Palaeomagnetic Analyses of the Leaf Rapids Area in Manitoba

by

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ABSTRACT

Conventional methods of analyses of palaeomagnetic data, leave a lot to be desired. Fisher statistics, by far the most popular technique, is a method that was developed long before computers were widely available. Understandably, it is not specifically a computer application. Furthermore, the necessary selective procedures used to identify "valid" palaeomagnetic samples, introduce a subjective form of analysis. In order to answer to these shortcomings in current analysis, two digital computer methods were developed. In one method, Gaussian distributions representing the probability of a position corresponding to the true value were fitted to measurements made at each cleaning field strength. The most probable orientation was taken from the location of the highest amplitude. In the second method, the same measurements were summed using vector addition. The final vector sum was assumed to the most probable orientation.

Rock core samples used in this study were obtained from the Leaf Rapids area and are of mid-proterozoic age (1800-1900Ma). These samples were analyzed in the laboratory and the results were used to test the above methods. The equipment used was a Schonstedt model DSM-1 spinner magnetometer, while magnetic cleaning was done by using an alternating frequency demagnetizer. The rock samples were collected during a reconnaissance survey carried out in 1974. The methods used in this study offers a better interpretation of the results than fisher statistics would allow.

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INTRODUCTION

This study was done on a set of rock core samples obtained from outcrops in the Canadian Shield in Northern Manitoba. The original intent of the study was to determine the apparent pole positions indicated by this sample set and to interpret the results. The author, in the early stages of the study, made investigations into the potential for resolving multiple components of remanence in individual samples. A significant amount of information is available describing the use of eigenvalue methods to accomplish such tasks in palaeomagnetic studies.[1] However, the conditions necessary for the success of this approach are very restrictive, and the results are very limited. In anticipation of applying an eigenvalue analysis, the samples were cleaned at intervals of field strengths that were finer than are usually applied. The intent of this was to provide more data and, potentially better information on the sample.

In resolving multiple components in palaeomagnetic samples, one must take great care that the individual components have some geological significance. There can be two sources of pitfalls. First, a resolved remanence may be due to an event that does not have any associated geological cause that would be considered interesting in

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[1] Eigenvalue techniques are widely applied in the fields of mathematics ,the physical sciences, and engineering sciences. It has a very general formulation. When applied to palaeomagnetics, it is restricted to the specific case of geometric forms in three-space.

a palaeomagnetic study. Remanences that are due to one or more lightning strikes, or due to weathering would be cases of no interest to the palaeomagnetist. Secondly, a remanence may be due to a flaw in the method by which the sample was analyzed. The resolved "apparent" remanence, may be the resultant partial sums of component remanences. Such a remanence would have no geological significance and would lead to faulty interpretations.

In consideration of the complexity of the general problem of resolving multiple components in palaeomagnetic samples, this thesis reviews the broader subject of material magnetizations, the behavior of the earth's magnetic field through history, and other general ideas on the topic of palaeomagnetics. This is particularly important for samples from Precambrian rocks that have had a complex geological history. This is both a detailed look that considers the immediate environment of the samples, as well as a broader picture that considers the behavior of the cratons and blocks in which the geological setting is located. Events occurring on both these scales can have profound effects upon the positions of the final apparent poles.

This thesis also presents and applies a new approach for the analyses of palaeomagnetic data. It was originally conceived as a method to represent palaeomagnetic data by using computer methods. It was later found, by application to the real data, to have significantly different computational results. As with any new method, until it has been repeatedly tested on real data and found to produce results that are consistent with both the palaeomagnetic and the geological perceptions, this method can only be accepted with a certain degree of scepticism.

Chapter II

THE MAGNETIC PROPERTIES OF SOLIDS AND ROCK MAGNETISM

2.1 Magnetic Properties of Solids

The study of magnetic materials is a quantum mechanical study. This is due to the fact that the magnetic properties of solids are primarily derived from the electron spins of orbiting electrons, the orbital angular momentum about the nucleus and changes of these motions due to externally applied fields. Contributions due to sub-atomic particles are insignificant (Kittel, 1976).

Microscopic principles of magnetic behavior have macroscopic expressions in the magnetic properties of materials. These include such things as spontaneous magnetic material, described in terms of its "magnetization" per unit volume (M), the magnetic susceptibility (X) of the sample, which is the ratio of the magnetic moment to an applied external field as well as other properties. If $X<0$ then it is termed as negative susceptibility and the sample is considered to be a "diamagnetic". If $X>0$ it is termed as positive susceptibility, and the material is considered to be "paramagnetic" (Cracknell, 1975).

Paramagnetic behavior is exhibited by materials made up of atoms or ions with permanent magnetic moments. These moments are due to spins of unpaired electrons, the orbital motions of the electrons, or a combination of both (Cracknell, 1975).

Ferromagnetic materials are materials that exhibit a spontaneous magnetic moment for sufficiently low temperatures. This can occur both with or without an external magnetic field being applied.

Ferrites are materials composed of moments from two types of sources that co-exist on different sub-lattice planes. The alignment between planes is anti-parallel. If the magnetization of the moments are different then there will be a net magnetic moment over the entire sample.

Antiferromagnetic crystals are similar to ferrimagnetic materials with the exception that with antiferromagnetic materials, the net contribution between planes is zero. This behavior is often temperature dependent.

A particularly useful property of ferromagnetic materials is that they can be ordered into domains of parallel alignment. These regions are defined by their "bloch walls". Magnetic behavior of the material can then be considered in terms of the behavior of these domains (Williams, 1966).

2.1.1 Magnetic Minerals

There are many forms of magnetic materials in nature. The particular minerals that are abundant, which are included in this class, are the oxides and the sulfides of iron. These minerals generally are found in compounds with titanium, but this is not necessarily the case (Parkinson, 1983). Often these minerals can be found in ore bodies in sufficient quantities and strengths that their fields dominate the local magnetic field.

Of all magnetic minerals, magnetite is the most common, and is also the dominant mineral where magnetic properties are concerned. Magnetite (Fe_3O_4) contains iron in both ferrous and ferric oxidation states. Other frequently occurring magnetic minerals include titano-magnetites, oxidized titanomagnetites, hematite, titanomaghemite, and pyrhotite.

When discussing optical and electron beam methods for studying magnetic materials, it should be noted that magnetic minerals can generally be easily detected. However, single domain grains can occur down to dimensions of .5 microns and these are barely within range of easy detection.

2.2 Rock Magnetism

2.2.1 Remanent Magnetization

Although there are many forms of remanent magnetization, the primary and most useful form for geological palaeomagnetic analysis are the thermal remanent components. This is the most common remanence found in igneous rocks and is directly related to thermal history of the rock formation.

The "blocking temperature" is that temperature at which the decay time of the remanence moment is at a macroscopic level.[2] The Curie temperature is that temperature above which the alignment of the magnetic dipoles become random (Williams, 1966). In the case of most igneous rocks, the blocking temperature is of the order of 50°C below the Curie temperature.

[2] It can be measured in a time frame of minutes (at least).

The actual processes which magnetically influence the rocks internally, are very complex. As they cool, reactions occur which change the crystal structures of the component minerals. Minerals which were stable at high temperature may become unstable and break down. Exsolution takes place at different rates. It is difficult to predict the properties of the individual samples as they undergo these changes. As far as the remanence is concerned, orientation of the domains is related to the external fields which are present while the rock mass cools below the blocking temperature. Long period cooling tends to average out short term fluctuations. Generally speaking, remanence grows as crystals grow beyond the blocking volume.

The remanence found in igneous rocks can usually be successfully applied to palaeomagnetic studies. Since igneous rocks generally have a less complex thermal history when compared to metamorphic rocks, it is safer to assume that the remanence reflects the earth's field at the time of emplacement; if the remanence has been correctly determined.

2.2.2 Forms of Remanent Magnetization

There are many terms used to describe remanent magnetization in rock samples. These terms relate to the way the magnetization was originally acquired.

Thermal remanent magnetism (T.R.M) is acquired when the temperature of the material is raised above the Curie point, and then subsequently lowered to below the blocking temperature. Above the Curie point, the magnetic domains are purely random (superparamagnetism). As the sample is cooled to below the blocking temperature, a magnetic ordering may be imprinted on the sample.

Many subaqueous sediments have weak remanences. This is due to the orientation of magnetic grains, by an external field, that was applied during the settling process. Once deposited, the orientation is preserved by cementation. This particular form of remanence is called detrital remanence (D.R.M.).

A material undergoing a chemical reaction in the presence of a magnetic field, often acquires a remanence parallel to that field. A material may acquire an individual moment in this manner which is due to a new crystal structure. This is called chemical remanent magnetism (C.R.M.).

Viscous remanent magnetism (V.R.M.), can be viewed as a change in the remanence under normal conditions of temperature and pressure. If the sample is left in an environment such as is found under field conditions or under laboratory conditions, then the remanence will change as it is subjected to the subtle influences of a magnetic and thermal origin. These changes may be rapid and large as would be the case for a "poor" palaeomagnetic sample, or small and over large geological time spans as would be found in a good palaeomagnetic sample. This change involves magnetic fields which have an internal or external origin. Since it is a change which is occurring in a rock sample under common in-situ conditions, its presence masks the primary remanence which is the remanence of interest. The "cleaning process" (which is to be discussed later), is directed primarily to the removal or identification of this particular form of remanence.

Two other forms of remanence are anhysteretic remanence (A.R.M.), and isothermal remanence (I.R.M.). They are commonly formed under laboratory conditions. Anhysteretic remanence is acquired by a sample which is subjected to simultaneously applied A.C. and D.C. fields. The A.C. field tends to imitate thermal agitation while the D.C. field provides an alignment that is favoured through energy considerations. Isothermal remanence is acquired due to the influence of an imposed D.C. field. Basically, this is similar to A.R.M. where thermal agitation at low temperature provides the impetus for change (room temperature is considered low in this context).

2.2.3 Secondary Magnetization

A rock with a primary magnetic remanence, is further subjected to processes that alter this magnetic remanence or superimposes others upon it. Viscous remanence is the alteration most often found in samples. It has a tendency to align itself with current magnetic fields.

Lightning strikes represent intense localized magnetic effects. The radius of alteration is of the order of 20 metres. Therefore, individual strikes have a minimal range of influence (Tarling, 1971).

Both mechanical and chemical weathering can form secondary magnetic remanences. Mechanical weathering produces little effect beyond the upper few millimeters. Chemical weathering, however, can cause extensive alterations to depths of hundreds of meters in porous material due to extensive solution and recrystalization. The primary chemical reaction is the oxidation of magnetic minerals.

2.2.4 Metamorphic Effects

Rocks that are subjected to pressures and/or temperatures which are sufficiently severe, will not retain their primary remanence. The processes involved can "wipe" the rocks clean of any of the original magnetic ordering, and then superimpose a new remanence associated with this latest event. This remanence can be considered primary in itself. Metamorphic influences can impose secondary remanences in a sample. Although there is no limit on the number of remanences that a sample can contain, generally the number of remanences that can be resolved is limited by the effectiveness of the laboratory and analytical procedures.

This research project found that some statistical methods can in many cases, resolve multiple remanences in single samples. It seems possible that the more severe the conditions were under which the particular remanence was imposed, the harder and more stable that remanence is (to a limit determined by the physical properties of the sample). This can be an extremely important property for the resolution of multiple components of remanence in a single sample. Since the total energy state of the Earth has decreased continually throughout history, the chance that an old remanence will survive increases with time. As well, the chance that the severity of the conditions under which the remanence is imposed is less, also imcreases with time. This increases the likelihood of resolving older remanences even though the sample has been reprinted with a new remanence. Since the energy of formation of a sample is usually the highest, subsequent remanences can usually be cleaned while still leaving the primary remanence. Of course it is local conditions alone determine the palaeomagnetic characteristics of a sample.

2.2.5 Self-Reversals

Generally speaking, the orientation of the primary remanence of a sample is aligned with the externally applied field that was present at the time of its imprinting. This is not the case for all mineral assemblages. It has been predicted that the orientation could be anti-parallel in particular cases. This prediction was made by Neel (1955), based on theoretical considerations, and is called "self-reversals". It has been supported by actual findings of such cases for example, Uyeda (1958). This is an effect which is due to a "negative exchange interaction". One phase of the sample is magnetized parallel to the external field, which causes the second phase to magnetize in response to this arrangement in an anti-parallel orientation. As the crystal evolves, the magnetic contributions due to the second phase dominate the magnetic properties of the sample.

2.2.6 Stability of Remanence

There are several ways to determine the stability of magnetization in a sample. One test, for example, is to compare rock specimens before and after storage in the laboratory. The time scale involved in comparison to the geological scale is very small, and any change in the magnetic properties of the sample will indicate gross instabilities (Tarling, 1971).

A particularly revealing test is to compare the orientations of rocks of a similar age and from a similar region. Because of their temporal and spatial correlation, their thermal and magnetic history and hence magnetic remanences can generally be expected to be similar. This comparison indicates a stability in the samples that better corresponds to the geological time scale which is involved in palaeomagnetic measurements.

Demagnetization processes can be used to study stability. More stable materials show smaller changes due to these processes. There are several types of demagnetization processes that are commonly used. Alternating field (A.F.) demagnetization utilizes an alternating field to cause random disordering of the magnetic moments. Thermal demagnetization utilizes the thermal effect to provide the disordering influence, while steady field demagnetization involves a D.C. field which opposes the direction of a particular remanence. The characteristic behavior of a stable remanence is very distinct when compared to an unstable remanence. When a "magnetically stable" sample is demagnetized, using an A.C. field, it maintains its direction and magnitude at stronger cleaning field strengths. A unstable sample shows a great deal of random fluctuations even at low cleaning field strengths. Conventional analysis requires the selection of one (or possibly two), magnetization vectors to represent the magnetic orientation(s) of a sample. In the case of unstable samples, it is difficult to select a particular vector in an objective manner and in the past such samples were discarded. However, this study has produced a method that effectively utilizes these samples. This method is described in Chapter III.

Chapter III

PALAEOMAGNETISM

3.1 Principles of Palaeomagnetics

3.1.1 Fundamental Assumptions of Palaeomagnetic Studies

The most fundamental principle underlying the use of palaeomagnetic measurements, is that the earth's geomagnetic pole provides a point of reference on the surface of the earth and that this reference point is consistent for observations made for any position on the earth's surface at a particular time. Measurements which do not correlate in time can be compared by using the apparent polar wandering paths to determine motion relative to this reference. Accompanying this principle are many assumptions that are necessary to make it use feasible. The value to determine is the virtual pole. This is the field source, axial dipole position, that by definition, is aligned with the axis of rotation; the geographic pole at that time.[3] The virtual pole is considered in terms of its position in the present-day geographical reference frame. It is described relative to the present location and orientation of the sample's magnetic moment. However, there are assumptions made as to the relationship which existed between the dipole component of the magnetic field and the axis of rotation, namely that they are, on average,

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[3] The geomagnetic pole is the vector sum of the "axial" dipole and the "equatorial" dipole.

co-linear. However, it is not critical to abide by these assumptions to obtain significant results. The choice to use the present day geographical reference frame provides a generally available frame of reference to describe the "Apparent Polar Wandering Path" (APWP).

A particularly intriguing feature of the palaeomagnetic method is that it provides information throughout the geological record. Rock magnetizations can be found that have been stable over time long periods (from as far back as the early Archean). In associating these remanent magnetizations with acceptable polar positions, it is critical to assume that over geological time, the magnetic field possessed many of the properties which are observed at the present time.

The current model of the magnetic field being considered when discussing the earth's magnetic field is one that consists of an axial dipole, a non-axial dipole, and higher order multiple components. All of which are superimposed to make up the total magnetic field. The axial dipole dominates the other two components, although they all contribute significantly to the total field. Since it is the axial field which is of interest, methods have been devised to isolate that particular component (Parkinson, 1983). Contributions due to the other sources are considered as dispersions in the statistical sense. Removal of their influence is done using statistical analysis which assumes that they are random over an acceptable time frame and an acceptable spatial frame.

It is not essential to have a full understanding of the behavior of the equatorial dipole. If its influence can be removed by whatever manner, then the remaining dipole component can be related to the geographical pole position (present at the time of magnetization). This particular component is referred to as dipole wobble about the axial position (McElhinny and Merrill, 1975). It has been shown that in recent time this particular component does average to zero (Bullard et al, 1950) but it is questionable as to whether this observation applies over geological time. It will remain an open question until the relationship which exists between the dipole moment and the axis of rotation is fully explained.

Variations of the non-dipole moment are also currently observed. These are both variations in intensity and direction, where changing directions are observed as drifting behavior (McElhinny and Merrill, 1975). The behavior of these higher order components are understood better than the behavior of the equatorial dipole. According to some authors, the ratio of the non-dipole to dipole field intensity has not shown much variation from its average value over the last two billion years: for example, Beck, 1970. For more recent time, time periods of approximately 10,000 years are sufficient, according to some authors, to statistically remove the higher order components (Creer, 1962a). Other authors, however, report that considerably more time is required (Doell, 1969). Generally speaking, given sufficient time, variations due to both these effects will average of zero , leaving an axial dipole model representation (McElhinny and Merrill, 1975).

The axial dipole exhibits variation of its own, although "wobble" which in other representations is accounted for by changes in the equatorial dipole component (McElhinny and Merrill, 1975). Considerable fluctuations in magnitude are recorded throughout geological time, including periods of reversal. Reversals are not significant in discussing tectonic activities using palaeomagnetic results, although they must be recognized for what they are. They can still be used in determining the apparent dipole orientation as opposed to actual apparent pole locations.

Palaeomagnetic results usually assume to be significantly influence by the effects of dispersion, including errors in measurement. The approach in dealing with this is to obtain a large number of samples taken over a long geological time frame and a large spatial area. As the sampling increases, so will the confidence in the results. Two factors that are commonly used to provide a measure of this confidence are dispersion (k), and angular dispersion (S), defined as follows (Wilson, 1959);

- $k = (N-1)/(N-R)$ -------------------- 1)
  - where $R = 0$ for observations randomly distributed.,
  - and $R = N$ for perfectly parallel observations
- $S = \arccos(R/N)$ -------------------- 2)

For the fisherian distribution, S is the best estimate of the standard deviation.

Palaeomagnetic results do not incorporate the complete tectonic history of the sample, nor do they consider the complete behavior of the sample in terms of its crystalline properties. The specific details of the magnetic fields that were present when remanence was acquired, cannot be determined with the method. Instead, by using statistical reasoning based on workable assumptions, a virtual pole can be determined. Accuracy of any individual pole that is based on results from samples that are up to five million years old, cannot be considered to be more accurate then five degrees from the true mean, although statistically, the results can be greatly enhanced (McElhinny and Merrill, 1975). As the age of the rock increases and errors in dating increase, confidence in a measurement will degrade. In spite of all these complicating factors, information can be obtained from samples that have been magnetically unaffected since the early Precambrian.

3.1.2 Applications of Palaeomagnetism

Palaeomagnetics can play a very enlightening role in geological studies. In general, as the data base increases in size, the amount of information that can be obtained increases. Although there is considerable controversy over the validity of the reference frames which are used, palaeomagnetism provides an accurate measure of relative motion between geological units. This is particularly important in considering the behavior of "plates" in the "plate tectonic" model of the Earth.

Using palaeomagnetic data to represent a time profile of pole positions, an APWP can be constructed. When the APWP 's associated with the units correspond, the bodies can be considered to have not undergone any relative motion (Cavanaugh, 1977). If there is divergence, then the plates have undergone relative motion.