Some Curious Magnetic Results From a Precambrian Granite

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Summary

The 1320 My Spavinaw granite from north-eastern Oklahoma is strongly magnetized, averaging about \(10^{-2}\) emu cm\(^{-3}\). The NRM directions are randomly oriented: steep and shallow, positive and negative inclinations are equally represented. Although very fine grained titanomagnetite and haematite are primary Fe-Ti oxides, demagnetization generally produces no change from the initial NRM directions whether up to 660 °C or in 1400 Oe peak A.F. This tends to rule out large amounts of secondary magnetization and self-reversal, particularly as there are no apparent compositional variations throughout the granite. We discount lightning because the same magnetic features are shown by samples from all the surface exposures, as well as by subsurface samples from deep wells. Among possible, but unsubstantiated, explanations are: (1) the NRM may be due to stable viscous components which have been acquired throughout the granite over an interval of the order of \(10^9\) years, (2) the granite may have recorded multiple reversals of the Precambrian field during cooling, and (3) there was some form of random motion in the crystal mush below 600°C, possibly associated with the injection of multiple granite sills.

1. Introduction

Small hills of Precambrian granite are exposed near Spavinaw (95.0° W, 36.4° N) in Mayes County, north-eastern Oklahoma, 80 km north-east of Tulsa. They protrude through shallow dipping Ordovician Cotter dolomite, belonging to the Ozark uplift (Huffman 1958, pp 15–18).

The Spavinaw granite is part of a large subsurface granite-rhyolite terrane which is found in numerous wells to basement along a broad south-west trending pre-Palaeozoic arch from south-west Missouri to central Oklahoma—a distance of 240 km. (Denison 1966; Muehlberger, Denison & Lidiak 1967). Denison (1966) infers that the sub-surface extent of the granite is approximately 14,000 km\(^2\). The rock is a micrographic granite porphyry which maintains a remarkably uniform texture throughout the sub-surface. Denison (1966) suggests that the most likely mode of emplacement was a series of multiple sills.

The isotopic age of the Spavinaw granite has been precisely determined by the Rb/Sr method (we have recalculated all ages using \(Rb^{87} = 1.39 \times 10^{-11}\) yr\(^{-1}\)). Muehlberger \textit{et al.} (1967) defined Spavinaw igneous activity as 1270 ± 30 My on the

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Our intention in studying the Spavinaw granite was to obtain a well-dated palaeomagnetic pole from a rock unit exposed in a structurally uncomplicated area. As we shall show, the magnetic results cannot be explained satisfactorily on a palaeomagnetic basis.

2. Previous work

Hawes (1953) reported on detailed vertical and total field intensity maps of the Spavinaw area. He measured the NRM of 97 cubes cut from 47 cores drilled from three surface outcrops: no demagnetization experiments were made. We comment briefly on Hawes’ findings.

1) The vertical field anomalies occur as highs and lows across the exposed granite with maximum gradients of 3000 gamma per metre. The anomalies are elliptical and roughly 15 m in diameter. Both the vertical and total intensity maps show that the anomalies continue beyond the surface outcrops of the granite.

2) We have collated Hawes’ NRM directions into conventional form in Fig. 1. Using the horizontal at the collecting site as a reference (this is in fact close to being the bedding plane of the overlying Palaeozoic sediments) about half of the NRM directions are downward seeking (hereafter arbitrarily referred to as ‘normal’) and half are upward (‘reverse’). There is no visible grouping about antiparallel axes. Steep and shallow inclinations are equally distributed among the normal and reverse directions, and there is no tendency for any streaking through the present field.

3) Hawes interpreted the anomalies in terms of a series of granite blocks, 15 m in diameter and from 8 to 50 m in length, with magnetizations alternately up and down. Despite the fact that he collected from the centres of the anomalies, NRM measurements of the surface samples show no preferred direction and not always constant polarity. In fact, both polarities are shown by different specimens from the same sample.

4) Log mean values calculated from the intensity data (Irving, Molyneaux & Runcorn 1966) show no difference between the log mean intensity for the normal specimens (8·4 × 10⁻³ emu cm⁻³) and that for the reversed specimens (9·9 × 10⁻³ emu cm⁻³). Both values are high for a granite.

3. New studies

To further investigate the NRM characteristics of the granite, we made a new collection from the various outcrops but without regard to the location of the vertical intensity anomalies. The 16 block samples each weighed about 7 kg and were oriented by Sun and magnetic compass methods (the two bearings differed by 10°, an error probably caused by the high magnetization intensity of the granite).

In the laboratory, several specimens were cut from each sample and at least one was subjected to progressive AF or stepwise thermal demagnetization using equipment described in Helsley & Spall (1972). Demagnetization to 1400 Oe peak field was carried out in a shielded room with a residual field of 200 gamma and for thermal demagnetization this was further reduced to ± 5 gamma using a Helmholtz system. All the NRM measurements were made on a PAR model SMI spinner magnetometer.
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Fig. 1. NRM directions of 97 granite specimens recorded in Figs 5, 6, 7 and 10 of Hawes (1952), plotted on an equal area projection, (a) normal and (b) reverse. Solid symbols are downward seeking directions; open symbols are upward seeking. Asterisk and diamond are the axial and present fields respectively.
4. NRM measurements

The initial NRM directions of all 37 specimens from the new collection are plotted in Fig. 2. Ten samples (23 specimens) have reversed polarity (using the arbitrary polarity designation of Section 2): only at one site was a single polarity observed, although Hawes found both polarities in his data from this site. As in Hawes' case the NRM directions are randomly oriented. The bars linking specimens from the same sample indicate the amount of within-sample scatter: it varies from 2° to 55°, and the average for the reversed specimens (11°) is twice that for the normal specimens (5°). Repeat measurements after six months showed direction changes of only a degree or two, so the within- and between-sample dispersions are not due to soft magnetization.

Table 1 summarizes the intensity and susceptibility data for the sets of normal and reverse specimens: the ratio of these two quantities, $Q'$, does not involve assumptions about the field intensity, either past or present. The susceptibility ranges of both sets

![Figure 2](https://academic.oup.com/gji/article-abstract/28/3/237/631304/128327651304)
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of specimens are very similar, which suggests that there is the same bulk magnetic content in each. Although the intensity range for both sets is the same, the log mean value for the reversed specimens is twice that for the normal specimens. However, this may be illusory because of the small number in the population: recall that Hawes found no intensity differences. Samples with shallow inclinations show intensity (and $Q'$) ranges very similar to samples of the same polarity with steep inclinations.

A more important observation is that all the $Q'$ values are greater than unity which generally is an indicator of magnetic stability (Irving 1964, p. 92).

5. Demagnetization studies

Representative demagnetization paths are given in Fig. 3. Of the 12 specimens thermally demagnetized, without exception, all show no direction changes up to 660 °C (e.g. specimens 8B, 9A, 10B and 16B in Fig. 3). (We have not plotted directions measured at 670 °C because the moment remaining at this temperature was less than one thousandth of the initial moment). This implies that a very stable component due at least to haematite is present in the granite. Of the 10 specimens subjected to AF demagnetization, seven showed no direction changes up to 1400 Oe (e.g. specimens 6A, 8A, 9B and 16A in Fig. 3). This also indicates a very stable component of magnetization, with a high coercive force, which could also be typical of haematite.

Despite these observations we see no tendency for the NRM directions to group within two antipodal zones—a feature that would usually be expected of such a highly stable NRM representing both normal and reverse polarities.

![Fig. 3. Demagnetization paths for several specimens plotted on an equal area projection. Legend as in Fig. 1. Fields are variously 88, 175, 350, 700 and 1400 Oe; temperature stages are in the neighbourhood of 350, 450, 520, 530, 550, 570, 600 and 660 °C. Numbers in boxes refer to specimens from those samples.](https://academic.oup.com/gji/article-abstract/28/3/237/631304)
During AF demagnetization, three reversed specimens displayed large direction changes (> 60°) along great circle paths, not related to the present field axis, and generally ending up on the opposite hemisphere, although in no way antiparallel to the initial NRM direction (e.g. specimen 10A in Fig. 3). This is the only evidence from the demagnetization experiments that the NRM of the granite is other than very stable.

Another possible difference between the normal and reversed specimens is observed in the normalized decay curves: typical examples are illustrated in Fig. 4. All the reverse specimens (e.g. 9A and 10B) have knee-shaped thermal decay curves (Fig. 4(a)), while those for the normal specimens are more linear (with respect to the log plotting scale). Irving & Opdyke (1965) have correlated the rectangular type of curve with a stable remanence and the convex–concave type with the acquisition of secondary magnetization. This implies that the reverse specimens are the more stable. Both sets of samples show a point of inflexion between about 550 and 600°C, suggesting that a magnetite contributes to the NRM as well as haematite. Note that the reversed specimens show a much greater contribution from haematite above 600°C than the normal specimens.

On the other hand the normalized AF decay curves show exactly the opposite correlation. Rather it is the normal specimens (6A, 8A and 16A in Fig. 4(b)) which show knee-shaped curves and the reversed specimens (9B and 10A) which have flatter curves. According to Saad (1969), the former shape indicates stability of the NRM and the latter instability. The three reversed specimens which showed large direction changes during AF demagnetization also display the flat profile curves.

Thus, if we consider only the NRM decay curves we have conflicting evidence on the relative stability of the normal and reversed specimens. Furthermore, the directional data indicates that demagnetization produces little change, and therefore that both sets are magnetically stable. Here we can recall the remark of Gough et al. (1964) who doubted that the shape of the demagnetization curves has much relevance to the validity of the results.

![Fig. 4. Normalized NRM decay curves for some of the specimens shown in Fig. 3. Thermal decay curves (a) are plotted on a semi-log scale; AF decay curves (b) are on a log-log scale.](https://academic.oup.com/gji/article-abstract/28/3/237/631304/0)
6. Opaque mineralogy

Reflected light studies do not suggest any pronounced mineralogic differences between specimens of either polarity. The main Fe–Ti oxides are titanomagnetite, haematite and goethite.

Specimens of both polarities contain titanomagnetites which are up to 300 microns across; their subhedral texture suggests a primary origin. They are oxidized along 111 planes to stubby lathes of ilmenite. In addition, there is an irregular development of haematite along titanomagnetite margins and occasionally along feather-shaped lamellae. This direct oxidation to haematite is probably martitization, although no maghemite was observed as a transitional phase in the process (Davies, Rapp & Wolawender 1969).

The largest numbers of opaques in both sets of specimens are submicroscopic (at x 1200 magnification), and thus have dimensions less than a micron.

This places the minerals in the single domain range (Stacey 1963) which should be characteristic of high stability and capable of acquiring a large moment (Larson et al. 1969). In fact stability and high intensity are well shown by the Spavinaw granite.

There is a great deal of haematite included in the feldspars. Boone (1969) considers that this process takes place immediately following crystallization of the magma, so we may regard this haematite as primary. It ought therefore to have acquired a TRM recording the ambient field at the time the granite was intruded. Furthermore, very stable remanences have been associated with Fe–Ti oxide inclusions in silicates (e.g. Murthy, Evans & Gough 1967).

Nevertheless there is also evidence for considerable low temperature alteration in the granite, perhaps due to surficial weathering. Irregular patchworks of amorphous goethite occur, showing little relationship with the other minerals.

No apparent petrographic differences were observed between the normal and reversed specimens. Quantitative measurements were not made because, firstly, haematite is pervasive throughout the whole rock; secondly, most of the Fe–Ti oxides are submicroscopic; and thirdly, the various phases are not crystallographically controlled as is the case in the usual classification of oxidation in lavas.

7. Curie points

Curie point determinations in a field of about 2000 Oe suggest that haematite and a titanium poor magnetite contribute to the saturation magnetization. Representative curves are given in Fig. 5. Both curves are reversible suggesting that no mineral changes occurred during heating. The Curie point of the haematite varies from 640 to 660°C but this should be considered to be a minimum estimate, because the higher strong-field magnetization of magnetite desensitized the balance to haematite. The curve for the normal specimen has a flatter profile than that for the reversed specimen: consequently the break in slope around 580–590°C (corresponding to magnetite) is less obvious.

8. Artificial thermoremanence (TRM)

An artificial TRM was given to several normal and reversed specimens by cooling them from 700°C in a field of about 0.3 Oe. The procedure was repeated with the specimen orientation at 90° to that in the first experiment. In all cases the TRM direction was ‘normal’ and within one degree of the applied field axis. This suggests that the reversed polarity is not a self-inducing feature and that the rocks are magnetically isotropic. The high intensity of the artificial TRM and its thermal demagnetization characteristics are very similar to the NRM in showing no direction changes to 660°C and knee-shaped decay curves. This implies that the NRM is a true TRM.
It could also imply that it is a CRM because this has similar characteristics to TRM (Kobayashi 1961). However, this CRM would have to be in both magnetite (or titanomagnetite) and haematite because the NRM directions are unchanged by demagnetization to 660°C.

9. Summary of observations

The Spavinaw granite has some ambiguous magnetic features. Therefore it is relevant to summarize the salient observations which we feel have to be explained.

(i) Of a total of 134 specimens collected during two studies of surface exposures of the granite, 68 have NRM directions which are upward seeking and 66 have downward NRM directions. These polarities are with respect to the horizontal at the sampling site, which is close to the bedding plane of the overlying Palaeozoic sediments.

(ii) The NRM directions of the specimens are equally distributed between shallow and steep inclinations, with no distinct grouping. There is not always agreement in direction between specimens from the same or adjacent samples. There is no clustering of the directions about the present field axis.

(iii) The granite is very strongly magnetized, of the order of $10^{-2}$ emu cm$^{-3}$. The susceptibility is uniform throughout the granite (i.e. the bulk magnetic content is the same) and all the $Q'$ ratios are greater than unity (implying magnetic stability).

(iv) Twelve specimens which were thermally demagnetized to 660°C showed no change from their initial NRM directions. Titanomagnetite and haematite are observed microscopically and in the Curie point determinations. Thus we have to
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conclude that the two minerals have the same direction of magnetization and were magnetized in the same field.

(v) Of 10 specimens AF demagnetized to 1400 Oe, seven showed no direction changes, which reinforces the argument that the granite is magnetically stable. If titanomagnetite and haematite both contribute to the NRM, they must be of very high coercive force. Three reversed specimens showed large direction changes.

(vi) There is no tendency of the NRM directions to converge about a preferred axis during demagnetization. Rather they maintain the random distribution observed in the initial NRM directions.

(vii) There are no apparent qualitative differences in opaque petrography between the normal and reversed specimens. There is primary titanomagnetite and haematite, exsolved ilmenite, secondary martite, and geothite and perhaps haematite formed by surficial weathering.

8. Discussion

The summary of observations in the previous section shows that we cannot with any confidence compute a single pair of normal and reversed palaeomagnetic poles for the granite. We now briefly comment on several possible explanations for the Spavinaw data.

(a) Lightning

The high intensity, the random directions and the resistance to demagnetization may be due to lightning strikes. We object to this on three grounds. First, the samples for both studies were collected from outcrops over several square miles in area, and all show the same magnetic features. One of the outcrops is in fact along Spavinaw Creek, in a valley several hundred feet lower than the other outcrops. Second, the vertical intensity highs and lows go under the sedimentary cover. Third, and we feel most important, high intensity and random directions are also shown by subsurface Spavinaw granite (Denison 1971, private communication).

(b) Self-reversal

The mixed polarities and the presence of titanomagnetite and several modes of haematite could suggest self-reversal of magnetization. We found circumstantial evidence for differences between normal and reversed specimens in the higher intensities of the reversed set and the different shapes of the NRM decay curves. Nevertheless, there are four important pieces of evidence against this: first, titanomagnetite and haematite have the same direction in 19 of 22 specimens; second, there is no evidence during demagnetization for anti-parallel components; third, there are no apparent qualitative petrographic differences between the normal and reversed specimens; fourth, only one polarity is reproducible in the laboratory.

(c) Secondary magnetization or CRM

The random NRM directions may be due to large amounts of soft secondary magnetization. We reject this on the grounds that 86 per cent of our specimens were stable to demagnetization. Alternatively the random directions may in part be caused by a hard magnetization of the CRM type (e.g. Storetvedt 1970). We cannot dismiss this entirely because we cannot say how the various modes of haematite may have contributed to such a CRM. It is possible that the large direction changes in those specimens during AF demagnetization are due to a CRM in martite or even goethite.
(d) Reversals of the geomagnetic field

The random but stable directions may be due to a single or multiple reversals of the geomagnetic field while the granite cooled. While a single field reversal would not be unique in a granite (e.g. Dunn et al. 1971), we consider this to be unlikely in the case of the Spavinaw granite for two reasons;

1. there is no systematic change in inclination even allowing for a rebound effect (e.g. Watkins 1969).

2. there is no variation in specimen intensity with inclination (it is commonly observed that inclinations during the transition stage of a field reversal are associated with lower intensities, e.g. Creer & Ispir 1970).

An alternative is that the granite cooled and was magnetized over a very long period of time, probably at least a million years, during which there may have been several reversals of polarity of the Earth’s field. Thus, the majority of the samples should reflect one or other polarity, with a minority reflecting intermediate inclinations. Multiple reversals and thus many transition paths would explain the lack of any systematic inclination changes. They also explain why divergent, yet very stable, NRM directions are obtained from specimens from the same sample: as Evans (1967) points out, the magnetic ages of adjacent specimens may differ by $10^3$ to $10^4$ years, which, during a polarity transition, could involve considerable movement of the field axis.

However, it does not explain why there is no variation of intensity with inclination. Nor does it account for the lack of direction changes up to 660 °C. We have argued that titanomagnetite and haematite are both primary minerals: thus, their Curie temperature being 100 °C different require that they be magnetized thousands of years apart. If some of the samples (those with intermediate inclinations) were magnetized during a transition we would have expected considerably different field directions to be represented by each mineral. Thermal demagnetization did not bring out any differences.

9. Conclusion

We cannot satisfactorily explain all the magnetic results from the Spavinaw granite using conventional palaeomagnetic methods. We are left with some philosophical speculations which we cannot substantiate. Among these are:

(a) Some kind of permanent interaction at the domain level between the very strong intergrain magnetic fields of two minerals (but why do both minerals end up with the same direction?).

(b) A viscous component (e.g. Sholpo 1967; Prévot & Biquand 1970) which has built up over 10$^9$ years during deep burial (but why is this unaffected by demagnetization?).

(c) The stable but randomly oriented magnetizations in the granite record ‘anomalous’ positions of the palaeofield axis (of the type discussed by Hospers & Van Andel 1970, pp. 37–38) associated with a reversal of the field (we can neither prove nor disprove this essentially ‘non-hypothesis’).

(d) Random movements in a semi-solid magma below 600 °C and thus after acquisition of the major portion of the TRM. Wet granite magmas, under confining pressures in excess of 10 kb, melt and crystallize at temperatures below 620 °C (Boettcher & Wyllie 1968). It is possible that the final stages of crystallization of the Spavinaw granite followed the initial acquisition of TRM by the titanomagnetite and haematite grains. Thus internal motions in the solidifying magma or the injection of multiple
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granite sills (see Introduction) may have disturbed some, if not all, of the grain moment orientations before final crystallization was complete.

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