Recent Advances in Archaeomagnetism

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This review of archaeomagnetism covers advances made during the last three years in (i) instrumentation for determining the direction and magnitude of the archaeomagnetic field, (ii) analytical and sampling techniques and (iii) the production of large data sets of both secular variation and field magnitude.

1. Introduction

There have been many advances in archaeomagnetism since the pioneering work of Thellier in the 1930s. During the 1960s interest in the subject decreased but in the past 10 years we have seen a major upsurge in archaeomagnetic research with the result that there has been a large number of major developments over the past three years. This review concentrates on this three-year period and attempts to draw thumbnail sketches of many of these developments and to direct towards more detailed reading.

2. Developments in Instrumentation

There have been several major advances in magnetometer design. KONO *et al.* (1981) developed a new type of spinner magnetometer that simultaneously rotated the sample about two orthogonal axes. Although the prototype magnetometer had limited sensitivity and was more suited to the measurement of volcanic rocks and ceramics rather than sediments, the tumbling action would allow a tumbling a.f. demagnetiser to be built into the system thus simplifying the automation of the measuring and demagnetising process.

With the exception of the above magnetometer most of the major advances in magnetometer design have been due to the availability of reliable SQUID's (Superconducting Quantum Interference Devices).

A SQUID allows the current flowing in a superconducting coil to be measured with great accuracy and without the current decaying. The magnetic field due to, say, a pottery sample, causes a magnetic flux change in a superconducting coil and the induced superconducting current will continue to flow as long as the sample remains in position.

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By constructing sets of orthogonal superconducting coils it is possible to build a SQUID magnetometer, normally three coils and three SQUID sensors are used (one coil and one SQUID for each axis). A SQUID magnetometer is a true static device because the output signal remains constant provided the sample remains stationary within the coil system.

Two major advantages of SQUID magnetometers are their unrivaled sensitivity and speed of measurement. Most of the early SQUID magnetometers were built simply to measure very weak samples using manual sample movement and a microprocessor for data capture and preliminary analysis. Walton was one of the first to realise that a SQUID magnetometer could be easily automated since the three axes can be simultaneously measured. He built a single SQUID magnetometer (WALTON, 1977) capable of three axis magnetic measurements by rotating the sample about one axis. Below the magnetometer he built a cylindrical oven and the sample was moved between the oven and the magnetometer by an air ram so that the complete system could measure and thermally demagnetise/remagnetise samples. It is currently in use at Oxford and can automatically carry out a Thellier type field magnitude determination (THELLIER and THELLIER, 1959) in just three hours because the very small samples used (3 mm cores) can be quickly heated and cooled.

SHAW *et al.* (1984) have further developed the single SQUID magnetometer and have incorporated a 3-axis a.f. demagnetiser and oven. The machine is capable of automatically measuring the direction and strength of magnetisation of sample using a single inclined pick-up coil (ROGERS, 1982), carrying out thermal and a.f. cleaning and installing ARM's and TRM's in any predetermined direction. It operates under microprocessor control and can automatically carry out complete field magnitude determinations or can be used for routine measurements of magnetic directions.

At the University of Cambridge, Walton is now using a SQUID biomagnetic probe to measure samples while they are being heated inside an oven. The probe has a double gradiometer pick-up coil that is balanced so well that it will operate without the need for mu-metal or superconducting shields. It was designed to measure the magnetic effects of natural currents in the human body. For archaeomagnetic use a small oven is placed under the probe with the sample fixed inside it. The probe measures the vertical magnetisation of the sample and the oven so care must be taken when building the oven to ensure that it is non-magnetic. By rotating the sample and oven it is possible to measure three components of magnetisation or by keeping the oven fixed one component can be continuously measured as the sample is heated or held at elevated temperatures (ROGERS *et al.*, 1984). The system is automated and operates under microprocessor control.

The three SQUID systems described above all use small samples (3 mm or 9 mm diameter cores) in order to reduce the heating and cooling time and increase the peak alternating field that can be used since this is related to the volume over which it must be maintained. The 9 mm cores can be used for

directional measurements without a significant increase in orientation error but the 3 mm cores can only be used for field magnitude determination.

Over the past three years we have moved from the view that SQUID magnetometers are just for measuring weak samples to the view that they can also be incorporated into complete automated systems able to perform repetitive demagnetisation and measurement quickly and accurately.

3. Developments in Techniques

Most of the major advances have been improving techniques for determining the ancient field magnitude. The effects of magnetic anisotropy are now well understood (ROGERS *et al.*, 1979; AITKEN *et al.*, 1981) but the effects of cooling rate on the acquisition of TRM (FOX and AITKEN, 1980; DODSON and MCCLELLAND BROWN, 1980) are not yet fully understood. It was first thought that a simple cooling rate correction could be applied when comparing NRM's to TRM's that were cooled at different rates in order to determine the ancient field magnitude. Recent work by ALCOCK (1982) indicates that different parts of the blocking temperature spectrum requires different cooling rate corrections. This is an additional problem that may be the cause of some of the scatter between contemporaneous field magnitude results from the same area.

A new technique for field magnitude determination was developed by WALTON (1982). By measuring samples while they are held at elevated temperatures (typically 200 to 300°C) the change of magnetic moment with time in an applied field can be determined. This information allows the ancient field magnitude and ancient cooling rate to be calculated. It was hoped that heating the sample to only moderate temperatures would avoid thermal alteration but in practice Walton has observed alteration at temperatures as low as 210°C.

This technique has now been modified (Walton, personal communication) and measurements of the decay of NRM in zero field and acquisition in an applied field, all at elevated temperatures, allows the ancient field magnitude to be calculated.

ROLPH *et al.* (1984a) have used the ARM data from the Shaw method (SHAW, 1974) to correct for curvature of the NRM/TRM plots due to thermal alteration. They use only the data obtained from the single domain region of the coercive force spectrum in an attempt to limit any change in the relationship between TRM and ARM due to thermal alteration. The technique has been successfully tested on modern samples from Mt. Etna (ROLPH *et al.*, 1984b).

Studies of the ancient field magnitude are usually restricted to an examination of ancient magnetisations formed by cooling from a high temperature in the Earth's magnetic field. In an attempt to obtain a continuous field magnitude record several techniques have been used on lake sediments, generally with little success. Recently, however, KING *et al.* (1983) have demonstrated that the DRM/ARM ratio in sediments with magnetic grains in the range of 1–15 μm diameter provides a good record of relative field magnitude. Their results agree

with the absolute but discrete data compiled by CHAMPION (1980) for the same region and time period.

GUBBINS and ROBERTS (1983) have been able to place an upper limit on the dipole component of the geomagnetic field by assuming that the conductivity of the core is effectively infinite over short periods of time. This means that the magnetic flux is 'frozen' into the core and that there is no loss or gain of total flux. By re-arranging the existing flux they calculate that the maximum allowable dipole is more than twice the present day dipole. If the frozen flux approximation is valid over archaeological time it may be possible to predict past changes in the field from a knowledge of recently observed trends.

For many years the MAKERETH (1958) piston corer has been the main means of sampling lake sediments. The original 6 m corer has been developed to sample shorter and longer cores. A mini-corer is used to sample the top (most recent) few cm of sediment which are usually disturbed by the 6 m corer. In an attempt to continuously sample much longer time periods the core barrel has been extended to 9 and 12 m but as yet the 12 m corer has not been fully developed. One of the main problems with the Makereth corer is that the core barrel twists about the vertical as it enters the sediment and so the magnetic declination measurements have no absolute reference.

READMAN (1984) has demonstrated that a conventional hydraulic rig mounted corer can be used to obtain oriented cores from soft sediments. As each section of core barrel is mounted it is oriented with a special telescope attachment thus ensuring that the declination measurements have a fixed reference.

4. Recent Results

One of the most outstanding archaeomagnetic data sets is the almost continuous 8000 year record of magnetic declination, inclination and field magnitude presented by KOVACHEVA (1982). The data was obtained in Bulgaria and when combined with the equally comprehensive data set from the Ukraine (ZAGNY, 1981) it provides us with a standard data set for Europe.

WEI and AITKEN (1983) has completed part of an analysis of Chinese ceramics and are in a position to compare these field magnitude results with those previously obtained from Crete, Cyprus, Greece and India. Although the two data sets are separated by 90° of longitude they both display the same major features contemporaneously. The data presented by BUCHA *et al.* (1970) and STERNBERG and BUTLER (1978) show similar behaviour especially during the period 1000 to 3000 BC when all of the data sets, including COX (1968) and BARTON *et al.* (1979) agree that the field magnitude is generally increasing with time (Fig. 1). This suggests that field magnitude values are predominantly controlled by the main dipole field but are modulated by the non-dipole field. The degree of modulation is variable and has influenced the field magnitude over the last 2000 years much more than the preceding 3000 years.

Attempts have been made to analyse the variations of field magnitude with

Fig. 1. Time Variation of the ancient field magnitude (F^A) to present day field magnitude (F_D) (from WEI and AITKEN, 1983).

time. COX (1968) suggested an oscillation with an 8000 year period; KONO (1972) concluded that the data did not support this suggestion. MCFADDEN and MCELHINNY (1982) performed an analysis of data covering the past 5 m.y., their findings did not agree with COX (1968) but showed that the distribution of dipole moments approximates a truncated Gaussian distribution. MCELHINNY and SENANAYAKE (1982) analysed data covering the past 50,000 years and found no conclusive evidence for a sinusoidal variation, this view was supported by BARTON *et al.* (1979).

Recently MCFADDEN (1984) analysed data covering the past 10,000 years. He concludes that if the dipole moment is observed at intervals of up to 1000 years then serial correlation is good. If however the observation interval is increased to 2000 years, there is no discernable correlation. This finding would seem to explain why periods of 4000 and 8000 years have been previously suggested by other workers and why analysis of data covering longer time periods does not support a regularly oscillating dipole moment. The main conclusion being that the average dipole moment changes with time but that these changes also have a time constant so they cannot be correlated over long periods.

European declination and inclination measurements have recently been enhanced by the work of THELLIER (1981) who published some 250 measurements ranging from 0 to 1800 A.D.; results falling between 0 and 800 A.D. have been added to by the work of LANGOUET *et al.* (1983). HEDLEY *et al.* (1984) have analysed this French data set and also the British data used by AITKEN (1970) and CLARK (1983) by using a least squares spline fit to both the declination and the inclination variation curves. The best fitting spline for each set of data was chosen by cross validation. The result of this work is that the Bauer curves presented by HEDLEY *et al.* (1984) are not the same as the 'hand drawn' curves of Aitken or Clark in that the closed loop during the mediaeval period is absent from the Hedley *et al.* plot. This is a significant step forward in the construction and use of local declination and inclination 'master curves'. These local 'master curves' can be used to date kilns of unknown age and, with some knowledge of the firing position, ceramics and roof tiles can sometimes be dated (GOULPEAU and LANGOUET, 1982). They have also been used to date or question the date of the historic lavas of Mt. Etna (TANGUY, 1982).

The most continuous and comprehensive data sets of declination and inclination are now coming from measurements of the magnetic record contained in lake sediments. There are four main areas from which characteristic curves have been obtained, North America (CREER and TUCHOLKA, 1982), Australia (BARTON and MCELHINNY, 1981), Argentina (CREER *et al.* 1983) and the U.K. (TURNER and THOMPSON, 1982). These areas extend back 10 to 12 thousand years from the present day and will eventually allow us to analyse the global field over this time period.

5. Conclusions

Archaeomagnetism is a thriving growing area of research in which considerable progress has been made over the past three years. The errors on both magnitude and directional measurements are decreasing and it is now becoming possible to use either or both as viable dating tools to reduce the errors on conventional dates (C14 etc.). SQUID magnetometers have allowed the use of very small samples (3 mm cores) with a resultant increase in the speed with which the sample can be heated and cooled when using the Thellier method.

The global distribution of archaeomagnetic and observatory records has allowed a detailed analysis of the geomagnetic field over the past 400 years (THOMPSON and BARRACLOUGH, 1982). The rapid accumulation of declination and inclination records from lake sediments will eventually allow us to analyse the field over the past 10,000 years. This will be one of the major achievements of archaeomagnetism.

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