

MAGNETIC ANISOTROPY AS AN AID TO IDENTIFYING CRM AND DRM IN RED SEDIMENTARY ROCKS

K.P. KODAMA^{1,2} AND M.J. DEKKERS²

- 1 Department of Earth and Environmental Sciences, Lehigh University, Bethlehem, PA, 18015, USA (kpk0@lehigh.edu)
- 2 Paleomagnetic Laboratory "Fort Hoofddijk", Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands (dekkers@geo.uu.nl)

Received: January 16, 2004; Revised: 16 June, 2004; Accepted: August 25, 2004

ABSTRACT

To further evaluate the potential of magnetic anisotropy techniques for determining the origin of the natural remanent magnetization (NRM) in sedimentary rocks, several new remanence anisotropy measurement techniques were explored. An accurate separation of the remanence anisotropy of magnetite and hematite in the same sedimentary rock sample was the goal.

In one technique, Tertiary red and grey sedimentary rock samples from the Orera section (Spain) were exposed to 13 T fields in 9 different orientations. In each orientation, alternating field (af) demagnetization was used to separate the magnetite and hematite contributions of the high field isothermal remanent magnetization (IRM). Tensor subtraction was used to calculate the magnetite and hematite anisotropy tensors. Geologically interpretable fabrics did not result, probably because of the presence of goethite which contributes to the IRM. In the second technique, also applied to samples from Orera, an anisotropy of anhysteretic remanence (AAR) was applied in af fields up to 240 mT to directly measure the fabric of the magnetite in the sample. IRMs applied in 2 T fields followed by 240 mT af demagnetization, and thermal demagnetization at 90 °C to remove the goethite contribution, were used to independently measure the hematite fabric in the same samples. This approach gave geologically interpretable results with minimum principal axes perpendicular to bedding, suggesting that the hematite and magnetite grains in the Orera samples both carry a depositional remanent magnetization (DRM). In a third experiment, IRMs applied in 13 T fields were used to measure the magnetic fabric of samples from the Dome de Barrot area (France). These samples had been demonstrated to have hematite as their only magnetic mineral. The fabrics that resulted were geologically interpretable, showing a strong NW-SE horizontal lineation consistent with AMS fabrics measured in the same samples. These fabrics suggest that the rock's remanence may have been affected by strain and could have originated as a DRM or a CRM.

Our work shows that it is important to account for the presence of goethite when using high field IRMs to measure the remanence anisotropy of hematite-bearing sedimentary rocks. It also shows that very high magnetic fields (>10 T) may be used to measure the magnetic fabric of sedimentary rocks with highly coercive magnetic minerals without complete demagnetization between each position, provided that the field magnetically saturates the rock.

Keywords: magnetic anisotropy, remanence, magnetite, hematite, red beds

1. INTRODUCTION

The magnetic fabric of sedimentary rocks can be used as an indicator of the origin of their natural remanent magnetization (NRM), i.e. to establish whether the NRM is a primary detrital remanent magnetization (DRM) or a secondary chemical remanent magnetization (CRM). Knowing the age of the NRM puts essential constraints on paleomagnetic interpretation. Magnetic fabrics are also important because they can be used to correct for directional inaccuracies of the NRM due to strain, compaction, or depositional effects. If the NRM is a DRM, erroneous paleolatitudes caused by an inclination error can be avoided. In red sedimentary rocks, magnetite and hematite typically coexist complicating interpretation. Being able to isolate the remanence anisotropy of low coercivity ferrimagnetic minerals, primarily magnetite, and high coercivity antiferromagnetic minerals, usually hematite, would provide a powerful diagnostic tool for paleomagnetic studies of red sedimentary rocks. Here we explore the potential of high field isothermal remanent magnetizations (IRMs), acquired in fields >10 T, to this end.

1.1. Magnetic fabrics

Remanence anisotropy has been shown to be the best parameter to correct for inclination shallowing in magnetite and hematite-bearing rocks (Kodama, 1997; Tan *et al.*, 2003). The presence of inclination shallowing will affect the accuracy of the paleomagnetic direction, and the accuracy of paleolatitudes calculated from the paleomagnetic inclination. A DRM's magnetic fabric will typically have a bedding parallel foliation while a CRM's magnetic fabric, based on experimental work, will not necessarily be constrained to bedding (Tauxe *et al.*, 1990; Kodama *et al.*, 2002, Kodama, submitted to *Earth Planet. Sci. Lett.*). When dealing with magnetite-bearing rocks, Kodama (1997) and Tan and Kodama (1998) have shown that the anisotropy of a partial anhysteretic remanent magnetization (AAR) is a useful way of obtaining the anisotropy of the magnetite grains carrying the characteristic remanence of a sedimentary rock.

Hematite is more of a challenge for remanence anisotropy measurements because of its high coercivity. Hematite's high coercivities make the AAR techniques used for magnetite-bearing rocks impossible for typical paleomagnetic laboratories. Tan *et al.* (2003) and Tan and Kodama (2002) have developed new techniques for measuring the remanence anisotropy of hematite-bearing rocks. They have used IRMs applied in 9 positions followed by heating at high temperatures (>600°C) after each IRM acquisition to isolate the remanence of the characteristic remanence-carrying grains and to remove the IRM before proceeding to the next position. Repeated heatings at high temperatures, however, can cause chemical changes of the magnetic minerals in a rock, thus affecting the accuracy of the anisotropy measurement.

Tan *et al.* (2003) and Tan and Kodama (2002) have also measured hematite anisotropy using a combination of chemical demagnetization and anisotropy of magnetic susceptibility (AMS) measurements. AMS measurements are quite straightforward to make, but chemical demagnetization, i.e. soaking the samples in concentrated HCl for up

to several months, is a time-consuming and messy procedure. Both techniques can give good results, but a technique that uses neither chemical demagnetization nor repeated heatings at high temperatures to measure the remanence anisotropy of hematite would be preferable. It would avoid the risk of chemical alteration and save a substantial amount of time. If it could be demonstrated to give reasonable results, it would probably be more widely used.

If high coercivity hematite could be magnetically saturated at each anisotropy measurement position, the problems caused by non-repeatable IRM intensities, i.e. the effects of magnetic history on IRM acquisition, as outlined by *Tauxe et al. (1990)*, would be eliminated. *Tauxe et al. (1990)* were forced to use low IRM acquisition fields to be able to demagnetize their samples between anisotropy steps by alternating field demagnetization. In *Tauxe et al.*'s anisotropy of isothermal remanence experiments, the magnetic state of the sample before the first and subsequent steps was not exactly equivalent, thus providing a tentative explanation for inability of low field IRMs to accurately measure remanence anisotropy (*Tauxe et al., 1990*). *Hodych and Buchan (1994)* proposed a simplified procedure to determine remanence anisotropy avoiding magnetic history effects. They introduced successively stronger IRMs (up to 800 mT) in a single direction oblique to the bedding plane (45° angle) chosen in such a way that the bedding-parallel component is parallel to the NRM declination of the sample. The IRMs are vectorially decomposed into a bedding-parallel direction and a direction perpendicular to bedding. To determine the hematite contribution thermal demagnetization up to 680°C had to be applied. Similarly, in the approach of *Tan et al. (2003)* and *Tan and Kodama (2002)* heating up to 700°C was deemed necessary to completely demagnetize the hematite IRM at each step. Preferably, this heating should be avoided. To saturate the hematite in each measurement position we have used magnetic fields of >13 T, available at the High Field Magnet Laboratory (HFML, Faculty of Physics, University of Nijmegen, The Netherlands). Complete demagnetization was not conducted after each position because the high fields totally reset the sample's magnetization at each application.

2. SAMPLES AND METHODS

The samples used for our experiments came from two areas. One set of samples came from the Tertiary basins of Spain. Haayfa Abdul Aziz (Fort Hoofddijk Paleomagnetism Laboratory) provided samples from the Orera section of the Calatayud Basin in NE Spain (the samples come from cycles 58 and 59 in the numbering scheme of *Abdul Aziz et al. (2000,2003a)*). During Middle Miocene times the Calatayud Basin was a closed lake environment. It has cyclic sedimentary deposits ranging from alluvial fan to lacustrine facies. The cyclicity is best expressed in the lithology referred to as 'cyclic mudflat-shallow lake lithofacies' (*Abdul Aziz et al., 2003b*) in the Valdelosterreros area where most sampling was done. Sediment accumulation was offset by crustal subsidence. Therefore, the delicate balance that yielded remarkably regular cyclic sediments enabling a record of climate variability, has existed for more than 2 Myr.

Red and grey mudstones and lake carbonates are recognized as lithological facies in the Calatayud Basin. Since we have studied samples from mudstones we concentrate here on briefly summarizing their most important features. More extensive descriptions can be

found in *Abdul Aziz (2001)* and *Abdul Aziz et al. (2003b)*. The red mudstones contain almost no carbonate; silt- and sand-sized quartz and feldspar grains range from 3 to 35%. Prominent clay minerals are illite, mixed layer illite-smectite, and smectite (dioctahedral). Kaolinite is minor, palygorskite occurs in appreciable quantities in some red mudstones. Root traces are rare. The grey mudstones contain up to 40% carbonate and up to 20% silt- and sand-sized minerals, so the red mudstones are slightly coarser than the grey ones. The larger fragments are angular to subangular. Texturally, they are referred to as a silty siliciclastic mudstone with dolomicrite and clay peloids in a clayey groundmass. Burrowing and root traces are common. Clay mineralogy is similar to the red mudstones with the exception that the smectite is more Mg-rich (trioctahedral). In cases where carbonate caps red mudstone, the top centimeter or so of the latter is grey. It is highly unlikely that grey rock which represents more reducing conditions than the red rocks was originally red. In the depositional model and paleoclimatic interpretation of *Abdul Aziz et al. (2003b)* the red mudstone reflects the driest conditions while the grey mudstone represents an intermediate depositional environment and the carbonate (dolomite) represents wet and warm climatic conditions. Red rocks represent dry mudflat, grey rocks wet mudflat, and carbonates shallow lake conditions. The rocks have never been buried deeply, so compaction-related phenomena are not expected.

The Orera rocks have been shown to carry a good quality magnetostratigraphy, indicating that they have a primary remanence (*Abdul Aziz et al., 2000, 2003b*). Moreover, they have been tuned astronomically (*Abdul Aziz et al., 2003a*), so the sequence is very accurately dated. Samples for the present study came from the TW series that is part of the VT-II section of *Abdul Aziz et al. (2000)*. Cycles 58 and 59 are of reversed polarity (Chron C5r.2r) just below chrytochron OCS-2 recognized in the area (*Abdul Aziz, 2001*). Stepwise thermal demagnetization of sister specimens from a red and a grey lithology show that the NRM residing in hematite i.e. from 600°C upward has a shallower inclination than that residing in magnetite (~400–600°C; cf. Fig. 1). Goethite is not observed as an NRM carrier. IRM component analysis by *Abdul Aziz (2001)*, according to *Kruiver et al. (2001)* and *Heslop et al. (2002)*, showed three coercivity components. Component 1 has a remanent acquisition coercive force ($B_{1/2}$) ranging from 25 to 52 mT, and is interpreted as PSD magnetite (which can be slightly oxidized). Component 2 occurs in two ranges depending on the lithology: from 130 to 195 mT (grey mudstones and carbonates), and from 400 to 800 mT (red mudstones), and is interpreted as very fine grained hematite while the higher range would indicate slightly coarser hematite. Component 3 is characterized by very high $B_{1/2}$ (900–2500 mT, occurring in grey mudstone with root bioturbation) and interpreted as goethite.

Samples were also obtained from the Daluis Formation, Dome de Barrot region (SE France) from Pauline Kruiver. These hematite-bearing red beds are Permian in age and may record ancient secular variation of the Earth's magnetic field, thus strongly suggesting that they carry a primary paleomagnetic signal (*Kruiver et al., 2000*). Red mudstones and siltstones make up the Daluis Formation which shows the features of a flood-plain deposit. The red mudstones (typically ~1 m thick) show macroscopically no sedimentary structures. Thin section study, however, revealed horizontal stratification and bioturbation (*Van den Ende, 1977*). Apparently NRM lock-in has taken place after the bioturbation had ceased since no lithology dependent discontinuities were observed when

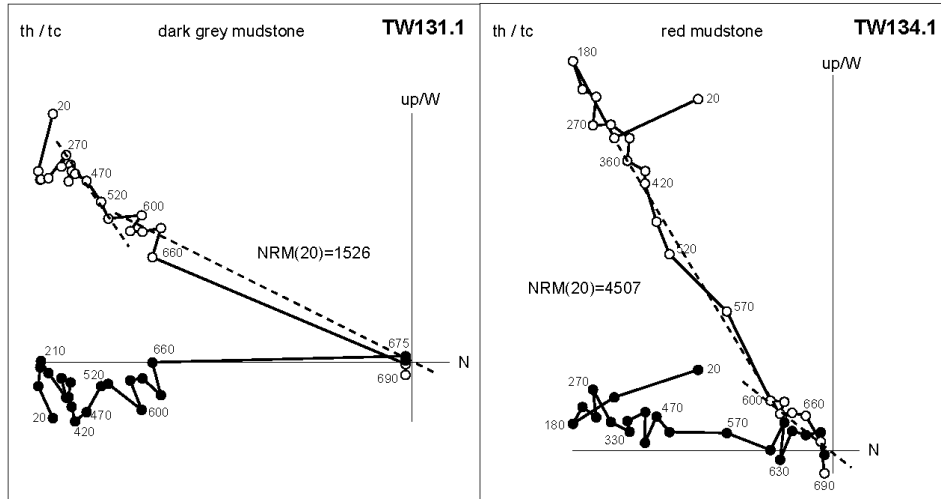


Fig. 1. Zijdeveld projections in stratigraphic coordinates of two sister specimens of samples investigated here (data kindly provided by Haayfa Abdul Aziz). Filled (open) symbols: projection onto the horizontal (vertical NS) plane. Numbers alongside the projection points indicate the demagnetization temperature in degrees Celcius. NRM(20) indicates the starting NRM intensity in 10^{-6} A/m. The dashed line segments in the inclination projection are estimates of the magnetite (trajectory 400–570°C) and the hematite inclinations (trajectory 600–675°C). The hematite inclination is shallower than that of magnetite.

analyzing the paleosecular variation record (Van den Ende, 1977; Kruiver *et al.*, 2000). The red mudstones alternate with laminated (often horizontally) purplish siltstones (typical thickness ~10 cm) which show desiccation features. The observed regular alternation suggests that hiati were short-lived when taking sedimentation rates and cycle durations into account, like in the Orera section. Thermomagnetic analysis and coercivity spectrum analysis indicated that hematite was the sole magnetic carrier in the Dome de Barrot sediments. Thin section analysis showed that the hematite grains (diameter ~2–5 μm) were evenly dispersed (3–5%) in the sediment matrix (Kruiver *et al.*, 2000). Microprobe analysis (Kruiver *et al.*, 2000) of individual hematite grains revealed a few percent Ti (expressed as TiO_2) which explains the magnetic hardness of this hematite (7 T required for complete saturation, P.P. Kruiver, unpublished data) as well as the absence of a Morin transition (Dekkers and Linssen, 1989). This result indicates a volcanic provenance and therefore the grains are most likely detrital. Bordet (1950, quoted by Van den Ende, 1977), argued for a rhyolitic source based on the similarity to Permian sediments derived from the Esterel volcanic province more to the south. Indeed, the sediments contain abundant quartz grains and some clay minerals.

The Orera samples are comparatively fragile so they were fit in plastic cylinders (standard size dimension of 25 mm outer diameter and 22 mm height) used for taking subsamples from bore-hole wet sediments. The samples were sized to fit the bore hole of

the HFML magnets (32 mm diameter) in all desired orientations. This required a cylinder height of 15 mm. Over the dimensions of the sample the field homogeneity in HFML magnets is better than 0.5%. (The HFML has an open-door policy: once a magnet time proposal passes certain criteria, they provide access to the facility. If remanence measurements are planned, one must bring one's own magnetometer, af demagnetizer, and furnace to remove the goethite contribution. To enhance through-put we currently use mini-samples (cubes of 3 mm size) that can be magnetized in batches of 8 samples.)

Four Orera samples were given IRMs in 13 T dc fields at the HFML of Nijmegen in 9 different orientations to measure their remanence anisotropy using the procedure of McCabe *et al.* (1985). The procedure of McCabe *et al.* (1985) was used in this study to measure remanence anisotropy. In this method a sample is given a laboratory remanence, either an anhysteretic remanent magnetization (ARM) or an IRM, applied in 9 different positions, in order to allow a least squares fitting of the data to a second rank anisotropy tensor. After each field application the samples were alternating field (af) demagnetized at 200, 240, 260, and 280 mT. The af demagnetization is used to separate the contributions of magnetite and hematite to the IRM of the samples, following observations by Dekkers (1990) that hematite IRMs decay linearly with peak alternating field. Preliminary af demagnetization of a 2 T IRM, applied with an impulse magnetizer, shows that a straight line can be fit to the 240–280 mT demagnetization steps. The line fit to the high field demagnetization data was assumed to delineate the hematite contribution to the remanence. Determining the line's *Y*-intercept would allow subtraction of the hematite remanence intensity from the total remanence intensity at each position, thus isolating the magnetite remanence intensity (Fig. 2). The low and high coercivity IRMs at each position were assumed to be nearly co-linear, so the total remanence direction measured at each position was used for the anisotropy tensor calculations. The hematite remanence anisotropy tensor was determined from data collected in this way at each of the nine positions. The hematite tensor was then subtracted, element by element, from the tensor derived from the undemagnetized 13 T IRM. The resulting tensor should be the magnetite tensor.

The Orera samples were known to contain the highly coercive mineral goethite, in addition to hematite and magnetite. It contributed only insignificantly to the natural remanence (NRM) of the rocks (Abdul Aziz *et al.*, 2000), however, it could contribute to the very high field IRMs being applied at the HFML. To see whether this was the case, samples with high field IRMs were thermally demagnetized at low temperatures (from 40°C to 110°C) in a drying oven in μ -metal shields. To see if the goethite had affected the remanence anisotropy tensors derived from very high field IRMs, a second anisotropy experiment was conducted with Orera samples. In this experiment, the remanence anisotropy of the low coercivity mineral (magnetite) in the rocks was measured directly by anisotropy of anhysteretic remanence (AAR) using standard techniques (McCabe *et al.*, 1985). In this experiment, five samples were used and given partial ARMs in 9 positions using af fields from 0 to 240 mT and a dc field of 0.03 mT. The samples were totally demagnetized at 300 mT, after measurement, between positions. In order to measure the hematite fabric, the same five Orera samples were given an IRM in a 2 T field, imparted by an impulse magnetizer, in each position then af demagnetized at 240 mT to remove the magnetite contribution, and finally thermally demagnetized at 90°C

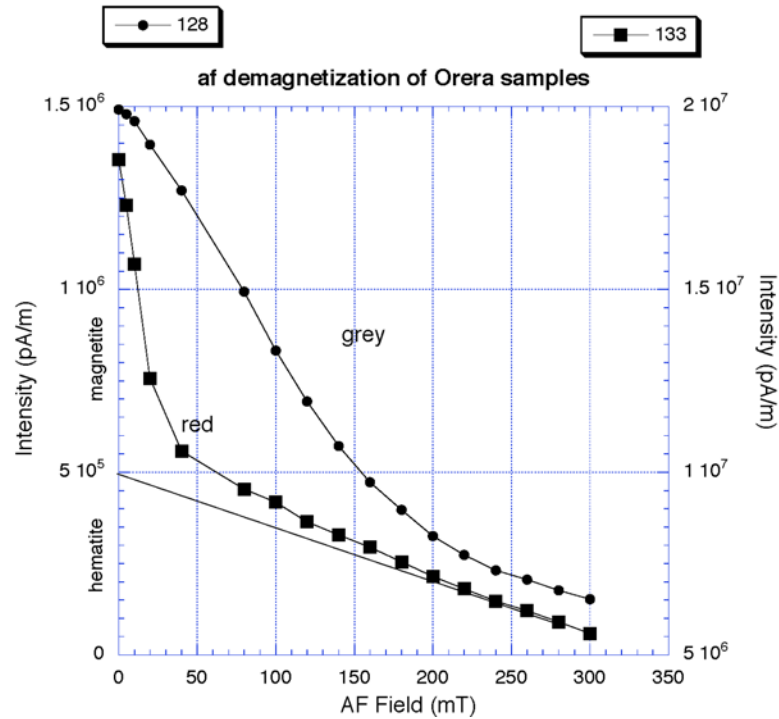


Fig. 2. Intensity loss during alternating field demagnetization for a grey and red Orera sample. The straight line fit to the 240, 260, and 280 mT demagnetization steps indicates how the total 2 T IRM can be separated into its hematite and magnetite contributions using af demagnetization.

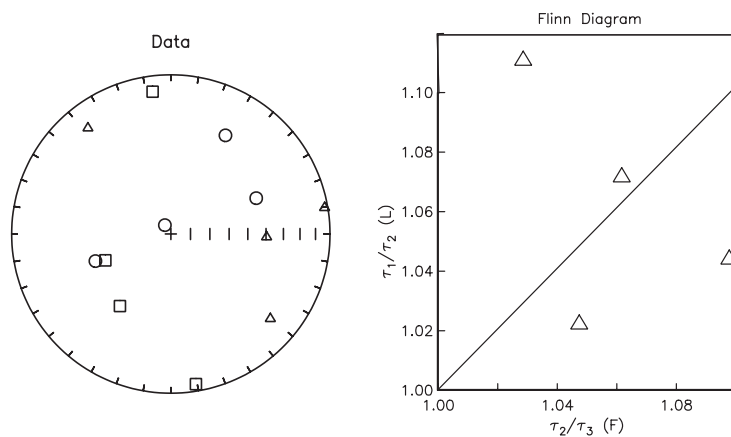
to remove most of the goethite contribution. Unfortunately, the samples could not be thermally demagnetized at the optimal temperature of 120°C to remove all of the goethite remanence, because the plastic sample holders would melt.

Six Dome de Barrot samples were measured for high field IRM anisotropy at the HFML at the University of Nijmegen. Because work by *Kruiver et al. (2000)* showed that these samples only contained hematite, it was hoped that a reasonable fabric could be obtained without the complications of other high coercivity minerals like goethite. In these experiments the samples were given IRMs in 13 T dc fields in nine different positions. No demagnetization was conducted between positions. Before IRMs were applied at Nijmegen, the AMS of the samples was measured in order to allow comparison with the remanence fabric.

All remanence measurements were made with an AGICO JR-5 spinner magnetometer. Af demagnetization at the HFML was conducted with a 2G alternating field demagnetizer loaned by the Marine Geophysics Group, Department of Geosciences, University of Bremen (Germany). Af demagnetization and AARs applied at the ‘Fort Hoofdijk’ Paleomagnetism Laboratory were conducted on a laboratory-constructed apparatus that uses 50 cps current from the mains for the alternating field. Helmholtz coils null out the

Earth's field. For the AAR measurements the Helmholtz coils nulling the field parallel to the af coil had their current reversed to allow application of a 0.03 mT field. The AMS was measured with an AGICO KLY-2 Kappabridge susceptibility meter. The impulse magnetizer was constructed by H. Boehnel, his PM4 model.

Hematite from 13 T AIR at Nijmegen



Magnetite from 13 T AIR at Nijmegen

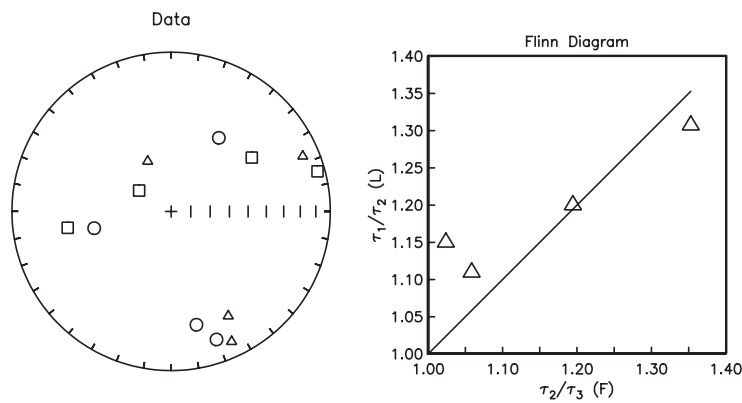


Fig. 3. Equal area stereonets showing the principal axes for the Orera samples using high field IRMs, af demagnetization, and tensor subtraction to isolate the hematite and magnetite anisotropies. AIR - anisotropy of isothermal remanent magnetization. The scatter in principal axis directions indicates that a meaningful fabric has not been isolated. Stereonets on the left show the mean axis directions and their circles of 95% confidence. Squares represent the maximum axes, triangles the intermediate axes, and circles the minimum axes. All points lower hemisphere. All stereonets in stratigraphic coordinates. Flinn diagrams on right show the eigenvalue axial ratios and the intensity of the samples' magnetic fabric.

3. RESULTS

In our preliminary alternating field demagnetization experiments, samples that were given IRMs in an impulse magnetizer set to provide a 2 T field were af demagnetized in the Fort Hoofddijk demagnetizer. Half of the samples measured from Orera were red in color, the rest grey in color. All samples appear to carry low and high coercivity magnetic minerals (Fig. 2). The curves also show a linear trend once demagnetization fields of 240 mT are reached. Therefore, demagnetization fields higher than 240 mT will be used to delineate the demagnetization behavior of the high coercivity magnetic mineral in the samples. The red colored samples showed a more pronounced break in slope in their intensity versus af demagnetization field curves than the grey samples.

Equal area stereonet plots, in stratigraphic coordinates, show that the principal axis directions of the high coercivity magnetic mineral, hematite, and the low coercivity magnetic mineral, magnetite, did not cluster in a way that could be interpreted geologically (Fig. 3). Lineation values for the high coercivity fabric range from 1.02 to 1.11; foliation values range from 1.04 to 1.09. Fabrics were much more intense for the low coercivity (magnetite) fabric with lineations between 1.10 and 1.30 and foliations between 1.05 and 1.35 (Fig. 3). Despite remanence and AMS evidence that the Orera samples should carry a primary depositional remanence (*Abdul Aziz, 2001; Abdul Aziz et al., 2000,2003*) a bedding parallel foliation for the remanence anisotropy was not observed. The total remanence fabric, derived from the total IRM acquired at each of the 9 positions, and the magnetite (low coercivity) fabric both showed clustering of minimum and intermediate principal axes either at low inclinations (magnetite) or intermediate inclinations (total), while the high coercivity remanence fabric showed virtually random scatter of the principal axes (Fig. 3).

These disappointing results can be explained by thermal demagnetization of the high field IRMs up to 110°C enabling the determination of the IRM part that resides in goethite (Fig. 4). Three of the four Orera samples used for the high field anisotropy experiments at the HFML show a large decrease in intensity (40%) after demagnetization at 110°C indicating significant contributions of goethite to the high field IRMs. Since goethite is grown *in situ* in the sediment, its magnetic fabric will be different from a depositional fabric (goethite is known to carry an inverse AMS fabric (cf. *Rochette et al., 1992*)). Therefore, the presence of goethite will complicate the remanence fabrics of the Orera samples. Interestingly, sample 129, a grey sample, had bedding parallel foliations for both its low and high coercivity remanence anisotropies. It did not contain any goethite, based on the low temperature thermal demagnetization data (Fig. 4). A primary DRM carried by the magnetic minerals would yield this type of fabric.

Hence, the second technique's measurement strategy was designed to cope with the potential presence of goethite. The anisotropy of low coercivity minerals and that of the high coercivity hematite was measured separately. AAR was applied in fields up to 240 mT for the low coercivity anisotropy and 2T IRMs were demagnetized by 240 mT af fields and by thermal demagnetization at 90°C to remove the goethite contribution. This approach yielded geologically interpretable magnetic fabrics. The AAR, which safely can be assumed to measure the fabric of magnetite because magnetite acquires a high specific ARM particularly when it is single domain (*Dunlop and Özdemir, 1997; Yu et al., 2002*),

showed anisotropy tensors with minimum principal axes perpendicular to the bedding plane (Fig. 5), as would be expected for a depositional remanence. There also appeared to be a weak N-S horizontal clustering of the maximum principal axes suggesting a lineation, that may reflect bottom currents present during deposition. An interpretable fabric was also obtained for the hematite (Fig. 6). Its fabric is not as well-defined as the magnetite fabric, probably because the goethite remanence was not totally removed by thermal demagnetization at 90°C, but it shows minimum axes clustered near the pole (but not at) to bedding and a SSW-NNE lineation indicated by a clustering of the maximum principal axes. Both of these features are consistent with either a primary, depositional origin for the Orera remanence.

The AMS fabric of the Dome de Barrot samples shows a typical depositional fabric that may have been modified by strain in the rocks (Fig. 7). Minimum principal axes are close to the pole to bedding, but are distributed along a NE-SW-trending, vertical plane. Maximum axes are horizontal and clustered in the NW indicating a strong lineation. The anisotropy of isothermal remanence (AIR) obtained from these samples (Fig. 8) is not as well defined, probably because of inaccuracies in the orientation of the samples in the high field magnet at the HFML at Nijmegen, but the fabric obtained is geologically interpretable. It shows a NW-SE horizontal lineation indicated by the clustering of the

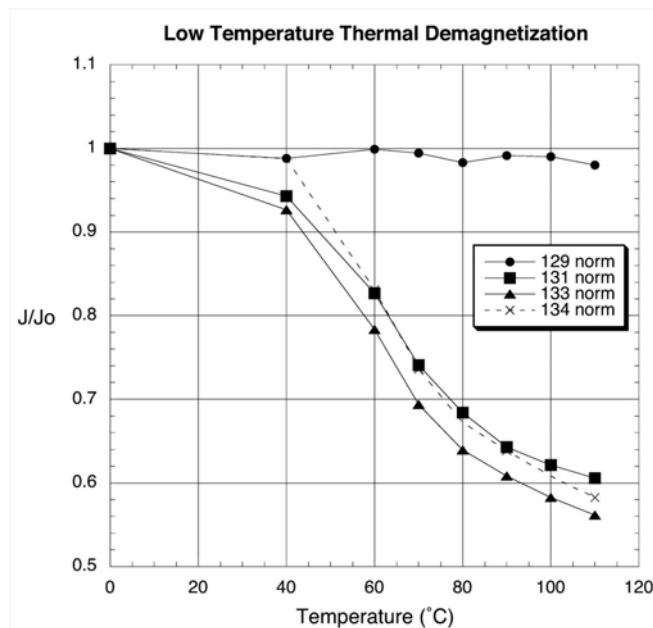


Fig. 4. Intensity loss during thermal demagnetization at temperatures up to 110°C of four Orera samples that carry an IRM acquired in a 13 T field. The samples have undergone a demagnetization up to 280 mT before to remove the magnetite contribution to the IRM. Note the large loss in intensity at very low temperatures indicating the presence of goethite in the rocks. Goethite contributes up to 40% of the total IRM.

maximum axes. The minimum and intermediate principal axes are tilted to intermediate inclinations and distributed along a great circle perpendicular to the maximum axes. This distribution of principal axes suggests that the hematite, the remanence-carrying mineral, has been affected by tectonic strain more than the AMS-carrying minerals.

Orera samples
AAR at 240 mT and 0.03 mT DC field

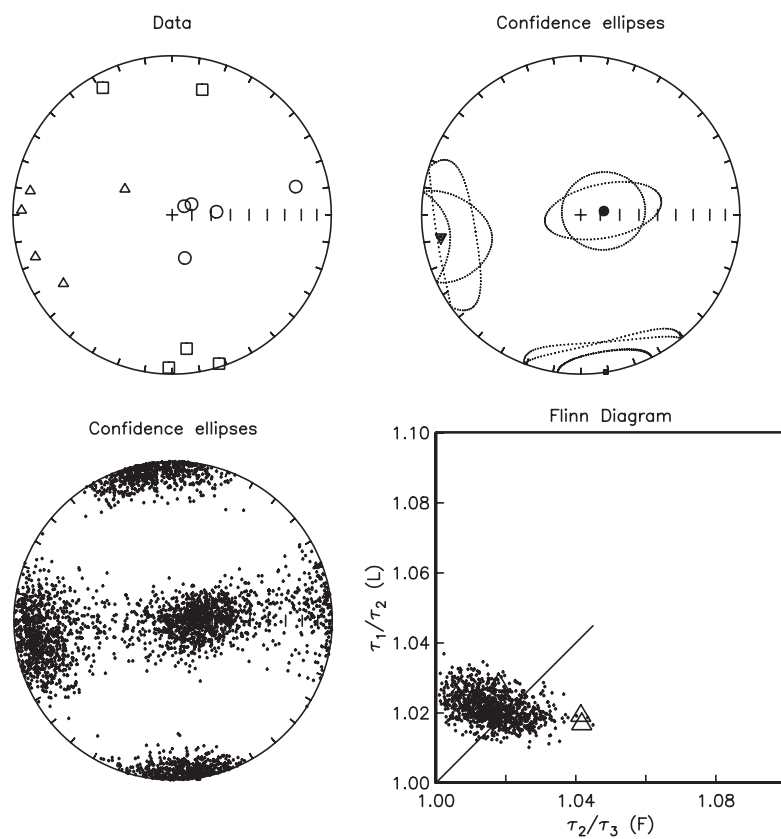


Fig. 5. Anisotropy of anhysteretic remanence (AAR) results for Orera samples indicating the fabric of the low coercivity magnetite in the samples. In the upper left the minimum axes (circles) are perpendicular to bedding. The maximum axes (squares) show a weak N-S lineation. The upper right stereonet shows the mean principal axes directions with the simple bootstrap (Tauxe, 1998) and Jelínek (1978) 95% confidence limits. The bottom left figure shows bootstrapping techniques (Tauxe, 1998) to estimate the confidence limits around the mean principal axis directions. The bottom right figure shows a plot of axial ratios ($\kappa_{max}/\kappa_{int}$ vs. $\kappa_{int}/\kappa_{min}$) in a Flinn diagram. The dots are calculated via bootstrapping techniques. The anisotropy ellipsoids show a scatter in shape from prolate to oblate.

4. DISCUSSION

4.1. The presence of goethite and tensor subtraction

Goethite often only marginally contributes to the NRM of red sedimentary rocks. However, it may be present in comparatively large amounts. It is thermodynamically stable with respect to hematite and water at temperatures between 25–80°C, at

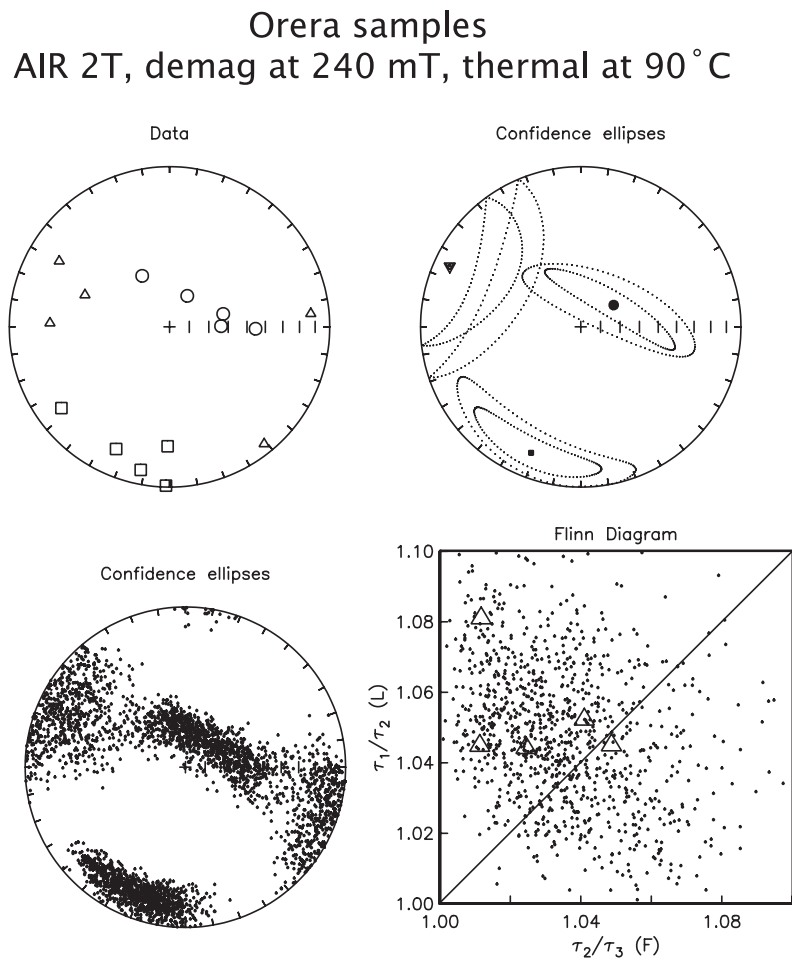


Fig. 6. Anisotropy of isothermal remanence (AIR) acquired in a 2 T field and then af demagnetized at 240 mT and thermally demagnetized at 90°C. The principal axes plotted on a stereonet (upper left) show minimum axes close to the vertical and maximum principal axes trending SSW-NNE. Confidence limits are shown in the upper right stereonet and, by bootstrapping, in the lower left stereonet. The Flinn diagram (lower right) shows that most of the anisotropy ellipsoids have a prolate shape.

atmospheric pressure, and at temperatures of 50–140°C at pressures of 400 MPa, depending on the grain size of the goethite (Langmuir, 1971). Hematite formation, likely from amorphous precursors, requires a very low moisture content. The goethite to hematite reaction requires a considerable structural rearrangement and therefore has a substantial activation energy, under laboratory conditions the goethite alteration reaction occurs at approximately 200–220°C for poorly crystalline goethite, for well-crystalline goethite the dehydroxylation reaction takes place at about 400°C. If goethite is present in a sample, it interferes with the high field IRM anisotropy procedure because it will acquire a measurable (S)IRM. As a rule goethite is grown *in situ* in the sediment and in cases where detrital hematite occurs together with secondary goethite the resulting fabric makes no geological sense as in the Orera case study. Therefore, if a rock may contain goethite, thermal demagnetization up to 110–120°C should be carried out to correct for the biasing influence of the goethite.

In the case of coexisting magnetite and hematite, determination of the individual high and low-coercivity mineral fabrics by subtraction of the low-coercivity tensor from a total measured tensor seems less accurate than direct measurement of the magnetic anisotropies by separate experiments, probably because of the error accumulation inherent to the subtraction procedure.

4.2. Orera

In the experiments with the Orera samples, the magnetite fabric appeared to be the most reasonable, probably because the low coercivity (<240 mT) AAR measurements separate these results most effectively from contamination by high coercivity hematite and especially goethite. The hematite fabric isolated by AIR, after demagnetization, and thermal demagnetization at 90°C, is more scattered and, while similar to a depositional fabric, is not as well defined as the AAR fabric (Fig. 5). At 90°C (higher temperatures would melt the sample containers) the goethite IRM contribution is not completely removed. Another possibility would be that the hematite is secondary and carries a chemical remanent magnetization (CRM). This option is rather remote as we will explain below. Hematite growth experiments on a filter paper substrate (Kodama *et al.*, 2002; Kodama, *submitted to Earth Planet. Sci. Lett.*) suggest that a moderate inclination CRM would lie near to the intermediate axis of the AMS and lie in a great circle defined by the maximum and intermediate axes, with the minimum axes clustered at moderate inclinations. The high temperature Orera remanence, interpreted to be carried by hematite, has a reversed direction with an inclination of approximately -40° and a declination of 180° . Under the proviso that the laboratory AMS experiments mimic behavior of remanence anisotropy in natural samples, the relationships between remanence and principal axes do not support a CRM origin for the hematite remanence in the Orera samples. Our results probably indicate that the hematite in the Orera samples carries a DRM. This is supported by the observation that the high temperature Orera remanence is consistently shallower, by about 10° , than the moderate temperature remanence (cf. Fig. 1 and Abdul Aziz, 2001). Work on hematite inclination shallowing suggests that a hematite DRM will be shallower than a magnetite DRM (Tan *et al.*, 2003; Tan and Kodama, 2002).

As a further check on the validity of the magnetite remanence fabric isolated by AAR from the Orera samples, the AAR data may be compared to AMS measurements collected

Dome de Barrot AMS

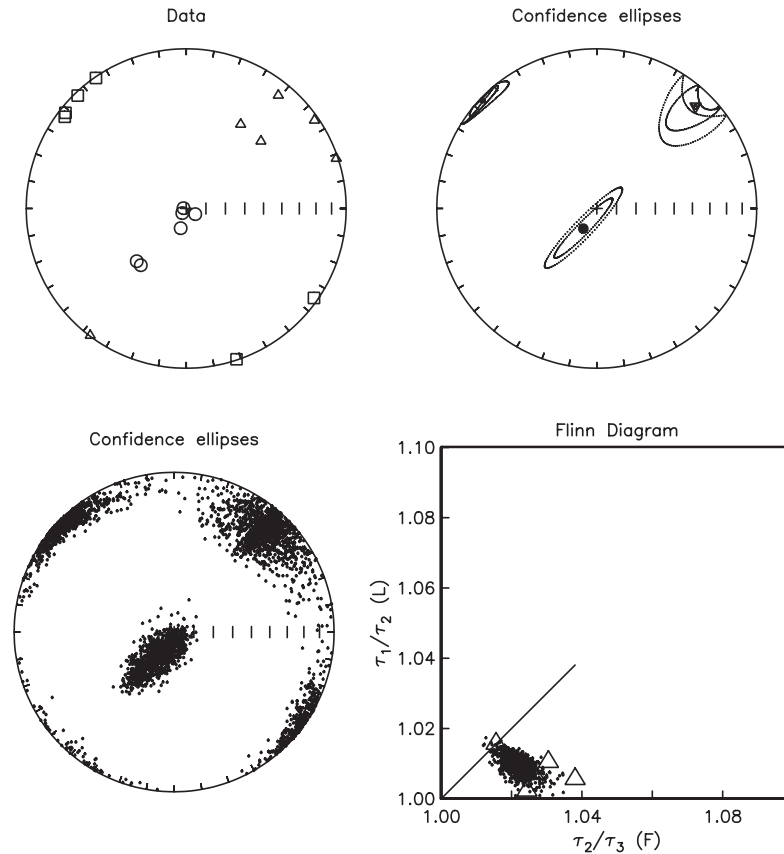


Fig. 7. Stereonets showing the principal axis directions for the AMS measured from the Dome de Barrot red beds. Note that the minimum axes are nearly perpendicular to the bedding plane and that the maximum axes show a strong NW-SE lineation. The Flinn diagram shows that the ellipsoids are mainly oblate. The confidence limits are relatively small.

by *Abdul Aziz (2001)* for the strata from which the remanence anisotropy samples were obtained. The Orera AMS results show a strong ESE clustering of the maximum axes near the horizontal. The minimum and intermediate axes are weakly clustered near the vertical and horizontal, respectively (Fig. 9). This pattern for the maximum and intermediate principal axes is switched for the remanence anisotropy results of magnetite (Fig. 5). Both AMS and AAR fabrics confirm a depositional origin for the magnetite remanence. The switch in the orientation between the intermediate and maximum axes between the AMS and AAR tensors may be due to the contribution of paramagnetics to the AMS fabric and a different response of the paramagnetic clay particles to bottom currents than the magnetite particles.

4.3. Dome de Barrot

For the Permian red bed samples from the Dome de Barrot, the AMS results show more of a bedding parallel foliation in agreement with data of *van den Ende (1977)* and *Kruiver et al. (2000)* for the corresponding site. The AIR results show a stronger horizontal lineation with minimum and intermediate axes clustered at moderate to low inclinations, respectively, the minimum axes to the SW and the intermediate axes to the NE. The contribution of paramagnetics to the AMS may be the reason for this discrepancy between remanence and susceptibility anisotropy principal axis directions.

Dome de Barrot-13 T AIR

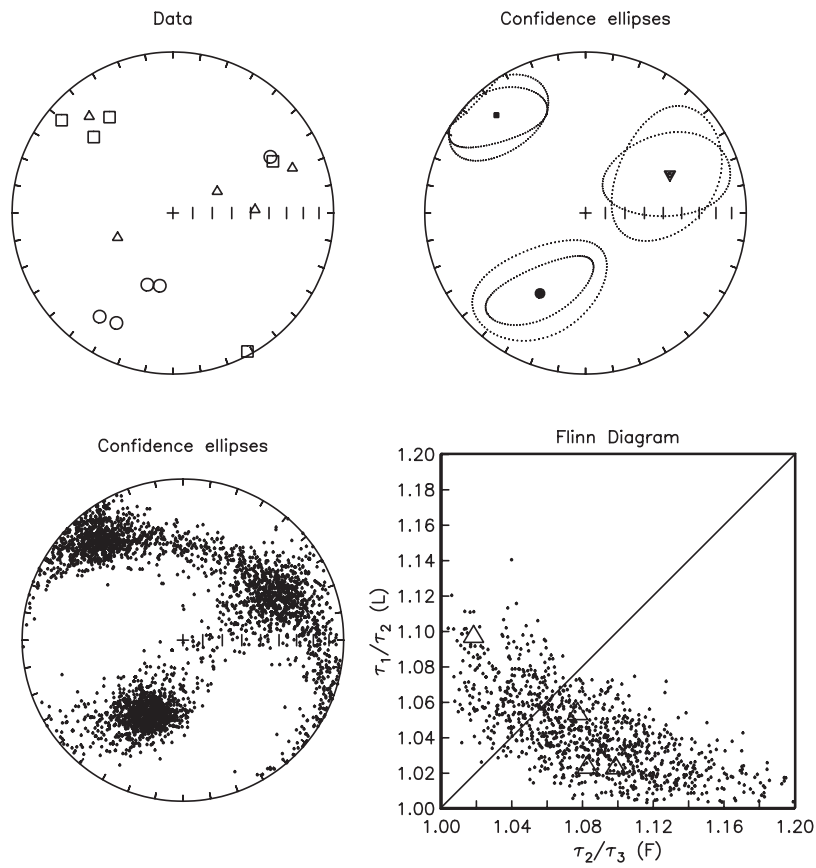


Fig. 8. Principal axis directions for a high field IRM anisotropy for Dome de Barrot red beds. The maximums show a NW-SE lineation similar to that observed for the AMS. The minimum and intermediate axes are tilted, however, with respect to the AMS results. The fabric probably represents a depositional remanence that has been modified by strain.

4.4. Correction for inclination error

It is difficult to attempt an inclination correction with the anisotropy measured by AAR and AIR in these experiments. There still may be a contribution of goethite to the AIR data from Orera because the samples could only be thermally demagnetized at 90°C to avoid melting the sample boxes. Therefore the high coercivity fabric may not be an entirely accurate representation of the hematite anisotropy. The AAR measure of the magnetite fabric would, therefore, perhaps, be a better candidate for calculating inclination corrections, but in order to get results with the highest signal to noise ratio the ARMs used for the AAR measurement were applied with af fields sweeping from 240 mT

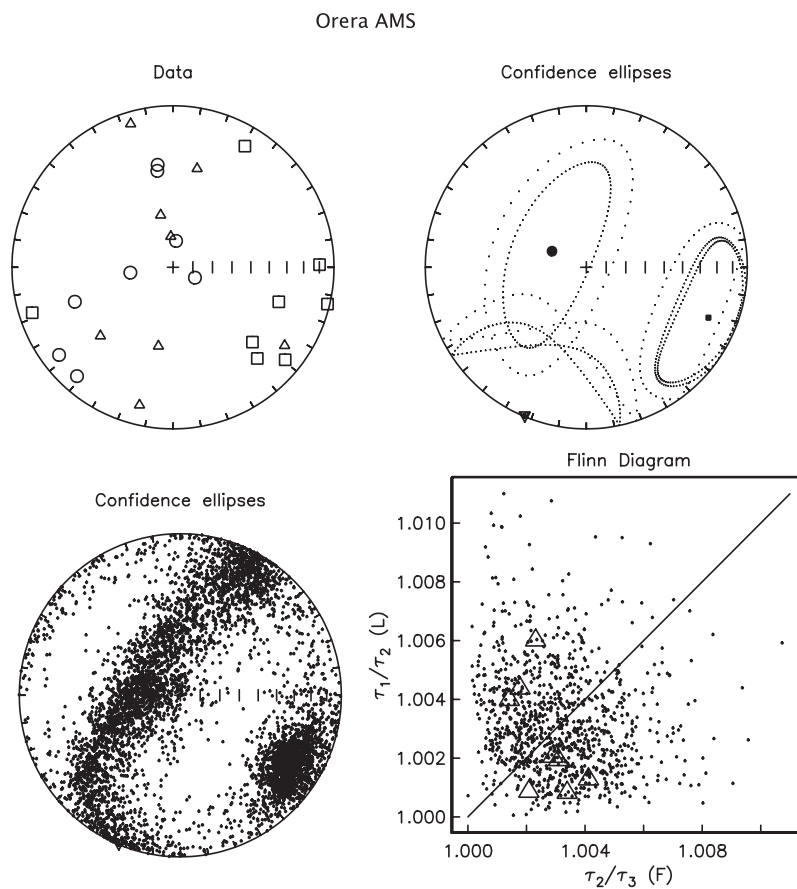


Fig. 9. Principal axis directions, 95% confidence limits (simple bootstrap and *Jelínek (1978)*), bootstrap estimates of confidence limits (*Tauxe, 1998*), and Flinn diagrams for AMS data from the Orera section. Samples are from cycles 58 and 59, the same stratigraphic horizons from which the remanence anisotropy samples were collected. Note the maximum and intermediate axes have their positions switched when compared to the low coercivity, remanence anisotropy results from these horizons (Fig. 4). Data measured and provided by *Abdul Aziz (2001)*.

to 0 mT. For the best inclination corrections using AAR, the ChRM-carrying grains should be targeted using partial ARMs applied over a coercivity range that isolated the magnetite remanence (Kodama, 1997). This approach could be used for a magnetite inclination correction in rocks that contain both hematite and magnetite. For a hematite inclination correction, assuming that the influence of goethite on the AIR has been totally removed, Tan and Kodama's (2003) theoretical correction approach may be used; however, if the samples contain multi-generational hematite, then high temperature thermal demagnetization may be needed to isolate the remanence anisotropy of the ChRM-carrying hematite grains.

In the Dome de Barrot samples, it appears that tectonic strain has modified the remanence anisotropy, with a strong lineation dominating the hematite's magnetic fabric. The effects at the site investigated are likely subtle, however. No distinct cleavage has developed. Cogné and Perroud (1985) showed that the directional effect of strain on the characteristic component of the NRM would be insignificant (their site B is close to the site investigated here) based on a correction procedure that makes use of the shape of reduction spots and other strain indicators. Van den Ende (*personal communication*) observed an inclination error in exploratory redeposition experiments of drilling mud from the Dome de Barrot sediments (moderate to steep inclination angle). A Permian paleolatitude of about 8° would imply only a small inclination error. Also, the lack of a strong oblate fabric with minimum principal axes perpendicular to bedding indicates that little or no inclination shallowing would be expected from this fabric. However, the declination may be deflected by the strong lineation toward the northwest. Interestingly, the remanence ($D = 210^\circ$ to 220° , $I = -20^\circ$ to -30° , Kruiver *et al.*, 2000) corresponding to the Permian direction of stable Europe lies approximately 90° from the lineation, close to the antipode of the intermediate principal axes. A remanence direction correction for the lineation would move the remanence further away from the lineation, but the remanence is already as far as possible from it, hence little correction is probably warranted. As for the possibility of a CRM for the Dome de Barrot remanence, the hematite growth experiments (Kodama *et al.*, 2002; Kodama, *submitted to Earth Planet. Sci. Lett.*) show that a CRM appears to lie in the plane defined by the intermediate and maximum AMS principal axes, close to the intermediate axes. Since this relationship is close to what is observed for the Dome de Barrot results, again assuming that the AMS of the growth experiments is a good indicator for the remanence anisotropy of the natural samples, a CRM cannot be ruled out. However, the observation that paleosecular variation may be recorded by these rocks and the presence of Ti within the hematite grains determined by microprobe analysis (Kruiver *et al.*, 2000) would argue for a depositional origin for the remanence. At the very least, it appears that strain has affected the Dome de Barrot red bed remanence but the fortuitous combination of remanence and strain orientations has resulted in a minimal effect.

The simplified anisotropy method proposed by Hodych and Buchan (1994), IRM acquisition in one direction oblique to the bedding plane with vectorial decomposition into bedding-parallel and bedding-perpendicular components, avoids the problems of magnetic history effects that occur when applying low field IRMs in nine different orientations. However, it assumes that the minimum principal axis of remanence anisotropy is perpendicular to the bedding plane and that the maximum principal axis of remanence anisotropy is parallel to the NRM declination. While anisotropy minima perpendicular to

bedding is expected for a DRM (or a pDRM) it is not obvious that the maximum principal axis would be parallel to the NRM declination. By measuring the full tensor, as proposed here, this interpretational constraint is circumvented; any orientation of the tensor can be measured and interpreted.

5. CONCLUSIONS

The presence of goethite in a red sedimentary rock can be a significant obstacle to determining the rock's remanence anisotropy. Even though the goethite may not contribute significantly to the NRM of the sedimentary rock, it could contribute significantly to a high field IRM applied to the rock for anisotropy measurements. Thermal demagnetization at low temperatures (approximately 100–120°C) removes the effects of the goethite and allows the fabric of the hematite to be determined. For best anisotropy remanence results using a high field SIRM, thermal demagnetization at 120°C should be used to totally remove the remanence of any goethite. Since goethite may be a common mineral in continental sediments and remanence anisotropy is the best way to determine the type and accuracy of the remanence, thermal demagnetization at low temperatures of high field IRMs should always be conducted to determine if goethite contributes significantly to the IRM before anisotropy determinations are made. Finally, in red continental sedimentary rocks that do not contain goethite, high field IRMs, without demagnetization after each position, can be used to determine the remanence anisotropy of the hematite. This fabric can be used to indicate whether the remanence is a DRM or a CRM and whether it has been modified by post-depositional processes.

Acknowledgements: Haayfa Abdul Aziz and Pauline Kruiver provided the samples for this study. Ulrich Bleil and Tilo von Dobeneck (Department of Geosciences, University of Bremen, Germany) kindly loaned us their 'single sample' alternating field demagnetizer for use in the High Field Magnet Laboratory (Nijmegen University, The Netherlands). The support of Jos Perenboom (High Field Magnet Laboratory, Faculty of Physics, Nijmegen University, The Netherlands) in running the high field equipment is appreciated. KPK acknowledges a Visiting Scientist Fellowship from ISES, the Netherlands Research Centre for Integrated Solid Earth Science.

References

- Abdul Aziz H., 2001. *Astronomical Forcing in Continental Sediments*, PhD thesis, University of Utrecht, Utrecht, The Netherlands.
- Abdul Aziz H., Hilgen F.J., Krijgsman W., Sanz E. and Calvo J.P., 2000. Astronomical forcing of sedimentary cycles in the Middle to Late Miocene continental Calatayud Basin (NE Spain). *Earth Planet. Sci. Lett.*, **177**, 9–22.
- Abdul Aziz H., Hilgen F.J., Wilson D.S., Krijgsman W. and Calvo J.P., 2003a. An astronomical polarity time scale for the middle Miocene based on continental sequences. *J. Geophys. Res.*, **108(B3)**, 2159, doi: 10.1029/2002JB001818.

Magnetic Anisotropy in Red Sedimentary Rocks

- Abdul Aziz H., Sanz-Rubio E., Calvo J.P., Hilgen F.J. and Krijgsman W., 2003b. Paleoenvironmental reconstruction of a middle Miocene proximal alluvial fan to cyclic shallow lacustrine depositional system in the Calatayud Basin (NE Spain). *Sedimentology*, **50**, 211–236.
- Cogné J.P. and Perroud H., 1985. Strain removal applied to paleomagnetic directions in an orogenic belt: the Permian red slates of the Alpes Maritimes, France. *Earth Planet. Sci. Lett.*, **72**, 125–140.
- Dekkers M.J., 1990. Magnetic properties of natural goethite - III. Magnetic behaviour and properties of minerals originating from goethite dehydration during thermal demagnetization. *Geophys. J. Int.*, **103**, 233–250.
- Dekkers M.J. and Linssen J.H., 1989. Rockmagnetic properties of fine-grained natural low-temperature hematite with reference to remanence acquisition mechanisms in red beds. *Geophys. J. Int.*, **99**, 1–18.
- Dunlop D.J. and Özdemir Ö., 1997. *Rock Magnetism - Fundamentals and Frontiers*. Cambridge University Press, Cambridge, U.K., 573 pp.
- Heslop D., Dekkers M.J., Kruiver P.P. and Van Oorschot I.H.M., 2002. Analysis of isothermal remanent magnetisation acquisition curves using the expectation-maximisation algorithm. *Geophys. J. Int.*, **148**, 58–64.
- Hodych J.P. and Buchan K.L., 1994. Early Silurian palaeolatitude of the Springdale Group redbeds of central Newfoundland: a palaeomagnetic determination with a remanence anisotropy test for inclination error. *Geophys. J. Int.*, **117**, 640–652.
- Kodama K.P., 1997. A successful rock magnetic technique for correcting paleomagnetic inclination shallowing: Case study of the Nacimiento Formation, New Mexico, USA. *J. Geophys. Res.*, **102**, 5193–5205.
- Kodama K.P., Tan X. and Newman K., 2002. The magnetic fabric and magnetization of sedimentary red beds. *Quaderni di Geofisica*, **26**, 79–81.
- Kruiver P.P., Dekkers M.J. and Heslop D., 2001. Quantification of magnetic coercivity components by the analysis of acquisition curves of isothermal remanent magnetisation. *Earth Planet. Sci. Lett.*, **189**, 269–276.
- Kruiver P., Dekkers M.J. and Langereis C.G., 2000. Secular variation in Permian red beds from Dome de Barrot, SE France. *Earth Planet. Sci. Lett.*, **179**, 205–217.
- Langmuir D., 1971. Particle size effect on the reaction of goethite = hematite + water. *Am. J. Sci.*, **272**, 147–156.
- McCabe C., Jackson M. and Ellwood B.B., 1985. Magnetic anisotropy in the Trenton limestone: results of a new technique, anisotropy of anhysteretic susceptibility. *Geophys. Res. Lett.*, **12**, 333–336.
- Rochette P., Jackson M. and Aubourg C., 1992. Rock magnetism and the interpretation of anisotropy of magnetic susceptibility. *Rev. Geophys.*, **30**, 209–226.
- Tan X. and Kodama K.P., 1998. Compaction-corrected inclinations from southern California Cretaceous marine sedimentary rocks indicate no paleolatitudinal offset for the Peninsular Ranges terrane. *J. Geophys. Res.*, **103**, 27169–27192.
- Tan X. and Kodama K.P., 2002. Magnetic anisotropy and paleomagnetic inclination shallowing in red beds: Evidence from the Mississippian Mauch Chunk Formation, Pennsylvania. *J. Geophys. Res.*, **107(B11)**, 2311, doi:10.1029/2001JB001636.

- Tan X. and Kodama K.P., 2003. An analytical solution for correcting palaeomagnetic inclination error. *Geophys. J. Int.*, **152**, 228–236.
- Tan X., Kodama K.P., Chen H., Fang D., Sun D. and Li Y., 2003. Paleomagnetism and magnetic anisotropy of Cretaceous red beds from the Tarim basin, northwest China: Evidence for a rock magnetic cause of anomalously shallow paleomagnetic inclinations from central Asia. *J. Geophys. Res.*, **108(B2)**, 2107, doi:10.1029/2001JB001608.
- Tauxe L., 1998. *Paleomagnetic Principles and Practice*. Kluwer, Dordrecht, The Netherlands, 299 pp.
- Tauxe L., Constable C., Stokking L. and Badgley C., 1990. Use of anisotropy to determine the origin of characteristic remanence in the Siwalik red beds of northern Pakistan. *J. Geophys. Res.*, **95**, 4391–4404.
- Van den Ende C., 1977. *Palaeomagnetism of Permian Red Beds of the Dome de Barrot (S. France)*. PhD thesis, Utrecht University, Utrecht, The Netherlands.
- Yu Y.J., Dunlop D.J. and Özdemir Ö., 2002. Partial anhysteretic remanent magnetization in magnetite 1. Additivity. *J. Geophys. Res.*, **107(B10)**, 2244, doi: 10.1029/2001JB001249.