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Are hydrodynamic shape effects important when modelling the formation of depositional remanent magnetization?

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ABSTRACT

Recent conceptual models have attributed the weak depositional remanent magnetizations observed in natural sediments to flocculation processes in the water column. Magnetic particles included into flocs have not only to rotate themselves into alignment with the geomagnetic field but also the larger particles to which they are attached, making remanence acquisition an inefficient process. Alignment is hindered further when the magnetization vectors of the particles in any given floc partially cancel, reducing the overall magnetic torque. Existing numerical simulations of flocculation effects on depositional remanence formation have been limited to spherical bodies with translational and rotational motion acting independently of each other. In the case of non-spherical flocs, the translational and rotational motion are coupled and such bodies will describe a complex trajectory through the water column. Calculations will be presented that show the torque exerted on a non-spherical floc by the surrounding water can be orders of magnitude greater than the magnetic torque. Non-spherical flocs will, therefore, align less efficiently with the geomagnetic field and hydrodynamic effects may play an important role in controlling the magnitude of sedimentary remanence.

Key words: depositional remanent magnetization, flocculation, torque.

1 INTRODUCTION

The processes by which a sediment acquires a depositional remanent magnetization (DRM) are still poorly understood. Experimental work involving the redeposition of sediments has demonstrated that DRM magnitude increases as a function of ambient field strength and it is this relationship which forms the basis of the relative palaeointensity determinations which are employed to study ancient configurations of the geomagnetic field (for a review see Tauxe 1993). The classical image of the first stages of DRM formation is one of individual magnetic particles descending through a perfectly still water column subjected to a torque that aligns them with the geomagnetic field. It is also possible that the remanence forms at a later stage, that is, post-depositionally within the unconsolidated sedimentary matrix, with free magnetic particles aligning with the ambient field. Whilst there is strong evidence to suggest that such post-depositional processes may be important (deMenocal *et al.* 1990; Carter-Stiglitz *et al.* 2006) they are not of primary interest to this work which is concerned with the processes of particle alignment within the water column.

A number of early theoretical investigations performed calculations showing that a sinking spherical magnetic particle would align rapidly with the ambient field (Nagata 1961; Collinson 1965; Nozharov 1966). Such a result implies that the magnetic particles held in a sediment should have fully aligned magnetizations, an idea that is clearly incompatible with the extremely weak DRMs found in natural and redeposited sediments. Disturbing influences, such as Brownian motion (Collinson 1965; Stacey 1972), which could inhibit the alignment of magnetic particles have also been investigated, but no satisfactory explanation has been found as to why natural DRMs are so weak.

Although early theoretical studies considered the sinking of isolated magnetic grains through a water column the majority of the suspended matter entering the oceans is actually held in flocs, which form due to the effects of organic bonding and electrostatic attraction. Redeposition experiments that controlled the size of the flocs into which magnetic particles were incorporated revealed an inverse relationship between floc size and DRM magnitude (Lu *et al.* 1990; van Vreumingen 1993a; Katari & Tauxe 2000). In a study of magnetic particles in a water column, van Vreumingen (1993b) showed that the extent of flocculation controlled the ability of particles to align with an external field and concluded that flocculation could be a more important controlling process in DRM formation than deposition or compaction. These experiments led to the development of a new theory that the increased viscous drag acting on larger flocs would impede their alignment with the ambient field during their residence in a narrow still zone above the sediment–water interface. Larger flocs would not have sufficient time to rotate into alignment with the geomagnetic field before deposition, therefore, the magnetic particles incorporated into the sediment would have partially cancelling vectors and the overall DRM would be weak (Katari & Bloxham 2001).

Recently, Tauxe *et al.* (2006) presented theoretical and experimental results to support the idea that magnetic particles do not sink through the water column as isolated grains but instead descend attached to larger particles such as clays, which in turn combine together to form bigger flocs. This hypothesis is supported by the redeposition experiments of Heslop *et al.* (2006), which showed that whilst in suspension magnetic grains tend to be attached to clay particles. Flocculation playing a key role in DRM formation is an attractive idea and it helps to explain why full alignment of the magnetic assemblage does not occur in nature. The key idea of Tauxe *et al.* (2006) is that any given floc will contain a number of magnetic particles with partially cancelling magnetization vectors. Thus a floc can be considered as a relatively large particle, some microns is radius, which must be rotated into alignment by a comparatively weak magnetic torque. Assuming a narrow still-water zone above the sediment–water interface, Tauxe *et al.* (2006) demonstrated numerically that many flocs would not have sufficient time to align with the ambient field and only a weak DRM would be produced. Given different floc size distributions and initial magnetizations it was found that many scenarios produced DRM acquisition which was not a linear function of applied field, bringing into question the rock magnetic normalization procedures used to obtain relative palaeointensities from natural sediments (Tauxe 1993).

The aim of this work is to demonstrate that the effect of flocculation on reducing alignment in the water column could be even greater than first suggested. The models of Katari & Bloxham (2001) and Tauxe *et al.* (2006) only considered spherical flocs, such an approach is limited because any spherical floc which experiences a magnetic torque will eventually align with the field irrespective of its size providing it has sufficient time to overcome the viscous resistance of the surrounding water. In contrast non-spherical flocs may never align with the field because of hydrodynamic effects which influence their orientation as they descend through the water column. A non-spherical body will experience a torque during its descent because the forces exerted by the surrounding water column and gravity will not always act at a common point. Thus, shape plays an important role in controlling both the translational and rotational motion of a body during sinking. An illustrative example of this phenomenon comes from the work of Belmonte *et al.* (1998) who studied the motion of thin flat strips descending through a fluid (Fig. 1). The vertical and horizontal translation are clearly coupled and the orientation of the sinking strip changes through time. Although the Reynolds number (the ratio of inertial forces to viscous ones) of the sinking strip is orders of magnitude greater than that expected for a sinking sediment floc, such an experiment leads to the hypothesis that for the case of DRM formation the final orientation of a floc will result from the complex competition of the magnetic torque and fluid effects.

Can shape potentially play a role in controlling the orientation of a floc which outweighs the magnetic torque? If this is the case it may be possible that a floc would never reach an equilibrium orientation with the ambient field no matter how long it was given to settle. Calculations will be presented to compare the magnetic and hydrodynamic torques acting on settling flocs of different sizes and shapes.

2 MODEL BACKGROUND

For the spherical bodies considered in previous models of DRM formation it is expected that sedimentation will occur on a downward straight trajectory where rotational and translational motion are independent. In the case of non-spherical bodies rotational and translational motion are coupled and a complex motion is expected which does not follow a vertical path. To obtain insights into the ability of a magnetic floc to align with the ambient field whilst sinking through a water column it is necessary to consider how flocs form and the relative strengths of both the magnetic and hydrodynamic torques. A full model which attempts to track floc alignment during sinking will not be constructed, instead simple order of magnitude calculations are presented that provide a first insight into the competition between magnetic and hydrodynamic effects.

Figure 1. The path of a sinking strip superimposed onto an image of the vortices it creates, taken from Belmonte & Moses (1999). This motion demonstrates the effect shape can play in controlling the vertical, horizontal and rotational motion of a sinking body.

2.1 Floc formation

Natural floc formation is controlled by a balance between the processes of aggregation and disintegration. At the initial stages of formation, aggregation dominates and floc sizes increase rapidly. Subsequently, disintegration gradually becomes increasingly important until an equilibrium point is reached where a balance between the two processes maintains a steady-state distribution of floc sizes (Dyer 1994; Jarvis *et al.* 2005). Environmental conditions will control structural characteristics of a floc and in turn physical properties such as floc size, shape, effective density and porosity will all influence sinking behaviour (Chen *et al.* 2005; Jarvis *et al.* 2005). Observation of both natural and laboratory formed aggregates have shown that a number of the physical characteristics of flocs are linked to each other, for example, as a floc grows in size its shape will become less spherical and its density will decrease (Ani *et al.* 1991; Jarvis *et al.* 2005).

A number of redeposition experiments performed to study DRM behaviour have shown a clear relationship between water chemistry and floc formation (Lu *et al.* 1990; van Vreumingen 1993a; Katari & Tauxe 2000). Tauxe *et al.* (2006) measured distributions of floc sizes in resuspended sediments and found that aggregate size increased with higher salinities, up to estimated floc radii of ∼18 μm. Comparative studies have shown that in general natural flocs tend to be larger than those measured in the laboratory (Ani *et al.* 1991), a good example of this is so-called 'marine snow', which is a class of aggregates with diameters >0.5 mm. Samples of marine snow collected from the nepheloid layer (the zone of the ocean between the sediment–water interface and the pelagic zone), were found to be relatively dense and clay-rich making them good candidates for transporting attached magnetic particles to the seafloor (Ransom *et al.* 1998).

The flocs employed in this study are assumed to be prolate ellipsoids, in addition, they are considered to be large enough to ignore the effects of Brownian motion and the water column is assumed to be perfectly still. Whilst is it clear that prolate ellipsoids are an oversimplified representation of natural flocs, which will be irregular in shape, porous and deformable, they have the advantage that their settling behaviour is well understood. This choice is also supported by *in situ* observations of larger aggregates, which have been found to have shapes and settling rates similar to prolate ellipsoids (Alldredge & Gotschalk 1988).

2.2 Magnetic torque

In the first numerical model of DRM formation in flocculated sediments Katari & Bloxham (2001) assumed each floc to have single magnetic particle at its centre. The radii of the magnetic particles was constant and, therefore, the magnetization of the floc was independent of its size. Tauxe *et al.* (2006) considered a more realistic model based on the known behaviour of natural floc formation. Their model invoked the idea of fundamental flocs which represent discrete grains, such as clay particles, to which much smaller magnetite particles are attached. The fundamental flocs represent the smallest unit in the sediment system and the first step of the flocculation process. As the fundamental flocs descend through the water column they will encounter and become attached to other flocs, forming larger, so-called, composite flocs. The number of magnetic particles included within a composite floc is, therefore, a function of equivalent radius, which is controlled by the number of fundamental flocs that have combined together.

Tauxe *et al.* (2006) modelled composite floc formation as the combination of a number of fundamental flocs with a radius of 1 μm and a magnetization of 0.33 $\mathrm{Am^{-1}}$. Assuming both the fundamental and composite flocs to be spherical, the equivalent radius of the composite floc could be calculated based on the combined volumes of the fundamental flocs from which it was composed. In turn, the net magnetic moment of a composite floc was found by calculating the vector sum of the individual fundamental floc moments under the assumption that they would combine in random orientations. Under such conditions the moments of the magnetic particles in a composite floc will be partially cancelling, so the overall moment of the floc will be reduced. To understand how this partial cancellation would behave, Tauxe *et al.* (2006) implemented a Monte Carlo model based on representing the orientations of fundamental flocs using random unit vectors dispersed uniformly across the surface of a sphere. The extent of cancellations within a composite floc could then be represented by drawing an appropriate number of random vectors and calculating their resultant magnitude. Using this approach a quadratic relationship was defined that allowed magnetic moment to be determined as a function of the equivalent radius of a composite floc.

Such a numerical procedure is not strictly necessary because an asymptotic expression was provided by Rayleigh (1919) which gives the probability density, f, of obtaining a resultant vector of magnitude, R, from the addition of N random vectors distributed uniformly across the surface of a sphere:

$$f(R) \simeq \frac{3\sqrt{6}R^2}{\sqrt{\pi}N^{3/2}} e^{-3R^2/2N}. \tag{1}$$

Shown in Fig. 2(a) is the variation of the mean resultant magnitude as a function of the number of combined vectors according to the expression of Rayleigh (1919), which for larger sizes is in clear disagreement with the expression defined by Tauxe *et al.* (2006). To understand this discrepancy a Monte Carlo simulation similar the one described by Tauxe *et al.* (2006) was constructed, employing random unit vectors generated using three Gaussian random variables (Muller 1959; Marsaglia 1972). In the original model of Tauxe *et al.* (2006) only 10 Monte Carlo trials were performed for each floc size, which is not enough to produce a representative sample of the distribution of possible values of R. For the Monte Carlo model shown in Fig. 2(a), 10^4 trials were performed yielding a more robust result, that agrees closely with the asymptotic function of Rayleigh (1919). When converted into a floc model, assuming a magnetization of 0.33 $\mathrm{Am^{-1}}$ and a fundamental floc radius of 1 μm, it can be seen the results coincide closely with those of Tauxe *et al.* (2006) for smaller equivalent radii, however there is disagreement for the larger flocs (Fig. 2b). Based on the results of this analysis the

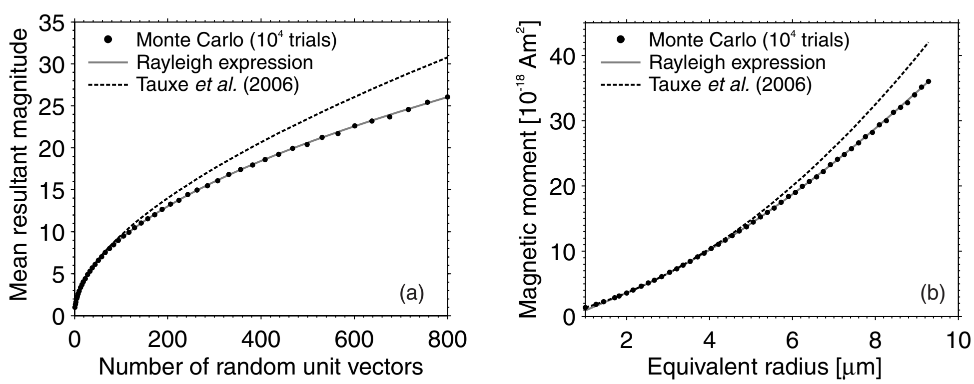

Figure 2. (a) The mean resultant magnitude of a given number of random unit vectors drawn uniformly from the surface of a sphere. The mean result from 10^4 Monte Carlo trials (black points) is consistent with the asymptotic Rayleigh expression (grey line). The Monte Carlo model of Tauxe *et al.* (2006) clearly overestimates the resultant magnitude for larger systems. (b) when converted to a floc model based on a fundamental floc size of 1 μm and a magnetization of 0.33 $\mathrm{Am^{-1}}$ it can be seen that the polynomial approximation employed in earlier models (dashed line) is in error for higher equivalent radii.

composite floc moments employed in this study will be calculated for spheres with the same volumes as the ellipsoids of interest using the expression of Rayleigh (1919). For the presented calculations only the maximum value of the magnetic torque, τ^m, acting on the floc is of interest. The torque will reach a maximum when the magnetic moment, *m*, of a floc is perpendicular to the applied field, *B*, and is given by:

$$\tau^m = mB. \tag{2}$$

All of the following models were calculated using $B = 50\ \mu\mathrm{T}$, which is typical of the geomagnetic field.

2.3 Hydrodynamic torque

The study of the trajectories of falling non-spherical bodies dates back to at least Newton (Viets & Lee 1971) and a vast body of experimental and theoretical work exists concerned with the behaviour of sedimenting bodies in viscous fluids (Leal 1980; Kim & Karrila 2005). Qualitative experimental observations of sinking ellipsoids were made by Pettyjohn & Christiansen (1948) and Becker (1959), but it was the theoretical work of Cox (1965) that first quantitatively described the effects of inertia on particle orientation during sinking. Cox (1965) showed that a prolate ellipsoid falling though a Newtonian fluid with a small but non-zero Reynolds number will travel with its broad-side perpendicular to the direction of descent. Thus the equilibrium orientation of the particle is independent of its initial orientation. This phenomenon has subsequently been confirmed by a variety of numerical models (Ristow 2000; Kuusela *et al.* 2001; Pan *et al.* 2002).

Since inertial effects will influence particle orientation it is important to assess if the hydrodynamic torque acting on an settling composite floc is sufficiently high to affect the alignment of the particle with respect to the ambient magnetic field. Using a system of reduced dimensions, Galdi & Vaidya (2001) showed that for an axisymmetric body falling due to the force of gravity through a Newtonian fluid with a small non-zero Reynolds number the magnitude of the torque, $|\tau^{GV}|$, exerted by the fluid on the body is within the limits:

$$\frac{1}{2} Re U_1 U_2 |G| \le |\tau^{GV}| \le \frac{3}{2} Re U_1 U_2 |G|, \tag{3}$$

where *Re* is the Reynolds number, assumed to be $Re \ll 1$, meaning that the viscous force greatly outweighs the inertial force. U_1 and U_2 are the components of the body's velocity parallel and perpendicular to the long axis of the particle, respectively, and *G* is the geometric factor, which is a dimensionless constant that is a function of the particle shape.

Oblate rather than prolate ellipsoids could be considered as a more realistic shape to represent some natural flocs. Currently an evaluation of *G* is not available for oblate ellipsoids, which are known to have complex sinking behaviour that can even become chaotic under certain conditions (Field *et al.* 1997). Prolate ellipsoids are acceptable given that the present study is only concerned with order of magnitude equations to determine if the hydrodynamic effects arising from non-sphericity can or cannot be ignored in DRM simulations. It can be seen immediately from eq. (3). that when the angle θ between the long axis and the vertical is 0 or $\pi/2$ the fluid torque acting on the particle vanishes. In addition, the direction of the torque is such that only the $\theta = \pi/2$ direction is stable, which is consistent with the work of Cox (1965).

To evaluate eq. (3) it is necessary to consider the velocity of a prolate ellipsoid sinking through a water column. First, the aspect-ratio, a_r, defines the shape of the prolate ellipsoid and is given by:

$$a_r = a/b, \tag{4}$$

where *a* is the radius of the semi-major axis and *b* the radius of the semi-minor axis (Fig. 3a). The eccentricity of the ellipsoid is then given by:

$$e = \sqrt{1 - a_r^{-2}}. \tag{5}$$

As a simplifying step in the calculations it is necessary to assume that a zone of still water exists above the sediment surface which is sufficiently large that the composite floc will reach its terminal velocity. In the case of a prolate ellipsoid the terminal velocity is also dependent on orientation and must be expressed as a combination of components parallel ($V_\parallel$) and perpendicular ($V_\perp$) to the direction of gravity (Kim & Karrila 2005):

$$V_\parallel(\theta) = V_\parallel^b \left(\frac{\sin^2\theta}{Y^A} + \frac{\cos^2\theta}{X^A} \right), \tag{6}$$

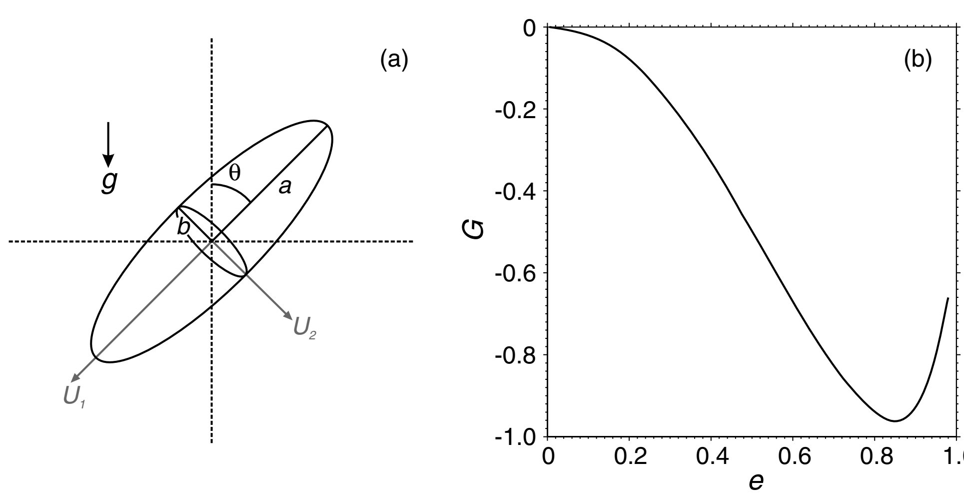

Figure 3. (a) The size and shape of the prolate ellipsoids employed in this study are described be their large and small radii, *a* and *b*, respectively. The orientation of the long axis of the ellipsoid to the vertical is given by the angle θ and *g* represents the direction in which gravity is acting. The components of the ellipsoid's velocity parallel and perpendicular to its long axis are given by U_1 and U_2, respectively. (b) The geometric factor, *G*, for a prolate ellipsoid versus eccentricity, *e*.

$$V\perp(\theta) = V_{\parallel}^{b} \sin\theta \cos\theta (Y^{A^{-1}} - X^{A^{-1}}), \quad (7)$$

where $V_{\parallel}^{b}$ is the terminal velocity of a sphere with radius b and the resistance functions X^A and Y^A of a prolate ellipsoid are given by:

$$X^A = \frac{8}{3} e^3 [-2e + (1 + e^2)L]^{-1}, \quad (8)$$

$$Y^A = \frac{16}{3} e^3 [2e + (3e^2 - 1)L]^{-1}, \quad (9)$$

and

$$L = \ln\left(\frac{1+e}{1-e}\right). \quad (10)$$

Using eqs (6) and (7), and taking into account the system of dimensions employed by Galdi & Vaidya (2001) the fluid torque, τ^{GV}, lying at the middle of the limits of eq. (3), will be given by (Kuusela 2005):

$$\tau^{GV} \approx \frac{16a^4 \rho_l^2 \left(V_{\parallel}^{b}\right)^3 G}{\eta} \sin 2\theta \left(\cos 2\theta \left[\left(\frac{\cos\theta}{X^A}\right)^2 - \left(\frac{\sin\theta}{Y^A}\right)^2 \right] - \frac{\cos 4\theta}{2X^A Y^A} \right) \sqrt{\frac{\sin^2\theta}{(Y^A)^2} + \frac{\cos^2\theta}{(X^A)^2}}, \quad (11)$$

where ρ_l and η are the density and viscosity of the water, respectively. Values of G for a prolate ellipsoid were given by Galdi & Vaidya (2001) as a function of eccentricity (Fig. 3b). As with the magnetic torque, only the maximum value of τ^{GV} is of interest and for each floc under consideration this was found numerically using a Nelder-Mead simplex method (Lagarias *et al.* 1998). A mean dry bulk density of 2600 $\mathrm{kg\,m^{-3}}$ was assumed for the material incorporated into the flocs. Natural flocs will, however, contain a large amount of water resulting in a lower overall density. Calculations were, therefore, made for two sets of flocs with mean densities of 2600 and 1300 $\mathrm{kg\,m^{-3}}$, in the latter case of high water content the floc must still be assumed to be hard, non-porous and homogenous for eq. (3) to hold. The Reynolds number for a floc with radius 20 μm and density 2600 $\mathrm{kg\,m^{-3}}$ is ∼0.06, thus the assumption of $Re \ll 1$ is valid.

3 RESULTS

Given the aims of this study it is a simple task to demonstrate the relative importance of magnetic and hydrodynamic effects on a sinking prolate ellipsoid. The magnitude of the maximum magnetic and hydrodynamic torques is shown in Fig. 4(a) for flocs with different equivalent radii and aspect-ratios. For the smaller flocs the magnetic torque is orders of magnitude greater than the hydrodynamic torque, however this situation changes for radii larger than ∼7.5 μm. Not surprisingly the flocs with the larger aspect-ratios are most strongly influenced by the hydrodynamic torque, but even for the case of $a_r = 1.1$ the maximum magnetic and hydrodynamic torques are equal at an equivalent radius slightly greater than ∼10 μm. For flocs with radii around ∼12 μm the hydrodynamic torque is orders of magnitude greater than the magnetic torque. For such flocs where the hydrodynamic torque dominates it would be expected that the geomagnetic field plays almost no role in controlling orientation in the water column.

The results of the calculations can be illustrated by finding the equivalent radius at which the maximum magnetic and hydrodynamic torques are equal for a given aspect-ratio (Fig. 4b). As the density of a floc decreases the equivalent radius at which the maximum magnetic and hydrodynamic torques are equal increases. Even for prolate ellipsoids that have aspect-ratios of 1.1 the radius at which the torques balance is still within the floc size range employed within earlier numerical models of DRM formation (Katari & Bloxham 2001; Tauxe *et al.* 2006) and those observed in redeposition experiments (Ani *et al.* 1991) and nature (Nowald *et al.* 2006).

It is difficult to extend the formulation presented in Section 2 in order to make precise predictions concerning DRM formation. The analytical representation employed here is limited because it assumes a perfectly still water column and thus does not take into account the history of the water through which the particle descends. Therefore, any effects which the particle may have on the water, inducing turbulence for example, are not represented. Some numerical models are available which can provide a more complete description of particle sinking but they are still limited to small numbers of particles and simple shapes because of their computational complexity (Kuusela *et al.* 2001; Pan *et al.* 2002).

It is possible to make predictions concerning processes such as inclination shallowing, which has been observed in a number natural settings (Arason & Levi 1990; Marco *et al.* 1998; Gilder *et al.* 2003; Kent & Tauxe 2005; Tauxe 2005) and laboratory experiments (Tauxe & Kent 1984; Levi & Banerjee 1990; van Vreumingen 1993a). For an isolated elongated magnetic grain in the single-domain to pseudo-single-domain grain size range the hydrodynamic torque which acts to align the particle is negligible compared to the magnetic torque, thus no inclination shallowing should occur. In the case of large

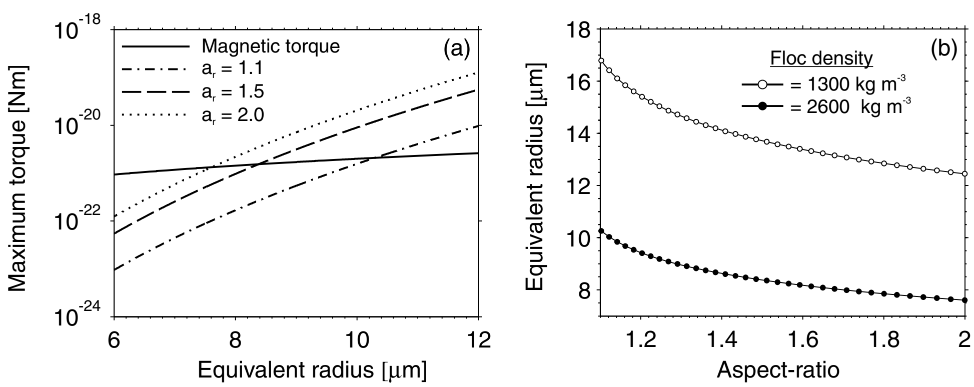

Figure 4. (a) A comparison of the maximum magnetic and hydrodynamic torques as a function of equivalent radius for prolate ellipsoids with aspect ratios of 1.1, 1.5 and 2.0 and a density of 2600 $\mathrm{kg\,m^{-3}}$. (b) The equivalent radius at which the maximum magnetic and hydrodynamic torques are equal for a prolate ellipsoid with a given aspect ratio. As the density of the floc decreases the equivalent radius at which the torques balance increases.

flocs, where hydrodynamic effects dominate, there will be a preferred orientation of the aggregate during sinking, but given that the magnetic particles are assumed to be attached to the floc in random orientations such hydrodynamic effects should not produce a preferred direction in the attached magnetic particles. Following this idea, it can be envisaged that in the extreme case where all magnetic particles are incorporated into large flocs, the combined magnetization of the flocs contained within a sufficiently large region of the water column would be effectively zero.

4 DISCUSSION AND CONCLUSIONS

A number of redeposition experiments and theoretical models have identified flocculation as a process which inhibits the formation of DRM (Lu *et al.* 1990; van Vreumingen 1993a,b; Katari & Tauxe 2000; Katari & Bloxham 2001; Tauxe *et al.* 2006). These studies have considered flocculation as a process that increases the effective size of the sinking magnetic particles, which then require more time to rotate into alignment with the geomagnetic field. Previous attempts to model this process employed spherical flocs because it is a relatively simple task to simulate their rotational behaviour as they descend through a water column.

The calculations presented in this study are not aimed at providing a quantitative model of DRM formation, but do demonstrate that even for simple bodies such as prolate ellipsoids, hydrodynamic effects due to shape can dominate over the magnetic torque. Therefore, our attempts to understand the formation of DRM must be extended still further to include the sinking behaviour of flocs in the water column.

In nature, flocs would be expected to be irregular in shape, porous and deformable when loosely bound together. Given these characteristics the prolate ellipsoids employed in this study can only be considered as a slightly more realistic representation of natural floc shape than spheres, however, the results of this study do make two important points. First, shape will control floc orientation and, therefore, act as an additional disturbing factor in DRM formation. It is not difficult to believe that in the case of large flocs magnetic torque will have a negligible influence on orientation. Given this idea hydrodynamic effects could be the primary reason why weak sedimentary remanences are observed in nature. Second, if it is accepted that the flocs responsible for transporting magnetic particles to the seafloor are non-spherical then a new generation of models must be employed to study DRM formation with full coupling between the sinking sediment flocs and the surrounding fluid. Such advanced models would not require spherical flocs and have the additional advantage that fluid motion can be incorporated into the model and the unrealistic assumption of a perfectly still-water column is no longer required.

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REFERENCES

Alldredge, A.L. & Gotschalk, C., 1988. In situ settling behaviour of marine snow, *Limnol. Oceanogr.,* **33,** 339–351.

Ani, S.A., Dyer, K.R. & Huntley, D.A., 1991. Measurement of the influence of salinity on floc density and strength, *Geo. Mar. Lett.,* **11,** 154–158.

Arason, P. & Levi, S., 1990. Compaction and inclination shallowing in deep-sea sediments from the Pacific Ocean, *J. geophys. Res.,* **95,** 4501–4510.

Becker, H.A., 1959. The effects of shape and Reynolds number on drag in the motion of a freely orientated body in an infinite fluid, *Can. J. Chem. Eng.,* **37,** 85–100.

Belmonte, A. & Moses, E., 1999. Flutter and Tumble in Fluids, *Phys. World,* **12,** 21–26.

Belmonte, A., Eisenberg, H. & Moses, E., 1998. From flutter to tumble: inertial drag and Froude similarity in falling paper, *Phys. Rev. Lett.,* **81,** 345–348.

Carter-Stiglitz, B., Valet, J.-P. & LeGoff, M., 2006. Constraints on the acquisition of remanent magnetization in fine-grained sediments imposed by redeposition experiments, *Earth Planet. Sci. Lett.,* **245,** 427–437.

Chen, M., Wartel, S. & Temmerman, S., 2005. Seasonal variation of floc characteristics on tidal flats, the Scheldt estuary, *Hydrobiologia,* **540,** 181–195.

Collinson, D.W., 1965. Depositional remanent magnetization in sediments, *J. geophys. Res.,* **70,** 4663–4668.

Cox, R.G., 1965. The steady motion of a particle of arbitrary shape at small Reynolds numbers, *J. Fluid Mech.,* **23,** 625–643.

deMenocal, P.B., Ruddiman, W.F. & Kent, D.V., 1990. Depth of p-DRM acquisition in deep-sea sediments—a case study of the B/M reversal and oxygen isotope stage 19.1, *Earth Planet. Sci. Lett.,* **99,** 1–13.

Dyer, K.R., 1994. Estuarine sediment transport and deposition, in *Sediment Transport and Depositional Processes*, Blackwell Scientific Publications, Oxford, pp. 193–218.

Field, S.B., Klaus, M., Moore, M.G. & Nori, F., 1997. Chaotic dynamics of falling disks, *Nature,* **388,** 252–254.

Galdi, G.P. & Vaidya, A., 2001. Translational steady fall of symmetric bodies in a Navier-Stokes liquid, with application to particle sedimentation, *J. Math. Fluid Mech.,* **3,** 183–211.

Gilder, S., Chen, Y., Cogné, J.-P., Tan, X., Courtillot, V., Sun, D. & Li, Y., 2003. Paleomagnetism of upper jurassic to lower cretaceous volcanic and sedimentary rocks from the western tarin basin and implications for inclination shallowing and absolute dating of the M-0 (ISEA?) chron, *Earth Planet. Sci. Lett.,* **206,** 587–600.

Heslop, D., Witt, A., Kleiner, T. & Fabian, K., 2006. The role of magnetostatic interactions in sediment suspensions, *Geophys. J. Int.,* **165,** 775–785.

Jarvis, P., Jefferson, B. & Parsons, S.A., 2005. Measuring floc structural characteristics, *Rev. Environ. Sci. Biotechnol.,* **4,** 1–18.

Katari, K. & Bloxham, J., 2001. Effects of sediment aggregate size on DRM intensity: a new theory, *Earth Planet. Sci. Lett.,* **186,** 113–122.

Katari, K. & Tauxe, L., 2000. Effects of surface chemistry and flocculation on the intensity of magnetization in redeposited sediments, *Earth Planet. Sci. Lett.,* **181,** 489–496.

Kent, D.V. & Tauxe, L., 2005. Corrected Late Triassic latitudes for continents adjacent to the North Atlantic, *Science,* **307,** 240–244.

Kim, S. & Karrila, S.J., 2005. *Microhydrodynamics: Principles and Selected Applications*, Dover, Mineola, New York.

Kuusela, E., 2005. Steady-state sedimentation of non-Brownian particles with finite Reynolds numbers, *PhD thesis*, Helsinki University of Technology.

Kuusela, E., Hofler, K. & Schwarzer, S., 2001. Computation of particle settling speed and orientation distribution in suspensions of prolate spheroids, *J. Eng. Math.,* **41,** 221–235.

Lagarias, J.C., Reeds, J.A., Wright, M.H. & Wright, P.E., 1998. Convergence properties of the Nelder-Mead simplex method in low dimensions, *SIAM J. Optim.,* **9,** 112–147.

Leal, L.G., 1980. Particle motions in a viscous fluid, *Ann. Rev. Fluid Mech.,* **12,** 435–476.

Levi, S. & Banerjee, S., 1990. On the origin of inclination shallowing in redeposited sediments, *J. geophys. Res.,* **95,** 4383–4389.

Lu, R., Banerjee, S.K. & Marvin, J., 1990. Effects of clay mineralogy and the electrical conductivity of water on the acquisition of depositional remanent magnetization in sediments, *J. geophys. Res.,* **95,** 4531–4538.

Marco, S., Ron, H., McWilliams, M.O. & Stein, M., 1998. High-resolution record of geomagnetic secular variation from Late Pleistocene Lake Lisan sediments (paleo Dead Sea), *Earth Planet. Sci. Lett.,* **161,** 145–160.

Marsaglia, G., 1972. Choosing a point from the surface of a sphere, *Ann. Math. Stat.,* **43,** 645–646.

Muller, M., 1959. A note on a method for generating points uniformly on N-dimensional spheres, *Commun. ACM,* **2,** 19–20.

Nagata, T., 1961. *Rock Magnetism*, Maruzen, Tokyo.

Nowald, N., Karakas, G., Ratmeyer, V., Fischer, G., Schlitzer, R., Davenport, R.A. & Wefer, G., 2006. Distribution and transport processes of marine particulate matter off cape blanc (NW-Africa): results from vertical camera profiles, *Ocean Sci. Discuss.,* **3**(4), 904–938.

Nozharov, P.B., 1966. On the theory of depositional remanent magnetization, *Pure Appl. Geophys.,* **64,** 52–58.

Pan, T.W., Glowinski, R. & Galdi, G.P., 2002. Direct simulation of the motion of a settling ellipsoid in Newtonian fluid, *J. Comp. Appl. Math.,* **388,** 252–254.

Pettyjohn, E.S. & Christiansen, E.B., 1948. Effect of particle shape on free-settling rates of isometric particles, *Chem. Eng. Proc.,* **44,** 157–172.

Ransom, B., Shea, K.F., Burkett, P.J., Bennett, R.H. & Baerwald, R., 1998. Comparison of pelagic and nepheloid layer marine snow: implications for carbon cycling, *Mar. Geol.,* **150,** 39–50.

Rayleigh, L., 1919. On the problem of random vibrations and random flights in one, two and three dimensions, *Phil. Mag.,* **37,** 321–347.

Ristow, G.H., 2000. Tumbling motion of elliptical particles in viscous two-dimensional fluids, *Int. J. Mod. Phys. C,* **12,** 127–139.

Stacey, F.D., 1972. On the role of Brownian motion in the control of DRM of sediments, *Pure Appl. Geophys.,* **98,** 139–145.

Tauxe, L., 1993. Sedimentary records of relative paleointensity of the geomagnetic field: theory and practice, *Rev. Geophys.,* **31,** 319–354.

Tauxe, L., 2005. Inclination flattening and the geocentric axial dipole hypothesis, *Earth Planet. Sci. Lett.,* **233,** 247–261.

Tauxe, L. & Kent, D.V., 1984. Properties of detrital remanence carried by hematite from study of modern river deposits and laboratory redeposition experiments, *Geophys. J. R. Astr. Soc.,* **77,** 543–561.

Tauxe, L., Steindorf, J.L. & Harris, A., 2006. Depositional remanent magnetization: toward an improved theoretical and experimental foundation, *Earth Planet. Sci. Lett.,* **244,** 515–529.

van Vreumingen, M.J., 1993a. The influence of salinity and flocculation upon the acquisition of remanent magnetisation in some artificial sediments, *Geophys. J. Int.,* **114,** 607–614.

van Vreumingen, M.J., 1993b. The magnetization intensity of some artificial suspensions while flocculating in a magnetic field, *Geophys. J. Int.,* **114,** 601–606.

Viets, H. & Lee, D., 1971. Motion of freely falling spheres at moderate Reynolds numbers, *Am. Inst. Aeronaut. Astronaut.,* **9,** 2038–2042.