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Reply to comment by K. Fabian on 'Detecting uniaxial single domain grains with a modified IRM technique'

R. Mitra, L. Tauxe and J. S. Gee

Scripps Institution of Oceanography, University of California, San Diego, 9500 *Gilman Drive, La Jolla, CA* 92093-0220*, USA. E-mail: rmitra@ucsd.edu*

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1 INTRODUCTION

Fabian in his comment to our paper titled 'Detecting uniaxial single domain grains with a modified IRM technique' starts with a brief synopsis of his earlier paper (Fabian 2006) and reiterates his primary hypothesis of undersaturation leading to high M_{rs}/M_s in mid-ocean ridge basalts (MORBs) (see earlier papers by Gee & Kent 1995, 1999). Subsequently he criticizes Mitra *et al.* (2011) for flawed numerical modelling as well as experimental design and argues that his comment invalidates the alternative hypothesis of multi-axial anisotropy in MORBs (Gee & Kent 1995; Tauxe *et al.* 2002; Lanci 2010). He also offers significant insights into the DIRM experimental protocol of Mitra *et al.* (2011) with phenomenological Preisach diagrams (Preisach 1935).

In this reply we discuss all the points raised by Fabian under the following headings: (1) Validity of the numerical model (2) Current status of the MORB controversy and (3) DIRM experiments revisited.

2 VALIDITY OF THE NUMERICAL MODEL

At the very beginning of his discussion section, Fabian comments about the validity of the model results and considers them to be 'problematic'. Subsequently, he outlines two reasons for this perception.

Fabian's first reason to doubt our numerical results stems from the M_{rs}/M_s ratios we reported for a random distribution of grains having haematite-like triaxial symmetry. According to him the value 0.94 is 'too high' and would be possible only for SD haematite with perfectly aligned basal planes. He further states that the value for a randomized ensemble should be lower than 0.638. In the absence of any calculation or cited references, we found it hard to track the logic behind this claim. Dunlop & Özdemir (1997) (p. 321) made a similar calculation and it might be worthwhile to compare the three results. Not only do Dunlop & Özdemir (1997) report a value of 0.955 for triaxial haematite, which is very close to our value, but they also state that such random assemblages would show M_{rs}/M_s ratios ranging from 0.750 to 0.955. Values higher up in the range are appropriate when the field is not high enough to draw the moment out of the easy plane; an assumption which was *explicitly* stated in Mitra *et al.* (2011). Also, the alternative value of 0.638, proposed by Fabian, is uncomfortably close to that of the uniaxial haematite model of Dunlop & Özdemir (1997) namely, 0.637. This, clearly, was not the assumption in our calculations.

Fabian's second reason to doubt our results stems from the erroneous assumption that field steps of our DIRM experiment were not tailored to take into account the chosen material constants for the alternative models in either the calculations or the experiments. For the model calculations, we chose a field step of 5 mT for the low coercivity magnetite model and a step of 50 mT for the high coercivity haematite. It is not clear why an order of magnitude difference in field step would not be sufficient to take into account the difference in coercivity of the alternative models. Further, in fig. 6(a) of Mitra *et al.* (2011), we see that the Tiva Canyon Tuff (SD magnetite) shows a coercivity of ∼40 mT while the field step chosen for the DIRM experiments on this specimen was 10 mT (fig. 7a). Arguably then, the chosen field cannot be inappropriately high as Fabian suggests. In the beginning of his discussion section, Fabian states that we have not considered the dependency of IRAT on coercivity distribution and field step. This is not entirely correct because fig. 4 in Mitra *et al.* (2011) shows how field step could affect IRAT values in multi-axial assemblages. The same analysis for uniaxial assemblages showed no change in IRAT with field step and/or coercivity and was therefore not included.

Having cleared all the concerns raised by Fabian about our model calculations we hope the reader will be able to better appreciate the theoretical predictions that followed.

3 CURRENT STATUS OF THE MORB CONTROVERSY

In Mitra *et al.* (2011), the central focus, as suggested by the title, was to find a technique to identify single domain uniaxial grains. Fabian does not seem to disagree with this primary assertion but disagrees with its application to the MORB controversy. In the introduction section of his comment, Fabian reiterates the major conclusions of Fabian (2006) and suggests that there is unequivocal and unilateral evidence in favour of uniaxial symmetry in MORB titanomagnetites. It was stated in Mitra *et al.* (2011) that we were not making a case against undersaturation of some MORB samples as it is indeed possible. We chose not to dwell on the details of his analyses as we believed it was outside the scope of our paper. However, as Fabian's comment to Mitra *et al.* (2011) reiterates the essential arguments put forward in Fabian (2006), we consider it now appropriate to include a broader synopsis of the MORB controversy. Also, it appears relevant at this stage to point out our reservations with some of the analyses in Fabian (2006).

Fabian (2006) primarily argues that the MORBs of Gee & Kent (1995) were undersaturated and that if a high enough field (>5 T)

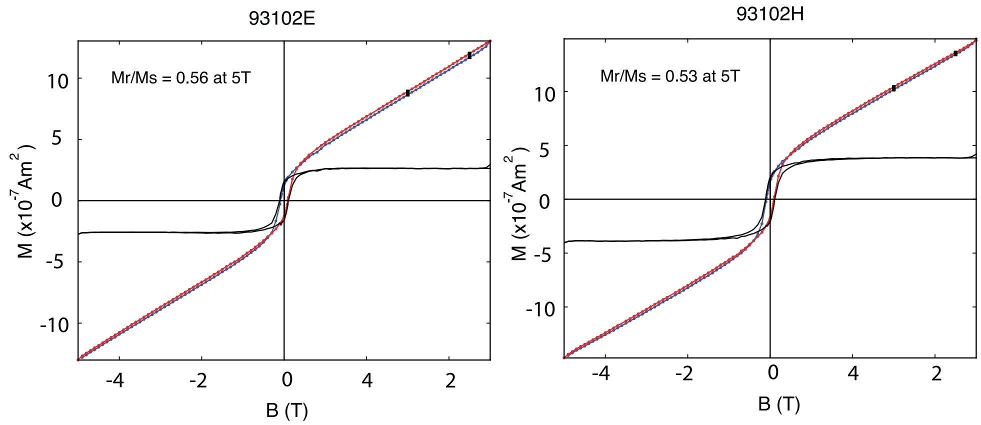

Figure 1. Hysteresis data at 5T. The M_{rs}/M_s ratios were calculated after correcting for the paramagnetic slope by least-squares regression of the data from 3 to 4.5 T (black squares). To correct for the instrumental drift, as seen in the offset between the ascending and descending branches in the raw data, we used the average 5 T intercepts of the two best-fit lines. No further adjustments to centre the loops were made and the M_{rs}/M_s values obtained from positive and negative field values differed by less than 0.002.

was used, then the M_{rs}/M_s ratios would fall below 0.5. Therefore, the ratios would not be high enough to justify an assemblage with dominant multi-axial (e.g. cubic) anisotropy (see Gee & Kent 1995). Tauxe *et al.* (2002) explained the high coercivity and high M_{rs}/M_s ratios observed in the MORBs with micromagnetic models of multi-axial (3-D cross-shaped) grains, a result later substantiated by Williams *et al.* (2011). Subsequently, Lanci (2010) found independent evidence to suggest that the anisotropy could indeed be multi-axial. We would like to note that the evidence from Mitra *et al.* (2011) is in agreement with what these other workers have suggested so far (Gee & Kent 1995; Tauxe *et al.* 2002; Lanci 2010).

Fabian (2006) measured hysteresis parameters on 76 specimens from a 12 cm transect of the pillow T787-R1 collected from the Juan de Fuca Ridge. In fig. 3 of Fabian (2006) the M_{rs}/M_s ratios seem to vary from as high as ∼0.7 within 1 cm of the margin to ∼0.52 nearly 5 cm away from the margin. Fabian (2006) further shows that a single specimen, when measured at a field of 7 T, had a much lower ratio of 0.39. Interestingly, he chose a specimen at ∼3.42 cm from the margin with a M_{rs}/M_s ratio of ∼0.5 at 1 T. We could not find any explanation about why a higher M_{rs}/M_s specimen was not used to show the same result when such specimens were abundant in the specimen set. Therefore we decided to recalculate hysteresis parameters of some of the specimens that showed very high M_{rs}/M_s ratios in our study. Two such specimens were sent to the Institute of Rock Magnetism, Minnesota, for high field hysteresis measurements. These specimens with M_{rs}/M_s ratios of 0.64 and 0.63 at 1 T yielded ratios of 0.56 and 0.53, respectively, when measured at 5 T. Evidently, the specimens were indeed undersaturated at 1 T, but measurements even at a high field of 5 T could not reduce the ratios to below 0.5 (Fig. 1).

A bigger concern we have about the analysis in Fabian (2006) is about the extrapolation used in removing the influence of MD grains on the M_{rs}/M_s ratio. Fabian (2006) used a mixing model for MD and SD grains with the transient hysteresis parameter, $E^{\Delta}{}_t/E_{hys}$, acting as a proxy for grain size (fig. 5 and section 4, in Fabian 2006). Once again, of the seven specimens, none had an M_{rs}/M_s ratio greater than 0.57 at 1 T. However, this time the interpretation is severely compromised as a result of this choice because more than ∼40 per cent of the linear relationship is extrapolated. Also, we do not find any secondary supportive argument in favour of the presumed linear relationship. This is critical because even with the presumed linearity and extrapolation, the M_{rs}/M_s ratio of the SD assemblage is 0.48 at 7 T, which is very close to the hard upper limit of 0.5 for a population with only uniaxial SD grains. As any value above 0.5 is unlikely to result from a uniaxial SD population it becomes imperative to include more high M_{rs}/M_s specimens in this type of analysis.

There is a brief mention that the samples were chosen thus to avoid significant SP contamination which occurs in specimens close to the margin and that could significantly affect the estimation of the grain size proxy $E^{\Delta}{}_t/E_{hys}$. High M_{rs}/M_s (>0.6) specimens occur between ∼0.8 and ∼2 cm in the T787-R1 sample used by Fabian (2006). A closer look at fig. 3 in their paper shows a very distinctive rise of M_{rs}/M_s of the specimens in the first ∼0.8 cm which is a telltale signature of a growing SD and shrinking SP contribution (see, e.g. Tauxe *et al.* 1996). Our work with other pillow basalts shows a very similar relationship (compare the FORCs in fig. 6 of Mitra *et al.* 2011)—the contribution of SP is restricted to the first few millimetres. In that case we find no compelling argument for not choosing specimens with the highest M_{rs}/M_s ratios, occurring well beyond the first centimetre, for the aforementioned analyses.[1]

We would like to reiterate, as we did in Mitra *et al.* (2011), that Fabian (2006) indeed makes some valid arguments for undersaturation in MORB specimens. However, our high field measurements have confirmed that Fabian (2006) might have overestimated the role of undersaturation. Further, we find the analyses of Fabian (2006) that demonstrate dominant uniaxial anisotropy in MORBs to be less than compelling.

4 DIRM EXPERIMENTS REVISITED

The DIRM experiment has its conceptual grounding in the work of Wohlfarth (1958) where it was first proposed that the inequality of a bidirectional remanence could be attributed to non-uniaxial anisotropy, domain state or particle interaction. While domain state and particle interaction have been often cited as the cause for similar inequalities, the role of anisotropy geometry in causing such inequalities got little traction. The reader is directed to the introduction of Mitra *et al.* (2011) and the references therein where we

[1] We calculated the distances from T787-R1 margin with the information supplied in the caption of fig. 3 of Fabian (2006). The quoted numbers are only approximate.

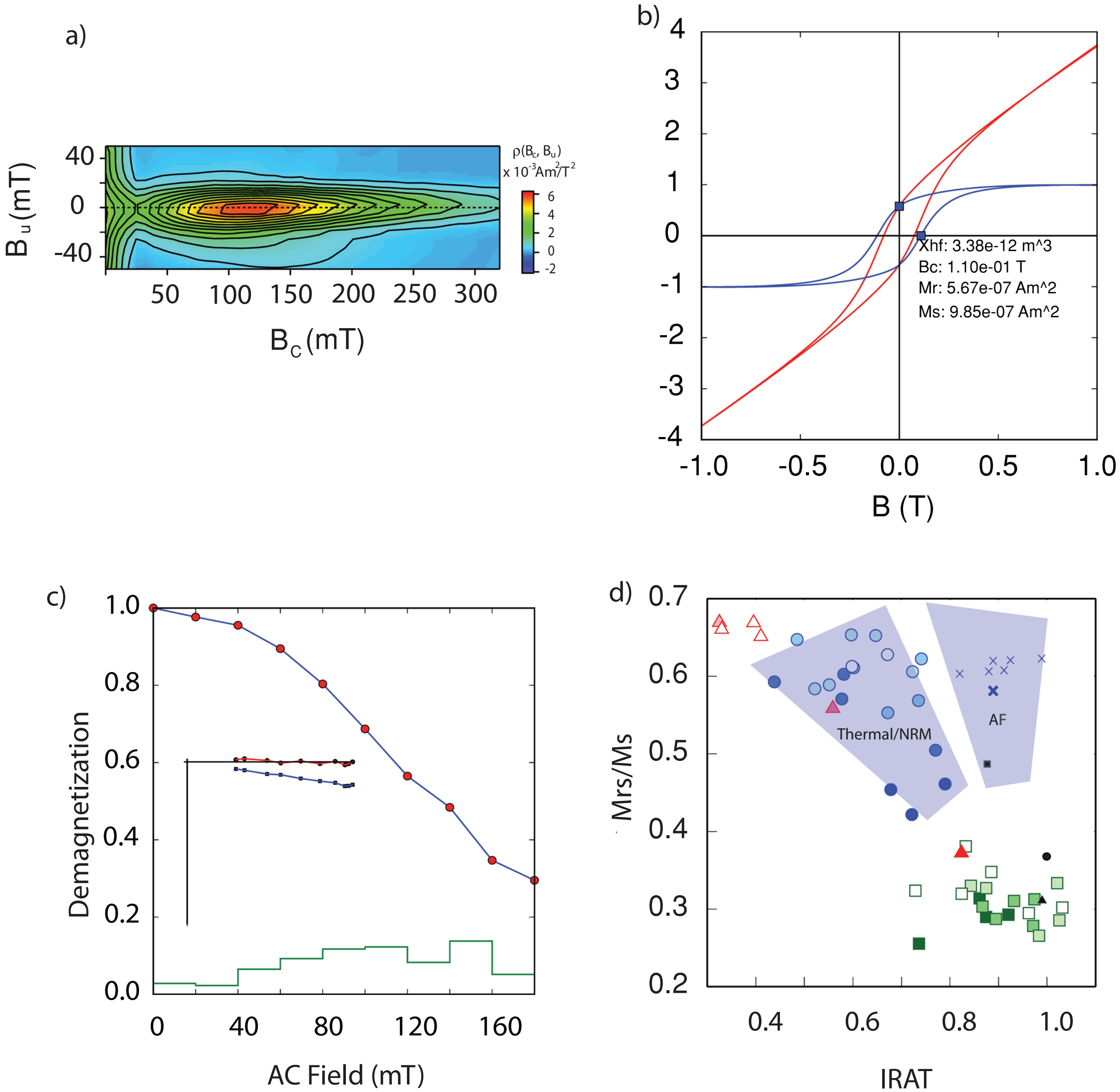

Figure 2. (a–c) FORC distribution (SF = 3), hysteresis loop and AF demagnetization of a representative specimen (991a); (d) fig. 10 of Mitra *et al.* (2011) redrawn with the new Ph99-1 specimens analysed in this study marked with blue cross. Specimen 991a marked with a thick cross. The polygons represent probable regions in the IRAT–M_{rs}/M_s space where specimens from PH99-1would plot depending on their initial remanent states.

have outlined other instances where such inequalities have become important but have often been attributed to domain state and/or particle interaction. Only recently it has been shown that multi-axial anisotropy can play a role and often goes undetected (Garcia-Otero *et al.* 2000).

In a way, what Fabian suggests is in accordance with this well-established line of thought. He has made valid arguments regarding the coercivity distribution and its role in the IRAT ratio. We agree that this could indeed result in depressed IRAT values. The question then becomes whether a spread in coercivity alone, caused by a contribution from PSD grains, can explain the low observed IRAT in high M_{rs}/M_s specimens.

To test this we decided to work with a small piece of the PH99-1 basalt that included the glassy margin. This time we crushed the first few millimetres from the margin and chose small chips for the analysis. This resulted in slightly coarser sampling than Mitra *et al.* (2011) where we had sliced very thin specimens starting from the glassy margin. Fig. 2(a) shows a representative FORC distribution. The closed contours at high coercivity and the spread along B_u at very low coercivity typically suggest a mixture of SP and SD grains. FORCs in Mitra *et al.* (2011) showed a much more distinctive gradation from SP to SD that testify to a much finer sampling resolution (see fig. 6 of Mitra *et al.* 2011).

Fabian's suggestion was to AF demagnetize the specimens along a single axis. This scheme of demagnetization is very unconventional and produced very low (<0.2) or very high (∼2.0) IRAT values, depending on the relative orientation of the specimen during single axis demagnetization and IRM acquisition. Neither result

Table 1. The IRAT measurements. The zero field step is the initial AF-demagnetized state. The field is positive along positive *z*-direction. Positive *z*-direction corresponds to positive inclination.

Specimens	IRAT field (mT)	Intensity (Am^2)	Declination (°)	Inclination (°)	M_{rs}/M_s	IRAT
991a	0	2.64×10^{-9}	339.4	8.6	0.58	0.89
	100	8.02×10^{-8}	302.9	84.3		
	−100	7.16×10^{-8}	359.9	−85.6		
991b	0	1.01×10^{-8}	321.8	21.3	0.62	0.89
	100	2.14×10^{-7}	314.3	85.6		
	−100	1.90×10^{-7}	342.8	−83.5		
991c	0	5.11×10^{-9}	280.1	−34.9	0.62	0.99
	100	1.16×10^{-7}	306.7	87.2		
	−100	1.14×10^{-7}	342.3	−85.7		
991d	0	2.16×10^{-9}	288.5	7.3	0.62	0.92
	100	5.29×10^{-8}	324.9	87.6		
	−100	4.89×10^{-8}	341.5	−85.7		
991e	0	2.64×10^{-9}	314.4	−22.4	0.60	0.82
	100	6.66×10^{-8}	307	88.7		
	−100	5.46×10^{-8}	347.3	−83.9		
991f	0	4.07×10^{-9}	106.7	71.7	0.61	0.91
	100	1.17×10^{-7}	26.9	88.5		
	−100	1.06×10^{-7}	47.3	−86.3		
991g	0	1.69×10^{-9}	255.9	23.3	0.61	0.88
	100	4.42×10^{-8}	271.8	88.2		
	−100	3.90×10^{-8}	6.4	−86.6		

conforms to the predictions of Fabian's model and we therefore decided that a three-axis demagnetization would be better suited to test Fabian's hypothesis. We AF-demagnetized the specimens along three axes (the usual palaeomagnetic procedure) to a peak field of 180 mT. Coercivities of all the specimens were high (Figs 2a and b; as has previously been observed for such high M_{rs}/M_s specimens) and the specimens could not be demagnetized below ∼30 per cent of the initial NRM (Fig. 2c). This should not be a problem to test Fabian's hypothesis as long as the IRAT field used is lower than 180 mT. This is because the non-demagnetized fraction does not form a part of his Preisach analysis (see fig. 2b in his comment) and also, arguably, would not influence the IRAT at a low enough field. We repeated the IRAT experiment with a field of 100 mT. In doing so, we have assumed that the fraction that could not be demagnetized with a peak field of 180 mT would not contribute to the IRAT at 100 mT because of their very high coercivity. Table 1 shows the measurement details. We take this opportunity to point out a potential source of confusion in the calculation of IRAT. If the baseline, or the moment after AF demagnetization, is subtracted from each of the two IRAT steps then a slightly different ratio is to be expected but that should not significantly affect the interpretation of the results. As subtraction of the baseline would not account for the small bias the baseline generates because of initial geometry—direction of moments at any step affects the magnetization of the following step—we do not recommend subtraction. Instead, a high initial field step should be used so that the baseline becomes negligible compared to the IRAT steps.

The specimens plot to the right of the previously measured PH99-1 samples (Fig. 2d). This shows that domain state and associated coercivity do play a role as proposed by Fabian and first postulated by Wohlfarth (1958). Although these specimens with high M_{rs}/M_s have IRAT values from 0.82 to 0.99, there is little indication that all values converge to 1.0 as suggested by Fabian. Also, noteworthy is the fact that the spread in IRAT for a particular M_{rs}/M_s is lower than that observed with PH99-1 specimens in Mitra *et al.* (2011). We attribute this to spread in coercivity, caused by PSD grains, as suggested in the comment. Also, the M_{rs}/M_s ratios seem to be more homogenous than that of Mitra *et al.* (2011). This is to be expected because of the coarser nature of sampling used in this study. As the shaded regions in Fig. 2(d) show, the slope of IRAT—M_{rs}/M_s would be much steeper if AF demagnetized state is chosen as the initial state. Therefore, if IRAT experiments are done on specimens with an AF demagnetized initial state, a statistically significant value below unity should be sufficient to indicate non-uniaxial grains.

5 CONCLUSION

Our response to each of Fabian's conclusions are outlined below.

(1) The initial state of the sample will definitely influence the outcome but not to the exclusion of the signal of anisotropy symmetry of the specimens. Therefore, it is not correct that any specimen can show IRAT = 1 depending on the initial state, as Fabian suggests. The reader is also cautioned not to use a single-axis AF-demagnetized state, as proposed by Fabian, as that can lead to biased results.

(2) We agree that thermally demagnetized specimens can show low IRAT. That does not mean that the anisotropy geometry cannot leave a detectable signal.

(3) The grains in the numerical model are treated as ideal SD particles (showing only coherent rotations) and are not expected to include PSD behaviour. PSD behaviour can affect IRAT obtained in the experimental results.

(4) $M_{rs}/M_s = 0.94$ is correct for the triaxial haematite model which we used and shows that our model calculations were not flawed.

(5) Conclusions 5 and 6 of Fabian are not correct as we have seen that the geometry of anisotropy, domain state and coercivity all play a substantial role in lowering of the IRAT ratio. If an AF-demagnetized state is used as a starting point for DIRM experiments then any ratio significantly less than unity indicates non-uniaxial anisotropy.

(6) Additionally, we have shown that even at very high fields, the M_{rs}/M_s ratio of some MORB specimens can be above 0.5. This is in direct contradiction to the primary thesis of Fabian (2006).

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