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Résumé de l'article

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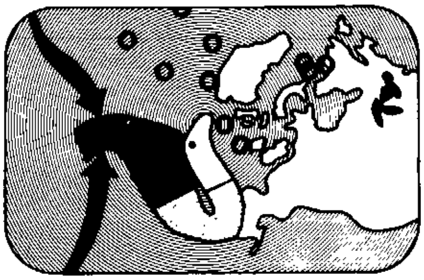

Dating Methods of Pleistocene Deposits and Their Problems: VI. Paleomagnetism

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Summary
Paleomagnetism is used in Pleistocene stratigraphic studies as a tool for correlation and relative age dating of equivalent strata or for the absolute dating of deposits. The method is based on the detection of changes in the earth's magnetic field and especially changes of polarity that are recorded by ferromagnetic sediments at the time of deposition.

The study of paleomagnetism as a geophysical dating method began in the 1960s and has grown geometrically since. Instrumentation has greatly improved and the statistical analysis of data, so essential to the proper interpretation of the magnetic record, would not have been possible without computer facilities.

Fine-grained sediments and lava flows are the two media most frequently used. Because reversals have occurred repeatedly in the past, their identification within incomplete sedimentary records is only possible through comparison with other stratigraphic or radiometric data collected for similar or related sedimentary sequences. Continuously deposited marine or terrestrial sediments which show a high sedimentation rate provide isochrons which can be used for worldwide correlation. The recent flourish of research activity into the secular variation of the earth's non-dipole field promises to greatly refine and embellish the geomagnetic time table for the Pleistocene.

Introduction
Dating of Pleistocene sediments beyond the range of radiocarbon dating as well as the dating of sediments which contain no datable carbon material has always been a problem. The new and the perfected absolute methods (potassium-argon, fission track, amino acid racemization and accelerated carbon-14) require media which are often lacking in Pleistocene sediments.

A new method of dating based upon the paleomagnetic characterization of sediments and rocks offers great promise for the partial alleviation of this problem. In the past ten years considerable use has been made of this technique in Canada, U.S.A., Japan, The Netherlands, Britain, the U.S.S.R., and elsewhere. Its major value in Pleistocene stratigraphic work will come in the near future, when a more detailed record of the secular variation of the non-dipole field becomes available.

A wide range of materials has been employed with the method. Silt to fine sand-size sediments work best, but in general any fine-grained sediment can potentially be analyzed. Marine as well as terrestrial sediments have been used. In addition, lava flows serve as excellent recorders of the earth's past magnetic field and can be sampled with relative ease. Baked pottery and other baked objects can also be used if the clay of which they are made took on a thermal remanent magnetization during the time of last baking.

Historical Review
Descriptions and measurements of the earth's magnetic properties and fields were made by von Humboldt (1797) who introduced nearly all basic principles of paleomagnetism except for the stability tests. The first descriptions of the origin of magnetism and experiments to prove it were made by Melloni (1853). Folgheraiter (1899) who studied bricks and pottery was one of the first to test the stability of the remanent magnetization found in rocks. Reversely magnetized rocks were described by Brunhes (1906), Mercanton (1926) and Matuyama (1929) and an attempt was made to date these rocks. Work by Johnson *et al.* (1948) provided an experimental basis for the acquisition of remanent magnetization in sediments through an alignment of magnetic grains in the earth's ambient magnetic field. Magnetic polarity stratigraphy has been extensively used on volcanic rocks by Roche (1951), Hospers (1954), Rutten and Wensink (1960), Cox (1973) and many others but its use in terrestrial deposits was limited. Russian workers were among the first to apply the technique to Pliocene and Quaternary sections in Turkmenia (Khramov, 1958). Other studies were carried out by Griffiths (1955), Bucha *et al.* (1969), van Montfrans (1971), Wensink (1972) and Johnson *et al.* (1975). It was with the construction of the magnetic polarity time scale (Cox *et al.*, 1964) that workers in other fields realized the potential uses of this new dating tool. The pioneering work of Cox *et al.* (1964), Opdyke (1972), Opdyke and Foster (1970) and Johnson *et al.* (1975) has provided much impetus for North American Quaternary researchers.

The purpose of this paper is to provide an overview of the method and its applications and to summarize the voluminous literature. It is intended for earth scientists unfamiliar with the technique and who have an interest in the absolute and relative age-dating of sediments. More exhaustive treatments may be found in Irving (1964), Collinson *et al.* (1967), Strangway (1970), Tarling (1971), Cox (1973), McElhinny (1973), and Zijderveld (1975).

Paleomagnetic Remanence and Susceptibility Analysis
The earth's magnetic field has two stable states: in its normal state the field is believed to wobble several tens of degrees about a dipole direction which, over the earth's surface, is directed toward the north. In its reversed state, it wobbles about a south polar direction. Transistion from one state to another takes an average of 10,000 years. A record of these changes remains in the form of remanent magnetization of sediments and rocks. In the case of volcanic rocks, this remanence, called thermoremanent magnetism (TRM) is very strong. Because of the sharpness of the transition zones, they provide very useful stratigraphic markers which are easily traceable and mappable in the field.

Two different types of geomagnetic polarity time units can be distinguished on the basis of their duration. The longer of the two is termed a geomagnetic polarity *epoch* and is defined as a time interval during which the earth's field was entirely or predominantly of one polarity; those for which we have adequate radiometric age control lasted 1 to 1.5 Ma. The shorter unit is a geomagnetic polarity *event* which occurs within an epoch and lasts about 1/10 as long. It exhibits opposite polarity to that of the epoch. The time scale for geomagnetic polarity epochs and events, constructed by Cox *et al.* (1964) and modified by other workers (see Fig. 1) is based on the potassium-argon dates and paleomagnetic mea-

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surements from about 60 lava flows from California, Hawaii, Alaska, Europe and Africa.

The lines of force in the earth's magnetic field are directed toward the magnetic poles and the angle in the horizontal plane between true north and the direction of the field is called the declination. The lines of force are also directed (except at the equator) toward or away from the center of the earth, and the angle above or below the horizontal is called the inclination (see Figs. 2 and 3). It is along these lines of force that 'memory elements' have been oriented. The memory elements are magnetic domains (local small zones within the ferromagnetic material that have a large uniform spontaneous magnetization within the various Fe-Ti oxide grains).

A 'good' sample from the sedimentary record should be fine-grained, strongly magnetized, free from secondary mineralization or weathering and unlikely to have a history of lightening strikes. Fine-grained samples are essential because minute grains of ferromagnetic material in the sediment must be oriented by the earth's ambient magnetic field rather than by the geologic agent that transported and deposited the minerals at the sampling site. Magnetization resulting from these oriented mineral grains is called detrital remanent magnetization (DRM) and conveys a record of the earth's magnetic field at the time of deposition. This DRM may be destroyed or weakened through weathering, secondary mineralization, or lightening strikes. These secondary magnetizations may be an unstable part of the original remanent magnetization and are referred to as a viscous remanent magnetization (VRM). The unwanted secondary magnetizations must be removed to isolate any existent primary magnetization which recorded the ancient earth's field. If paleomagnetism is to provide a valuable dating tool, the magnetic record must be stable and of a single component.

It has been shown by As and Zijderveld (1958) that one cannot simply divide samples into magnetically stable and unstable ones, but that each rock usually contains several natural magnetizations of different stability and often different directions. The total natural remanent magnetization (NRM) obtained by simply measuring a sample is the resultant of these different magnetizations. If a stable magnetization remains after 'quality' cleaning it is inferred to be primary. However, a primary magnetization need not necessarily be stable if, for example, it was

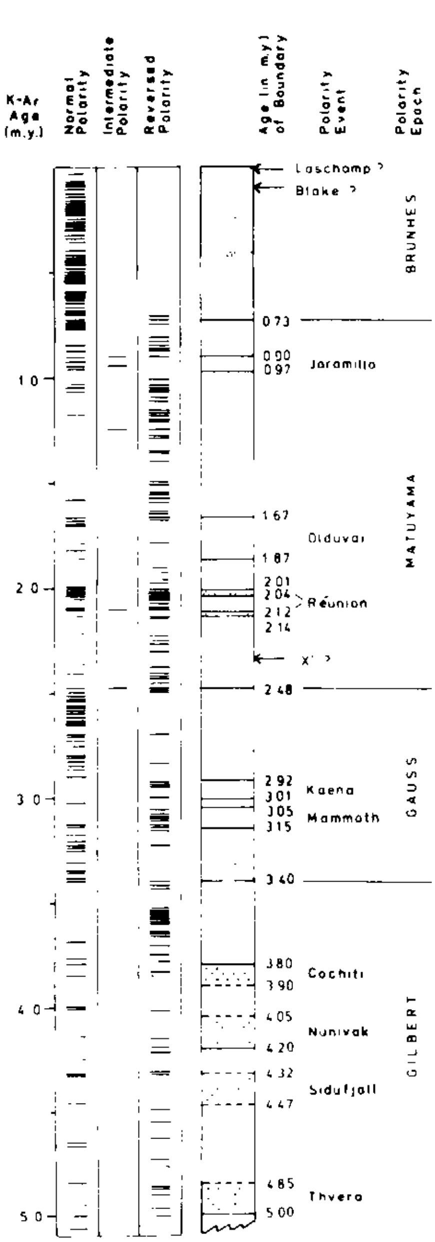


Figure 1 *Revised Late Cenozoic polarity time scale reconciled to the new K-Ar constants. Each short horizontal line indicates a potassium-argon age and magnetic polarity determined for one volcanic cooling unit. Stippled pattern indicates periods of normal polarity with coarse stippled pattern indicating events whose limits are poorly defined. Arrows indicate possible brief polarity events. The time scale is based on volcanic cooling units and deep-sea cores. (Figure is from Mankinnen and Dalrymple, 1979).*

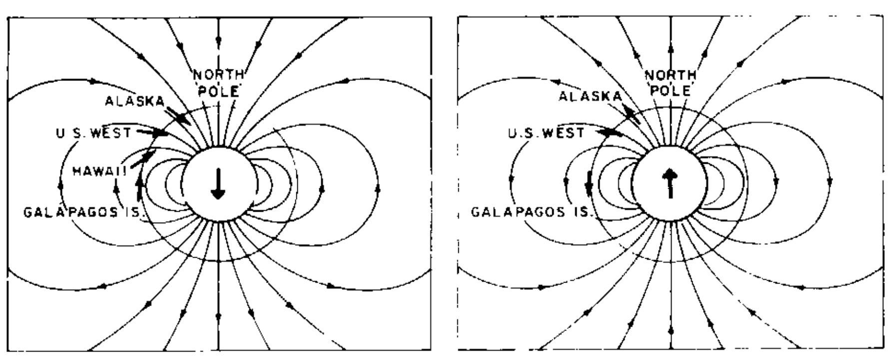
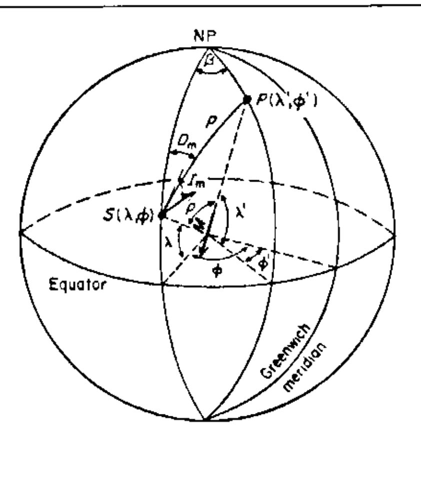


Figure 2 *Inclination angles from flows in Alaska, the U.S. (California, Idaho and New Mexico), Hawaii and the Galapagos Islands are shown by the heavy inclined arrows. The flows range up to three million years in age. The angles fall into two distinct groups: a "normal" group aligned with the earth's present field, that of a bar magnet pointed toward the South Pole (left), and a "reversed" group appropriate to an oppositely oriented field (right). All the flows on Hawaii had normal magnetism. (Figure is from Cox* et al.*, 1973).*

Figure 3 *Calculation of paleomagnetic pole from average directions of magnetization (D_m, I_m). The sampling site S has latitude and longitude (λ ϕ) and the pale P has coordinates (λ'' ϕ''). (Figure is from McElhinny, 1973).*



recorded by soft multi-domain particles.

Various field and laboratory tests have been devised to determine stability of magnetization and are outlined in all textbooks of paleomagnetism. The most commonly used method involves alternating field (a.f.) demagnetization and is best described by Zijderveld (1975). If a sample is placed in a magnetic field of a certain intensity, a part of its remanent magnetization will become unblocked from its fixed position and aligned in this ambient field. Upon intensifying this ambient field, more and more of the remanence will be unblocked and redirected. When the applied field is alternating and is slowly decreased from its peak value the unblocked grains are randomized (eliminated) leaving behind the more stable remanence fraction. The sample can be demagnetized stepwise with increasingly stronger alternating magnetic fields by which fractions with higher and higher unblocking fields are randomized. Complete measurement after each treatment gives the magnetization remaining after each demagnetization step. By vector subtraction the direction and intensity components are determined. The strength of the alternating field entirely eliminating the secondary magnetization lies at the point where the resultant vector stops changing direction. This is an important value since it is just with an alternating magnetic field of that strength, that the sample is said to be magnetically 'cleaned' at which time the remaining vector is *assumed* to be the DRM. It must be pointed out however, that vector subtraction will only yield the direction and intensity of the subtracted vector when a single component is removed. Components of remanence may have overlapping coercivity spectra so that two or more components may be removed simultaneously in the same proportion. Furthermore, 'cleaning' may in some cases leave a stable secondary remanence as for example in sediments where the smallest grains (i.e., magnetite) were finally fixed in position sometime after the main DRM. These smallest grains may be the most stable component through being single domained. Similarly a chemical overprint such as deuteric oxidation may leave a stable secondary remanence.

To better understand the means by which sediments become magnetized it is necessary to identify the magnetic minerals responsible for the NRM (see Lovlie *et al.*, 1971). If for example, the principle magnetic mineral is magnetite and the deposits are not substantially weathered, their remanence is most probably a detrital remanent magnetization (DRM) and dates from the time of deposition of the sediment.

In addition to magnetic remanence characteristics, sediments exhibit magnetic susceptibility characteristics which can be used in their differentiation. Magnetic susceptibility is a measure of the degree to which a substance is attracted to a magnet, that is, the ratio of the intensity of magnetization to the magnetic field strength in a magnetic circuit. In a mineral grain this susceptibility may be isotropic or anisotropic depending on the shape and crystallography of the grain. In general the maximum susceptibility of an irregular-shaped grain lies along its greatest dimension and minimum susceptibility across it. Magnetite, which is isotropic, has no strong crystallographic anisotropy of susceptibility. Any anisotropy in magnetite is due to the deviation in shape of the grain from a sphere. Therefore, unless most magnetite grains in a sediment are equant, the susceptibility anisotropy will reflect their alignment. In a rock or sediment however, the effects are observed only if either the crystallographic or shape axes of many grains are aligned. A primary fabric is associated with conditions at the time of deposition and is generally characterized by minimum susceptibility aligned about the normal to the bedding plane. Thus a strong anisotropy in magnetic susceptibility tends to rotate the direction of magnetization into the plane of maximum susceptibility (Uyeda *et al.*, 1963).

Gravenor and Stupavsky (1974) and Barendregt *et al.* (1976) have shown that bulk magnetic susceptibility values of glacial sediments can be used as a rapid and accurate diagnostic technique for the geologist to 1) identify the source area of sediments and 2) differentiate deposits. Gravenor and Stupavsky (1974) also showed that there is a significant correlation between the amount of magnetite and the amount of heavy minerals in a till, thus allowing magnetic susceptibility measurements to replace the tedious task of heavy mineral separation, identification and counting which is often required for till differentiation.

Absolute Age Dating

In the past, geochronological determinations using paleomagnetism have been carried out almost entirely on deep-sea sediments and lava flows. Although some evidence for reversals of the earth's field was recognized long ago, it was not until 1963 that attempts were made to define the geomagnetic polarity history. Reversals are global phenomenon and thus provide useful marker horizons for the stratigrapher.

Since several reversals have occurred in the last 2 Ma some other dating tools or stratigraphic control must identify the reversal before an absolute correlation can be made. The polarity time scale and associated nomenclature was first outlined in detail by Cox (1969) and has been refined by a sub-commission of the International Commission on Stratigraphy (International Union of Geological Sciences). A new version of the time scale (Fig. 1) has been based on more complete K-Ar data (Mankinnen and Dalrymple, 1979). The best radiometric age in the scale obtained by multiple K-Ar dates of ashes and lavas, fixes the base of the Olduvai event at 1.8 $\pm$.1 Ma (Curtis and Hay, 1972). The other dates marking boundaries between normal and reverse epochs are much less accurate.

Opdyke *et al.* (1977) have shown from work in Anza Borrego State Park in California that faunal changes from Blancan to Irvingtonian land mammal ages can be accurately dated using the magnetic record of the sediments in which the bones occur. Johnson *et al.* (1975) have shown from work in California, Texas and Kansas, that the oldest Irvingtonian fauna based on the occurrence of Lepus (hare) and other small mammals occurs within the Matuyama reversed polarity epoch in the region of the Olduvai event, while Blancan faunas occur in the Gauss normal polarity epoch and range into the lower Matuyama epoch. This correlation has also been found in Saskatchewan by Foster and Stalker (1976). Many more fossil ages will undoubtedly become fixed with continued correlation between the paleomagnetic and fossil records in terrestrial sediments (Barendregt and Stalker, 1978).

Correlation and Relative Age Dating

In addition to absolute dating, paleomagnetic studies can be used to correlate equivalent horizons and to relative age-date horizons provided they show one or more of the following: 1) secular variations, i.e. oscillations of the local magnetic vector originating principally from the non-dipole field which can be recognized over a relatively large area. (The non-dipole field is the result of local complexities in the magnetic field, having an average value of about 5 per cent of the main field at the earth's surface and showing some eight regions, of continental dimensions displaying positive or negative values with an amplitude of around .15 Oe. The non-dipole field has a westerly drift of some .2 to .3 degrees of longitude per year and is thought to originate from regions near the core-mantle boundary, where local centers of fluid motion may distort the main toroidal field locally). 2) comparable total intensity oscillations of the NRM, and 3) similar magnetic susceptibility characteristics (Gravenor and Stupavsky, 1974; Barendregt *et al.*, 1976). In these cases magnetostratigraphy affords a convenient and simple means of correlating Pleistocene deposits of either terrestrial or marine origin (see Fig. 4). One of the more exciting prospects emerging from such chronologic correlations is calibration of evolution rates and directions of dispersal in restricted mammalian species (Opdyke *et al.*, 1977; Lindsay *et al.*, 1976; and Johnson *et al.*, 1975).

The secular variation record whose basic period generally varies from 4 to 10^4 years (McElhinny and Merrill, 1975) has been shown to be of some use for regional correlations by Stober and Thompson (1977) (see Fig. 4) as well as by Turner and Thompson (1979) and Vitorello and van der Voo (1977). Turner and Thompson have shown that secular variation is not caused by wobbling of the main geomagnetic dipole as suggested by Kawai and Hirooka (1967) but rather results dominantly from more localized non-dipole changes involving both westward and eastward drift (see also Denham, 1974). They arrive at this conclusion because their 0-7000 years B.P. secular variation record from Loch Lomond sediments in Scotland does not compare with Japanese archaeomagnetic records or with North American sediment data from this same period. It is likely that secular variation generally must be due to both non-dipole and dipole changes. The matter is still under intensive discussion in the literature.

Verosub (1979) has shown that the geomagnetic pole can make large shifts of 10° or more in less than 200 years. This implies that a sudden change in the paleomagnetic directions as recorded by sediments may not be interpreted as evidence for the occurrence of a diastem (minor depositional break). Many studies have shown no magnetic anomalies in locations and sediments where they would be expected on the basis of other correlations. Though gaps in the record may be present and dating errors are possible, it is not unlikely that some apparent polarity excursions are only very localized geomagnetic occurrences or are the result of mechanical disturbance of strata. (The Internal commission on stratigraphy of the International Union of Geological Sciences defines polarity excursion as "a sequence of virtual geomagnetic poles which may reach intermediate latitudes and which may extend beyond 135° of latitude from the pole, for a short interval of time, before returning to the original polarity" (Watkins, 1976).) Much more data is needed before conclusions about the utility of secular field oscillations for stratigraphy can be made.

Correlation on the basis of intensity fluctuations presents yet another relative dating tool. Cox (1968) constructed a curve showing the variation in the dipole moment (intensity) of the geomagnetic field. The composite curve obtained by Opdyke *et al.* (1972) from deep-sea cores is similar. One must of course be confident that intensity changes are not related to lithologic or mineralogical changes. Correlation on the basis of intensity requires correction to a common datum such as the equator, since intensity varies according to latitude. It was found that a gradual drop in sample intensity often corresponds with shallowing of inclination and declination swings. Kean *et al.* (1979) have shown that bog and lake cores from Cedarburg bog and Lake Michigan have intensity records which afford good correlation having

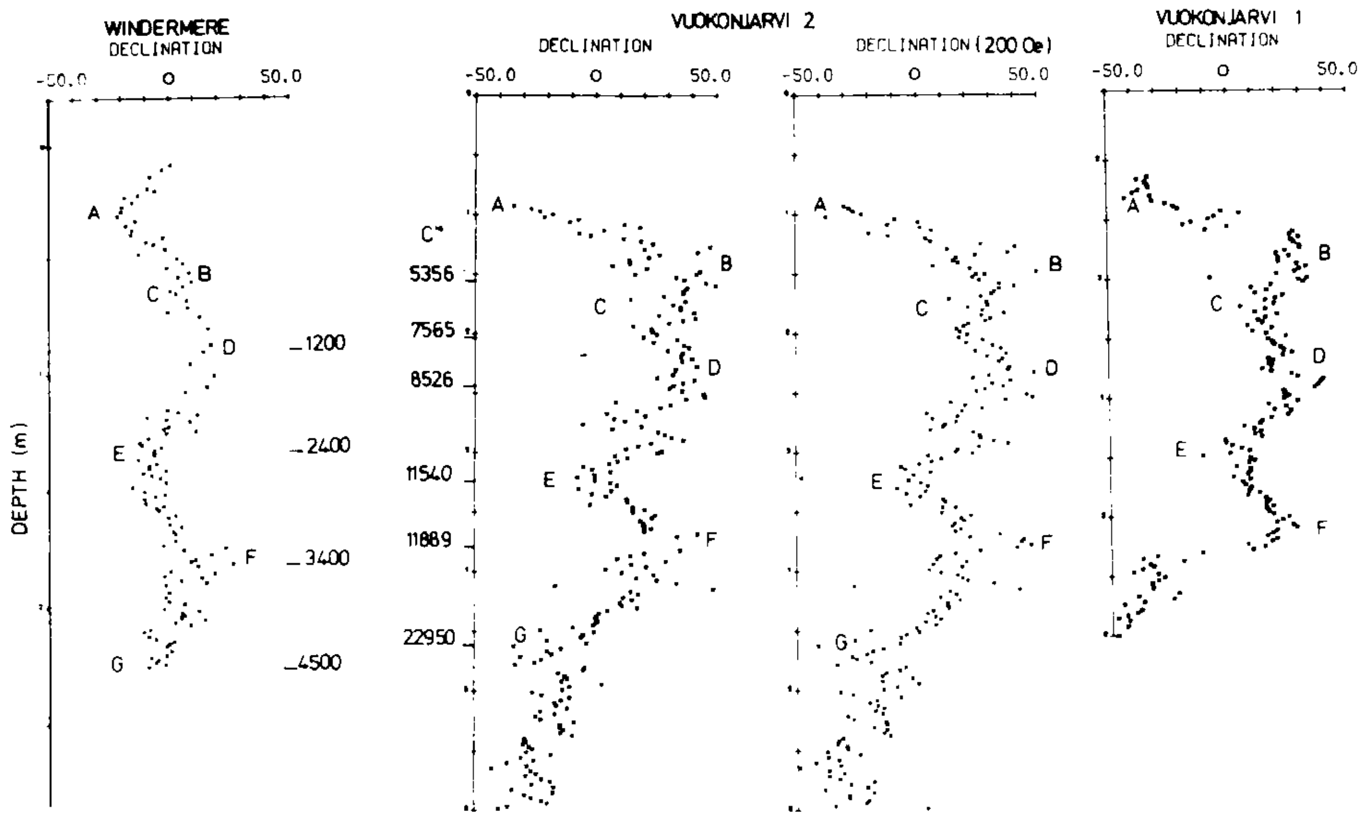


Figure 4 *Paleomagnetic relative declination logs for a core from Lake Windermere (England). Vuokonjarvi (Finland). Core 2 (NRM and partially demagnetized at 200 Oe) and Vuokonjarvi core 1 (200 Oe demag.). Windermere data is from Mackereth (1971). Figure is from Stober and Thomson (1977).*

similar long and short wavelength features, and both records are correlatable with records from Lake St. Croix described by Lund and Banerjee (1979).

Paleomagnetism can also be used to provide relative age dates for important climatic changes as revealed in changes in warm and cold water planktonic foraminiferal faunas in deep-sea sediment cores as well as ranges of sedimentation rates, and carbonate cycles. Over short term periods it has been suggested that a few per cent change in the geomagnetic field occurring over 30 years can be correlated inversely with a few degrees Celsius change in temperature (Wollin *et al.*, 1973). Over long periods of time it has also been suggested that some species of Radiolaria become extinct during certain geomagnetic polarity reversals (Hays, 1971). Similarily, lake sediments which carry both organic and mineral components can provide a biological record reflecting the climate, and a magnetic record reflecting changes in the earth's field.

Using deep-sea core data Doake (1978) has suggested that there is a correlation between changes in climate and the earth's magnetic field, the relationship being that a climatic event may cause a magnetic field reversal. One possible causal mechanism for a link could be that changes in global ice volume will affect the speed of rotation of the earth as well as either the topography or temperature field on the core-mantle boundary.

Grey (1971) and Kigoshi and Hasegawa (1971) attempted to demonstrate the importance of the geomagnetic field strength in controlling long-term carbon-14 variations and from carbon-14 data Grey predicts that the Laschamp magnetic event must have occurred between 13,500 and 29,000 years B.P. However, Barton *et al.* (1979) advise caution in using the correlation between field strength and carbon-14 variations.

Until recently Quaternary chronology was based solely on biostratigraphy: the terrestrial system on specific events of mammalian evolution and the marine system based on foraminiferal or molluscan events. The correlation between terrestrial and marine strata was very difficult because their depositional environments preclude the frequent interdigitation of diagnostic faunas and floras (Johnson *et al.*, 1975). However, with the development of magnetic polarity stratigraphy refined correlation of marine records was made possible. This technique is now being applied to the mammal-bearing terrestrial sediments providing relative and absolute time correlations with the marine record. This will hopefully make possible the construction of a comprehensive chronology for the Quaternary.

The discrepancy that exists between the climatic history as reconstructed from deep-sea sediments and the one derived from land records has long been noted. Numerous global climate changes as seen in continuous Pleistocene sequences at the sea bottom, in large lakes and in loess areas did no doubt occur. This discrepancy is not surprising since many events of the climatic record were not preserved on land because of a lack of faithful biostratigraphic recorders, or the reworking of sediments. Furthermore, the cyclic nature of the geologic record during the Quaternary caused many investigators to ignore or restructure their findings on the basis of the existing simple climatostratigraphic sequence of 4 glacials/4 interglacials. The most effective way to solve these problems is to correlate between marine and terrestrial records through use of magnetic polarity stratigraphy using both the absolute and relative dating tools it provides (see for example van Montfrans, 1971).

Problems and Limitations in Paleomagnetic Analysis

There are a number of possible reasons why the natural remanent magnetization of sediments should not always faithfully reproduce the directions of the ambient magnetic field in which they were deposited. These are outlined by van Montfrans (1971), Verosub (1975), Verosub and Banerjee (1977) and are summarized here. The reasons include the following:
1) Inclinations may be systematically low due to the preferential alignment of elongated, tabular or flat shaped magnetic particles. Inclination error may also be due to compaction after deposition.
2) The presence of currents during the deposition of the sediment, may result in systematically deviating directions of magnetization. 3) The presence of magnetic material that is too coarse to be aligned by the ambient field during or shortly after deposition and thus fail to record the directions of the magnetic field. 4) Bioturbation after deposition of the sediment results in randomly distributed directions of magnetization or a realignment of particles in a field direction different from the one present during original deposition. 5) Collapsing of sediment on a small scale during decalcification. 6) The presence of cryoturbatic structures resulting in randomly distributed directions in these structures.
7) Deformation of sediments as a result of glacial pushing (over-riding), turbidity currents, slumping, liquifaction or other processes which moves sediments away from their original depositional orientation. 8) Possible self-reversal, as a result of post-secondary alterations in the ionic ordering of the crystal framework of the magnetic constituents of the sediment (Irving, 1964). 9) Formation of new magnetic minerals during a time when the polarity of the geomagnetic field was different or opposite to the period of original deposition. 10) Instability of the natural remanent magnetization, allowing for viscous components of magnetization to set in. 11) Small inaccuracies in field sampling and preparation of specimens in the laboratory (i.e., drying). 12) Errors and misorientations, made during field sampling or labelling of samples. Coring operations may result in breaking and twisting of the sediments which may then be interpreted as an excursion. These errors can usually be traced.

For the above reasons, some sample data must be discarded because the analytical results show: 1) a remanent magnetization which makes too large an angle with the direction expected from the field of an axial geocentric dipole, taking into account secular variation,
2) the sediments were not stably magnetized, 3) the presence of a stable secondary magnetization.

The glacial sediments of the Quaternary represent special problems in magnetostratigraphic correlation. Just as glaciers picked up, transported and deposited bedrock blocks (Stalker, 1976) they may well have picked up, transported and deposited blocks of frozen glacial sediments and placed them in anomalous stratigraphic positions. Also, over-riding of glacial sediments by renewed glaciation may have induced stress deformation (Stupavsky *et al.*, 1979) and given rise to structures which will yield 'apparent' magnetic excursions, such as those described by Verosub (1975). Other mechanisms of deformation and disturbance of glacial (lake) sediments include seismic activity, turbidity flows, density currents, and periglacial activity such as cryoturbation and congelifluction. Glacial sediments often lack continuous fine-grained sediments or contain large hiatuses or were subject to erosion, all of which represent interruptions in their paleomagnetic record.

Glacial tills also represent special problems (Barendregt *et al.* 1977). Time stratigraphic lines within tills are often not horizontal due to different rates of erosion and/or deposition. Stupavsky *et al.* (1979) in a discussion of the Meadowcliffe till show a lack of correlation of the remanence characteristics over short interprofile separations leading them to conclude that the till deposition was nonuniform with rapid and variable rates of deposition from point to point within the til. In a study of the Seminary till, Gravenor *et al.* (1979) and Symons *et al.* (1980) have proposed that the thixotropic effect reported by Garnes (1977) for adobe bricks, is a probable cause for some reversed directions. According to them, the lack of correlation in remanence directions between two profiles .7 m apart and the large within-core variation of 13° between specimen pairs, suggest the possibility of remanence resetting caused by the hammer blows on the plastic tube sampler which they used.

It has been suggested that tills exhibit a magnetic remanence that is largely the result of the direction of ice movement, and not due to the presence of a layer of water at the ice/sediment interface which would have allowed the magnetic grains to become aligned in the earth's ambient field. The former has been ruled out by anisotropy of magnetic susceptibility measurements carried out by Gravenor and Stupavsky (1974) who have shown the remanence and the anisotropy of magnetic susceptibility of tills to have distinctly different directions.

Inclination errors are also commonly reported for tills. Laboratory experiments conducted by Verosub *et al.* (1979) showed the partial realignment of artificial sediment slurries on stirring by 'shear-induced liquifaction' to give a post-depostional DRM. In the same study, inclination errors of up to 30° were produced in thin-till slurries while in thick-till slurries no significant errors were noted. The above mentioned variability as well as the shock-induced thixotropic resetting as a result of sampling procedures may explain the far-sided VGP (Virtual Geomagnetic Pole) positions for tills sampled in Ontario (Symons *et al.*, 1980) and in Alberta (Barendregt *et al.*, 1977). Inclination error due to the preferential alignment of irregular-shaped magnetic particles may also explain some of the far-sided VGP positions.

A recurring problem facing the student of Quaternary paleomagnetism today, is the large number of reported excursions which cannot be properly correlated or are based on measurements of doubtful accuracy. Conclusions are sometimes drawn from incomplete data (Opdyke, 1976) or are based on insufficient sampling sites (Kukla and Nakagawa, 1977). For the novice the following guideline might be useful: "a negative inclination doth not a reversal make".

In several parts of the world, terrestrial paleomagnetic records show excursions during the Brunhes normal polarity epoch. These excursions are reported in great numbers for sediments which are between 8,000 and 20,000 years in age. However, in deep-sea records and the Aegean Sea, there is no evidence for a reversal or excursion of the field during this time (Opdyke *et al.*, 1972). True reversed magnetizations in sediments are caused by a reversal of the main dipole field and should be seen world-wide. Excursions of the field (deviations of the direction of the field greater than the normal secular variation of a few tens of degrees) could also be caused by the main dipole field tilting at a large angle to the rotation axis and then returning to the same orientation as before. Such excursions should also be seen worldwide. However, sources of the non-dipole field could also produce an excursion that could change the direction of the field at one point by 180°, resulting in an apparent reversal at that point. Such conditions would be indistinguishable from a reversal of the dipole field, unless observations at exactly the same time interval from another part of the earth do not show a reversal.

In determining the zone of disturbance of a dipole field caused by a pseudoreversal (i.e., one not involving the main dipole field) at one point in the earth's surface, Harrison and Ramirez (1975) developed a model which placed a vertical dipole at the surface of the earth's core whose magnetic field is opposite to that of the main dipolar field. They show that the areal coverage of the disturbed magnetic field around such a pseudoreversal can be quite small, such that observations made only a few thousand km away would show no anomalous direction. If this model is applicable there are no contradictory observations of the existence of a reversal at Laschamp and other locations having similar age, provided they are pseudo-reversals caused by non-dipole field sources. Harrison and Ramirez further show that if the vertical dipole model for the non-dipole field is correct, then pseudo-reversals should be much less common at low latitudes than at high latitudes.

Geomagnetic excursions during the Brunhes epoch are more and more being considered as magnetostratigraphic markers. These excursions are apparently sharp movements of the Virtual Geomagnetic Pole (VGP) towards or beyond the equator followed by a return to the stable position, all within the timespan of a few thousand years. Table I provides a list of some of the better documented excursions. A useful discussion of these excursions is given by Verosub and Banerjee (1977).

The Gothenburg event (labelled as a magnetic 'flip' in the literature) is especially problematic since the authors suggest that the event lasted only some tens of years while the inclination switch only took a few years (Morner, 1977). This would make it the most rapid magnetic polarity change known at present. The mechanism for such an abnormally rapid 'flip' is difficult to imagine. Recently Thompson and Berglund (1976) reported finding no evidence for the Gothenburg event in a detailed study of cores from Sweden. They attribute previous reports of anomalous directions as an example of the 'reinforcement syndrome' (Watkins, 1972; Watkins, 1976). From continuous records of the geomagnetic field for the period 0-16,000 years B.P. in sediments of two post-glacial lakes in Minnesota and a re-examination of the primary data related to the Gothenburg event and Erieau excursion, Banerjee and Lund (1979) conclude that both excursions might in fact be artifacts of the lithology (see also Banerjee *et al.*, 1979).

Thus it becomes obvious that paleomagnetic records as reported in the literature must be critically weighed. Even from deep-sea cores taken over the past 20 years, there is evidence for 'stable' and 'unstable' cores. According to Verosub and Banerjee (1977): "A stable core is one which gives a clean paleomagnetic record with simple features that are generally consistent with the accepted reversal sequence. An unstable core on the other hand gives a complex paleomagnetic record with many apparent changes in paleo-magnetic direction. These cannot be correlated with those in other cores."

On land, North American studies of lake sediments have often been made on single samples per horizon, carbon-14 dates are few and frequently have large error limits. Verosub and Banerjee (1977) observe that: "Most disturbing of all is the fact that the observed excursions are frequently observed near lithologic boundaries reflecting a change from glacial to post-glacial times with concomitant rapid fluctuations expected in the depositional conditions in the lakes."

Harrison and Ramirez (1975) have shown that the smallest lateral distance over which a geomagnetic fluctuation would be observed is around 1000 km. For this reason, an excursion should be recorded in nearby areas in sediments of similar age and as Verosub and Banerjee (1977) clearly point out: "Failure to detect a paleomagnetic excursion in an adjacent lake or ocean basin is an important result which should not go unreported because it is uninteresting."

Table I *Paleomagnetic Polarity Excursions and Proposed Ages During Brunhes Epoch*

Name[1]	Researchers	Proposed age (Years B.P.)
Laschamp event	Bonhommet and Babkine (1967) Bonhommet and Zahringer (1969) Hall et al. (1979); Heller (1980)	8,000-20,000
Mono Lake Excursion	Denham and Cox (1971), Denham (1974)	24,000
Gothenburg Event	Morner et al. (1971) Morner and Lanser (1974); Morner (1977)	12,350-12,400
Blake Event	Smith and Foster (1969) Denham et al. (1976); Denham et al. (1977)	105,000
Lake Mungo Event	Barbetti and McElhinny (1976)	29,500
Lake Biwa Excursions	Nakajima et al. (1973) Yaskawa et al. (1973)	18,000 and 104,000-117,000
Erieau Excursion	Creer et al. (1976)	7,600-14,000
Lake Michigan Excursions	Vitorello and van der Voo (1977)	7,500 and 13,000
Gulf of Mexico Excursions	Freed and Healy (1974) Clark and Kennett (1973)	15,000-18,000 and 30,000-33,000
Maple Hurst Lake and Basswood Road Lake Excursion	Mott and Foster (1973)	12,500
Meadowcliffe Excursion	Stupavsky et al (1979)	30,500
Port Dover Excursion	Morner (1976)	13,300
Maelifell Event	Peirce and Clark (1978)	40,000 (?)
Rubjerg Excursion	Abrahamsen and Knudsen (1979)	23,000-40,000

[1]Location names are used only to identify the reported excursions and are not necessarily established names

Using a similar model to that of Harrison and Ramirez, Denham *et al.* (1976) showed that the Blake event may not have been felt over more than nine per cent of the earth's surface. On the other hand, Smith (1967) and Verosub and Cox (1971) have shown that paleomagnetic excursions may reflect global geomagnetic phenomena resulting from the change in the relative sizes of the dipole and non-dipole fields

All this is not to say that localized excursions are not useful. The Quaternary stratigrapher must first come to realize that they can be local in nature or may have a worldwide occurrence, and then he must be able to determine their age so that they can be used as stratigraphic markers. If an excursion can be shown to be of global extent and dipolar in origin, a very useful marker horizon has indeed been found.

Finally, if each of the reported excursions listed in Table I represents a distinct excursion, then the geomagnetic field is much less stable than had previously been thought. Such a high degree of instability when extended back over geological time would produce a magnetic field far more complex than has been observed in the record (Verosub, 1975).

Concluding Remarks

Dating by paleomagnetic characterization and geomagnetic polarity history is a relatively new technique. The large-scale features of the earth's magnetic field character have been well worked out for the past 5 million years or so. The detailed small-scale features for this period are still being discovered and defined through analysis of terrestrial sediments. Because of the much greater sedimentation rate on land, these are more likely to show short-lived events and record the excursions which ultimately will become useful correlative tools.

The only practical way of demonstrating the validity of interpreted magnetostratigraphy is to show that results are reproducible in widely separated sections with different lithology and sedimentation rates. In Canada, where Pleistocene deposits are largely glacial in origin, and were thus episodic, one must be aware that these deposits may only have recorded the earth's magnetic field in short time intervals. Possible subsequent alteration of these sediments by the processes outlined earlier, must be borne in mind. Great Lake sediments, glacial lake sediments and deposits such as those described by Foster and Stalker (1970) in western Canada provide excellent opportunity for magneto-stratigraphic correlation and dating

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