.

6.6 Turning Point Temperatures

Though the Mountain Home and Peshastin tuning point temperatures fit the Middleton and Schmidt nomographs reasonably well, it is important to note that the ages obtained for the moraines are based on the average turning point temperatures for all qualifying samples. The range of ages resulting from the spread of turning point temperatures for all of a moraine's qualifying samples is very large; for Mountain Home, between 10ka and 1Ma. The Peshastin results are less substantial, based on the average of 210^{o}C and 275^{o}C. Obtaining more qualifying samples would increase confidence in the age results for this moraine. For Mountain Home and Peshastin in particular, due to under-predicting the anticipated turning point temperature, I had reduced the frequency of temperature steps by the time the turning point was reached. This resulted in coarse measurements and a larger spread of turning point temperatures compare to qualifying samples within the two younger moraines.

The Rat Creek and Leavenworth moraines did not produce as accurate of ages as the two older moraines using the Middleton and Schmidt nomographs. Smaller demagnetization temperature

step intervals did, however, reduce the spread of turning point temperatures within each moraine. An additional point to note is the difference of 30^{o}C in the average turning point temperatures of qualifying samples between the original pilot study within the Leavenworth moraine (November, 2011) and the temperatures obtained from a different part of the moraine (July, 2012) as part of the four-moraine suite of sampling. Though the two sets of data are from Leavenworth I and Leavenworth II, the moraines should appear the same within the age resolution of the TVRM dating method. Differences could be attributed to drilling in different seasons, or more likely, slightly different laboratory methods and time stored between demagnetization steps.

There is a clear "break" in this method's success between the two older moraines and two younger moraines. Turning point temperatures for the two older moraines, Peshastin and Mountain Home, yield results within an order of 2 of what cosmogenics predict. Using the same method, assumptions, and constants, the younger moraines, Rat Creek and Leavenworth, produce emplacement ages that differ by greater than an order of magnitude from published cosmogenic ages. Explanations for the discrepancy between the old and young moraines include source rock variations, different TVRM acquisition conditions, such as different climates and rates of TVRM acquisition, and significantly different amounts of boulder weathering and that effect on TVRM acquisition.

7.0 CONCLUSIONS

The results of my research indicate that the TVRM dating method can relatively date boulder emplacement for a group of different-aged moraines. The technique does not yield precise quantitative ages, as small variations in turning point temperature, which is somewhat subjective, can result in large variations of age within a single moraine. The wide spread in ages obtained from a single moraine indicate that numerous qualifying samples are needed from a moraine to get a reasonable average for turning point temperature and therefore age.

Assuming the cosmogenic ages predicted by Porter and Swanson (2008) are correct, my results indicate that the Middleton and Schmidt (1982) nomographs are more likely to predict accurate moraine deposition ages of the Icicle Creek moraines. This, along with the results of my VSM and hysteresis data, indicates that the magnetic carrier of my samples is pseudo-single or multi domain magnetite, in contrast to Housen et al.'s (2003) conclusion of single-domain magnetite dominating the source rock.

Ultimately, many questions remain about the acquisition and removal of TVRM. With further insight into these mechanisms, the TVRM dating method could be developed into a more reliable, quantitative dating method. At present, TVRM is a useful relative dating method to confirm geomorphic interpretations, and may provide approximate age constrains where no other methods are applicable.

8.0 REFERENCES CITED

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.

Borradaile, G., & Almqvist, B. (2006). Installation age of limestone masonry determined from its viscous remagnetization. Geoarchaeology, 21(1), 29-60

Brown E.T. 1981. Rock Characterization, Testing and Monitoring: ISRM Suggested Methods. Pergamon Press.

Burbank and Anderson (2012), Tectonic Geomorphology, 2nd Edition, Chapter 3 (pp 45-70)
Butler, R. F. (1992), Paleomagnetism: Magnetic Domains to Geologic Terranes, Blackwell Scientific Publications, 1st edition, Chapters 2, 3 and 5.

Colman, S. M., & Pierce, K. L. (1986). Glacial sequence near McCall, Idaho; weathering rinds, soil development, morphology, and other relative-age criteria. Quaternary Research, 25(1), 25-42.

Constable, Catherine (2007), "Dipole Moment Variation", in Gubbins, David; Herrero-Bervera, Emilio, Encyclopedia of Geomagnetism and Paleomagnetism, Springer-Verlag, pp. 159–161

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.

Crider, J, Miller, B, Burmester, R, Thackray, G, & Housen, B 2010, '(Re)assessing the application of viscous remanent magnetism to dating geomorphic events', Abstracts With Programs - Geological Society of America, 42, 5, p. 522

Crook, R. r. (1986). Relative dating of Quaternary deposits based on P-wave velocities in weathered granitic clasts. Quaternary Research, 25(3), 281-292.

Dunlop, David J. 2002. "Theory and application of the Day plot (M (sub rs) /M (sub s) versus H (sub cr) /H (sub c)); 1, Theoretical curves and tests using titanomagnetite data." Journal Of Geophysical Research 107, no. B3:

Dunlop, D. J., and Ozdemir, O., 1997, Rock magnetism: fundamentals and frontiers: Cambridge, Cambridge University Press, 573 p. 297

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., Ozdemir, O., 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.

Foit, F. r., Mehringer, P. r., & Sheppard, J. C. (1993). Age, distribution, and stratigraphy of Glacier Peak tephra in eastern Washington and western Montana, United States. Canadian Journal Of Earth Sciences = Revue Canadienne Des Sciences De La Terre, 30(3), 535-552

Gillespie, A. (1982, January 1). Quaternary glaciation and tectonism in the southeastern Sierra Nevada, Inyo County, California.

Heyman, J., Stroeven, A. P., Harbor, J. M., & Caffee, M. W. (2011). Too young or too old; evaluating cosmogenic exposure dating based on an analysis of compiled boulder exposure ages. Earth And Planetary Science Letters, 302(1-2), 71-80.

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.

Housen, B, Beck, M, Burmester, R, Fawcett, T, Petro, G, Sargent, R, Addis, K, Curtis, K, Ladd, J, Liner, N, Molitor, B, Montgomery, T, Mynatt, I, Palmer, B, Tucker, D, & White, I 2003, 'Paleomagnetism of the Mount Stuart Batholith revisited again; what has been learned since 1972?', American Journal Of Science, 303, 4, pp. 263-299

Irving, E., 1985, Whence British Columbia?: Nature, v. 314, p. 673–674.

Kent, D.V. (1985). Thermoviscous remagnetization in some Appalachian limestones. Geophysical Research Letters, 12, 805–808.

Kim, B., & Kodama, K. P. (2004). A compaction correction for the paleomagnetism of the Nanaimo Group sedimentary rocks; implications for the Baja British Columbia hypothesis. Journal Of Geophysical Research, 109(B2)

Krijgsman, W., & Tauxe, L. (2006). E/I corrected paleolatitudes for the sedimentary rocks of the Baja British Columbia hypothesis. Earth And Planetary Science Letters, 242(1-2), 205-216

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.

Middleton, M.F., & Schmidt, P. W. (1982). Paleothermometry of the Sydney basin. Journal of Geophysical Research, 87, 5351–5359.

Neel, L., Theorie du trainage magnetique des ferromagnetique en grain fins avec applications aux terres cuites, Ann. Geophys.5, 99-136, 1949.

Page, B 1939, 'Multiple Alpine glaciation in the Leavenworth area, Washington', Journal of Geology, 47, 8, pp. 785-815

Paterson, S. R., Miller, R. B., Anderson, J. L., Lund, S., Bendixon, 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.

Porter, S. C. (1969). Pleistocene geology of the East-central Cascade Range, Washington. United States: Univ. Wash. : Seattle, WA, United States

Porter, SC 1976, 'Pleistocene glaciation on the southern part of the North Cascade Range, Washington', Geological Society Of America Bulletin, 87, 1, pp. 61-75

Porter, SC 1978, 'Glacier Peak tephra in the North Cascade Range, Washington; stratigraphy, distribution, and relationship to late-glacial events', Quaternary Research, 10, 1, pp. 30-41

Porter, S, & Swanson, T 2008, '36Cl dating of the classic Pleistocene glacial record in the northeastern Cascade Range, Washington', American Journal of Science, 308, 2, pp. 130-166

Pullaiah, G, Irving, E, Buchan, K, & Dunlop, D 1975, 'Magnetization changes caused by burial and uplift', Earth and Planetary Science Letters, 28, 2, pp. 133-143

Putkonen, J., & Swanson, T. (2003). Accuracy of cosmogenic ages for moraines. Quaternary Research, 59(2), 255-261

Smith, R, & Verosub, K 1994, 'Thermoviscous remanent magnetism of Columbia River Basalt blocks in the Cascade landslide', Geophysical Research Letters, 21, 24, pp. 2661-2664

Swanson, T. W., & Caffee, M. L. (2001). Determination of (super 36) Cl production rates derived from the well-dated deglaciation surfaces of Whidbey and Fidalgo islands, Washington. Quaternary Research, 56(3), 366-382.

Tauxe, L., Essentials of Paleomagnetism, University of California Press, 2010

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.

Verwey, E. J., 1939, Electronic conduction of magnetite (Fe3O4) and its transition point at low temperature: Nature, v. 144, p. 327–328.

Waitt, Rr 1977, 'Guidebook to Quaternary geology of the Columbia, Wenatchee, Peshastin, and Upper Yakima valleys, West-central Washington', Open-File Report - U. S. Geological Survey

Waitt, R. r., Yount, J. C., & Davis, P. (1982). Regional significance of an early Holocene moraine in Enchantment Lakes basin, north Cascade Range, Washington. Quaternary Research, 17(2), 191-210.

Walton, D. 1980. "Time-temperature relations in the magnetization of assemblies of single domain grains." Nature [London] 286, no. 5770: 245-247

Warnock, A. C., Kodama, K. P., & Zeitler, P. K. (2000). Using thermochronometry and low-temperature demagnetization to accurately date Precambrian paleomagnetic poles. Journal Of Geophysical Research, 105(B8), 19

Zreda, M. G., Phillips, F. M., Elmore, D., Kubik, P. W., Sharma, P., & Dorn, R. I. (1991). Cosmogenic chlorine-36 production rates in terrestrial rocks. Earth And Planetary Science Letters, 105(1-3), 94-109.

TABLES

Table 1: Relative and pseudo-quantitative dating methods of boulders and moraines, partially reproduced from Burbank and Anderson, 2012

Method	Age Range	Materials Needed	References
Clast seismic velocity	1 – 100 ka	Boulders	Crook (1986), Gillespie (1982)
Mineral Weathering	10 ka – 1 Ma	Boulders	Colman and Pierce (1986)
***Relative location**	1 – 300 ka+	Moraines	

Table 2: Evolution of Icicle Creek glacial nomenclature

Page (1939)	Porter (1969)	Waitt (1977)	Porter and Swanson (2008)
Stuart	Leavenworth IV	Leavenworth V	Rat Creek I and II
Leavenworth	Leavenworth I-III	Leavenworth I-IV	Leavenworth I and II
Not recognized	*Not recognized*	*Not recognized*	Mountain Home
Not recognized	*Not recognized*	*Not recognized*	Pre-Mountain Home
Peshastin	Chumstick	Mountain Home	Peshastin
Not recognized	Peshastin	Boundary Butte	Boundary Butte

Table 3: Moraine population mean and oldest cosmogenic ages. Table modified from Porter and Swanson (2008).

Moraine	Mean Cosmogenic Age (Porter and Swanson, 2008)	Oldest Cosmogenic Age (Porter and Swanson, 2008)
Rat Creek II	12,500 +/- 500 (n=9)	13,500 +/- 600
Rat Creek I	13,300 +/- 800 (n=6)	14,500 +/- 500
Leavenworth II	16,100 +/-1100 (n=11)	17,000 +/-1000
Leavenworth I	19,100 +/- 3000 (n=17)	24,700 +/- 1100
Mountain Home	71,900 +/-1500 (n=5)	72,200 +/-1400
pre-Mountain Home	93,100 +/- 2600 (n=3)	94,900 +/- 3100
Peshastin	105,400 +/- 2200 (n=8)	112,800 +/- 1700

Table 4: Boulders, cores, and specimens collected for each moraine

	Rat Creek	Pilot LE	LW	MH	PE	Total
Boulders	7	9	9	3	5	33
Cores	14	13	18	5	12	62
Specimens	23	17	31	10	19	100

Table 5: Weathering classification; reproduced from Brown (1981)

Class	Term	Description
I	Fresh rock	No visible sign of rock material weathering
II	Slightly weathered rock	Discoloration indicates weathering of rock materials and discontinuity surfaces
III	Moderately weathered rock	Less than half of the rock material is decomposed and/or disintegrated to soil
IV	Highly weathered rock	More than half of the rock material is discomposed and/or disintegrated to soil
V	Completely weathered rock	All rock material is decomposed and/or disintegrated to soil. The original mass structure is still largely intact
VI	Residual soil	All rock material is converted to soil. The mass structure and material fabric are destroyed

Table 6: Summary of boulder petrologic conditions and weathering amounts

Moraine	Boulder	% Mafics (Biotite)	Avg. Grain Size (mm)	Fabric Present	Weathering Class (Brown, 1981)
Leavenworth (Pilot)	**LE01**	20	3	none	1
	LE02	30	2	none	1
	LE03	25	3	none	1
	LE04	20	3	slight	2
	LE05	30	4	none	1
	LE06	35	3	slight	1
	LE07	30	4	none	1
	LE08	25	3	none	1
	LE09	30	3	none	1
	LE10	20	3	slight	2
Rat Creek	**RC01**	40	2	moderate	1
	RC02	40	2	moderate	1
	RC03	35	3	slight	2
	RC04	40	2	moderate	1
	RC05	40	2	moderate	1
	RC06	40	2	slight	1
	RC07	30	2	moderate	2
Leavenworth	**LW01**	25	4	none	1
	LW02	25	3	none	1
	LW03	25	3	slight	1
	LW04	25	3	none	2
	LW05	20	4	none	1
	LW06	30	2	slight	1
	LW07	40	3	moderate	1
	LW08	20	2	none	2
	LW09	35	2	none	1
Mountain Home	**MH01**	15	3	none	2
	MH02	20	2	none	2
	MH03	20	3	none	3
Peshastin	**PE01**	35	2	slight	2
	PE02	20	3	none	3
	PE03	15	4	none	3
	PE04	25	2	none	2
	PE05	20	3	none	3

Table 7: Summary of demagnetization behaviors by moraine. Note, numbers don't match those in Table 4: some samples were removed before fully demagnetizing in order to perform other magnetic tests using the VSM.

	Rat Creek	LE1 Pilot	Leavenworth	Mountain Home	Peshastin	Total	Percent
Two-component	5	6	6	4	4	25	26%
Cluster	13	7	15	3	4	42	44%
Linear	4	3	9	1	8	25	26%
Fluctuating	0	1	0	0	1	2	2%
Curving	0	0	0	1	0	1	2%

Table 8: Turning point temperature statistics by moraine, for all samples with a TVRM and TRM.

	Rat Creek	LE-2011	LW-2012	LW-combined	Mountain Home	Peshastin
Max	265	190	230	230	275	360
Min	160	130	190	130	197	200
Mean	199	172	200	186	221	271
Standard Deviation	32.1	19.3	14.3	22.2	25.7	51.5

Table 9: Short list of samples with TVRM components in the direction of magnetic north,, the steradians between TVRM/TRM samples, and the turning point temperatures of these select samples

	TVRM		TRM		Steradians between TVRM and TRM	Adjusted Turning Point Temperature (^{o}C)
Sample	**Declination**	**Inclination**	**Declination**	**Inclination**		
12RC02B1	12.6	40.4	185.6	-14.9	26	195
12RC06B1	19.5	66.3	346	60.7	30	192
12RC07A1	15	70.5	324	0.4	70	160
12RC07C2	67.5	29.1	298	-4	27	194
12LE03B1	121	53	24	12	55	190
12LE04A2	185.8	75.3	84.4	-31.4	72	180
12LE05A1	0.4	39.7	348.4	21.9	19	175
12LE07A1	128.4	73.2	309	-14	59	175
12LE08A1	87	85	272.5	16.1	101	174
12LW05AT	45	57.3	322	30	59	205
12LW06A2	336.9	38.9	311	29	17	220
12LW08A2	26.1	68.6	91	69.5	60	207
12MH02AT	38.4	59.1	111	6	58	250
12MH02A1	7.6	50.7	137	-17.8	41	212
12MH03AT	10.6	64	89	11	62	225
12MH03A2	289.6	49.1	102	11.6	61	209
12PE02A1	354.7	51.6	197	45	94	210
12PE04AT	25	71	7.5	74	17	275

Table 10: Average moraine turning point temperatures for qualifying samples

Moraine	**Average Turning Point Temperature (^{o}C)**
Rat Creek	185
Leavenworth	191
Mountain Home	224
Peshastin	242.5

Table 11: Predicted Ages from Acquisition Temperatures

		Predicted Ages from Acquisition Temperatures				
Moraine	**Moraine Age**	**0^{o}C**	**5^{o}C**	**10^{o}C**	**20^{o}C**	**30^{o}C**
Rat Creek	13,500	900	400	200	80	20
Mountain Home	62,200	85,000	35,000	10,000	7,000	1,500

Table 12: TVRM dating method age outputs and comparison with cosmogenics

Moraine	TVRM Age	+5°C	-5°C	Cosmogenic Age	Error
Rat Creek	300	230	670	13,500	98%
Leavenworth	1,000	800	2,200	17,000	94%
Mountain Home	35,000	15,000	80,000	72,200	51%
Peshastin	160,000	120,000	360,000	112,800	42%

FIGURES

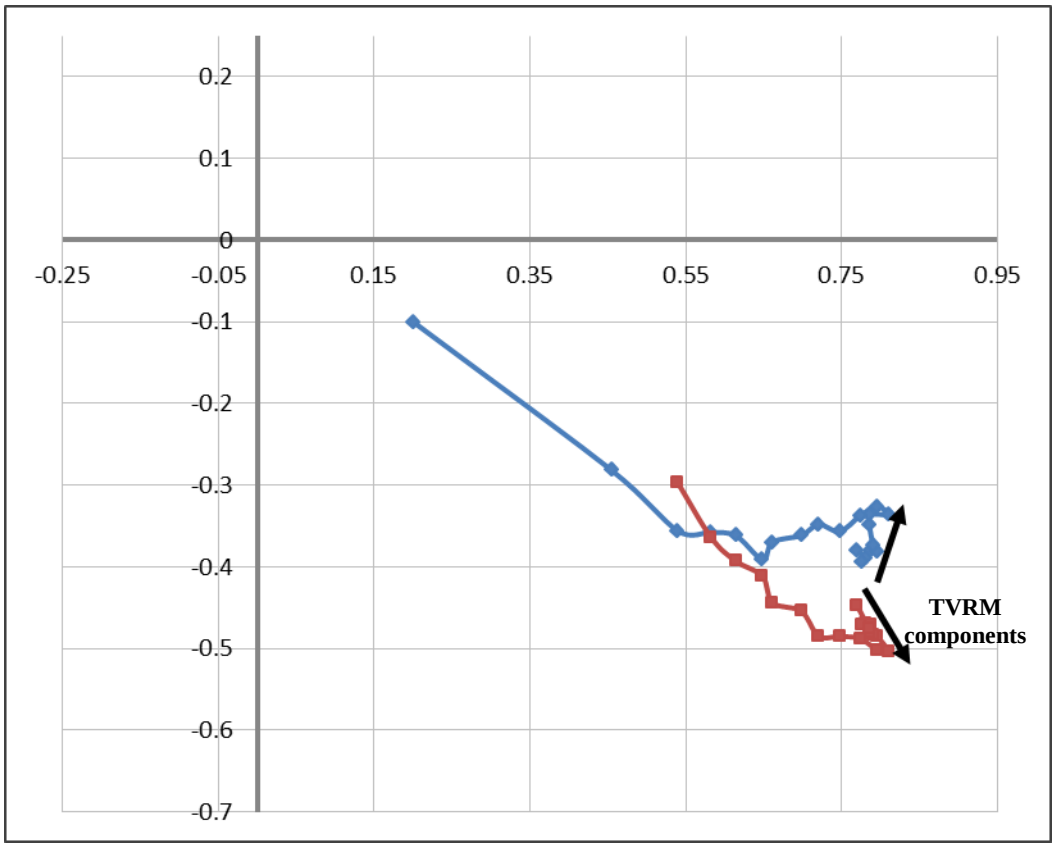


Figure 1: Example Zijderveld diagram with both TVRM and TRM components, plotted in polar coordinates. Declination vs. moment plotted as blue diamonds, inclination vs. moment plotted as red squares. The TVRM is the segment of line in each demagnetization trail furthest from the origin. Upon reaching the turning point the demagnetization plot turns and decays linearly towards the origin (the TRM). Units of micro emus.

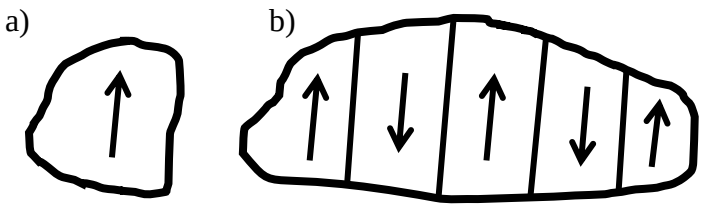


Figure 2: General representation of different domain states of magnetite. a) Uniformly magnetized, single-domain magnetite. b) Multi-domain magnetite with multiple anti-parallel magnetic moments separated by domain walls. Modified from Tauxe, 2010.

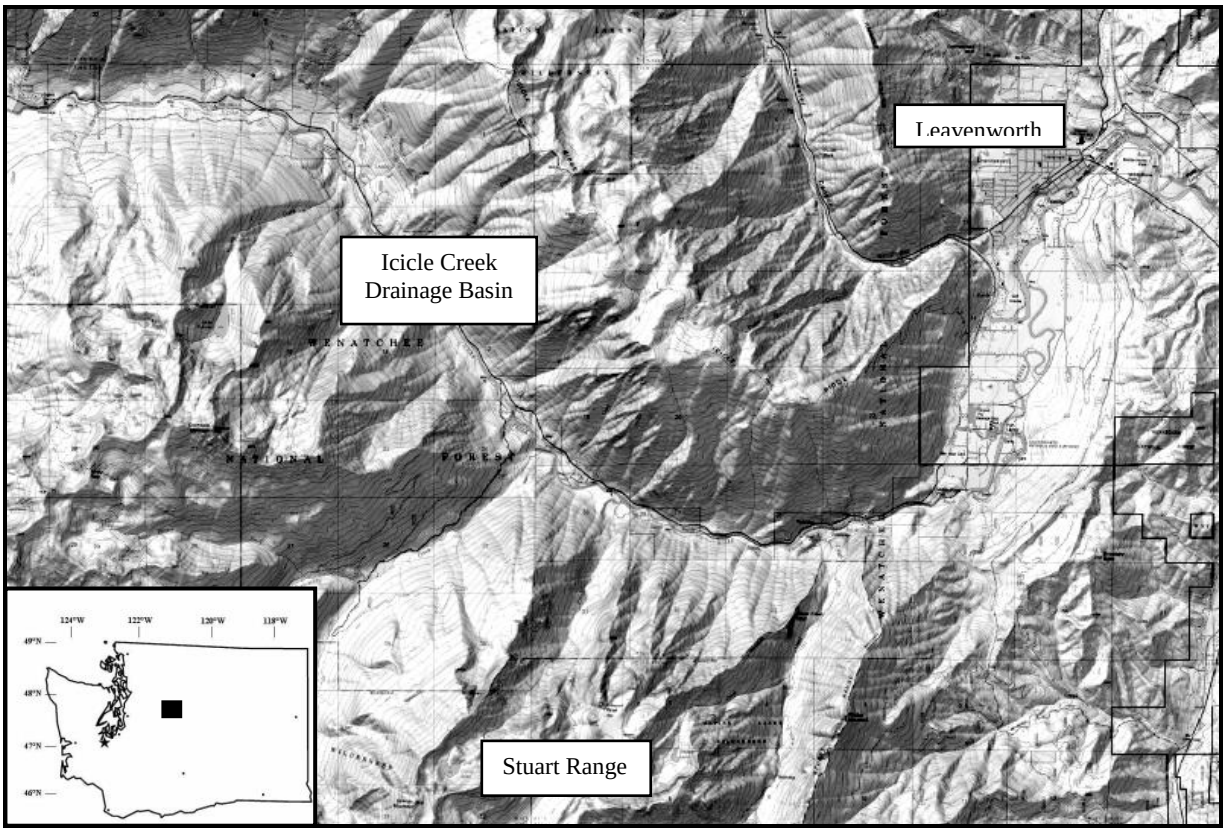


Figure 3: Map of southern part of the northeastern Cascade Range, showing the Icicle Creek Drainage Basin, the town of Leavenworth, and other geographic features referred to in this study.

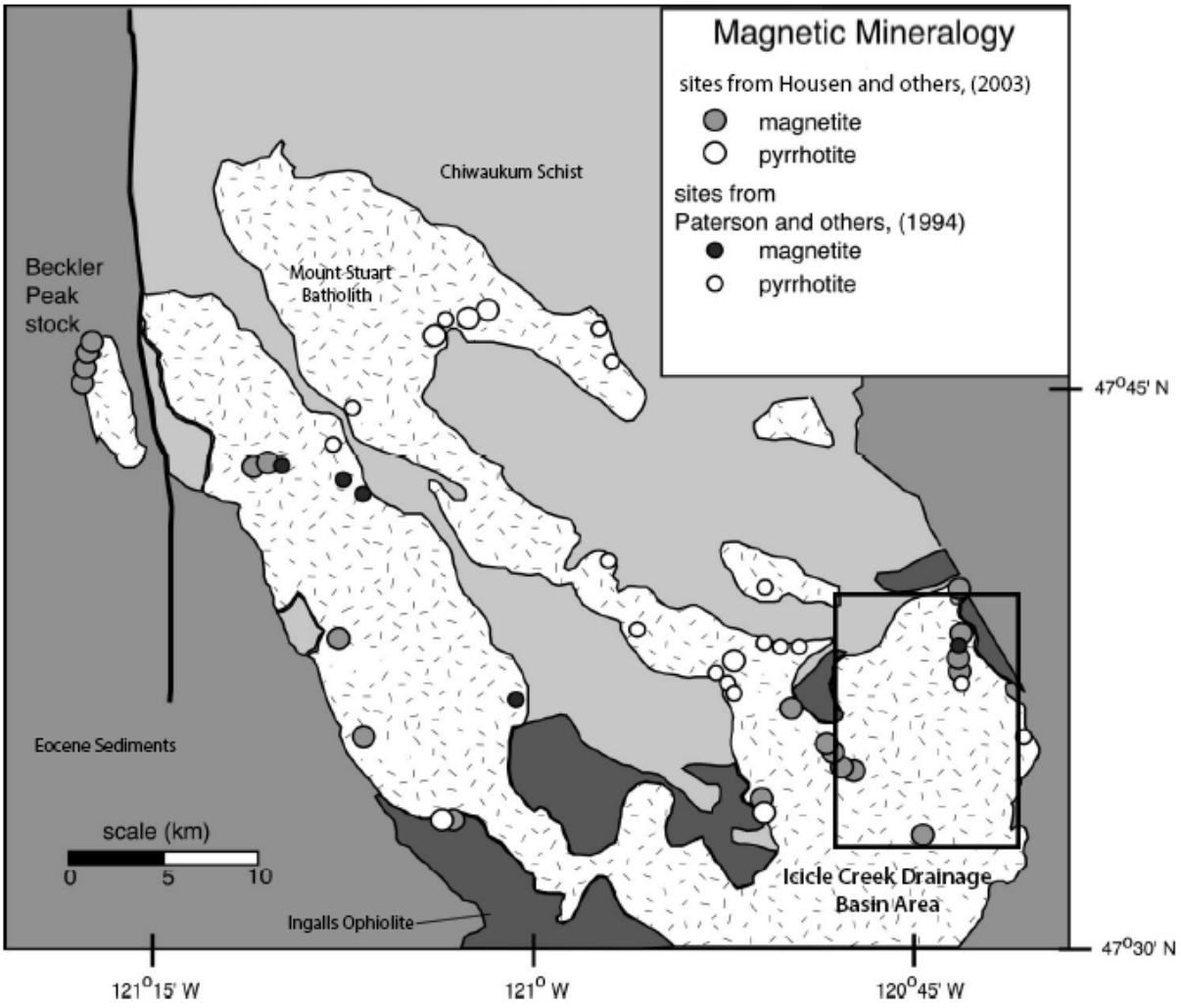
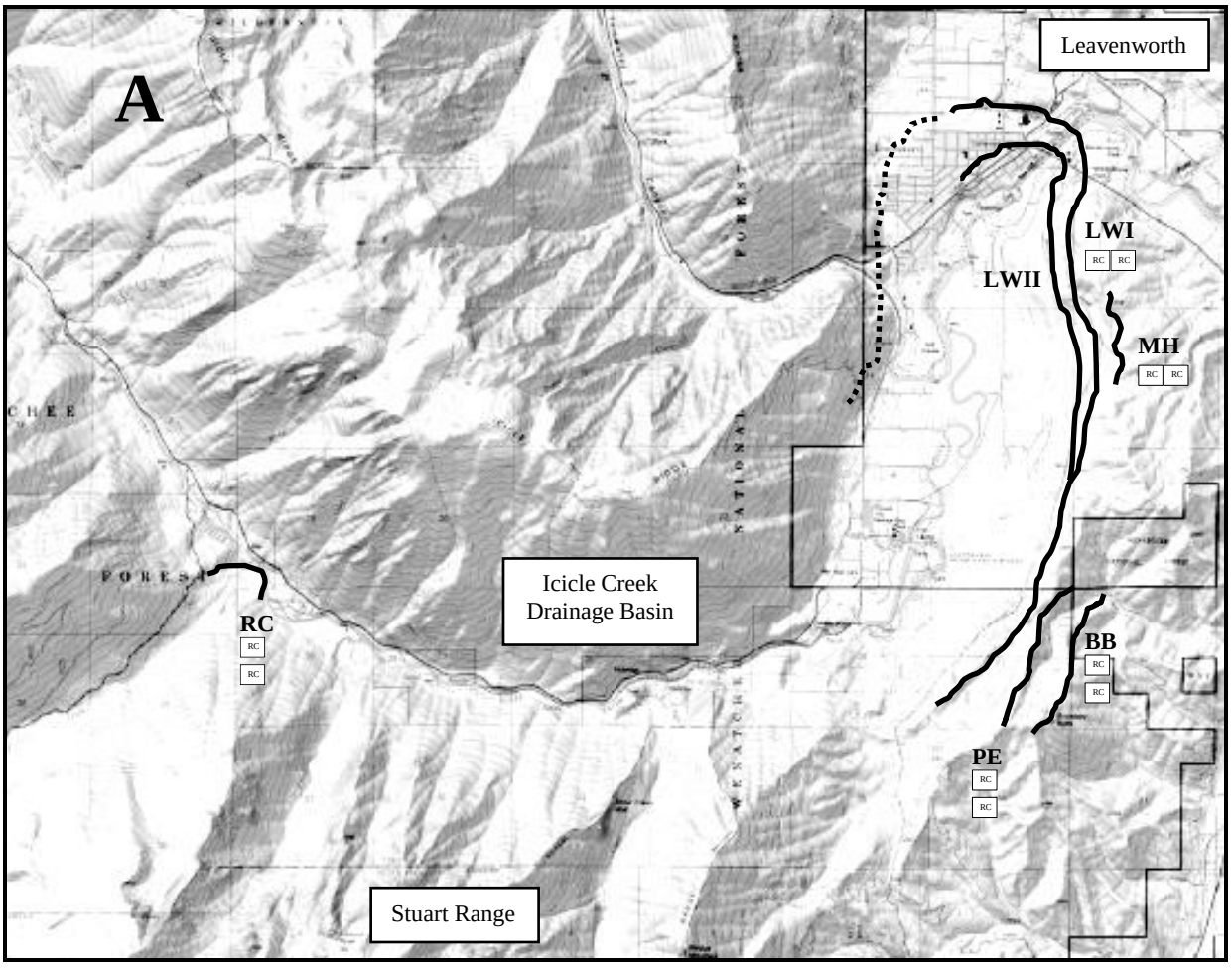
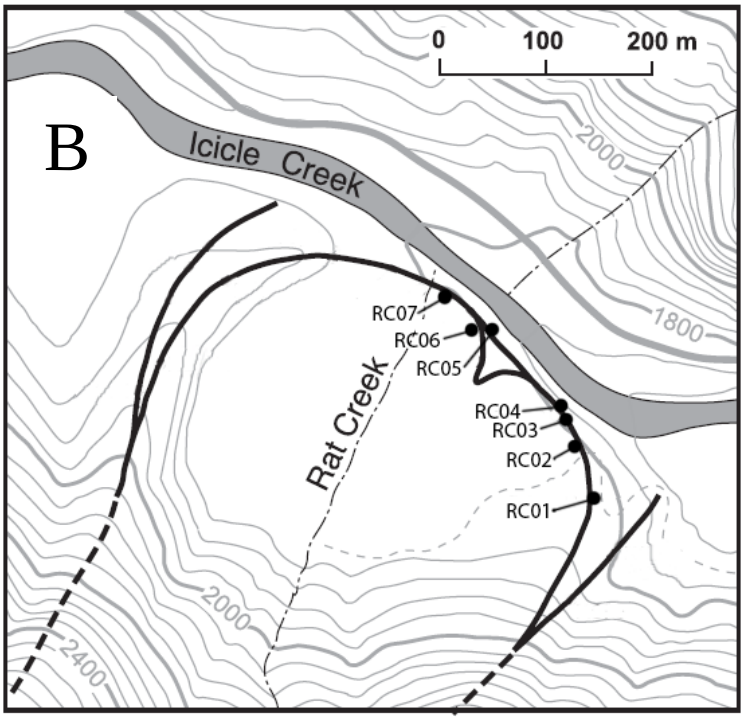


Figure 4: Map of the Mount Stuart batholith region, after Housen et al. (2003), showing locations where the principal magnetic mineralogy has been determined by either thermal demagnetization of NRM or of mIRM. Data are from Housen et al. (2003), and Paterson and others (1994). Note that both studies found pyrrhotite to be confined to the hook-shaped part of the batholith, and near the batholith margins.


A
Leavenworth
LWI
RC RC
LWII
MH
RC RC
Icicle Creek
Drainage Basin
RC
RC
RC
BB
RC
RC
PE
RC
RC
Stuart Range


B
0 100 200 m
Icicle Creek
2000
1800
RC07
RC06
RC05
Rat Creek
RC04
RC03
RC02
RC01
2000
2400

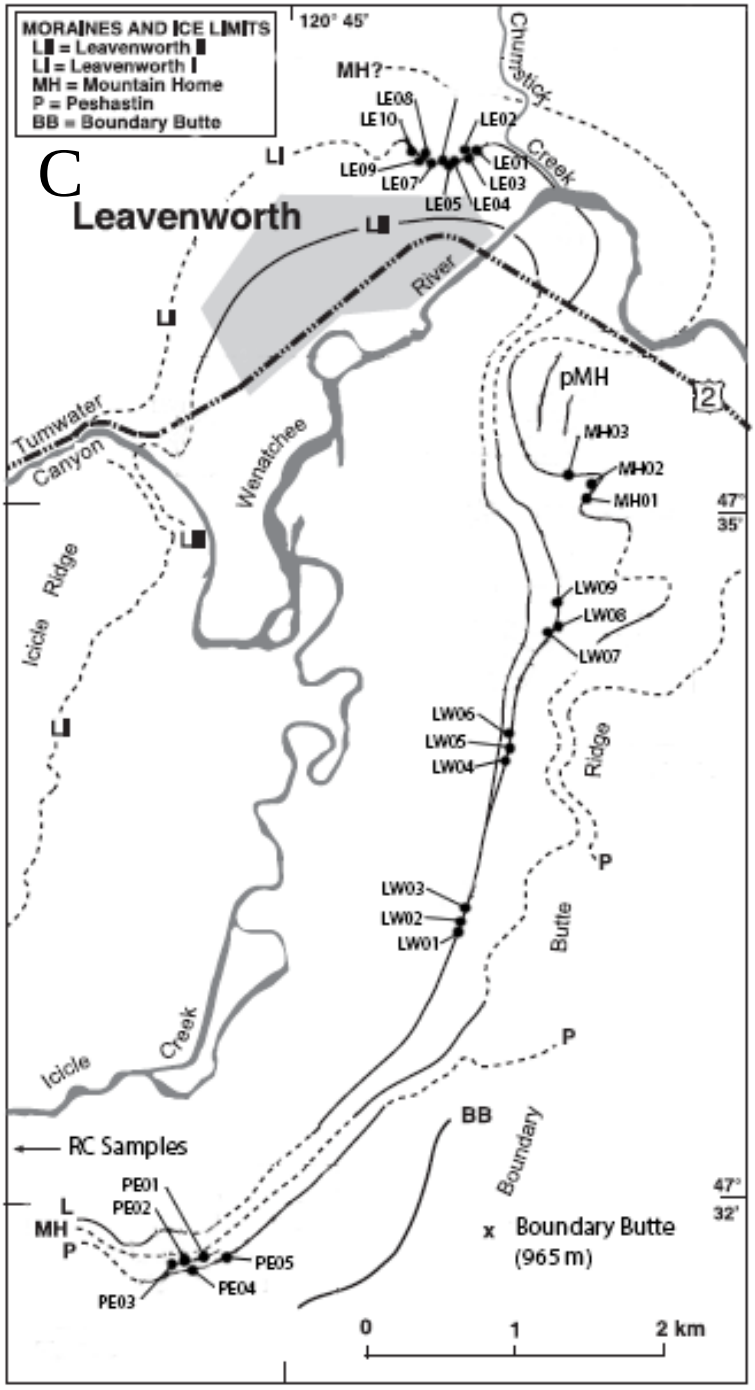


Figure 5: Maps of A) The Icicle Creek drainage basin with general locations of moraine crests outlined in heavy black lines. RC = Rat Creek, LWI = Leavenworth I, LWII = Leavenworth II, MH = Mountain Home, PE = Peshastin, and BB = Boundary Butte. B) Rat Creek moraine with boulder sampling locations identified. C) Leavenworth, Mountain Home, and Peshastin moraines and sampling locations. Boundary Butte and pre-Mountain Homes moraine crests shown but boulders were not sampled. Figure modified from Porter and Swanson (2008).

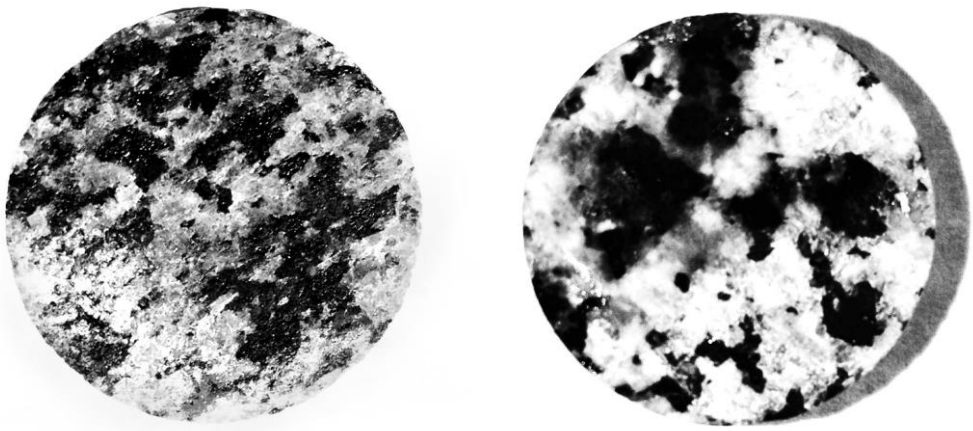


Figure 6: Example of boulder petrologic fabric observed in drilled cores. A) Displays the end member texture A, consisting of ~40% mafics, 2mm grain-size, and mineral alignment. B) Displays the end member texture B, consisting of ~20% mafics, 4mm grain-size, and no noticeable mineral alignment.

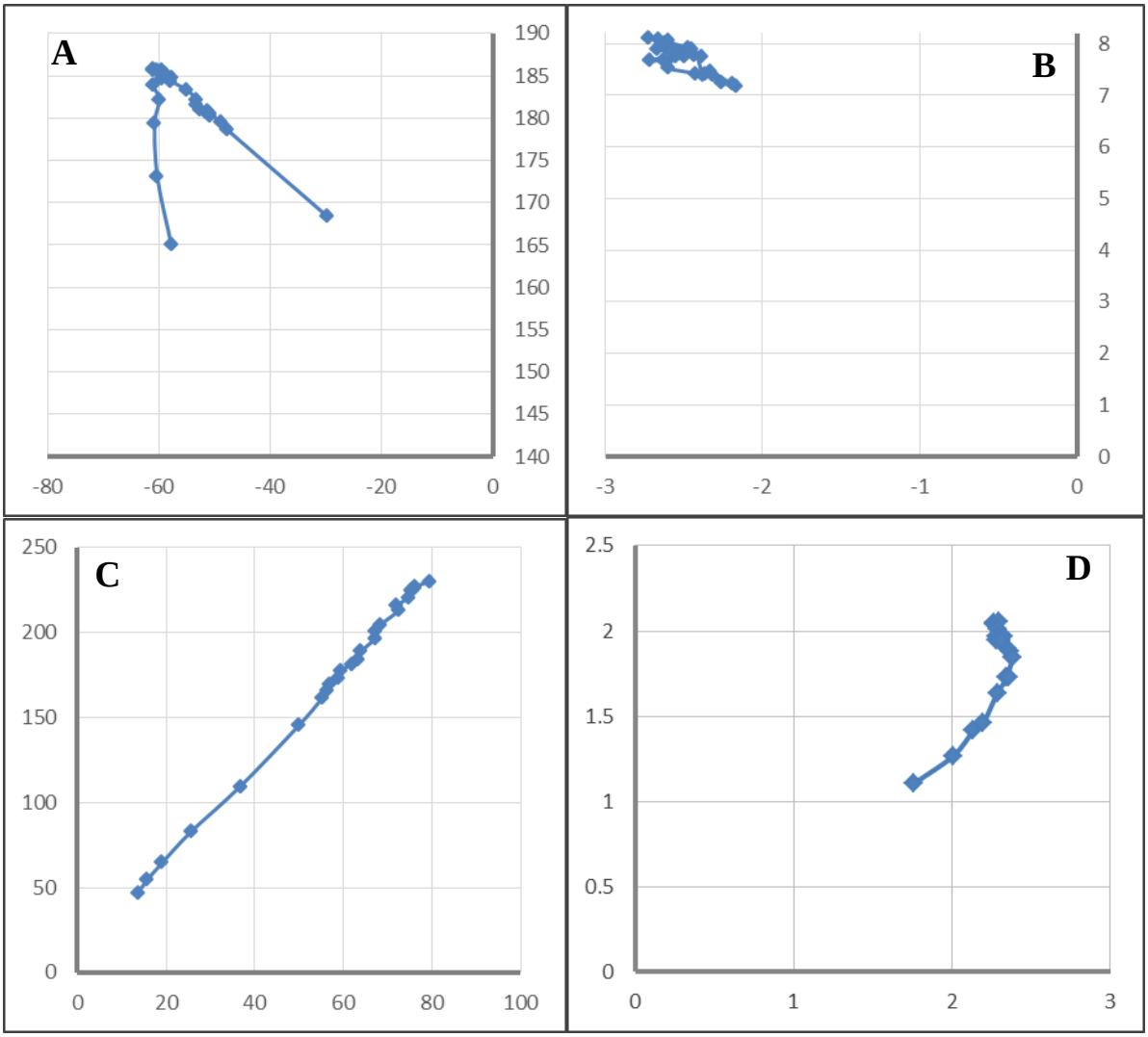


Figure 7: Zijderveld diagrams of characteristic demagnetization behaviors, plotted in polar coordinates. Declination vs. moment plotted as blue diamonds, inclination vs. moment not plotted for simplicity. Examples of: A) Two-component behavior, B) Cluster, C) Curving, D) Linear decay to origin. Units of micro emus.

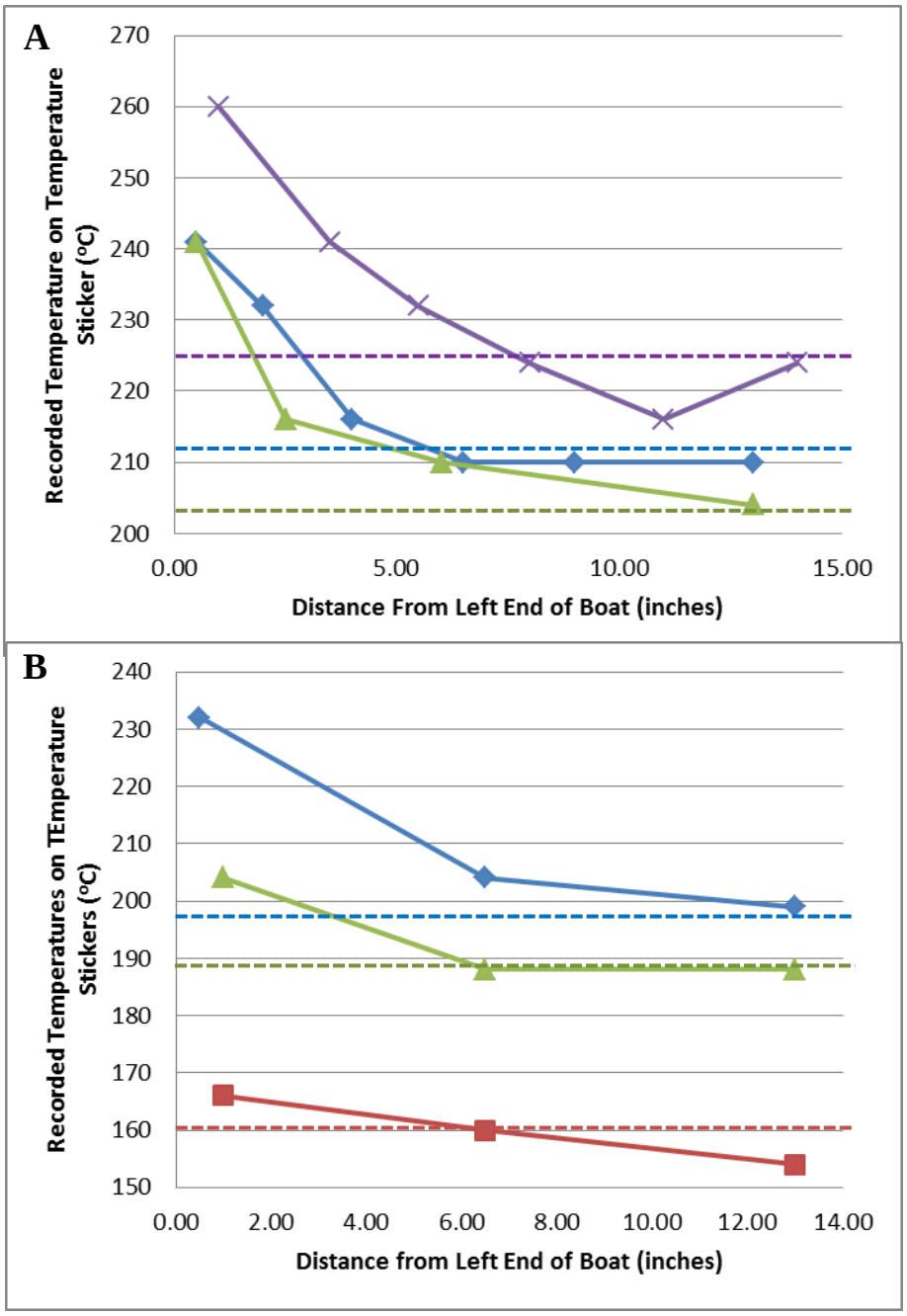
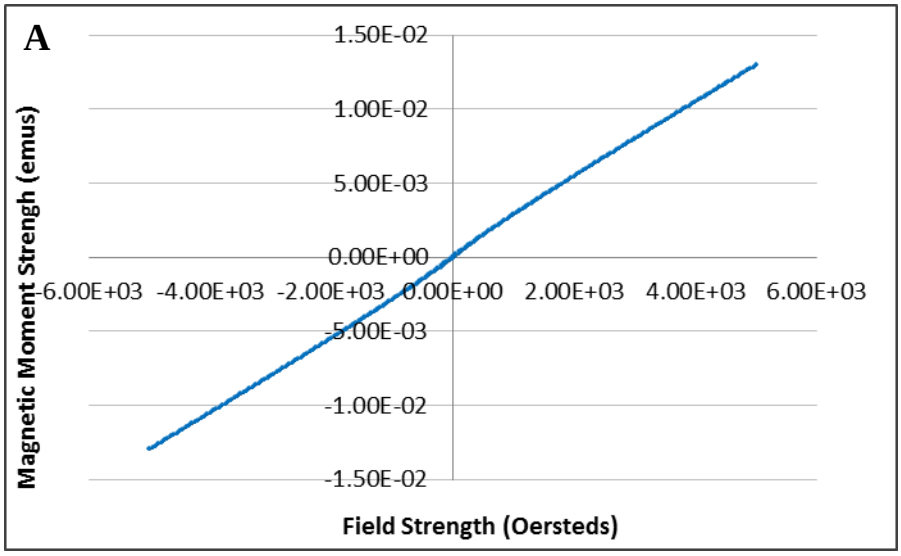
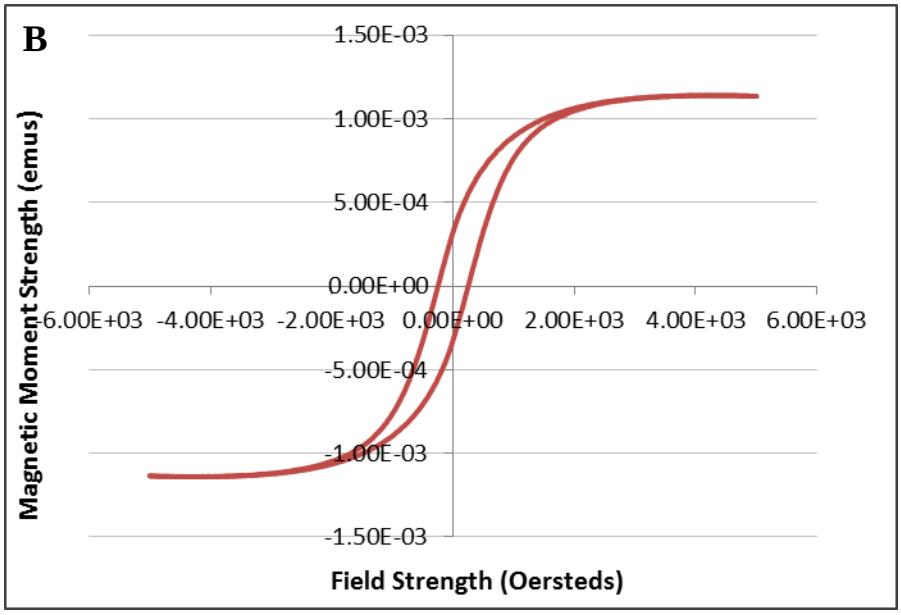


Figure 8: Oven temperature gradients observed from temperature stickers placed on samples inside the oven. A) High temperature (>200°C) demagnetization steps: Blue=LW 212°C, Red=LW 197°C, Green=MH/LW 204°C, Purple=Rat Creek 225°C. Dashed Lines with corresponding colors indicate the temperature shown on the digital display for that particular boat. B) Low temperature (<200°C): Blue=Leavenworth 197°C, Red= Leavenworth 160°C, Green=RC 188°C.


A
1.50E-02
1.00E-02
5.00E-03
0.00E+00
-5.00E-03
-1.00E-02
-1.50E-02
-6.00E+03 -4.00E+03 -2.00E+03 0.00E+00 2.00E+03 4.00E+03 6.00E+03
Magnetic Moment Strengh (emus)
Field Strength (Oersteds)


B
1.50E-03
1.00E-03
5.00E-04
0.00E+00
-5.00E-04
-1.00E-03
-1.50E-03
-6.00E+03 -4.00E+03 -2.00E+03 0.00E+00 2.00E+03 4.00E+03 6.00E+03
Magnetic Moment Strength (emus)
Field Strength (Oersteds)

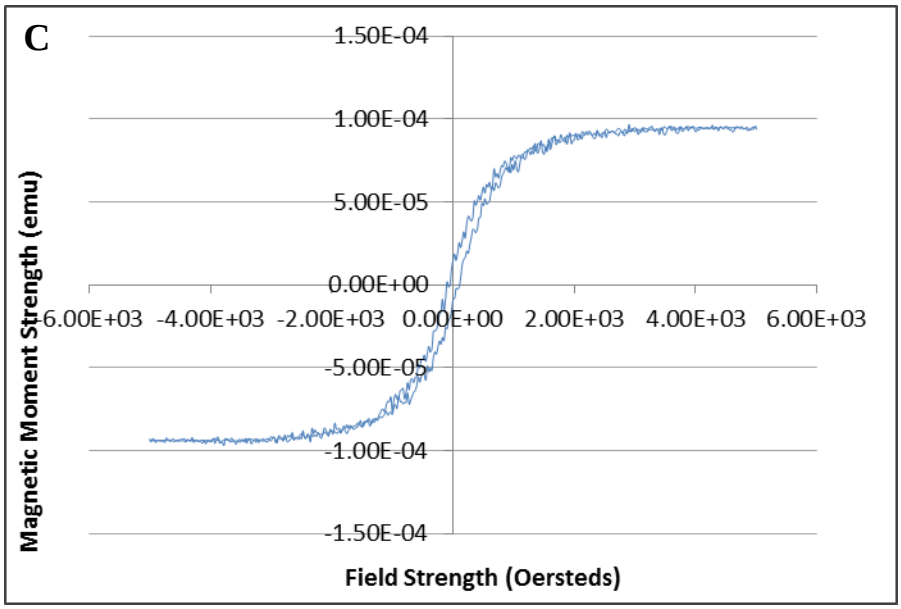


Figure 9: Hysteresis loops for A) LE01AT, a whole-rock specimen with hysteresis dominated by the paramagnetic behavior of biotite, B) LW09B2, a specimen crushed to powder and segregated into felsics and mafics. Felsics were placed in a gel capsule. Hysteresis shows curving but open loop, indicating uniaxial single domain magnetite. C) Hysteresis loop for RC02B2, showing a curving but narrow loop, indicating pseudo-single domain magnetite.

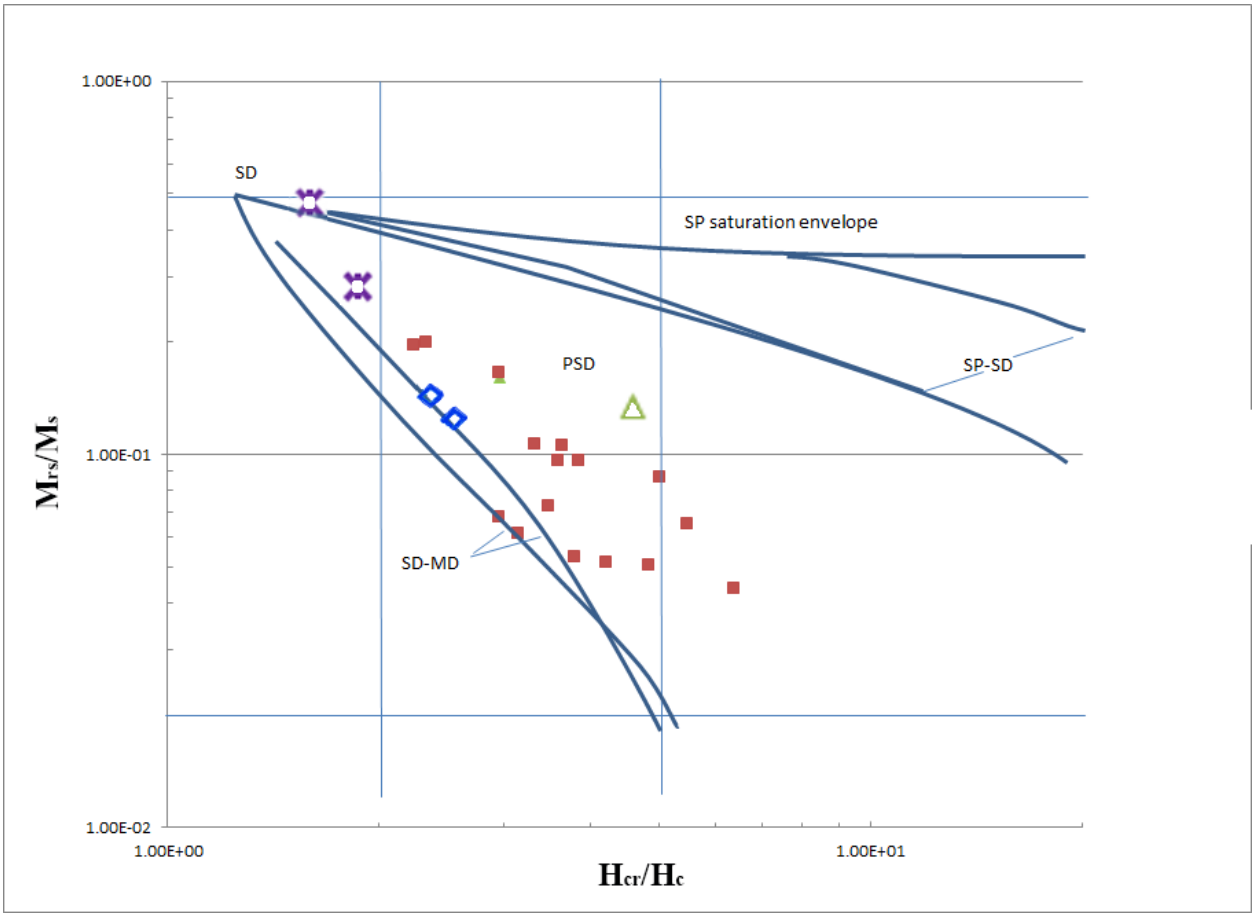


Figure 10: M_{rs}/M_s vs. H_{cr}/H_c ratios plotted on a Day Plot for samples subjected to vibrating sample magnetometer testing. Filled symbols represent whole rock specimens, open symbols represent powdered specimens. Leavenworth I= red squares, Leavenworth II=purple crosses, Rat Creek=blue diamonds, Peshastin=green triangles. Single domain (SD), multi-domain (MD), and super-paramagnetic (SP) domain boundary lines shown. Pseudo-single domain (PSD) and SD zones shown. With few exceptions, all samples from this study fell into the PSD zone, indicating PSD magnetite is the magnetic remanence carrier.

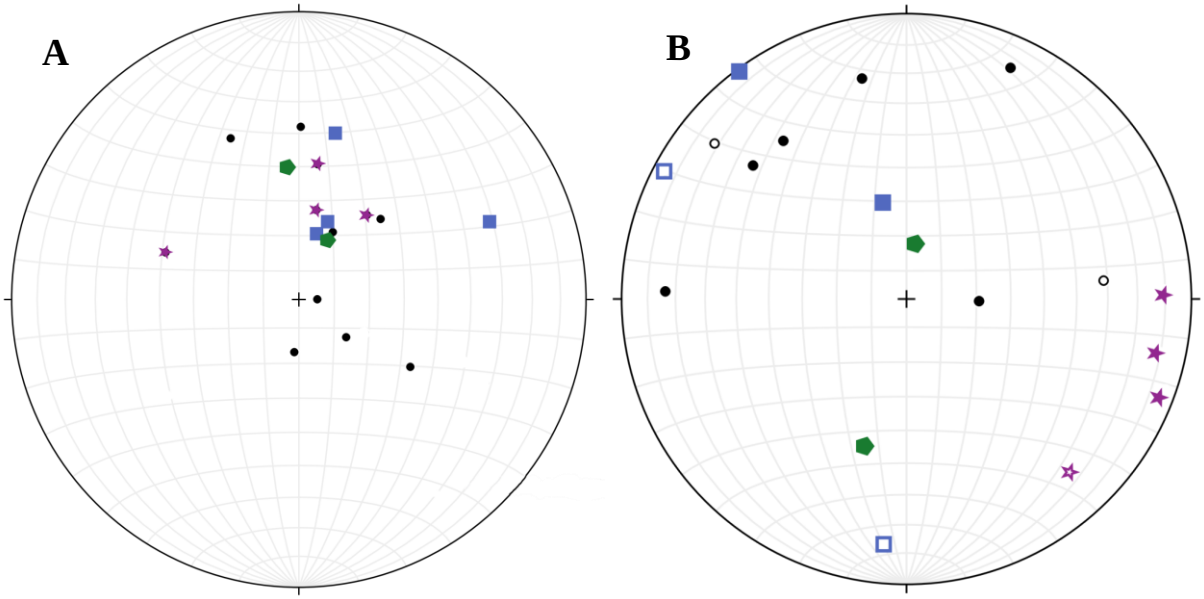


Figure 11: Stereonets of A) TVRM and B) TRM components of qualifying samples. Using a conical best fit for qualifying samples returns a trend of 26^{o} and plunge of 72^{o}. By contrast, current magnetic north in the study area has a declination of 16^{o} and plunge of 70^{o}. Whereas the TVRM components are clustered around magnetic north, the TRM directions are randomly distributed, as expected. Rat Creek=blue squares, Leavenworth=black circles, Mountain Home=purple stars, Peshastin=green hexagons.

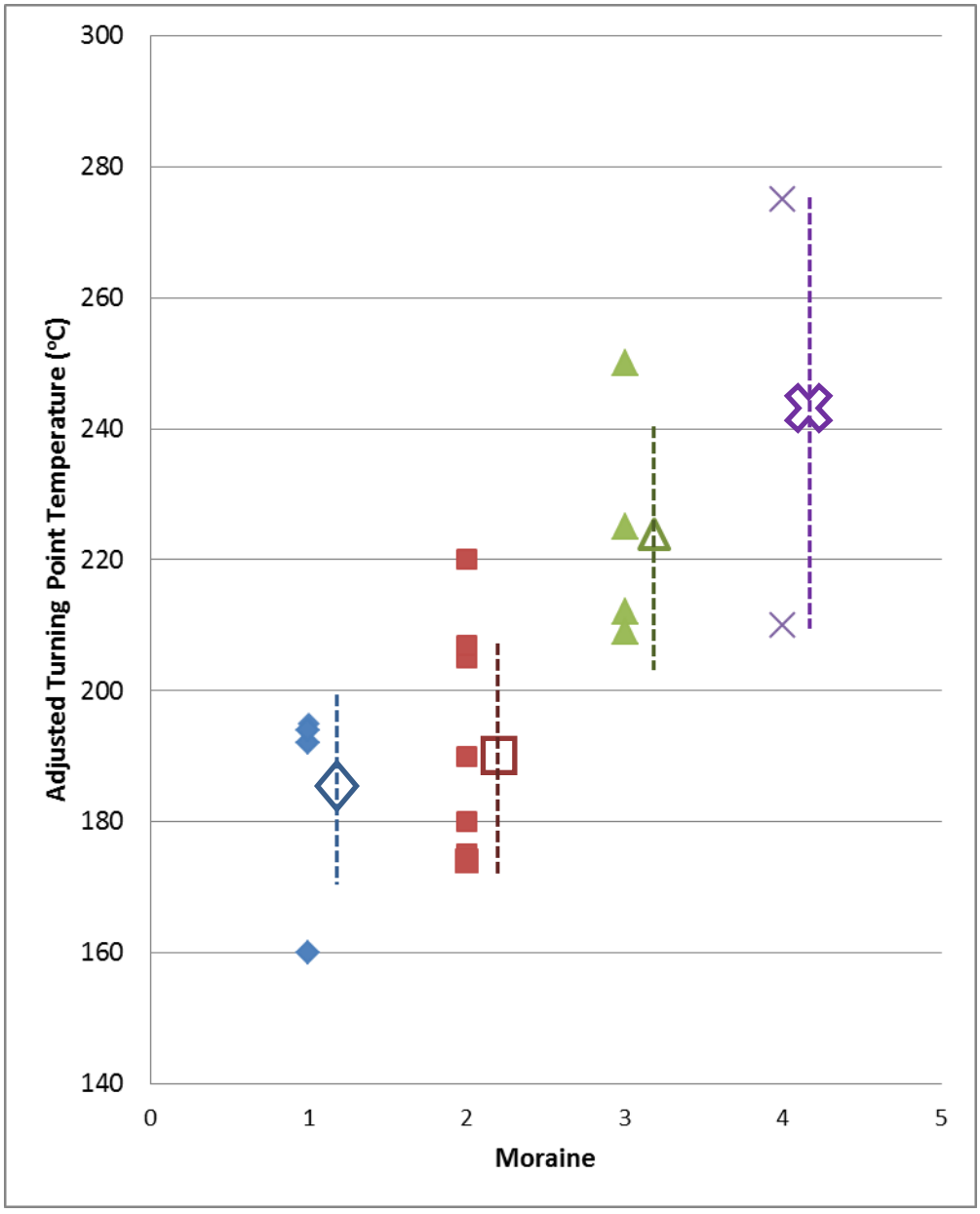


Figure 12: Adjusted turning point temperatures for qualifying samples, by moraine. Pilot LE and LW are combined, since we assume they are too closely spaced in time to distinguish with paleomagnetism. Mean turning point temperatures are shown as matching hollow shapes. Standard deviation ranges are shown as dashed lines intersecting the mean temperatures adjacent to specimen turning points. Rat Creek is represented by blue diamonds, Leavenworth by red squares, Mountain Home by green triangles, and Peshastin by purple crosses.

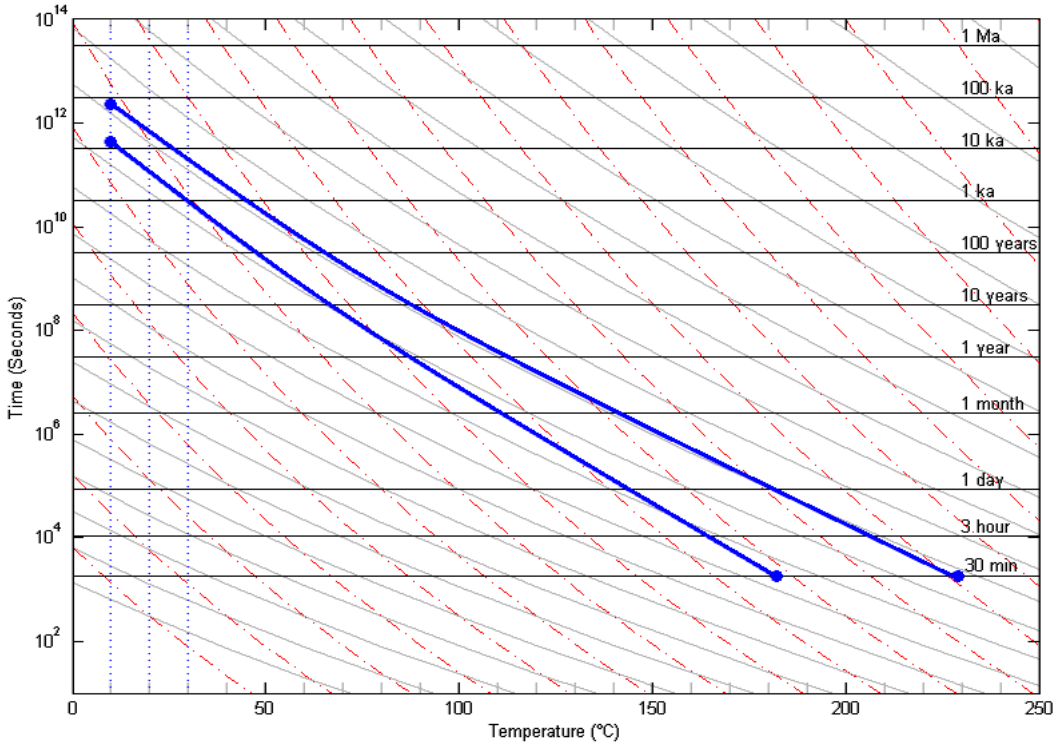


Figure 13: Time-temperature nomographs for thermal demagnetization of magnetite according to Pullaiah et al.(1975) (red dashes) and Middleton and Schmidt (1982) (black solid). Laboratory conditions for Rat Creek and Mountain Home moraines shown as solid blue circles. Thick blue lines connect laboratory conditions to field acquisition conditions, shown in solid blue diamonds in the upper left.

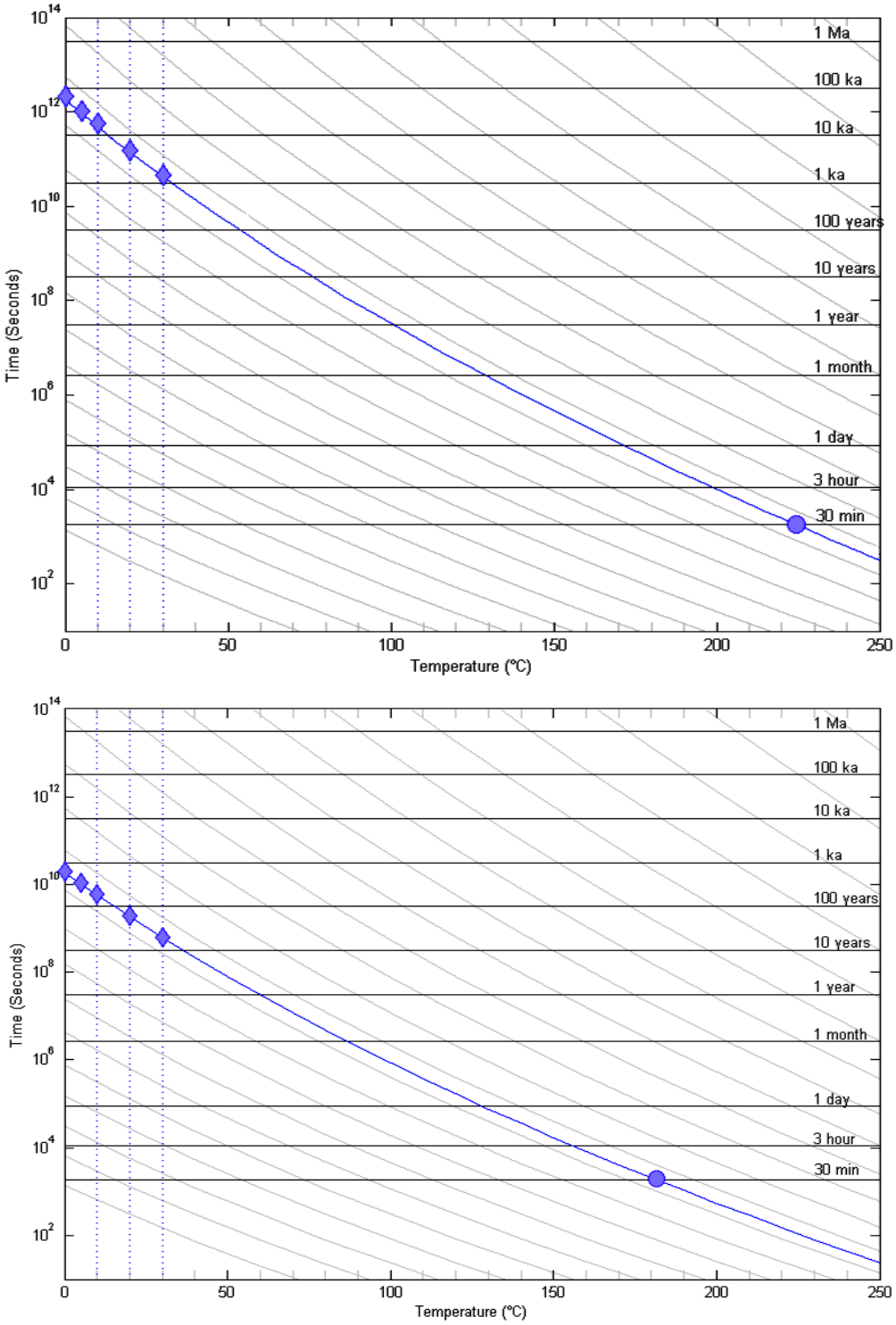


Figure 14: Following Middleton and Schmidt (1982) time-temperature nomographs, TVRM laboratory acquisition conditions shown as a circle with a suite of possible field acquisition temperatures represented as diamonds, for A) Mountain Home and B) Rat Creek. Assigning a field acquisition temperature between 0°C and 5°C results in a moraine age most in agreement with cosmogenic results of Porter and Swanson (2003).

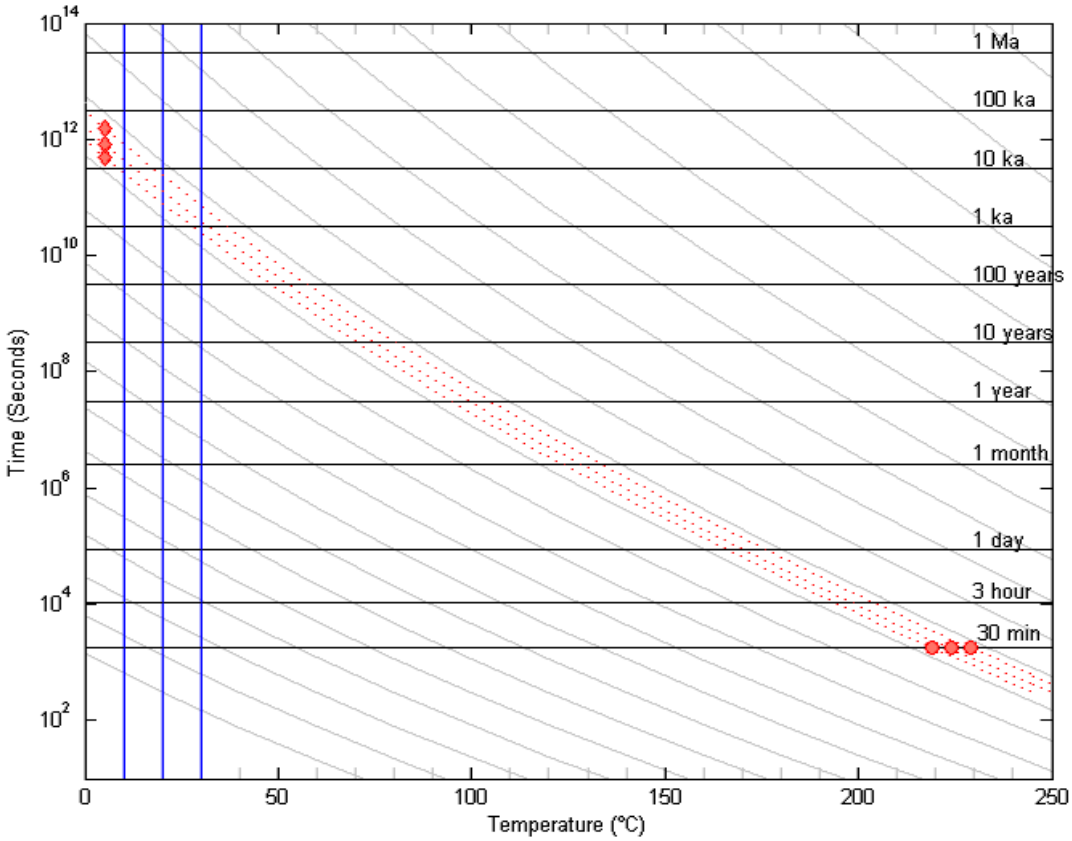


Figure 15: Mountain Home TVRM laboratory acquisition conditions plotted as the center of the three circles, with adjacent points plotted to show the error if the turning point temperature is mis-located by +/- 5°C. Following Middleton and Schmidt (1982) time-temperature nomographs and assuming a field-acquisition temperature of 5°C, we obtain moraine ages of 15ka, 35ka, and 80ka, plotted as diamonds in the upper left.

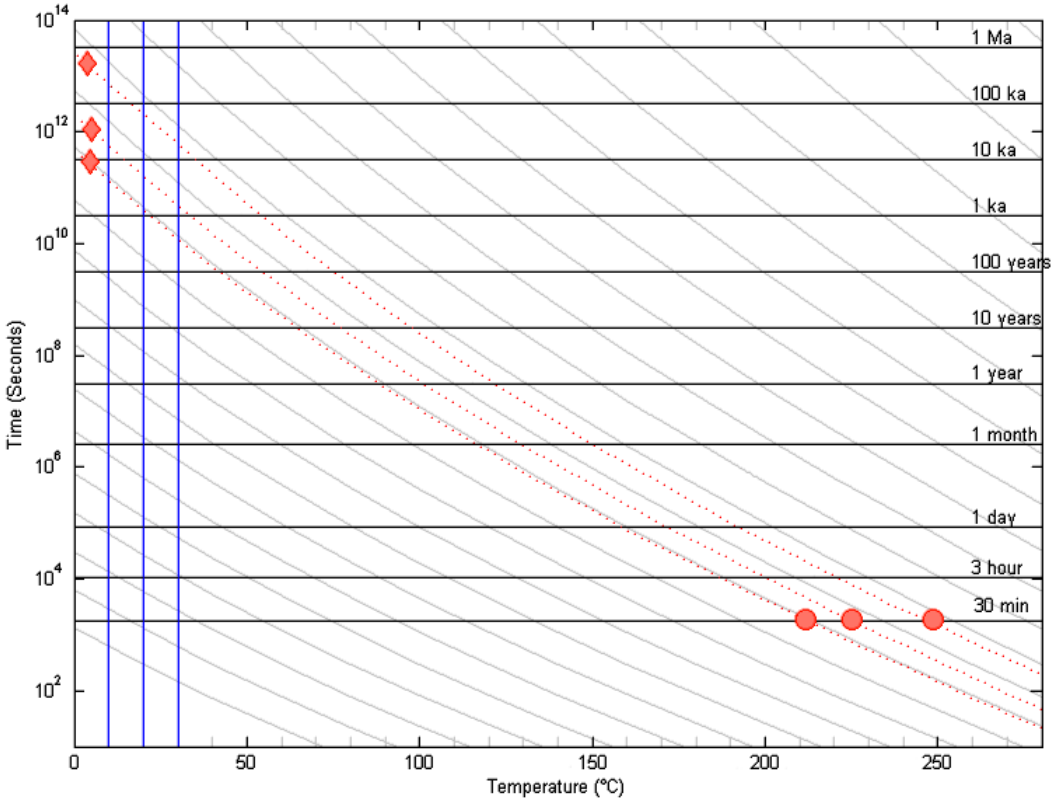


Figure 16: TVRM laboratory acquisition conditions for individual qualifying samples of the Mountain Home moraine plotted as circles, connected to field acquisition conditions assuming a field acquisition temperature of 5°C. Points are connected by Middleton and Schmidt (1982) time-temperature nomographs

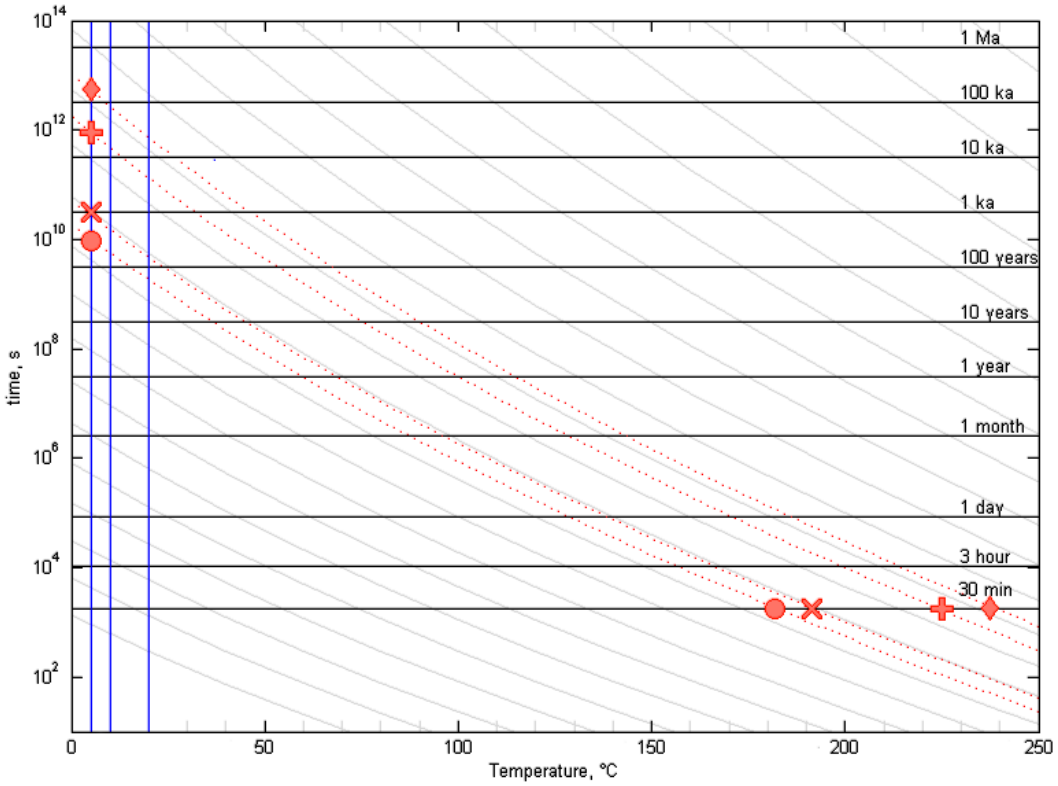


Figure 17: Laboratory acquisition conditions plotted in the bottom right for all four moraines: Rat Creek = circle, Leavenworth = x, Mountain Home = plus sign, Peshastin = diamond. Following Middleton and Schmidt (1982) time-temperature nomographs and assuming a field-acquisition temperature of 5°C for all moraines, we obtain moraine ages of 300, 1ka, 35ka, and 160ka, for Rat Creek, Leavenworth, Mountain Home, and Peshastin, respectively, plotted in the upper left as field acquisition conditions.