Self-Reversal and Field Reversal in Palaeomagnetism

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Summary

This work arose out of investigations into the magnetic minerals of a Dunedin (New Zealand) lava suite, part of which is reversely magnetized. Results of those investigations are published elsewhere.

Because of possible oxidation, whole rock Curie points are an unreliable guide to the identification of magnetic minerals, especially titanomagnetites in volcanic rocks, although this is often the only diagnostic criterion used.

Oxidized titanomagnetite is common in igneous rocks and where it occurs the possibility of self-reversal should be more seriously considered, especially as oxidation commonly takes place only after a considerable post-eruption interval.

Some normally magnetized rocks containing strongly oxidized titanomagnetites could have undergone self-reversal after originally cooling in a reversed ambient field. Oxidation could also lead to self-reversals in sediments containing detrital titanomagnetite.

Self-reversal is unlikely to have occurred in the Dunedin lavas, because their magnetic minerals are only weakly oxidized. The reversely magnetized part of the sequence was probably erupted during a reversed polarity episode between about 13 and 11 million years ago. The frequency of Cainozoic field reversals is briefly discussed.

Introduction

Palaeomagnetic measurements made recently on the Dunedin volcanic complex of southern New Zealand showed evidence of a reversed field episode near the Mio-Pliocene boundary (Coombs & Hatherton, 1959). Some interesting features of the rocks prompted an investigation into their magnetic minerals, details of which will be presented elsewhere (Wright, in press). The purpose of this communication is to offer some conclusions arising from those results, with particular reference to reversely magnetized rocks.

Whole rock Curie points and titanomagnetite composition

Curie points of rock specimens collected for palaeomagnetic study are often high, approaching the value of pure magnetite (e.g. Creer 1962, Cox et al. 1963a). The Dunedin lavas examined are no exception, but their magnetic oxides have cell

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dimensions and Curie points consistent with titaniferous magnetites containing 40-55 mol per cent ulvospinel. They are homogeneous and oxidation is confined to variable but generally minor development of titanomaghemite. The high whole rock Curie points appear to be the result of further oxidation by air and by volatiles in the rock during even the comparatively short period of thermomagnetic treatment (Wright, in press, cf. Meitzner 1963).

Oxidation raises the Curie point of titanomagnetite either by maghemitization (Akimoto et al. 1957) or by separation of a rhombohedral phase removing titanium from the host magnetite, so that its composition changes towards pure Fe$_3$O$_4$ (Wright & Lovering 1965). If oxidized titanomagnetite is already present, therefore, it will have a high Curie point not differing greatly from that of the parent rock (cf. Ade Hall et al. 1965, Vollstädt & Suwalski 1965). Low values for whole rock Curie points, consistent with minimal oxidation (or even reduction, cf. Wright 1959) during thermomagnetic treatment, are relatively rare (e.g. Ade Hall et al. 1965, Babkine 1965).

Erroneous identification of the magnetic phase in igneous rocks can therefore easily be (and has been) made on the basis of whole rock Curie points alone. It should also be emphasised that heating experiments on rock specimens to test for self-reversal (e.g. Cox et al. 1963b) are unlikely to be conclusive because of possible structural changes through concomitant oxidation.

**Relation between oxidation and magnetic reversals**

For some igneous suites there is no obvious correlation between polarity and the state of the iron–titanium oxides (e.g. Doell et al. 1966, van Zijl et al. 1963, Watkins 1965). In others, however, good correlation has been established between reversed magnetization and advanced oxidation (e.g. Ade Hall 1964, Wilson & Haggerty 1966, Wilson 1966), indicative of a self-reversal mechanism related to oxidation.

O’Reilly & Bannerjee (1966) have shown theoretically that self-reversal in titaniferous spinels could be caused by strong oxidation, with separation of titanhematite-rich rhombohedral lamellae; and Meitzner (1963) found evidence of transitory reversals accompanying such oxidation during his heating experiments. Maghemitization on the other hand, is generally considered unlikely to lead to self-reversal, although Powell (1963) has suggested it may cause unstable and scattered magnetization. This view is supported by recent detailed examination of a reversely magnetized and variably oxidized Icelandic basalt (Watkins & Haggerty 1965), in which samples showing only maghemitization of the titanomagnetite had scattered magnetization; while more strongly oxidized portions with hematite, rutile and pseudobrookite, were more strongly as well as more coherently magnetized. The authors were not certain whether the reversed polarity was self-induced, although on balance they considered it unlikely.

**Low temperature oxidation**

Watkins & Haggerty (1966) concluded from careful study that the extreme oxidation in the Icelandic basalt they investigated had occurred during cooling, but they did not rule out the possibility of subsequent low temperature agencies being responsible. Many petrologists are agreed that newly erupted lavas are very fresh and this can be attributed to the escape of volatiles during cooling, so that only slight deuteric alteration is in general to be expected. This takes place at temperatures still sufficiently high (Peck et al. 1965) to be fairly uniform throughout sizable volumes of rock. The distribution of oxidized titanomagnetite in a rock tends to be patchy, however, so that grains in different stages of oxidation can be seen within even the same polished section (e.g. Wright 1964, Ade Hall 1964, Doell et al. 1966), suggestive
of alteration at quite low temperatures. Furthermore, in some volcanic sequences the proportion of oxidized titanomagnetite can increase with age, as in the ignimbrite plateau areas of New Zealand's North Island (Dr A. Ewart, personal communication).

The zeolites which fill vesicles and other interstices in lavas are of low temperature hydrothermal origin and probably formed only after a considerable post-eruption interval (Walker 1952). While the possibility of considerable deuteric alteration (and oxidation) during initial cooling is not ruled out, later low-temperature, hydrous, zeolite-forming fluids are more likely to be responsible for extensive but patchy oxidation of titanomagnetites.* Support for this view is provided by recent results of direct oxygen fugacity measurement on basalt cooling in Hawaiian lava lakes (Sato & Wright 1966).

Ade Hall et al. (1965) have suggested that subsequent oxidation of this kind could result in titanomagnetite being remagnetized in a reversed ambient field—but this implies an initial demagnetization as oxidation commences, whereas available evidence points to progressive increases in magnetic parameters with progressive oxidation.

Titanium content and self-reversal

O'Reilly & Bannerjee (1966) also suggest that titanium-rich titanomagnetites are the most likely to undergo self-reversal on oxidation. The presence of separate ilmenite can sometimes be correlated with reversed polarity (Wilson 1966), perhaps because it can indicate high Ti : Fe ratios in the melt (Wright 1961) and hence in the titaniferous magnetite also. It cannot, however, provide information on the oxidation state of the latter (Wilson 1966), it can merely provide a guide to titanomagnetite composition at the time of crystallization, and then only provided (a) that there was equilibrium crystallization, (b) that the original ilmenite composition is known (Buddington & Lindsley 1964), and (c) that the original equilibria have not been destroyed by oxidation.

Self-reversal and field reversal

Study of recent literature reveals a tendency to regard field reversal and self-reversal as mutually exclusive, with some bias towards the former. There is no good reason for this, since it seems likely that both processes occur. In particular the discovery of both reversely and normally magnetized rocks in the same unit (e.g. Ade Hall et al. 1965, Wilson 1966) is additional evidence that self-reversals have occurred. Some of the ambiguities and anomalies in attempted correlations between petrology and polarity might be resolved if this duality were more widely accepted. It should be remembered, however, that the likelihood of finding self-reversed titanomagnetites will depend on their composition and oxidation state (O'Reilly & Bannerjee 1966), a point which may not always be appreciated (e.g. Larson & Strangway 1966). Attempts should also be made to test the proposition that strongly oxidized but normally magnetized rocks may have undergone self-reversal after originally cooling in a reversed field.

It is worth adding that hydrothermal or diagenetic oxidation of detrital titanomagnetite is a viable mechanism for self-reversal in sediments.

The Dunedin results and Cainozoic polarity epochs

The reversely magnetized rocks of the Dunedin sequence are confined to the Middle and Upper parts of the Second Eruptive Phase (Coombs & Hatherton 1959). Since the magnetic minerals in the rocks are only very weakly oxidized (see page 00),

* An explanation along these lines is now considered to be more realistic for the origin of strongly oxidised grains in New Zealand ironsands (cf. Wright 1964, Wright & Lovering 1965).
self-reversal is unlikely and the reversely magnetized lavas were therefore probably erupted during a period of global field reversal, as originally concluded by Coombs & Hatherton.

Recent age determinations gave $15.0(\pm 3\%) \times 10^6$ years for the Initial Eruptive Phase and $11.1(\pm 2\%) \times 10^6$ for the Third Eruptive Phase of the Dunedin volcano (reported in Coombs 1965). This would place the period of reversal between approximately 13 and 11 million years ago, possible 12.5 to 11.5, i.e. close to the Miocene–Pliocene boundary and correlating quite well with a reversed episode of similar age recorded in France (Roche 1951).

Watkins (1965) recognized a reverse to normal polarity change in Oregon, dated at slightly more than $14.5 \times 10^6$ years, and therefore (if valid and not due to self-reversal) distinctly older than the Dunedin episode. A younger mid-Pliocene reversal has also been postulated from results in France (den Boer 1957, quoted in Coombs et al. 1960), while collation of palaeomagnetic results from several countries (e.g. Doell et al. 1966) suggests the strong possibility of at least three global field reversals in the last four million years. The late Cainozoic would thus appear to have been a period of high frequency reversals in the Earth's field. It may be that such periods have alternated with much longer ones of settled normal or reverse polarity throughout geological time (e.g. Irving & Parry 1963), or that these rapid fluctuations are a comparatively late development in the Earth's history. If Simpson's (1966) correlations between field reversals and major evolutionary surges are to be valid, long periods of field stability would seem to be necessary.

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