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MAGNETIC ANISOTROPY IN THE TRENTON LIMESTONE: RESULTS OF A NEW TECHNIQUE, ANISOTROPY OF ANHYSTERETIC SUSCEPTIBILITY

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Abstract. A new method for determining magnetic anisotropy using anhysteric remanence susceptibility is described. The magnetic fabric of a collection of Trenton Limestone specimens has been determined using this method, as well as by conventional anisotropy of magnetic susceptibility. The results demonstrate the usefulness of the new method for finding the magnetic fabric of rock units such as the Trenton in which the bulk magnetic susceptibilities are low. A model is proposed to explain the observed foliated and lineated fabric as a consequence of overburden compaction and regional horizontal stresses. The original fabric is inferred to have been isotropic; the anisotropy resides in secondary magnetite of Late Paleozoic age. It is argued that the observed magnetic fabric must therefore be Alleghenian or younger in age. Our method has the potential to determine paleostress directions in carbonates elsewhere, provided our assumptions are correct.

Introduction

Anisotropy of magnetic susceptibility (AMS) has long been used as a method for quantifying sedimentary fabric [Ising, 1942; Graham, 1954; Granar, 1958; Rees, 1965; Hamilton and Rees, 1970; Kent and Lowrie, 1975]. Taira and Lienert [1979] compared AMS with photometric and microscopic point-counting methods of fabric determination and found that all three methods gave concordant results. AMS has also been useful in igneous and metamorphic rock studies [Stacey, 1960; Khan, 1962; Uyeda et al., 1963; Stone, 1963; Fuller, 1963; Van der Voo and Klootwijk, 1972; Irving and Park, 1973; Rathore, 1979; Ellwood and Abrams, 1982], both for petrofabric analysis, and for estimation of the fidelity with which the rocks are able to record a magnetic field orientation.

However, measurement of AMS has proven to be difficult and somewhat dependent on the method of measurement [Hrouda et al., 1983; Schmidt and Ellwood, 1983; Ellwood, 1978, 1984]. In this paper we propose a new rockmagnetic method, anisotropy of anhysteretic susceptibility (AAS), based on the ability of rock samples to acquire an anhysteretic remanent magnetization (ARM). An anhysteretic remanence is acquired by a sample when it is subjected to an alternating field in the presence of a small direct magnetic field. The anhysteretic remanence intensity is normally proportional to the strength of the direct field. This proportionality, a specific magnetization for unit applied direct field, is termed anhysteretic susceptibility by King et al. [1982]. An important difference between initial or low-field susceptibility and anhysteretic susceptibility is that in the latter there is no contribution from paramagnetic and diamagnetic components in the sample. Further, because of their coercivities, typically much higher than the normal range of alternating fields applied, hematite and goethite contribute minimally to anhysteretic susceptibility. The contribution of magnetite is thus enhanced, which can be important in rocks where the concentration of magnetite is particularly low, e.g., limestones (in a limestone with 10 ppm magnetite by weight, for example, magnetite and diamagnetic calcite contribute about equally to the initial susceptibility). For this reason, we feel that AAS may be a more robust quantity than AMS, and may provide more reproducible results on different measuring instruments (i.e. different cryogenic magnetometers).

However, the sources of AAS and AMS in rocks may differ. ARM is carried preferentially by stable single domain and pseudo-single domain grains, and the effects of superparamagnetic or large multidomain grains, which can dominate the initial susceptibility, are minimized. The results of Banerjee et al. [1981] and King et al. [1982] indicate that the ratio of initial to anhysteretic susceptibility for 2-micron grains is about 0.2, while for 200-micron grains it is 10. Thus the relative contributions of the two grain sizes to initial and anhysteretic susceptibility differ by a factor of 50. For this reason, AAS should be considered a complementary method rather than a substitute for AMS.

In light of these considerations, we can identify several potentially useful applications for AAS. First, for rocks such as limestones with very low magnetite content, the contributions of other magnetic minerals and of the matrix are diminished, which may result in more pronounced and hence more reproducible measured anisotropies. Second, the method should be useful when an anisotropy in the carriers of stable remanence is of concern. One such case is investigation of detrital remanent magnetization, which originates by physical alignment of single domain and pseudo-single domain grain axes with an external field [King and Rees, 1966; Stacey, 1972]. Another would be evaluation of the ability of foliated or lineated rocks to faithfully record an external

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field orientation, for paleomagnetic purposes. Finally, because the informational content of AMS and AAS are to some extent complementary, a comparison of both may provide more information than either one alone.

In this study we have examined one of these potential applications, fabric analysis of limestone, and we show preliminary experimental results for the Trenton Limestone. The Trenton was chosen because two previous sets of AMS data are available for comparison for the same rocks from the same locality [Graham, 1966; McElhinny and Opdyke, 1973].

Methods

Trenton Limestone samples were collected from exposures at Trenton Falls, New York. The AMS of oriented 2.5 x 2.2 cm cores was determined using a torsion magnetometer at University of Texas, Arlington. AAS of the same sample cores was determined using the following procedure: 1) the specimen is demagnetized in a peak alternating field of 40 mT to establish a base level natural magnetization; 2) an ARM is imparted along a specified sample axis in a peak alternating field of 30 mT with a coaxial direct field of 0.1 mT; 3) the remanent magnetization is measured with a cryogenic magnetometer, and the component due to the ARM is found by vector subtraction of the base level natural magnetization; 4) this ARM is then demagnetized in a peak alternating field of 40 mT. We have found that this treatment is sufficient to completely remove the previously given ARM in Trenton specimens. 5) An ARM is then imparted along a different sample axis and the process repeated for 9 different sample axes using Girdler's [1961] procedure, which was originally developed for AMS determinations using a susceptibility bridge. In this procedure, the anisotropy is determined with sufficient redundancy and the best fit anisotropy tensor is determined using a least squares method. The tensor thus obtained is used to find calculated susceptibilities along the 9 axes. Residual (observed minus calculated) susceptibilities along the 9 axes are computed. Small residuals indicate that the data are of high quality, and that the assumption that the anisotropy may be described by a triaxial ellipsoid is valid. A computer program was used to determine the best fit anisotropy tensor, along with its eigenvalues and eigenvectors.

Results

Results are shown in Figure 1 where directions of the maximum and minimum axes of AMS and AAS are presented in equal area plots. A histogram of % anisotropy is given below each plot (% anisotropy=100(Kmax-Kmin)/Kint). A well defined foliation is apparent in both data sets: in all cases the minimum axes are nearly vertical. For our AMS data the maximum axes are horizontal and dispersed in declination, but show the suggestion of a westerly, or west-southwesterly lineation. % AMS values are low, averaging about 1.6%. The AAS data on the other hand show a well defined west-southwesterly lineation and give a higher % anisotropy, about 6.2% (Figure 1). Residual (observed minus calculated) ARM susceptibilities are in all cases very low, indicating that the anisotropy is well described by a triaxial ellipsoid.

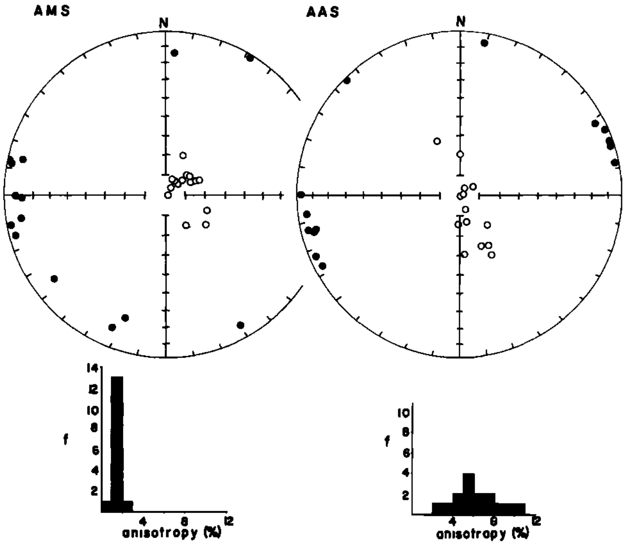

Fig. 1. Directions of maximum (closed circles) and minimum (open circles) axes of AMS and AAS (see text) on equal area plots. Histograms of percent anisotropy accompany each plot.

Discussion

The AMS of Trenton samples from the same Trenton Falls locality has been studied twice before [Graham, 1966; McElhinny and Opdyke, 1973]. Results from the former study were obtained by spinning samples in an AC susceptibility bridge and the latter study employed a PAR spinner magnetometer. The results of both studies indicate minimum axes of magnetic susceptibilities that are vertical. The results of Graham [1966, p. 633] show a west-southwesterly lineation. On the other hand, the results of McElhinny and Opdyke [1973, p. 3702] indicate a south-southeasterly lineation. The difference between the two studies was ascribed by the latter authors to the difference in the method employed to determine the anisotropy. We note further that all methods for determining AMS are difficult for rocks with low bulk susceptibilities such as the Trenton.

Our AAS results show % anisotropies that are larger than those from AMS studies, and they give a lineation in agreement with that found by Graham (Figure 1) although more clearly defined. The reason that the AAS results show a better defined lineation than AMS results is that the intensities of ARM (about 10 mA/m) are several orders of magnitude larger than the sensitivity of the cryogenic magnetometer and are therefore measureable with great precision. The higher % anisotropies for AAS are probably due to the fact that there is no contribution due to the diamagnetic susceptibility of matrix calcite, which is likely to attenuate the total AMS.

In a related study [McCabe et al., 1984] it was demonstrated that the stable ancient component of natural remanent magnetization in Trenton samples is of Late Paleozoic (Kiaman Interval) age and is a chemical remanent magnetization residing in magnetite of postdepositional (diagenetic) origin. This leads to the conclusion that the observed AAS is also a secondary feature that must be Late Paleozoic or younger in age. There is another reason to expect that the anisotropy is secondary: McElhinny and Opdyke [1973, p. 3702] state that the minimum axes of susceptibility are vertical and not systematically related to bedding even in a highly contorted syndepositional slump structure, and so the anisotropy must postdate this feature.

Models to explain the origin of magnetic anisotropy in undeformed sedimentary rocks usually assume that a foliation is due to the shape related anisotropy of magnetic grains that come to rest during deposition with their long axes parallel to the bedding plane, and that a lineation is due to ambient currents. Clearly this model cannot be applied in the case of the Trenton since the AAS resides in grains that are of postdepositional origin. Therefore we propose an alternative model in which 1) an original (perhaps isotropic) magnetic fabric occurs due to the formation of postdepositional magnetite, 2) a foliation is developed through overburden compaction and pressure solution and, 3) a lineation results from regional horizontal stress.

We note that the lineation found from our AAS results is consistent with a north-northwesterly paleostress direction, in agreement with structural studies in nearby areas of New York State [e.g. Engelder, 1979]. In addition, AMS results from the Onondaga Limestone [Graham, 1966; Kent, 1979] indicate a similar lineation and therefore a similar paleostress direction. Since the stress-induced magnetic lineation resides in magnetite grains of Late Paleozoic age [McCabe et al., 1984] the stresses that gave rise to the observed anisotropy must be Alleghenian or younger.

Conclusions

A new method for determining magnetic fabric in rocks, AAS has been described. This method has advantages over conventional AMS because it 1) gives the anisotropy of grains capable of holding a remanent magnetization only and is therefore of potentially greater value as an adjunct rock magnetic technique in paleomagnetic studies and 2) it may be applied to rock types in which the bulk susceptibilities are too low to employ AMS.

A model for the secondary development of magnetic anisotropy in sedimentary rocks has been proposed in which compaction and horizontal stresses play a primary role. Thus AAS may be useful in structural studies as a very fast and easy method of determining the directions of regional paleostresses in flatlying rocks. Further, since the anisotropy must postdate secondary magnetite formation, the AAS method can provide temporal constraints for paleostress fields in cases where the age of secondary magnetite can be determined using paleomagnetism.

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