Palaeomagnetic applications in the Iberian Peninsula: An introduction and assessment

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INTRODUCTION

The principles and instrumentation of palaeomagnetic techniques are now well established (Collinson, 1983; Tarling, 1983; O'Reilly, 1984) and will not be discussed here, but the scale and variety of problems to which palaeomagnetic techniques can be applied are still not widely appreciated. Different types of application will be discussed in the context of previous, present and future studies within the Iberian peninsula. Some lessons learnt from some unpublished «negative» results from Iberia will be outlined, but no specific references are made to subsequent articles in this publication as this article is NOT intended as a review of current activities. However, most of the following papers illustrate many of the points made here concerning palaeomagnetic applications. The potential for magnetic fabrics and of archaeomagnetic studies will also be discussed, although a magnetic fabric does not have any direct relationship with the natural remanence associated with conventional palaeomagnetic analyses. The topics discussed are (a) dating, (b) structural studies, (c) magnetic fabrics, (d) sedimentation, diagenesis and sediform ore deposits, (e) depth and duration of burial, (f) intrusive mechanisms and duration of burial, (f) intrusive mechanisms and igneous ores, and (g) archaeomagnetic and Recent volcanic activity.

DATING

Palaeomagnetism can be used for both absolute and relative dating. On scales of 10^{2-4} years using secular variation, 10^{3-7} years using polarity reversals, and 10^{6-8} years using apparent polar wander paths.

i) The geomagnetic secular variations in direction take place at some 0.2-0.4° / year. As directions of remanence are generally determinable within about ± 1°, and systematic errors (refraction, magnetic interaction, etc.), are of the order of 3-5°, the *potential* accuracy for magnetic dating over archaeological time-scales is of the order of ± 10-15 years. This level of precision is much greater than for most scientific dating methods over archaeological time scales. Clearly, the dating of pre-historic lavas in the Canary Islands could readily be undertaken by extrapolation of archaeomagnetic records from southern Spain and Morocco. No archaeomagnetic studies are currently being undertaken in the Iberian Peninsula, yet the establishment of a secular variation reference curve would have immediate value for dating over this time-scale and, particularly with palaeo-intensity determinations, would also provide significant information for understanding the long-term behaviour of the geomagnetic field. The establishment of an archaeomagnetic record for the Iberian Peninsula is also of considerable importance for determining the spatial variation of the geomagnetic field during the last 2,000 years or so as such records could be directly related to those established in France and currently being investigated in North Africa. It is also relevant that the symmetrical shape and scale of the Iberian Peninsula means that results from any one locality can be extrapolated over the entire Peninsula with errors of less than 1° if using an inclined dipole model for the geomagnetic field to correct to a central location, such as Madrid.

ii) The fact the geomagnetic field periodically, but irregularly, changes polarity provides a global, essentially instanteneous series of time markers. The duration of a polarity change appears to be some 10,000 years in intensity, with the change in direction taking some 3,000 years. The frequency of such changes are very variable, with about three per million years during the Cenozoic, possibly even more rapidly during the Triassic, but there was constant (normal) polarity for some 50 million years in the Cretaceous and well over 50 million years of reversed polarity which included the entire Permian period. Relative dating, using this method, is simple. Rocks with different polarities must have acquired their magnetization at different times, although the converse is not necessarily true. Absolute dating is difficult, unless the approximate age is already known, as no magnetic properties are yet known to distinguish between polarity zones of different ages. The two most common absolute dating applications are (a) the use for sea-floor magnetic anomalies in which the relative durations of each polarity zone can be determined assuming constant sea-floor spreading rates - the polarity sequence then being compared with the established polarity scale. (b) In Miocene-Recent times in particular, the approximate ages, based on either radiometric or biostratigraphy methods, can be supplemented using the more detailed Miocene-Pliocene polarity sequence. However, the absence of normal polarities within the Permian can be used to distinguish between, for example, Permian and Triassic sandstones. It is also relevant that polarity changes are global and hence the determination of the absolute age of any polarity change is of worldwide importance. For example, the recognition of the same polarity transition in the Carboniferous sequences in the Iberian Peninsula could be used to match with similar zonations in North America, U.S.S.R., China, Gondwanaland, etc., and hence test models for global sea-level change, etc.

iii) The geomagnetic field, when averaged over >6-8,000 years, corresponds to a field that would be produced at the surface as if the Earth's magnetic field was caused by a simple bar magnet at the centre of the Earth, i.e. a geocentric dipole field, which, over last few million years has been aligned along the Earth's axis of rotation. However, over geological time, each tectonic plate moves relative to the average geomagnetic pole position. This, in effect, results in a gradual change in the location of the geomagnetic pole relative to that plate, i.e. it results in an «apparent palaeomagnetic polar wander curve», with the apparent rate of polar change in fact reflecting the rate of motion of the plate, particularly any rotations about a vertical axis and changes in paleolatitude. The determination of the palaeomagnetic pole for rocks of unknown age thus enables the dating of their magnetization by comparison with the established polar wander path for that tectonic plate. The uplift of previously buried rocks can be dated by this means, as can the cooling following thermal heating associated with fault activity, regional igneous events, etc. In the case of Iberia, dating by this method is complicated by the independent motion of Iberia, relative to both Europe and Africa. At the moment, correction for these motions are required for dating using either the European or African pole path. Obviously an Iberian polar wander path is urgently required, but the internal tectonic mobility within the Peninsula makes this particularly difficult for pre-Permian times. Nonetheless, such problems only temporarily inhibit absolute dating and relative dating - based on the simple comparison of palaeomagnetic pole positions - can be of major importance as this still enables, for example, the distinction between syngenetic and epigenetic ore deposits on the basis of their relative magnetic ages.

STRUCTURAL ANALYSES

The application of palaeomagnetic studies for the determination of continental drift is well known and studies of Triassic rocks in northern Spain were amongst the first to demonstrate inter-continental motions although the more detailed studies of structurally allochthonous areas of western North America are now more widely known. This largely reflects the paucity of subsequent palaeomagnetic studies in the Iberian Peninsula, although some of the earlier (unpublished) studies in the late 1960s and early 1970s, by the author and colleagues, were hampered by sedimentological and structural difficulties. Two examples of the former are Permo-Triassic red beds in the Balaeric Islands and the Betics, while an example of the latter is of Cretaceous ophiolites in the northern Asturias. The study in the Betics also involved igneous rock problems, thought to be associated with magnetic anisotropy.

a) *The Balearic Islands.* Extensive sampling by E. Halvorsen and E.A. Hailwood of Permo-Triassic sandstones yielded stable, but very scattered directions, although mostly falling into a single hemisphere and thus indicating a reversed polarity. The conclusion was that coarse grained, particularly cross-bedded, sandstones are inadequate recorders of the past geomagnetic field; sampling in such areas needs to be concentrated on silt-grade sediments and on carbonates. (No study of the Iberian carbonates was made at that time as these were considered unmeasurable, but these now offer some potential, although carbonates are now turning out to show complex magnetic histories that are commonly difficult to decipher.) It was also of interest to note the difficulty in determining tectonic tilt corrections in beds showing differential compaction. In one outcrop, in central Mallorca, the beds can be seen to be dipping as a single tectonic unit, but in a road cutting through the unit, local dips of the most shaly horizons differed by up to 40°. It is on this experience that it is suggested that the largest errors in palaeomagnetic studies derive from the determination of the true tectonic tilt.

b) *The Betic and Rif Arc.* Extensive sampling of Permo-Triassic sandstones on both sides of the Alboran Sea were undertaken by E.A. Hailwood, E. Halvorsen and D. H. Sutton. The rocks showed similar properties to those of the Balaeric Islands, i.e. stable, but very scattered directions of remanence, generally with a southerly declination. These properties are now well documented in many other sandstones.

Miocene volcanics were also studied from these two areas. These showed quite stable, but internally inconsistent directions of remanence. No detailed examination was made of the cause of such observations, although it was considered that the most likely cause would have been magnetic anisotropy probably associated with the visible flow banding in these lavas.

c) *Cretaceous ophites.* Outcrops of these rocks were sampled by K. W. Stauffer in order to test models for the opening of the Bay of Biscay. Although of generally poor stability, the directional scatter was still excessive for any standard tectonic interpretation. The reason for this is not clear, but it is almost certainly due do the complexity of the local tectonics in the area. These are now better understood than at that time, and proper tectonic corrections could possibly be applied to these data now.

Conversely, such data could now be used to delineate some of the structural controls within this region, but these are no longer available.

Such examples demonstrate the need for very careful selection of the lithologies being sampled, and that the interpretation can only be as good as the limits of local geological controls are known. It is particularly important that any palaeomagnetic results only apply, strictly, to the sampling locality itself. This could, for example, turn out to be an isolated tectonic unit - or even a large isolated block exposed in a road-cutting but not connected to the local basament. In such circumstances, apart from paleolatitude, the palaeomagnetic data cannot be interpreted in terms of regional tectonics and the extrapolation of such data to a wider area can only be undertaken on the basis of good field work, preferably supplemented by further palaeomagnetic sampling to determine the degree of autochthony of the sampled area.

A further major problem is that the dating of the rotations must be based on a knowledge of the age of the remanence, which may be significantly younger than the age of the rocks themselves. Demagnetization analyses to show that the remanence is stable is only evidence that the observed remanence *could* have been acquired at the time of formation of the rock itself, i.e. primary, but is not, in itself, sufficient evidence that it is primary. As most rocks usually contain several components of magnetization, the age of each component must be determined before a full interpretation can be attempted. Again, an assessment of the age of each component is critical and it is inadequate to assume that the most resistant (highest coercivity or highest blocking temperature) component is necessarily the oldest. Secondary haematite, for example, may well carry a much more stable remanence than a primary magnetization carried by magnetite.

Age determinations of magnetic components are almost entirely based on consistency tests, i.e. each group of sites of similar age should have a similar direction of remanence associated with that age. If rocks are successively rotated back through the sequence of rotations induced by tectonic activities, then such consistency should be detected at or during one of the rotations, or, if pre-folding and hence possibly primary, after all tectonic corrections have been applied. Nonetheless, such tests are not simple, statistically or geologically. Statistically, extensive sampling is desirable within each of the separate tectonic units and the sites being compared should be at similar stratigraphic levels. There is also uncertainty as to which level such tests should be conducted - specimen, sample, site, etc.; the site level being the most conservative. However, such problems are small compared with the need to undertake corrections, gradually going back in time, for each phase of tectonic rotation. Furthermore, most simple tectonic rotations assume simple block tilting, but ductile deformation is commonly present and corrections also need to be made for the effects of plunging fold axes, etc. Even when completed, the data may only then indicate that the remanence was acquired prior to the deformation and the age of the remanence could still be associated with pre-folding chemical changes long after the formation of the rocks themselves. The most important realiability criteria is, therefore, that the directions of magnetization correspond with other directions known in age, i.e. dating by comparison with an already established polar wander curve. However, such curves are still poorly defined for even the major crustal blocks, particularly in the Mesozoic, and there is inadequate definition of the present Iberian polar wander curve for this period also. For older times, it seems probable that different parts of Iberia may well have formed parts of separate tectonic plates, each requiring their own curve to be defined. However, it is important to note that, even for Precambrian and Palaeozoic rocks, secondary magnetizations can still be used to define later tectonic activity, particularly if the age of such magnetization can be determined, e.g. many Lower Palaeozoic and older rocks possess a Permian remagnetization that can be used to determine the position of each unit at that time and then to determine the summation of post Permian tectonic rotations or tilts. The number of structural problems within the Iberian Peninsula is almost infinite, and reflect many radically different tectonic regimes. The application of palaeomagnetic techniques could therefore be not only locally interesting but would enable different hypotheses of tectonic evolution of global interest to be tested.

MAGNETIC FABRICS

A wide variety of methods exist for determining petrofabrics. In zones of strong deformation, field measurement of deformation structures is particularly effective, but these often need to be supplemented by analyses of the petrofabrics of individual oriented samples.

Most of these methods are tedious, e.g. the determination of the orientation of the c-axes of quartz or x-ray analyses of the orientation of clay minerals requires skilled operators and considerable time. In contrast, measurement of petrofabrics by magnetic methods takes only 2 or 3 minutes and is remarkably precise for low strains, i.e. it can distinguish a difference in grain shape associated with magnetic susceptibility differences of some $1{:}10^6$. However, the method is not so effective for large deformations, e.g. $> 10{:}1$ although such large strains are, in any case, usually readily measured in the field. However, the magnetic fabric is a summation of the grain shapes of the magnetic minerals (or paramagnetism an/or electrical conductivity in rocks containing no magnetic minerals) and different components are not normally distinguishable. Nonetheless, the high sensitivity for low strain and the speed of measurement make this method ideal for the analysis of weakly deformed rocks, e.g. sedimentary and diagenetic fabrics, weak folding, etc., and the speed of measurement but summation effects means that it has potential as a reconnaissance technique which can be used to determine the areas requiring more detailed, time-consuming study by standard methods.

In the Iberian Peninsula, there are innumerable problems where such techniques could, and should, be applied. It is, for example, possible to determine the strain history of a region by examining rocks of different competence within it - the most competent reflecting the highest strain imposed, and the lowest competence reflecting the last strain. As the size of oriented samples for both magnetic fabric and palaeomagnetic measurements are the same, it is sensible to combine both forms of analysis. However, it is important to stress that magnetic fabric determinations are based on the entire magnetic mineralogy present in a rock, while the remanence used in palaeomagnetic analyses is usually only carried by <5 % of the total magnetic minerals. Both methods are, in fact, absolutely and entirely independent of each other, but each interpretation is enhanced by the controls provided from the other method.

SEDIMENTATION, DIAGENESIS AND SEDIFORM ORES

The processes of sedimentation and diagenesis involve both physical and chemical processes. (a) The physical processes can cause complete or partial alignment of already magnetized particles - depositional or post-depositional remanence - and the net orientation of all of the magnetic minerals can be determined from their magnetic fabric. The latter can then be interpreted in terms of the previous current direction, because of the imbrication of the magnetic minerals, and the velocity is indicated by their alignment either parallel or perpendicular to the imbrication. (b) The chemical processes usually involve magnetic minerals directly as these are particularly sensitive to the redox conditions, but new magnetic minerals commonly form from changes in other iron-bearing minerals. The diagnetic changes of olivines, pyroxenes, amphiboles and micas, for example, commonly result in the formation of authigenic magnetite or haematite. Such chemical changes have associated chemical remanences which, if isolated, can then be used to determine the age of the chemical change. Similarly, the magnetic fabrics change from those associated with deposition.

The mode of formation of sediform minerals is still largely uncertain. Studies of the influence of palaeomagnetic factors, as indicated by the paleolatitude of the associated remanences, combined with magnetic age relationships, are begining to provide vital constraints that enable an assessment of the relative importance of igneous, sulphide or sulphate sources, and the precise structural regimes in which such palaeoclimatic influences can have an effect on the original mineralization or its supergene enrichment. Such studies are thus of global importance as well as being of local economic interest for the prediction of the nature and characteristics of particular sedi-form ores.

METAMORPHIC ROCKS AND THE DEPTH AND DURATION OF BURIAL

The gradual change from diagenesis to metamorphic is difficult to define, but is generally taken to be the onset of greenschist grade at about 300° C. If the past burial temperature can be determined on the basis of the relationships of the metamorphic minerals, the duration of burial can be determined by determining the amount by which the observed blocking temperature exceeds the burial temperature as this directly reflects the duration of the burial at that temperature. Unfortunately, such calculations are usually complicated by accompanying chemical changes, with associated remanences, at such times. Nonetheless, the time of uplift can be determined as the magnetization associated with either cooling or late-stage chemical changes. This magnetic vector can also be used for determining the three-dimensional orientation of the tectonic unit at the time that the magnetization was acquired.

INTRUSIVE MECHANISMS AND IGNEOUS ORES

The width of metasomatic activity associated with an intrusive, and particularly the ore deposits associated with such hydrothermal activity, are very dependent on the dryness of the country rocks and of the intrusion. The magnetic mineralogy of the country rocks is particularly affected by such activity - with the most widespread chemical activity associated with the highest fluid content. The zone of mineralogical alteration is therefore commonly delineated by the occurrence of magnetic mineral enhancement. The age of magnetic minerals, and the associated mineralization, can then be determined.

Magnetic fabrics can be used to compare the petrofabrics in the country rock, metamorphic zone and within granites to determine whether the intrusions were pre-, syn- or post-tectonic. The fabrics in the metamorphic aureole also define the intrusive mechanism, while the fabrics in the intrusives, whether granites or dykes, provide information on the source and motion of the magma.

ARCHAEOMAGNETISM AND RECENT VOLCANISM

Although no archaeomagnetic work has been published for the Iberian Peninsula, such data are of fundamental geophysical interest. It is particularly relevant that some of the most extensive geomagnetic record in the world are available, e.g. at Coimbra, which would enable direct evaluation of the technique. The main geological application of such observations is likely to be for dating Quaternary volcanism and sedimentation. Similar techniques may be applicable for older deposits, possibly evaluating the rate of deposition of sediments, but these are, as yet, largely untried applications.

CONCLUSIONS

The potential for palaeomagnetic techniques in Iberia is clearly vast. However, this is also an indication of some of the fundamental problems. The major problem, in most cases, is that the age of the magnetization may well post-date the geological age of the rocks themselves, although it is commonly assumed that a stable remanent magnetization is likely to be of primary origin. Such later magnetization can also arise as a result of time, subsequent chemical change or later heating and cooling. In many instances, the time dependent magnetization does not create difficulties, but it is commonly difficult to isolate later remanences associated with burial heating and cooling, from those associated with chemical changes, possibly associated with the same event. In many instances, it is not relevant whether the secondary magnetizations are of termal or chemical origin, as they still enable the study of that event. Nonetheless, in most cases, it must be assumed that these two remanent components are separable, or that one is so dominant that the other can be ignored. Such assumptions must be evaluated during the final interpretation.

One of the main features of palaeomagnetic studies is that they are relatively cheap and the results are interpretable in terms of a range of geological problems. However, as with most techniques, they are optimized when other constraints can be placed on the problem. It is vital that palaeomagnetic studies in Iberia, and elsewhere, are undertaken in the closest possible collaboration with field geologists familiar with the local area. Nonetheless, other than completely unstable remanences, it is rare that the magnetic properties of rocks do not provide highly significant information on the ages and tectonic structure of a region.

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