Direct Measurement of Magnetostriction in Rocks using Capacitance Micrometry

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Summary

A capacitance micrometer, sensitive to displacements as small as 1 Å, has been used to measure directly the magnetostriction curves of several Canadian and Australian basalts both parallel ($\lambda_\parallel$) and perpendicular ($\lambda_\perp$) to applied fields. They are found to be similar to magnetization curves in general shape, with $\lambda_\parallel = -\frac{1}{2} \lambda_\perp$ within the precision of measurement ($\sim 2$ per cent) in high fields, but relatively stronger $\lambda_\perp$ in low fields, indicating negative volume magnetostriction in low fields. Saturation magnetostrictions $\lambda_\parallel$ are found to correspond to the fractional contents of magnetic minerals, in confirmation of values inferred from stress-induced magnetic anisotropies. Hysteresis is not apparent and magnetostriction associated with saturation remanence is unmeasurably small ($<0.005 \lambda_\parallel$) showing that negligible permanent domain rotation accompanies the temporary application of a high field and that the domain structures of individual grains are intrinsically isotropic.

Introduction

An understanding of the magnetostrictions of rocks is implicit in the developing study of tectonomagnetism (Nagata 1969), but direct measurements have been lacking. While magnetostriction can be inferred from the converse effect of stress upon magnetization, the results obtained are more complicated than current theories and a new experimental lead is desirable.

It has always been assumed that the magnetostrictions of rocks are directly proportional to the magnetostrictions of their constituent minerals, but this has been demonstrated only indirectly and only for saturation magnetostriction (Stacey 1960). This assumption cannot be extrapolated with confidence to magnetization in low fields, which is of more direct geophysical interest, since low field magnetization is controlled by crystal orientation and so is correlated with the anisotropy of elasticity, whereas saturation magnetization follows the magnetizing field regardless of the alignments of crystal axes. In fact the experiment reported here shows the assumption to be invalid. Direct observation of magnetostriction also throws light upon the magnetization process itself since domain rotation or movements of $71^\circ$ or $109^\circ$ domain walls are magnetostrictive but $180^\circ$ wall movements are not.

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Another problem to which a solution has been at hand for several years, but without a convincing demonstration of its validity, is the intrinsic isotropy of the domain structures of individual magnetic grains. Bhathal & Stacey (1969) found that the anisotropy of susceptibility induced in a rock by a strong alternating field applied along a selected axis was very small. It is also readily removed by heating (Bhathal, Gillingham & Stacey 1969). This was taken to imply that the preferential alignment of domains parallel and antiparallel to the selected axis was very small and therefore that individual multidomain grains were intrinsically isotropic (except in so far as they may be geometrically elongated). Measurements of magnetostriction associated with remanent magnetism in rocks provide a direct test for this inferred isotropy since a parallel–antiparallel domain arrangement has the same magnetostriction as saturation magnetization, whereas reversion to an isotropic domain structure gives no magnetostriction.

Measurements

The capacitance cell, illustrated in Fig. 1, was a simple adaption of the displacement transducer described by Stacey et al. (1969) and was used with a commercial version of the ratio transformer bridge circuit (Model 305 by Auckland Nuclear Accessory Co.). Interferometric calibration of a similar transducer (Gladwin & Wolfe 1975) has confirmed the sensitivity and linearity originally claimed (Stacey et al. 1969). The measurements, which are very simple in principle, are based on the unbalance of a

![Fig. 1. Illustration of the mechanical construction of the capacitance cell.](https://academic.oup.com/gji/article-abstract/44/1/1/663602/1163822)
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capacitance bridge by small movements of a two-sided electrode, which is fixed to one end of a rock specimen, relative to an outer pair of electrodes, which are fixed together and to the other end of the specimen. The complete cell was suspended in the gap of an electromagnet, with the measurement axis either parallel or perpendicular to the field, and was surrounded by plastic foam boxwork to minimize thermal drift (which arises from the differing thermal expansions of the specimens and the construction material of the cell—selected ‘non-magnetic’ brass). Thermal noise, arising at least partly from eddy currents induced in the metal components of the capacitance cell as the applied field was changed, limited the accuracy of magnetostriction measurement to $\pm 2 \times 10^{-8}$ in high fields and about $\pm 0.5 \times 10^{-8}$ in low fields, about 2 per cent of the measured values. Measurements with plastic ‘specimens’ verified the absence of any systematic error.

The measurement results are all so similar that only one set is reproduced here (Fig. 2). They each show:

(i) An initial magnetostriction which varies as the square of the applied field strength, as for magnetization in the initial, Rayleigh, region.

(ii) A familiar magnetization-type curve which saturates in a field of several kilo-oersteds, in which the domains must be completely aligned.

(iii) Saturation magnetostrictions correlated well with measured percentage of opaques (Fig. 3); correlation with susceptibility was also obvious but with more significant departures from a simple linear relationship.

(iv) Magnetostrictions parallel and perpendicular to the field are related by $\lambda_\perp = -\frac{1}{2} \lambda_\parallel$ precisely in high fields, but $|\lambda_\perp|$ is always found to be stronger than $|\lambda_\parallel|/2$ in low fields.

(v) Hysteresis loops in magnetostriction are so narrow that measurements in increasing and decreasing fields are superimposed within the uncertainty of measurement and no perceptible magnetostriction ($<0.5$ per cent of $\lambda$) is associated with the remanence when the applied field is removed.

![Graph](https://academic.oup.com/gji/article-abstract/44/1/1/663602/fig-2.png)

**Fig. 2.** Magnetostriction curves for a sample of pre-Cambrian basalt from northern Canada. The inset shows the low field range with the Rayleigh region in which $\lambda \propto H^2$ and $(\lambda_\parallel + 2\lambda_\perp) < 0$. 

Field strength (kilo-oersteds)
Magnetic properties of all of the specimens examined were dominated by grains in the true multidomain size range (up to 60 μm). Table 1 gives references to earlier geological and magnetic work on these rocks and summarizes our measurements of susceptibility, saturation magnetostriction and percentage opaques.

**Discussion of results**

The correspondence between titanomagnetite content and magnetostriction was expected but the correlation with measured opaques (Fig. 3) is unexpectedly good, especially as it is better than the correlation with susceptibility. The Queensland samples in particular had several Curie points and were obviously magnetically complicated with appreciable titanium contents, which we supposed would enhance the magnetostrictions since titanium in solution increases the intrinsic magnetostrictions of titanomagnetites (Syono 1965). It appears that this effect is compensated by the presence of opaques which are effectively non-magnetic. For the purpose of tectonomagnetic calculations it is obviously convenient if we can assume the magnetostrictions of rocks to be given simply by the volume percentage of opaques, assumed to be pure magnetite.

The approximate dependence of 'initial' magnetostriction on the square of the inducing field (as in the inset to Fig. 2) simply reflects the proportionality of magnetostriction to magnetization in the Rayleigh region of the magnetization curve, but the breakdown of the relationship \( \lambda_1 = \lambda_2 \) was not expected. Our data show this relationship to be obeyed very precisely in high fields, but that it becomes progressively poorer at lower fields. Since \( \lambda_2 \), the fractional change in length of a specimen, is positive and in low fields \( -\lambda_1 > (\lambda_2 / 2) \), there is a negative volume magnetostriction \( (\lambda_2 + 2\lambda_1) \). This is a subtle effect which is not accommodated by current theories of piezomagnetism (e.g. Stacey & Johnson 1972). We do not suppose that it represents a breakdown in the equation for magnetostriction of an isolated single crystal of magnetite:

\[
\lambda = -\frac{1}{2}\lambda_{100} + \frac{3}{2}\lambda_{100}(a_1^2 \beta_1^2 + a_2^2 \beta_2^2 + a_3^2 \beta_3^2) + 3\lambda_{111}(a_1 a_2 a_3 \beta_1 \beta_2 + a_2 a_3 a_1 \beta_1 \beta_3 + a_3 a_1 a_2 \beta_2 \beta_3)
\]

which gives zero volume magnetostriction, the \( a \)'s being direction cosines of the magnetization with respect to the principal crystal axes and the \( \beta \)'s being direction cosines.
cosines for the direction in which the magnetostriction is $\lambda$. Rather we suggest that the volume magnetostriction is a consequence of elastic constraint to the magnetostrictions of magnetite grains, which being mainly single crystals cannot be treated as elastically isotropic. This presents a new and significant problem in magnetoelasticity which we are not in a position to pursue further here. However, we can see immediately that the stress-sensitivities of low field susceptibility of a rock perpendicular and parallel to a compression are not in general related by the factor $(-\frac{1}{3})$. Another implication is that hydrostatic pressure causes an increase in susceptibility of a rock, but not its saturation magnetization.

The observed absence of significant magnetostriction hysteresis indicates that domain rotations (or 71° and 109° domain wall movements) which contribute to magnetization are essentially reversible. In retrospect this may not be particularly surprising, but it carries an important implication for the domain structures of magnetite grains in rocks and for theories of thermoremanence and other properties. A grain in which the domains were aligned alternately parallel and antiparallel would show the same magnetostriction as a magnetically saturated grain. Therefore the anti-parallel-structure does not represent the state of domain relaxation after saturation (or alternating field treatment), but the domain structure of an assembly of grains (and by inference of individual grains) spontaneously relaxes to the condition that all pairs of easy directions of magnetization are equally populated. This does not imply the absence of remanence, as opposite pairs of easy directions may be unequally populated, but it does reveal a nearly isotropic domain structure, as inferred from the experiments of Bhathal & Stacey (1969).
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