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Résumé de l'article

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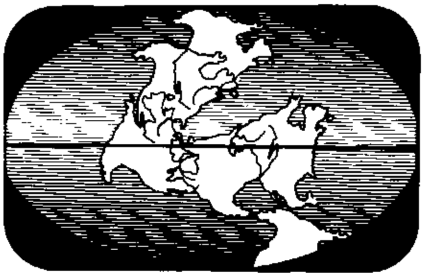

Paleomagnetism for Geologists

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Summary

Paleomagnetism is a useful tool for geologists. It gives simple data on remanent and induced magnetizations in rocks, which may help to distinguish or characterize them, determine their structural relationships with respect to other units, unravel their geological histories and infer their latitude of formation. Magnetic parameters separately, together or combined with density may also be used to identify and map various primary and secondary geological processes. In view of the utility of paleomagnetic methods, geologists and paleomagnetists should become routinely involved in joint projects.

Introduction

Paleomagnetism is now firmly established as an important branch of the earth sciences. Previously it was regarded largely as a geophysical tool: vital for studying global tectonics, the long-term properties of the geomagnetic field and the earth's core. But it is also a geological tool, whose usefulness does not appear to be widely appreciated by geologists; hence, this review paper.

Geologists may be unaware of the geological potential of paleomagnetism for several reasons. First, paleomagnetists have concentrated their efforts on deriving paleomagnetic poles and apparent polar wander (APW) paths. This preoccupation fostered the misconception that paleomagnetism had little to offer the geologist except in the study of the macro-evolution and movement of continental plates.

Second, geologists have held a lighthearted view of paleomagnetists as "paleomagicians", and this attitude has perhaps inadvertently cast doubts on paleomagnetic methods. This view grew mainly from an ignorance of the methods and from skepticism about certain results. Precambrian results, especially, invoked doubts about the validity of paleomagnetic poles. It seemed that every worker had a different interpretation of the poles and therefore a different APW path. Poles that did not fit a favoured path often seemed to be arbitrarily rejected. The result was a proliferation of APW curves, many interpreting essentially the same data. But there were natural reasons for this proliferation. First, the data base was and is insufficient to represent adequately the Precambrian period. Second, individual magnetizations have often been inadequately analyzed, and therefore sometimes wrongly identified as primary. Third, magnetizations have sometimes been wrongly dated using isotopic methods. Fourth, large errors are often associated with both poles and isotopic dates. All these reasons have provided a large leeway for the interpretation of paleomagnetic results (Roy and Lapointe, 1978; Roy, 1983).

Despite these shortcomings, paleomagnetism has a sound theoretical basis which has been justified by rock magnetic studies and by Cenozoic and Mesozoic paleomagnetic results. These results have provided important direct evidence for the movement of continents from the construction and correlation of continental APW paths. Continental movement is indirectly supported by the evidence for sea-floor spreading. But both continental drift and sea-floor spreading taken together provide strong proof of paleomagnetism's validity through the correlation of the "magnetic stripe" pattern of oceanic crust with the dated magnetostratigraphic record of reversals on land (e.g., Lowrie, 1979). In addition, many of the results and implications of paleomagnetism have been verified by other disciplines.

The same methods used for studying global tectonics are also appropriate for solving various geological problems. In his comprehensive book on paleomagnetism Irving (1964) stated that "The ultimate aim of paleomagnetic work is to build up a picture of the time variations in the earth's field in the geological past..." (p. 9), hence, the main preoccupation of paleomagnetists. However, Irving called his book "Paleomagnetism and its application to *Geological* and Geophysical Problems". He thus devotes over 100 pages to a comparison of paleomagnetic results with geological evidence and to examples of application. I will review some of these applications and many others recently developed.

Basic Assumptions of Paleomagnetism

The first assumption of paleomagnetism is that one can use rocks as fossil compasses that record the earth's field direction of the past. Experiments have proved that sedimentary and igneous rocks acquire an initial, or primary, magnetization shortly after formation, which is usually aligned along the earth's field direction. But determining whether the natural remanent magnetization (NRM) or residual permanent magnetization of rocks is primary is often problematical. The original magnetization may be unstable to later physical (temperature, pressure) or chemical processes, and so be eliminated or modified over time. If it survives, it may coexist with later, secondary, magnetizations, and be difficult to isolate and identify. Secondary, like primary, magnetizations can also reflect the ambient field direction, but may not, depending on the intensity of the preexisting magnetization and the relations between the magnetic carriers (e.g., Bailey and Hale, 1982).

The second assumption of paleomagnetism is that the time-averaged paleomagnetic field is produced by a geocentric axial dipole (GAD), so that the calculated paleomagnetic pole coincides with the paleogeographic axis (Fig. 1) (Hospers, 1954). The present configuration of the earth's field is modelled fairly closely by a geocentric dipole inclined at 11-1/2° to the geographic axis. The component left after subtraction of the dipole field from the measured field is called the non-dipole field, and amounts to some 5% of the dipole field at the earth's surface. Temporal variations in the dipole and non-dipole fields together constitute the secular variation. Despite the non-axiality of the present earth's field, the field for the past 20 million years, when averaged over periods of several thousand years comparable to those of the secular variation, approaches the GAD model (e.g., McElhinny, 1973). From the principle of uniformitarianism, this model has subse-

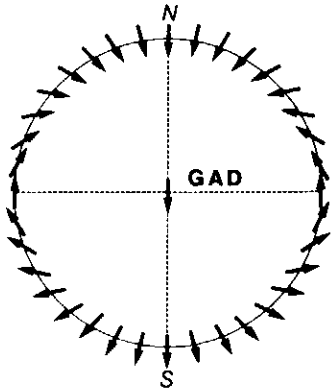

Figure 1 *Present configuration of the earth's magnetic field at the surface assuming a geocentric axial dipole (GAD). All arrows would be reversed for a reversed polarity.*

quently been assumed for progressively earlier time periods. Good agreement exists among poles obtained from rocks of roughly similar age across regions of continental extent, indicating that the model is correct to at least the Carboniferous Period (Morel and Irving, 1981). In addition, paleolatitude changes calculated from paleomagnetic data are broadly consistent with paleoclimatic changes; the distributions of various paleoclimatic indicators are latitude dependent (Irving, 1964). The GAD assumption of course does not apply to "instants" of geological time or to periods of field reversal when the dipole component diminishes.

The GAD assumption is unaffected by the possible presence of true polar wander (TPW) (e.g., Dickman, 1979; Jurdy, 1981). Apparent polar wander (APW), the concept used by paleomagnetists, denotes the apparent movement of the pole throughout time relative to some reference, usually a continental plate. APW, in fact, is largely the result of the relative movement of the lithospheric plates themselves. It may, however, contain a component due to TPW, that is, polar wander resulting from the relative movement of the lithosphere as a whole with respect to the mantle, or the mantle relative to the core. Such movements would affect equally all the calculated poles of a given age and so not affect geological conclusions based on these poles.

The Separation and Identification of Remanence Components

Paleomagnetic analysis involves resolving the NRM—the total of all magnetizations carried by a rock—into its components and establishing their sequence of acquisition. This process may be simple and straightforward, or impossible, given the techniques currently available. Generally, the NRM of older rocks is more complicated and thus more difficult to analyze. Standard techniques employed for separating magnetic components include the stepwise treatment of samples by alternating magnetic fields (AF) and by heating. Either of these techniques or a combination of them (e.g., Park, 1981) might be successfully applied to resolve the components of a particular rock. If a single magnetic component is eliminated within a discrete treatment range, it can be accurately defined by using vector subtraction (Buchan and Dunlop, 1976) or vector diagrams. Where two or more components are concurrently removed, they can sometimes be resolved or approximated by using special methods (Halls, 1978; 1979a; Hoffman and Day, 1978; Park and Roy, 1979). One of these methods, involving remagnetization circles, is particularly useful for resolving either one or both of two superimposed components (Halls, 1978). The vector resultant of two components has a direction that lies on the great-circle between the two. If a sample is subjected to stepwise AF or thermal treatment, sequential remanent magnetizations will trace out an arc of this great-circle. With sufficient dispersion in one of the components over a suite of samples, the great-circle arcs of individual samples can be extended to a convergent point, which defines the direction of one of the components. Another type of treatment, used for analyzing the NRM of red beds, involves the physical separation of magnetic phases by acid leaching. Analysis often requires the use of all these treatments, together with special directional or vector representations of the data, to fully resolve the NRM. Mineralogical, petrographical and miscellaneous physical or geophysical evidence often help in interpreting the order in which the magnetizations were acquired and whether a component is primary. Thermomagnetic analysis, which involves the measurement of saturation magnetization during heating and cooling of a sample, helps to identify the magnetic minerals and their oxidation states.

Once the NRM has been analyzed, the next problem is to obtain a relative or absolute age for each magnetic component. The problem becomes increasingly more difficult with increasing geological age as the NRM and isotope distributions become more complex.

Parameters used in Paleomagnetism

Parameters of remanent (RM) and induced (IM) magnetization are measured in paleomagnetic studies. The former relates to paleomagnetism *per se*. The latter, often routinely measured, is discussed below.

RM is described by the basic parameters of direction and intensity. Directional elements include the declination or azimuth with respect to true north and the inclination or dip from the horizontal. If the magnetic inclination is directed downward (positive), the magnetization is normal or has normal polarity. The paleomagnetic pole is calculated from the direction, irrespective of polarity, and the geographical coordinates. Because the paleomagnetic and paleogeographic poles essentially correspond, the ancient latitude (or paleolatitude) can be derived by measuring the angular distance between the site and the paleomagnetic pole. However, because the GAD field is rotationally symmetric about the paleogeographic pole, the absolute paleolongitude (or paleoazimuth) is indeterminate. Thus, from the basic RM parameters we derive the site paleopole and paleolatitude. With repeat data from other samples we calculate various associated statistical parameters. These statistics relate to the dispersion of directions owing to secular variation and to the errors of measurement and data reduction.

Although the calculation of paleomagnetic poles is based on the GAD hypothesis, working models of the earth's field are not required for using these poles to solve purely local geological problems (Blundell, 1961).

Applications using Remanent Magnetization

To Define Structural Relationships between Coeval Units. Relations between units may be inferred by comparing the directions of their primary or secondary magnetizations. The method requires good stratigraphic and paleomagnetic control, so that any measured differences that are due to APW can be ruled out. Directional differences that are solely due to structural changes can be interpreted as relative movements of translation, rotation, or tilt between sites. These differences may also help to define geological structures. Generally, the reference frame for paleomagnetic interpretation is the horizontal and the theoretical paleopole.

Translations are detectable by paleomagnetism if they result in a magnetic inclination change of greater than about 3°, that is, displacements must have a paleolatitude component of greater than 200 to 700 km, depending on the paleolatitude north or south of the paleoequator. Large translations of several thousand kilometres or more have been detected for displaced terranes located in the North American Cordillera (e.g., Beck, 1976; Irving, 1979). Similar translations have been detected between adjacent terranes along the Great Glen Fault of Scotland (Van der Voo and Scotese, 1980). Such displacements are manifested by a discrepancy in a north-south sense between calculated poles, either with respect to one another or to the standard APW path (Fig. 2).

Relative movements of tilt or rotation between sites are likewise detected by paleomagnetism, but the true amount of motion may be indeterminate owing to a complex deformational history. In general, the true amount of movement can only be calculated if it has occurred either about a horizontal axis, as in tilt, or about a vertical axis, as in "rotation". In this paper, tilt only refers to rotation about horizontal axes; rotation may refer to general turning about any axis, but here it will be clear from the context.

True relative tilt between two sites may be detected by a change of inclination between pre-tilt remanent directions or poles (Fig. 2). This measurement assumes that the sites are separated by the equivalent of a simple fold structure with horizontal axis. If the axis is inclined, more than one deformation has occurred. In this case, a simple correction of the beds to the horizontal about the line of strike will produce a declination anomaly in which the pre-tilt directions show greater variation in declination than in inclination (MacDonald, 1980). It resembles the effect of rotation about a vertical axis, which results in small-circle arcs of paleomagnetic directions. Averaging such data will lead to a direction with steeper inclination than actual, and thus a pole nearer to the site (near-sided pole) than in reality. Measurement of the apparent tilt and magnetic direction of sites on each limb of a fold enables one to calculate the orientation of the fold axis. This can be done by rotating the magnetization and bedding directions of one site into those of another (Fig. 3). The technique may be more accurate than using bedding data alone. Anomalous fold axial directions derived by this method may indicate a hidden structure, perhaps a fault oblique to the fold trend (MacDonald, 1980).

True relative rotation between two sites about a vertical axis may be detected by a declination change between pre-rotation remanent directions or poles (Fig. 2). Rotations will relate either to plate tectonics or local deformation. Paleomagnetism has been successful in defining the rotation of plates and of large land masses, such as Spain (Carey, 1958; Irving, 1964). It may be used to test whether the curvature of mountain ranges and arcuate structures is primary or secondary (Carey, 1958). On a local or regional scale, paleomagnetism may define the rotation of allochthonous, fault-bounded or differentially-folded terranes. Under favourable circumstances and with a suitable sampling scheme it should be possible to define the size, distribution, bounds and rotation axes of rotated terranes (MacDonald, 1980).

Many of the applications just mentioned imply the use of pre-deformational magnetic directions. Several tests are available having general application to geological problems that may establish whether a magnetization is pre-deformational. Three classic tests, the fold test, the "baked-contact" test and the conglomerate test are illustrated in Figure 4.

The fold test directly applies to this problem (Graham, 1949). It has been touched on briefly. It compares the coherency of paleomagnetic directions in a singly-folded and otherwise undeformed unit both before (Fig. 4d) and after (Fig. 4c) "unfolding" of the beds. Directions with lower dispersions after unfolding imply that the magnetization is pre-folding. These directions as noted will be inaccurate, and may be misleading, if the beds were folded about inclined axes (MacDonald, 1980).

The baked-contact and conglomerate tests may require additional evidence to prove whether a magnetization is pre-deformational. Both tests simply indicate whether a magnetization is primary or secondary. If the latter, it may or may not be pre-deformational.

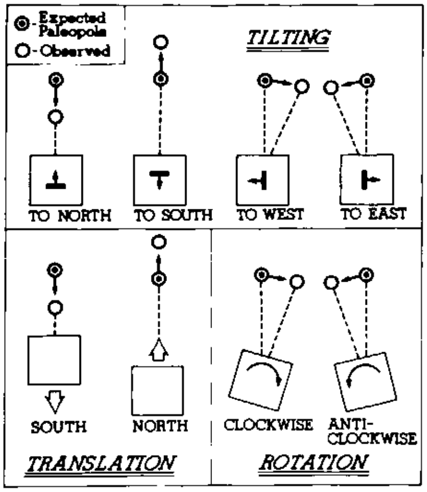

Figure 2 *Effects on the calculated pole of translating, tilting or rotating a rock body. Figure from Irving (1979; Fig. 4), used by courtesy of the author.*

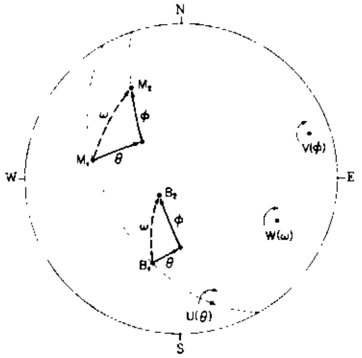

Figure 3 *Determining the axis of a fold. M_1 and M_2 are directions of magnetization on each side of the axis; B_1 and B_2 are the respective bedding directions (strike, dip). Sequential rotations of U(θ) and V(φ) rotate M_1 and B_1 into M_2 and B_2. The equivalent axis of rotation is W(ω). After Fig. 6 of MacDonald (1980).*

The baked-contact test is a powerful one in identifying a primary magnetization (Everitt and Clegg, 1962). Rocks heated by a magma will be partially or completely remagnetized in the ambient field, depending on their distance from the contact (Fig. 4). The magnetization of an igneous body is proved to be primary when its direction

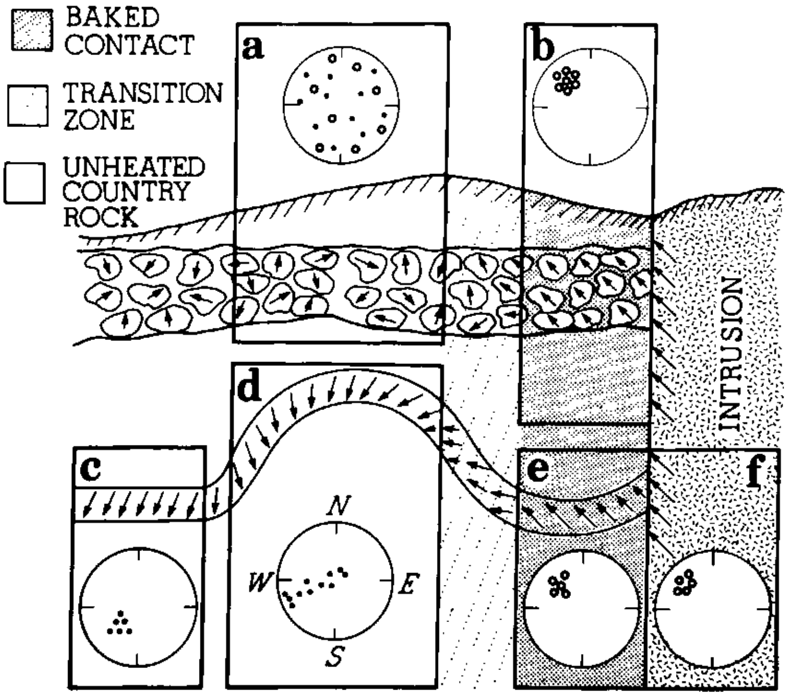

Figure 4 *Stylized geological section showing examples of three basic field tests of magnetic stability: the conglomerate test (a, b), the fold test (c,d), and the baked-contact test (c,e,f). See text for details. The circles represent stereograms oriented according to (d) with the magnetic directions in the rocks plotted with respect to the horizontal and true north. Downward (positive) directions are plotted as dots; upward (negative) directions as circles.*

(Fig. 4f) agrees with that of the baked contact (Fig. 4b, e), but disagrees with that of the unheated country rock (Fig. 4c). The agreement between the intrusion and baked contact alone does not provide unequivocal evidence of a primary magnetization, since reheating of the region or the introduction of a later chemical magnetization may produce a similar effect.

The conglomerate test (Graham, 1949) is not as conclusive as the baked-contact test. If the directions in individual cobbles of a conglomerate are random (Fig. 4a), the magnetization probably predates the formation of the conglomerate. But if the directions are grouped (Fig. 4b), the magnetization is probably secondary. In the latter case, uniform directions could result from the process of conglomerate formation, and thus be primary relative to the conglomerate itself.

To Define Structural Relationships between Subjacent Units. This comparison involves time and its absolute or relative measurement by APW paths. Absolute measurement requires well-established reference paths, such as those for the Mesozoic and Cenozoic of North America and of Europe. These paths are becoming increasingly more accurate with additional data and through precautions taken to eliminate that data possibly affected by secular variation (Harrison and Lindh, 1982). It is generally feasible to establish such paths for most of the Phanerozoic rock sequences of the world because the stratigraphic record of this period is sufficiently complete and dated fossils allow the paths to be calibrated. As yet, though, Phanerozoic paths for pre-Carboniferous rocks are not firmly established, but may be in the next decade. However, complete APW paths for the Precambrian will probably never be established because of the missing record and the pervasiveness of metamorphism. For datable Precambrian sequences the precisions of radiometric and other dating methods generally need improvement to eliminate the large absolute errors often incurred by present techniques (Roy, 1983). But even with accurate dating of Precambrian reference paths, the accuracy of pole determinations in general (~3°) will at best mean possible errors of 20 to 50 Ma. These errors can sometimes be lessened by using magnetostratigraphy to compare dated, coeval rock units.

Relative time measurements using APW paths, or magnetostratigraphic records derived from geological sections, are useful within and between sequences. They are especially useful where fossil evidence is poor or lacking (Fig. 5; e.g., 2B, 3B). Within rock sequences, time intervals of non-deposition may be dated, both very long periods or hiatuses (e.g., see Morris and Aitken, 1982) and geologically-short periods (Fig. 5; 5C). Comparisons between sequences are especially aided by the presence of reversals in the magnetic record. The reversal pattern is well-established for the past 150 Ma (McElhinny, 1973) and makes possible global correlations and the establishment of geologic time boundaries and marker horizons (Butler and Opdyke, 1979). For example, an important time-stratigraphic horizon of possible global significance has been recognized in Carboniferous strata from the Canadian east coast (Roy, 1977; Roy and Morris, in press). In Precambrian terranes, where a continuous magnetostratigraphy has not been established and the absolute polarity of magnetization is not known owing to the extensive movement of continental plates, distinct patterns of reversals and/or secular variation could be used to establish such marker horizons.

To Distinguish and Characterize Rock Units. Rock units may be characterized by their magnetic directions, polarity, or intensity. For example, the secular variation direction has been used to characterize widely separated Columbia River basalt flows (Bogue and Coe, 1981). Similarly, rock units may be distinguished by their directions. Within apparently single units it may be possible to use directions to distinguish between different phases. In another application sills and flows may be differentiated. Here, the contact test is used to indicate whether one or both contacts have been heated.

Magnetic intensities of samples are generally not as useful as directions for distinguishing or characterizing rock units. Intensities are more valuable as displayed on aeromagnetic maps, which record the combined effect of RM and IM. Here, IM is the magnetization induced in the present earth's field. Making geological interpretations from aeromagnetic maps is generally qualitative because of the often complex detail. Sometimes individual anomalies are so well-defined that they can be separated from adjacent effects; then quantitative estimates of the size and shape of the body can be made. But its position may be anomalous because of the presence of magnetic anisotropy which may deflect magnetizations from the ambient field direction (see below). Thus the body may appear to occupy a different position than its signature indicates (Hrouda, 1982).

To Determine Temperature and Depth. Secondary temperatures can sometimes be ascertained by thermal-magnetic studies. The basis of these studies is that magnetic minerals have discrete temperatures at which they acquire or lose their magnetization. Thus, magnetization is lost (becomes unblocked) at the same temperature at which it was acquired (became blocked). But there are possible complications. A magnetic carrier with high unblocking temperatures, such as hematite, may have been formed, and therefore its magnetization blocked, at very low temperatures. Or the magnetic minerals may have existed for long periods under essentially isothermal conditions. In this case the phenomenon of magnetic viscosity gradually reorients magnetic grains having progressively higher blocking temperatures—that is, those grains not initially affected by the thermal overprint.

A thermal demagnetization study can document maximum secondary heating temperatures, if they have not exceeded the Curie points of the magnetic minerals. Locally, secondary temperatures recorded in country rock may indicate the primary temperature of an intrusion (Brown, 1981) and its original depth (Schwarz, 1977; Symons *et al.*, 1980). Calculation of depth is based on both a detailed study of the magnetization with distance from the margin and on assumptions about the intrusion temperature and the geothermal gradient.

Secondary heating temperatures may also be measured by using the mineral pyrrhotite as a geothermometer (Brodskaya, 1980). Its magnetic properties vary as a function of temperature prehistory, and may be correlated to temperatures in the range 150°C to 600°C using thermomagnetic analysis.

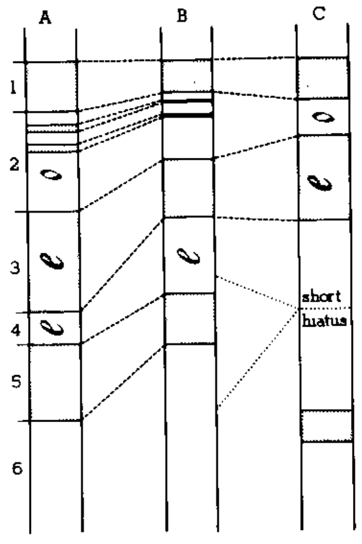

Figure 5 *Establishing the synchroneity of rock sequences by magnetostratigraphy. Shaded zones represent reversals, symbols represent fossils, numbers refer to polarity zones and letters refer to geological sections. See text for a discussion of the figure.*

Sometimes primary temperatures of volcanoclastic deposits can be estimated (Aramaki and Akimoto, 1957; Kent *et al.*, 1981). Those units deposited above their Curie point will have coherent magnetic directions; those below, incoherent directions.

To Define the Geologic History of Ores and other Units. Economic applications of the paleomagnetic method abound. Most mineral deposits contain pyrrhotite, magnetite, or hematite whose magnetization and nature can change under varying thermal and chemical conditions. Some contain special magnetic minerals, such as the spinels magnesioferrite (Mg Fe_2O_4), franklinite (Zn Fe_2O_4), jacobsite (Mn Fe_2O_4), and chromite (Fe Cr_2O_4) (Kropacek and Krs, 1968), or the tin mineral, cassiterite (Hanus and Krs, 1965). The last has varying amounts of iron bound into its lattice. These minerals may preserve a record of the mineralization and serve to delineate this history, either in a relative or absolute manner.

Absolute ages may be estimated by relating magnetic poles to calibrated polar paths or to isotopic ages. Standard APW paths are somewhat crude at present, but may be useful for dating under some circumstances. They have been used to date stable hematite remanences associated with mineralization. Thus epigenetic (hydrothermal) deposits have been dated (Hanus and Krs, 1963; Krs and Stovickova, 1966) and different ages of mineralization have been distinguished (Hanus and Krs, 1963). In the last case, hydrothermal mineralization of Cretaceous age in the Western Carpathian Mountains of central Europe was distinguished from subvolcanic polymetallic mineralization of Tertiary age. Standard curves have also been used to date pyrrhotite aggregates of hydrothermal origin, and so used to delineate the thermal history of a deposit (Hanus and Krs, 1968).

Magnetic ages in general do not relate to the isotopic ages. A recent advance has been made in dating thermal remanent magnetization (TRM) by using the $^{40}Ar/^{39}Ar$ method. With this technique the argon closure temperatures for minerals such as biotite and hornblende can be directly related to the blocking temperatures of magnetic minerals such as titanomagnetite. Thus the TRM can be directly dated. This fact may be applied to document the uplift and cooling history of orogenic belts, since magnetic minerals become magnetized as they cool through their blocking temperatures. A case study involves the Grenville Structural Province of the Canadian Shield (Berger *et al.*, 1979). However, it should be realized that absolute dating by paleomagnetism is still rather crude, with errors of "tens of millions of years at best" (Hanus and Krs, 1963).

Paleomagnetism finds greater use for determining relative ages and the order of geological events. A common application is in determining whether a mineralization is epigenetic or syngenetic. Thus, if the directions of the ore and its host differ, the ore was formed epigenetically, but if the directions coincide, both were either formed syngenetically or remagnetized post-genetically. A remagnetization could be detected by testing whether the magnetizations were primary or secondary. For example, a question had existed about the Sen-nin deposits of Japan: were they contact metasomatic deposits related to nearby granitic rocks or hydrothermal metasomatic deposits related to Miocene plagiorhyolite? The latter interpretation proved to be correct. The ore and plagiorhyolite have similar reverse directions contrary to the granitic bodies, which have normal directions (Ueno, 1975). A previous, similar, study on magnetite ore in the Hanawa black ore deposit revealed that a dacite intrusion had caused the mineralization (Ueno and Yamaoka, 1969). The method is also applicable to Mississippi-type lead-zinc deposits, where radiometric ages based on galena may be misleading (Beales *et al.*, 1974).

The relative age of mineralization may sometimes be revealed by the conglomerate test. Mineralization is often associated with conglomerates or breccias because of their permeability to ore-bearing fluids. A conglomerate test can indicate whether the magnetization associated with the ore is primary or secondary. This test has been applied to the copper mineralization of the Copper Harbor Conglomerate of Michigan (Palmer *et al.*, 1981; Halls and Palmer, 1981). It revealed that the mineralization was pre-folding, possibly produced during the formation of secondary minerals and the acquisition of a secondary, chemical remanent magnetization.

Using these techniques and others previously mentioned, a sequence of geological events may be established. The same holds true for tectonic reconstruction: a tectonic history may be documented.

An elegant example of tectonic reconstruction and the synthesis of geologic history is provided for the Sudbury Basin of Ontario by Morris (1980, 1981a, 1981b, 1981c, 1982). In this study, Morris unravelled seven distinct remanent magnetizations from the ores and rock units and then applied contact tests, tectonic corrections, blocking temperature data, and so on, to unfold the tectonic history.

Another example is the reconstruction of the deformational history of crater formation (Halls, 1979b). This involves the use of shock remanent magnetization (SRM) as found in shatter-coned rocks. Because SRM is apparently aligned along the ambient field direction at the time of impact, it serves as a reference for reorienting disrupted blocks. Thus the meteorite impact point may be found. SRM is also a sensitive indicator of shock, and may serve "to extend the range of shock effects to lower pressures"

To Test for Earth Expansion. This test has geological implications rather than applications. Several attempts have been made to document earth expansion using paleomagnetic data and triangulation techniques. The method involves comparing the past and present latitudes of separation between sampling sites of the same geological period by calculating the paleomagnetic inclination at each site. Another method involves using all the paleomagnetic results from a given period for a single continental block, and calculating the dispersion of poles for different earth radii using Fisher (1953) statistics (Ward, 1966). With this method McElhinny (1978) found that since the Devonian there has been "no systematic change of radius with time".

Parameters of Induced Magnetization

The basic IM parameter of interest to the paleomagnetist and geologist is the magnetic susceptibility, k, which is a measure of the ability of a rock to acquire a temporary magnetization in a magnetic field. The acquisition of magnetization in the present earth's field contributes to the anomalies of aeromagnetic maps. As k increases, so does the IM component of the magnetic anomalies. k generally depends on the type of magnetic mineral present, its quantity and grain size distribution. Where magnetite is present, it usually dominates the susceptibility.

When k is the same for all directions of an applied field, the rock sample is magnetically isotropic; but when k changes, the sample is magnetically anisotropic. Maximum (k_1), intermediate (k_2) and minimum (k_3) susceptibility directions may therefore be defined, and a mean called the bulk susceptibility. The anisotropy of magnetic susceptibility (AMS) is due either to a preferred alignment of magnetic grains because of shape (shape anisotropy), as in the case of magnetite, or to the alignment of strongly-magnetic anisotropic crystals, such as hematite or pyrrhotite (magnetocrystalline anisotropy). Measurement of AMS determines the attitude of magnetic grains or crystals and in general, by extension, suggests the attitude of silicate grains. These measurements are used to define fabric elements. They allow one to investigate whatever has caused or disrupted the magnetic alignment in a rock and to determine other information by using the magnetic fabric as a reference. Hrouda (1982) gives a good review of the subject.

Analysis of magnetic fabrics has special application for sedimentologists, metamorphic petrologists and structural geologists (Schwarz, 1978). The AMS method is rapid and sensitive, and measurements are potentially less error-prone than are those using standard petrographic techniques. It is particularly useful for defining fabrics that are weak or not obvious, such as igneous fabrics (Graham, 1954). However, it fails to define fabrics that are superimposed, except in the case of lineations in a plane. Therefore, where superimposed fabrics are suspected, such as in deformed rocks, corroborative geological studies should be carried out. It is also a good practice during AMS investigations to carry out standard paleomagnetic studies both to determine the possible effect of RM on the IM results and to ascertain the nature and magnetic characteristics of the magnetic minerals. Although the AMS method does not replace geological methods, it provides one with an additional set of data that can yield vital information about the silicate fabric.

Applications using Induced Magnetization

Parallel Applications to those of Remanent Magnetization. Relative movements of rotation or tilting between rock units may be discovered by using the magnetic fabric as a reference. Ellwood and Whitney (1980), for example, by assuming an original horizontal magnetic fabric, determined from field evidence that the Elberton granite of northeastern Georgia had tilted by as much as 35° about a N-NE strike. Later work corroborated and detailed various stages of the tilting by the use of RM and isotopic data (Ellwood, 1982).

A second application is in distinguishing or correlating units, especially from measurements of bulk (mean) susceptibility. Magnetic susceptibility is primarily a measure of the quantity of magnetite present; therefore it may be used to correlate units where boundaries are not visible, particularly within stratigraphic columns (Thompson *et al.*, 1975). Ellwood (1980b) has used downcore measurements of k to detect and correlate ash-layer concentrations from core to core.

Exclusive Uses of Induced Magnetization. In AMS studies of undeformed igneous and sedimentary rocks a good correspondence is generally obtained between the primary petrofabric and the magnetic fabric (Hrouda and Janak, 1976). In sedimentary rocks AMS may determine the bedding plane from anisotropic, detrital magnetite or hematite grains, or from later, chemically-formed, hematite (Hrouda and Janak, 1971). Coal banding planes may similarly be defined (Ellwood and Noltimier, 1978). AMS may also determine lineations in water-laid sediments, both direction (Hamilton and Rees, 1970; Ellwood, 1980a) and degree of development (anisotropy degree) or variation (Ellwood and Ledbetter, 1977, 1979). Although lineations *along* the flow direction are the most common, grain alignments are in some cases normal to flow, particularly when the flow has been strong (Hrouda, 1982). Both AMS and standard petrographic methods have corroborated this alternate alignment (Ellwood, 1978), which is consistent with laminar flow.

In igneous rocks the AMS method defines flow and other structure. Flow fabric generally correlates with the principal susceptibility directions unless deformation has occurred. It is thus usually characterized by magnetic foliations near or parallel to the flow direction. In lavas the lineations are occasionally perpendicular to the flow (Khan, 1962). Also, most flow fabric has a low degree of anisotropic susceptibility because of various disorienting effects present during genesis. These disruptive forces apparently affect lavas more than dykes; thus AMS results for most lavas may be unreliable (Ellwood, 1978). AMS has been used to determine the emplacement direction of dykes and the flow direction of lavas (Ellwood, 1978). In dyke and other tabular bodies AMS may help to establish attitudes.

In most metamorphic and other rocks subjected to ductile deformation AMS defines deformational elements. Generally the deformational petrofabric elements are closely correlated with the principal susceptibility directions (Hrouda *et al.*, 1978). Thus the cleavage or schistosity usually coincides with the maximum susceptibility plane and the directionally-oriented silicate grains with the maximum susceptibility directions (Howell *et al.*, 1958; Khan, 1962; Stone, 1963). But AMS results may prove to be ambiguous, owing to either the incomplete elimination of earlier fabrics under weak deformation (Borradaile and Tarling, 1981) or to the recrystallization of magnetic minerals under high deformation. In the absence of these effects delineation of the deformational fabric by AMS may serve to determine strain patterns. For example, it was shown that slates in the English Lake District that underwent the Caledonian orogenesis have magnetic foliations that parallel the cleavage planes and closely reflect the regional Caledonian strain pattern (Rathore, 1980). AMS studies may also relate the degree of directional anisotropy to the regional metamorphic grade and degree of deformation. It was demonstrated that the degree of magnetic anisotropy increases up to low-grade metamorphism represented by phyllites, and then consistently decreases with progressive regional metamorphism through schistose, gneissic, granulitic and eclogitic rocks (Fig. 6; Hrouda *et al.*, 1978).

Measurement of bulk susceptibility is potentially useful for studying various rock-forming and rock-altering geological processes, especially when combined with other physical and chemical parameters. Henkel (1976), using sample and *in situ* measurements, has documented many applications in his studies of the Precambrian shield region of northern Sweden (see below).

Bulk susceptibility studies use single measurements, continuous profiles or statistical distributions. Continuous susceptibility profiles, particularly obtained from well-logging of drillholes or from borecores, are useful to hydrogeologists and uranium prospectors. They may be used with other geophysical techniques. Susceptibility logs are useful for locating fracture zones; these zones are usually associated with low susceptibility values characteristic of altered rock (Lapointe *et al.*, 1982). Such measurements are being carried out under the Nuclear Fuel Waste Management Program of the Canadian government to ascertain the suitability of certain geological formations as radioactive waste repositories. Somewhat ironically, such borehole logs or borecore measurements of permeable sandstones may help to locate ura-

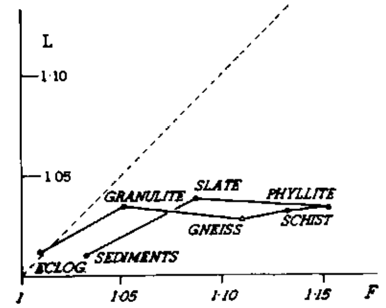

Figure 6 *Magnetic anisotropy path constructed from AMS results from about 150 rock units representing all grades of metamorphism. About 75% of the data are from rocks of Czechoslovakia. The distance from the origin represents the degree of magnetic anisotropy.* $L = k_1/k_2$ *(lineation) and* $F = k_2/k_3$ *(foliation).* k_1, k_2 *and* k_3 *are respectively the maximum, intermediate and minimum susceptibilities. The dashed line separates the regions of flattening (left of line) and constriction (right), characterized predominantly by oblate and prolate spheroids respectively. Figure from Hrouda* et al., *(1978; Fig. 2), used by kind permission of the authors.*

nium deposits (Hafen *et al.*, 1976). A third application involves the use of susceptibility contrasts to document heterogeneities within the rock column, and thus provide a technique for geological mapping (Lapointe *et al.*, 1982).

Simple plots of susceptibility distributions have several uses (Henkel, 1976). Susceptibility distributions of acid and intermediate plutonic rocks are often lognormal. Those of basic plutonic and volcanic rocks are usually complex, but can be separated by statistical methods into a set of simple lognormal distributions (Larsson, 1977), which may reflect such features as layering, grain size variations and secondary alteration. Distinct patterns repeated in related rocks may serve to relate or distinguish various rock bodies. For example, Currie and Muller (1976) used bulk susceptibility measurements to distinguish between various volcanics on Vancouver Island, and Ellwood (1978) used them to distinguish in most cases between subaerial lavas on the one hand and intrusives and deep sea lavas on the other.

Susceptibility may be combined with density (Henkel, 1976). Rock density is closely related to mineral composition, which in turn in dependent on genetic processes and subject to change by secondary processes. Magnetite is a useful indicator of primary and secondary processes that affect the density. Therefore, a study of susceptibility-density covariance may map the intensity and extent of the past activity of these processes in a rock. The primary process of differentiation in basic magmas, undersaturated or saturated in magnetite, has thus been studied (Henkel, 1976). In the undersaturated case, where the paramagnetic susceptibility is a function of the amount of mafic minerals containing iron, Henkel observed trends in both volcanic and gabbroic rocks (Fig. 7). In the saturated case, for strongly-differentiated mafic intrusions, he also observed a parallel trend forming an upper susceptibility limit (Henkel, personal communication). Similarly, he investigated certain secondary processes, such as serpentinization, uralitization, and chloritization. The serpentinization of ultramafic rocks results in an increase in the susceptibility from a growth of multidomain magnetite, and a profound decrease in the density (Fig. 7). Using certain assumptions it is possible to calculate changes in density and susceptibility for any degree of serpentinization. Resultant trends make it possible to calculate the approximate initial compositions of the silicates and their position on the magmatic differentiation trend. In the processes of uralitization and chloritization the incorporation of iron oxides into new silicates may affect the susceptibility. It is thus possible to investigate those processes operating during regional metamorphism (Henkel, 1976). The secondary process of granitization was mentioned by Henkel in reference to correlating granitized rocks (perthite granites) with acid volcanics (Fig. 8). He has since reinterpreted the considered perthite granites as being plutonic equivalents of the latter (personal communication).

Combination of Remanent and Induced Magnetization. A combination of RM and IM can be used to investigate genetic processes and grain size distributions (Henkel, 1976). Much use can be made of the covariance of the Königsberger ratio (Q_n) with either remanence parameters or susceptibility. Q_n is the ratio of the intensities of NRM and IM in the present field. Henkel has suggested from auxiliary plots of NRM directions that observed trends in Q_n/k are due to variations in the coercivities. Such plots may provide a basis for subdividing apparently homogeneous rocks into magnetic units. Henkel notes that distinct magnetic units within a particular granite seem to relate to the type and degree of the exsolution phenomena occurring among the magnetic minerals.

In a study of sediments, Ellwood (1980b) has used the AMS method in conjunction with remanence to investigate depositional processes.

Conclusion

I have shown that the rock magnetic study of RM and IM can provide geologists with useful data, which either is unavailable using other methods or corroborates existing information. The few examples noted indicate new trends in RM and IM studies and hint at a vast field of application. Just as a study of the rock-forming minerals allows for a detailed description and history of a rock unit, so a parallel study of the magnetic minerals may potentially yield some similar and perhaps additional information. Logically, geologists and paleomagnetists should collaborate and become involved in joint projects on a routine basis. For example, the Geological Survey of Sweden carries out systematic studies of susceptibility and other petrophysical properties along with their geological mapping program (Henkel, 1980).

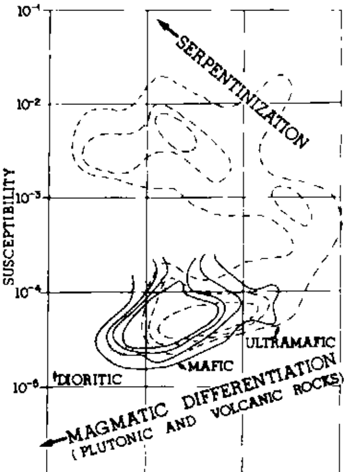

Figure 7 *Density—susceptibility trends in some plutonic and volcanic shield rocks of northern Sweden. Individual points are contoured. Susceptibility is in cgs units (x 4 π for SI units). Density is in g/cm. Figure from Henkel (1976; Fig. 6), used by kind permission of the author.*

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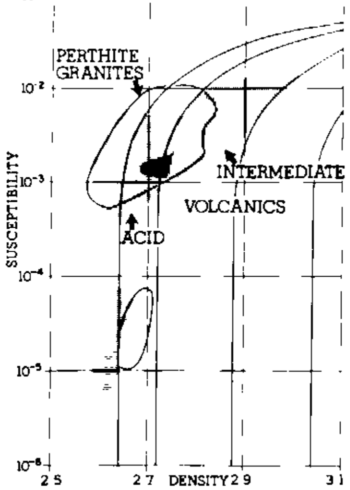

Figure 8 *Density—susceptibility plot used to infer a relation between some plutonic (enclosed solid lines) and volcanic (screens) shield rocks from northern Sweden. Solid trend lines represent the effect of increasing magnetite content on the density of the rocks. See Figure 7 for units. Figure from Henkel (1976; Fig. 8), used by kind permission of the author.*

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