Figure 1. The Canadian Cordillera showing terranes studied here. Rectangles denote sampling regions: 1—southeastern British Columbia for Cache Creek, Quewel, and Kootenay samples (KO = Kootenay terrane proper); 2—Wells-Backer River region for Quewel, Slide Mountain and Kootenay/Cassiar-equivalent samples; 3—Nootlin assemblage at Little Salmon Lake, Yukon.
Most terrane maps focus on Canada; map at right extends this into US.
Paleomagnetism and latitude

A cooling igneous rock or a new sedimentary rock can record the direction of the magnetic field.

\[ I = \tan^{-1}(2\tan \lambda) \]

Paleomagnetism is one of the most powerful physical observations of ancient rocks, as it is capable of revealing paleolatitude independent of climatic inference, rotation of large regions, and can provide resolve stratigraphic ties to under 10,000 years under the right conditions. The idea is that the rocks record the Earth's magnetic field faithfully; that field tells of the position of the magnetic pole and the polarity of the Earth's field. The problem is, sometimes it doesn't work out that way. To use this tool correctly, you need to know how to figure out when it works and when it does not.


The Earth's Magnetic Field

The basic field of the Earth is that of a dipole; thus the strength of the Earth's field is

\[ F = \frac{M}{a^3} \left( 1 + \frac{3}{2} \sin^2 \varphi \right) \]

where \( \lambda \) is the latitude, \( M \) is the Earth's dipole moment, and \( a \) is the radius of the Earth.

The direction of the field is towards the north (magnetic) pole, so the declination of the dipole field is 0°, and the inclination of the field, \( I \), is

\[ I = \tan^{-1} \left( \frac{\sin \varphi}{\cos \varphi} \right) \]

So far as we know, this part of the Earth's field remains pretty sensitive over geologic time other than the amplitude and the polarity. There are higher harmonics of the modern field, and they change with time (there is some debate over whether a couple of those terms exist at very long (million year) time scales). These somewhat smaller changes are termed secular variation, and the changes in inclination and declination they produce are observed by magnetic measurements over the past few centuries. Thus an instantaneous measurement of the Earth's magnetic field will not point to geographic north, but one averaged over thousands of years will. When using a paleomagnetic direction for estimating paleolatitude or rotations, it is necessary that the measurement average enough time that equation (2) holds true.

While at this point, we note the equations governing the position of the apparent pole at latitude \( \lambda' \) and longitude \( \phi' \) from a measurement of the paleomagnetic field declination \( D \) and inclination \( I \) made at a latitude \( \lambda \) and longitude \( \phi \):
Paleomagnetism is one of the most powerful physical observations of ancient rocks, as it is capable of revealing paleolatitude independent of climatic inference, rotation of large regions, and can provide resolve stratigraphic ties to under 10,000 years under the right conditions. The idea is that the rocks record the Earth's magnetic field faithfully; that field tells of the position of the magnetic pole and the polarity of the Earth's field. The problem is, sometimes it doesn't work out that way. To use this tool correctly, you need to know how to figure out when it works and when it does not.


The Earth's Magnetic Field

The basic field of the Earth is that of a dipole; thus the strength of the Earth's field is

\[ F = M a^3 \left( \frac{1}{2} \sin^2 \lambda \right) \]

where \( \lambda \) is the latitude, \( M \) is the Earth's dipole moment, and \( a \) is the radius of the Earth.

The direction of the field is towards the north (magnetic) pole, so the declination of the dipole field is 0°, and the inclination of the field, \( I \), is

\[ I = \tan^{-1} \left( \frac{2 \tan \lambda}{1} \right) \]

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\[ \sin \varphi' = \sin \lambda' \cos \varphi + \cos \lambda' \sin \varphi \]

or

\[ \varphi' = \lambda' \pm \tan \frac{D}{\cos \lambda} \]

when \( \cos \varphi < \sin \lambda' \sin \lambda \) and \( I = 2 \cot \varphi \) when \( 0 \leq \varphi' \leq 180° \).
International Geomagnetic Reference Field Model -- Epoch 2020

Main Field Declination (D)

Map Date: 2020

Units (Declination): degrees (red contours positive (east), blue negative (west))

Contour Interval: 2 degrees

Map Projection: Mercator

-180˚ -150˚ -120˚ -90˚ -60˚ -30˚ 0˚ 30˚ 60˚ 90˚ 120˚ 150˚ 180˚

https://www.ngdc.noaa.gov/geomag/data/mag_maps/pdf/
Crystallization of muscovite because they may not have enough aluminum or enough hydrogen to make the OH complexes that are necessary for mica minerals. Typical felsic rocks are granite and rhyolite (Figure 3.3.5).

The cooling behaviour of intermediate magmas lie somewhere between those of mafic and felsic magmas. Typical mafic rocks are gabbro (intrusive) and basalt (extrusive). Typical intermediate rocks are diorite and andesite. Typical felsic rocks are granite and rhyolite (Figure 3.3.5).

A number of processes that take place within a magma chamber can affect the types of rocks produced in the end. If the magma has a low viscosity (i.e., it's runny)—which is likely if it is mafic—the crystals that form early, such as olivine (Figure 3.3.6a), may slowly settle toward the bottom of the magma chamber (Figure 3.3.6b). This process is known as fractional crystallization. The crystals that settle might either form an olivine-rich layer near the bottom of the magma chamber, or they might remelt because the lower part is likely to be hotter than the upper part (remember, from Chapter 1, that temperatures increase steadily with depth in Earth because of the geothermal gradient). If any melting takes place, crystal settling will make the magma at the bottom of the chamber more mafic than it was to begin with (Figure 3.3.6c).

**Igneous remanent paleomagnetism**

Earth's field

Curie temperature

Earth's field

Earth's field

800°C

magnetic grains

500°C

<300°C

If $T_b > 300°C$
to the geomagnetic field. As subsequent material is deposited on top of it, the dip the grain initially had from the horizontal may be flattened significantly, leading to shallowing of the inclination of the paleomagnetic vector (Fig. 1). Several authors have explored the issues related to inclination shallowing and developed statistical techniques to calculate the degree of shallowing expected for various sediments (e.g., King, 1955; Anson and Kodama, 1987; Deamer and Kodama, 1990; Jackson et al., 1991; Sun and Kodama, 1992; Hodych and Bijaksana, 1993; Kodama and Davi, 1995; Tan et al., 2002, 2007; Kent and Tauxe, 2005; Bilardello and Kodama, 2010; Kent and Irving, 2010).

Fig. 1 (A) Schematic diagram of detrital remanent magnetization showing magnetic mineral grains settling out of a water column with some compaction (and thus inclination shallowing) in the lower sediments. (B) Schematic diagram of chemical remanent magnetization showing development of a magnetic mineral cement, such as hematite, in interstitial spaces. In both, large arrow represents the ambient magnetic field and smaller arrows represent the magnetization of the grain or cement.
Note that the latitude of the pole must be between \(-90°\) and \(+90°\) and that the paleocolatitude is \(p\) (compare the last equation with eqn 2).

You can also worry about the reverse problem of predicting the direction given an apparent pole position:

\[
\cos p = \sin \theta \sin \gamma + \cos \theta \cos \gamma \cos \phi
\]

\[
\tan I = 2 \cot p \text{ where } 0° \% p \% 180°
\]

\[
\cos D = \sin \theta \sin \phi \sin \gamma + \cos \theta \cos \gamma \cos \phi
\]

\[
\text{where } 0° \% D \% 180° \text{ for } 0° \% \gamma \% 180° < D < 360° \text{ for } 18° < \gamma < 360°
\]

### Magnetic Minerals

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Composition</th>
<th>Curie Point</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetite</td>
<td>Fe(_3)O(_4)</td>
<td>580°C</td>
<td>Magmatic, occasional metamorphic and chemical</td>
</tr>
<tr>
<td>Titanomagnetite</td>
<td>Fe(_2)Fe(<em>x)Ti(</em>{1-x})O(_4)</td>
<td>150-580°C</td>
<td>“</td>
</tr>
<tr>
<td>Hematite</td>
<td>(\alpha)-Fe(_2)O(_3)</td>
<td>675°C</td>
<td>Often sedimentary, chemical, sometimes magmatic, metamorphic</td>
</tr>
<tr>
<td>Maghemite</td>
<td>(\gamma)-Fe(_2)O(_3)</td>
<td>590-675°C — goes to hematite above 250-750°C</td>
<td>Chemical</td>
</tr>
<tr>
<td>Pyrrhotite</td>
<td>FeS(_{1+x}), 0&lt;x(\leq0.14)</td>
<td>320°C</td>
<td>Magmatic, chemical</td>
</tr>
<tr>
<td>Goethite</td>
<td>(\alpha)-FeOOH</td>
<td>120°C (dehydrates 100-300°C)</td>
<td>Chemical (weathering)</td>
</tr>
<tr>
<td>Lepidocrocite</td>
<td>(\gamma)-FeOOH</td>
<td>Below room temperature (dehydrates 250°C to maghemite)</td>
<td>Chemical (weathering)</td>
</tr>
<tr>
<td>Greigite</td>
<td>Fe(_3)S(_4)</td>
<td>~330°C</td>
<td>Chemical (anoxic sediments)</td>
</tr>
</tbody>
</table>
3.3 Crystallization of Magma

Muscovite because they may not have enough aluminum or enough hydrogen to make the OH complexes that are necessary for mica minerals. Typical felsic rocks are granite and rhyolite (Figure 3.3.5).

The cooling behaviour of intermediate magmas lie somewhere between those of mafic and felsic magmas. Typical intermediate rocks are diorite and andesite. Typical felsic rocks are granite and rhyolite (Figure 3.3.5).

A number of processes that take place within a magma chamber can affect the types of rocks produced in the end. If the magma has a low viscosity (i.e., it's runny)—which is likely if it is mafic—the crystals that form early, such as olivine (Figure 3.3.6a), may slowly settle toward the bottom of the magma chamber (Figure 3.3.6b). This means that the overall composition of the magma near the top of the magma chamber will become more felsic, as it is losing some iron- and magnesium-rich components. This process is known as fractional crystallization. The crystals that settle might either form an olivine-rich layer near the bottom of the magma chamber, or they might remelt because the lower part is likely to be hotter than the upper part (remember in Earth because of the geothermal gradient). If any melting takes place, crystal settling will make the magma at the bottom of the chamber more mafic than it was to begin with (Figure 3.3.6c).

- **800°C**: Earth's field
- **500°C**: Curie temperature
- **<300°C**: Earth's field

If \( T_b < 300°C \)
Igneous remanent paleomagnetism

\[ M(t) = M_0 e^{-t/\tau} \]
\[ \tau = \frac{1}{C^2} \left( \frac{k}{kT} \right) \]

Earth's field
Curie temperature
Earth's field
Earth's field

800°C
500°C
<300°C

No magnetic remanence acquired at 800°C
Igneous remanent paleomagnetism

M(t) = M_0 e^{-t/\tau}

\[ \tau = \frac{1}{C} \left( \frac{K}{cT} \right) \]

Magnetic remanence at high sub-Curie temperatures

No magnetic remanence acquired at 800°C

800°C

Earth's field

500°C

Curie temperature

<300°C

Earth's field

Typical mafic rocks are gabbro (intrusive) and basalt (extrusive). Typical intermediate rocks are diorite and andesite. Typical felsic rocks are granite and rhyolite (Figure 3.3.5).

Dikes and sills (Figure 3.3.6) are common in Earth's field. Mafic and felsic magmas tend to separate, with mafic magma forming a dunite-rich layer near the bottom of the magma chamber (Figure 3.3.6b). The overall composition of the magma near the top of the chamber (Figure 3.3.6b) means that the overall composition of the magma near the top of the chamber (Figure 3.3.6b) is more mafic than it was to begin with (Figure 3.3.6c).

A number of processes that take place within a magma chamber can affect the types of rocks produced in the end. If the magma has a low viscosity (i.e., it's runny)—which is likely if it is mafic—the crystals that form early, such as olivine (Figure 3.3.6a), may slowly settle toward the bottom of the magma chamber (Figure 3.3.6a). The crystals that settle might either form an olivine-rich layer near the bottom of the magma chamber (Figure 3.3.6b), or they might remelt because the lower part is likely to be more mafic (Figure 3.3.6c). The cooling behaviour of intermediate magmas lie somewhere between those of mafic and felsic magmas. Typical mafic rocks are gabbro (intrusive) and basalt (extrusive). Typical intermediate rocks are diorite and andesite. Typical felsic rocks are granite and rhyolite (Figure 3.3.5).

No magnetic remanence acquired at 800°C.
Magnetic remanence at high sub-Curie temperatures

No magnetic remanence acquired at 800°C

Magma type

Granite
Rhyolite
Diorite
Basalt

Igneous remanent paleomagnetism

Overprinting magnetic remanence acquired by low-blocking temperature minerals

M(t) = M(0)e^{-t/\tau}

\tau = \frac{1}{C}e^{\left(\frac{MV}{KT}\right)}
Magnetic remanence at high sub-Curie temperatures

No magnetic remanence acquired at 800°C

3.3 Crystallization of Magma

measured on raw sample:
Total paleomagnetic Magnetization (NRM)

typical felsic rocks are granite and rhyolite

typical mafic rocks are gabbro (intrusive) and basalt (extrusive).

Igneous remanent paleomagnetism

Earth’s field

Curie temperature

800°C

500°C

<300°C

M(t) = M_0 e^{-t/\tau}

\tau = \frac{(k_B T)}{C}

Overprinting magnetic remanence acquired by low-blocking temperature minerals

Magnetic remanence at high sub-Curie temperatures

No magnetic remanence acquired at 800°C

Total paleomagnetic field measured on raw sample: Natural Remanent Magnetization (NRM)

A number of processes that take place within a magma chamber can affect the types of rocks produced in Earth because of the geothermal gradient. If any melting takes place, crystal settling will make the magma at the bottom of the chamber more mafic than it was to begin with (Figure 3.3.6c). A number of processes that take place within a magma chamber can affect the types of rocks produced. Overprinting magnetic remanence acquired by low-blocking temperature minerals.

Overprinting magnetic remanence.

There is yet another wrinkle: the length of time the crystal can hold on to a direction depends on the temperature. This is similar to diffusion of atoms in crystal structures that have differing magnetizations. Moving the boundaries (domain walls) within these very large grains, there are domains rather than the weak behavior expected of multidomain crystals. These have much of an energy barrier to changing direction, and their behavior is pseudo single-domain because they may not have enough aluminum or enough hydrogen to make the OH complexes. Why the two responses?
Igneous remanent paleomagnetism

So raw measurements of rocks rarely reveals the “original” primary magnetization.

Demagnetization seeks to run the acquisition of magnetization backwards…

Thermal demagnetization is perhaps most intuitive

\[ T_1 \ln C \tau_1 = T_2 \ln C \tau_2 \]
Igneous remanent paleomagnetism

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Demagnetization seeks to run the acquisition of magnetization backwards...

Thermal demagnetization is perhaps most intuitive

\[ T_1 \ln C \tau_1 = T_2 \ln C \tau_2 \]

Even though this is most straightforward for igneous rocks, thermal demagnetization often is effective on sedimentary rocks as well (many low-temperature overprints are from weathering minerals than lose remanence at higher temperatures)
Figure 8. Vector end-point plots showing laboratory demagnetization behavior of samples from type A or type B sites. (A–F) Thermal and alternating field (AF) demagnetizations of companion specimens. The samples are from three sites in the central (unfaulted) structural domain with well-defined ($\alpha_{95} < 7.5^\circ$) site-mean directions. (G–H) Thermal demagnetizations of samples from reverse polarity site 1K407 and nearby normal polarity site 3K216. Solid (open) points are the end points of remanence vectors projected onto the W-N (Up-N) planes. Diamonds indicate natural remanent magnetization (NRM); labels by squares indicate demagnetization level (in °C for thermal or in mT for AF).

Rusmore et al., Lithosphere, 2013
Solid are horizontal projection, open are vertical.
Fold test:

Magnetization acquired at deposition will maintain constant angle with bedding.
Paleomagnetism tests

Reversal test:

Normal and reversed directions will be antipodal
Paleomagnetism tests

**Conglomerate test:**

Magnetization in cobbles
will be random if not
overprinted
Sedimentary remanent paleomagnetism: Flattening

Water
Depositing sediments

Earth’s field

magnetic grains

Ziegler and Kodama, Terrestrial Depositional Systems, 2017
to the geomagnetic field. As subsequent material is deposited on top of it, the dip the grain initially had from the horizontal may be flattened significantly, leading to shallowing of the inclination of the paleomagnetic vector (Fig. 1). Several authors have explored the issues related to inclination shallowing and developed statistical techniques to calculate the degree of shallowing expected for various sediments (e.g., King, 1955; Anson and Kodama, 1987; Deamer and Kodama, 1990; Jackson et al., 1991; Sun and Kodama; 1992; Hodych and Bijaksana, 1993; Kodama and Davi, 1995; Tan et al., 2002, 2007; Kent and Tauxe, 2005; Bilardello and Kodama, 2010; Kent and Irving, 2010).
Remanent paleomagnetism: Hemispheric ambiguity

In tectonically active areas, large rotations about a vertical axis are possible, so could be in either hemisphere.
Igneous remanent paleomagnetism: Paleohorizontal ambiguity

Fig. 3. Equal-area projection on the lower hemisphere, showing site-mean directions of magnetism for the Mt. Stuart batholith. Symbols are keyed to Fig. 4; eastern sites are shown by triangles, western sites by circles. The solid square represents the Cretaceous expected direction at the present latitude and longitude of the Mt. Stuart rocks, calculated from Mankinen [19].

Beck et al., EPSL, 1981

Ague & Brandon, GSA Bull, 1996

Attention focused on one pluton for what could be wrong in pmag...
Igneous remanent paleomagnetism: Paleohorizontal ambiguity

Fig. 5. A tectonic-transport ("microplate") solution. MSP = location of Mt. Stuart Batholith; MSP = Mt. Stuart paleomagnetic pole; $K$ = Cretaceous reference pole for North America. The heavy curve bisects the distance between $K$ and MSP and therefore is the locus of all possible Euler poles about which $K$ can be displaced to MSP by a single finite rotation. The triangle shows the unique rotation pole that results from assuming that the Mt. Stuart Batholith originated on the edge of North America. MSP is shown rotated back to western Mexico about this pole.

Fig. 6. A tilt solution. Circle is the Cretaceous expected direction, with circle of confidence; triangle is the observed direction for the Mt. Stuart Batholith, also with circle of confidence. A rotation of 34.5° about a fold-axis trending N59W will bring the two into coincidence. Tilt to the southeast or west does not reduce the discordance.

Beck et al., EPSL, 1981

could translate or tilt....
Igneous remanent paleomagnetism: Paleohorizontal ambiguity

![Graphical representation of paleomagnetic data and reconstructions](image)

**Figure 10.** Depth contours computed from the best-fit paleo-surface by determining the intersection of the present topography with surfaces of constant crystallization depth (cf. text and Fig. 2A).

Beck et al., EPSL, 1981

Ague & Brandon, GSA Bull, 1996