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Understanding DRM acquisition of plates and spheres: a first comparative experimental approach

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SUMMARY

Since King presented the 'plates and spheres' model in an attempt to investigate the origin of the inclination error in sediments, no one to date has conducted specific experiments designed to separate the individual contribution of platy and spherical particles to depositional remanent magnetizations (DRMs). It is commonly accepted that it is the flattening of plates, rather than the rolling of spheres that is the main source of inclination error in sediments. Recently, however, Bilardello *et al.* have shown that spheres alone may lead to significant amounts of shallowing.

A comparison of experiments run in parallel using synthetic platy and spherical particles is presented. Experiments of the duration of 24 hr were run in 100 µT field intensity ($\mu_0 H$) and varying field inclinations (I_F) from vertical to horizontal. A systematic dependence of the magnetization on field inclination is apparent. Results indicate that magnetic moment measurements are more repeatable for spherical particles than for plates, yielding smaller uncertainties. Inclination measurements, however, are more repeatable for platy particles, with a more linear relationship of inclination error to applied field inclination. Moreover, plates yield smaller inclination error than spheres. A clear field inclination dependency of the inclination error also exists, with the error decreasing through field inclinations of 30°, 60° and 90°. A continuous acquisition experiment involving plates was also run up to 10 d of deposition in $\mu_0 H = 100\ \mu\mathrm{T}$ and $I_F = 60°$. The acquisition curves for moment, inclination and thickness of depositing sediment are compared to the mean curves measured for spheres by Bilardello *et al.* under the same field conditions. No unequivocal evidence of compaction of the platy particles is observed, while the inclination error is acquired virtually instantaneously for all particles.

These preliminary results contradict the widespread understanding that inclination shallowing is more prominent for platy particles (e.g. hematite) than it is for more spherical particles (e.g. magnetite). It is true that larger amounts of shallowing have been commonly observed in natural hematite-bearing rocks, but the overall ranges of shallowing are also larger. The particles used in these experiments may not be a reliable proxy for natural crystals and one must exercise caution when extrapolating to the natural scenarios; however, the results provide insight into the behaviour of differently shaped particles.

Key words: Palaeointensity; Palaeomagnetism applied to geologic processes; Rock and mineral magnetism.

1 INTRODUCTION

The process through which sediments acquire a magnetization, a depositional remanent magnetization (DRM), is complex and still incompletely understood. A variety of factors contribute to the acquisition of a DRM. In the water column, particle size and shape distributions, viscosity, pH and Eh of the fluid, contact forces between particles and Brownian motion are only but a few examples of contributing factors. On and below the surface, mechanical interactions may then reorient the particles, together with possible flow and/or shear of the still unconsolidated sediment layer. Subsequent bioturbation, diagenetic effects, burial/compaction, dewatering or even variations in the Earth's magnetic field will contribute to a modification of the magnetization which will give rise to a post-DRM (pDRM; see Tarling & Turner 1999, and references therein).

The fundamental physics of DRM acquisition have been often simplified to the case of spherical magnetic particles falling through a stagnant water column (Rees 1961; Collinson 1965; King & Rees 1966; Stacey 1972; Tauxe & Kent 1984; Shive 1985; von Dobeneck 1996; Katari *et al.* 2000). The properties of a DRM for sediments whose remanence is carried by magnetite have been studied since the late 1940s and 1950s (e.g. Johnson *et al.* 1948; King 1955). Laboratory redeposition experiments reveal that the magnetization intensity of sediments grows in proportion to the strength of the applied field and that the net magnetization is orders of magnitude lower than the saturation remanence (i.e. if all the particle moments are parallel; e.g. Barton *et al.* 1980; Tauxe & Kent 1984). Several experiments demonstrate that the net effect of a DRM is to shallow the remanent inclination measured (I_{M}) with respect to the applied field inclination (I_{F}; King 1955; Løvlie & Torsvik 1984; Tauxe & Kent 1984). Misalignment of declination is negligible.

Several explanations were offered for the existence of such inclination error. King (1955) suggested that the error is due to the combined effect of spherical magnetic particles carrying the remanence, which would align with the field, and of platy magnetic carriers, which would flatten due to gravity and remain aligned in the horizontal plane. In his 'plates and spheres' model, the resulting inclination error would thus be defined by the equation: $\tan(I_{\mathrm{M}}) = f \tan(I_{\mathrm{F}})$, the flattening factor f representing the fraction of platy particles.

While King (1955) assumed that spherical particles record the average field inclination and that the error is solely due to plates, Griffiths *et al.* (1960) suggested that rolling of the spherical particles as they encounter the substrate could generate shallow inclinations. Rolling of particles in different orientations would create no net change in declination, but inclinations would be on average shallower than the applied field (other than horizontal). In this model f can be interpreted as being a function of the average angle through which particles roll.

Other models were later influenced by both approaches, incorporating also compaction (Blow & Hamilton 1978; Anson & Kodama 1987) and the rotation of prolate objects (Arason & Levi 1990). Tauxe & Kent (1984) conducted redeposition experiments with sediment containing both hematite and magnetite and tried to determine which particles were responsible for the inclination error, however their work yielded inconclusive results for the problem addressed here.

In most recent years, redeposition experiments and theoretical studies on DRM have focussed on the aspect of aggregation of sediments, or flocculation. This well-documented phenomenon leads to lowering of magnetic intensity and inclination, and varies as a function of clay content, clay mineralogy, salinity, pH and the conductivity of the clay slurry (e.g. Ellwood 1979; Scherbakov & Scherbakova 1983; Deamer & Kodama 1990; Lu *et al.* 1990; Sun & Kodama 1992; Van Vreumingen 1993a,b; Katari & Tauxe 2000). A strong correlation between the rheological properties of the suspension and the recorded intensity of the magnetic field exists, explaining the large scatter in relative palaeointensity and inclination shallowing records and highlighting the complex nature of DRM acquisition (Katari & Bloxhamm 2001; Tauxe *et al.* 2006; Scherbakov & Sycheva 2008, 2010; Mitra & Tauxe 2009). Other complicating aspects of the depositional process are present in the natural realm: Roberts & Winklhofer (2004), following the study of Bleil & Von Dobeneck (1999), state that sedimentation rate and the lock-in depth (the depth at which magnetic grains are mechanically prevented from reorienting) are also very important to DRM so that flocculation itself may not always be a controlling process. The depositional environment and confining conditions thus become of fundamental importance.

More recently, Jezek *et al.* (2012) and Bilardello *et al.* (2013) took the alternative approach of isolating one process by oversimplifying the experimental conditions. They conducted a series of deposition experiments and parallel numerical simulations investigating the role of spherical particles only. They found that spheres alone lead to considerable amounts of inclination shallowing and that this is also field-dependent: the importance of rolling is damped as field intensity increases, which in turn leads to less inclination shallowing and heightened magnetizations. The numerical models improved on the model of Griffiths *et al.* (1960) by calculating the amount of rotation produced by mutual interaction of spherical particles in the water column and their rolling on a surface created by randomly falling particles (the sediment/water interface). Their model also included a component of slipping of particles past one another, when a surface threshold angle was exceeded (Smart *et al.* 1993). They found that flocculation poorly fitted their data in terms of moment acquisition, inclination shallowing and accumulation of sediment during the experiment runs. Compaction also poorly explained the relationship between the volume of accumulated material and the acquisition of remanence. The roll/slip formulation predicted a difference in moment acquisition and inclination shallowing between experiments run at different sediment concentrations, with increased likelihood for particles to collide at higher concentrations (lower moments, and higher amounts of inclination shallowing). In fact, in the experimental results of Bilardello *et al.* (2013) for the more concentrated sediments higher inclination errors and lower moments were not always observed. This discrepancy was attributed to the fact that the experimental sediment concentration may have exceeded the applicability of the model.

To date, no published work reports on a direct comparison between DRM acquisition for spherical and platy particles. Only the aforementioned study of Tauxe & Kent (1984) attempted to discriminate between the two particle shapes. They conducted deposition experiments with disaggregated natural red beds containing both hematite and magnetite, in a range of applied field intensities and field inclinations. Tauxe & Kent (1984) extrapolated the behaviour of both particles from their results and tried to explain the observed field dependence of the remanent intensity using alignment time calculations for settling magnetic particles (Collinson 1965) and estimated settling velocities of oblate particles (Komar 1980). More details of their approach are provided in the results and discussion sections below. In order to address specifically the original proposition of King (1955), a series of experiments involving only synthetic platy and spherical particles was commenced. Experiments were conducted in one single field intensity with varying field inclinations and over different time intervals. Although limited in extent, such experiments highlight important aspects of DRM acquisition for differently shaped particles.

It is important to stress again, that deposition experiments in the laboratory cannot replicate natural conditions. Natural systems are extremely heterogeneous in terms of particle shape and size, magnetic properties, surface charges, clay and organic matter content, water pH and Eh, salinity and general composition. Water also undergoes great viscosity changes with temperature and pressure, so the majority of deposition experiments performed in still water at best achieve simulating a mass wasting event in a shallow pond. With this in mind, the only purpose of the experiments described here is to isolate a specific process in an attempt to define the 'building blocks' of DRM: here specifically, the different depositional behaviour of spherical and platy particles is investigated.

2 MATERIALS AND METHODS

2.1 Material characterization

The platy particles used are produced by Kremer Pigments Inc. (www.kremerpigments.com) and sold as 'glass flakes' with an average grain size of 15 μm. Grain size was qualitatively evaluated using an optical microscope at the Ludwig-Maximilians University (LMU) in Munich, Germany. The micrograph in Fig. 1 confirms the approximate mean grain size, however, it is apparent that grains may reach up to 50 μm across. Magnetic characterization was performed at the Institute for Rock Magnetism, University of Minnesota (UMN), on a Princeton Measurements Corp. (Princeton, NJ) Vibrating Sample Magnetometer (VSM) and Quantum Designs (San Diego, CA) Magnetic Property Measuring System (MPMS). Preliminary measurements had been attempted at the LMU using a Petersen Instruments (Munich, Germany) Variable Frequency Translation Balance (VFTB), however the signal to noise ratio obtained from this instrument was unfavourable.

Before any magnetic measurements were attempted, the particles were rinsed in dilute HCl. In order to obtain a measurable magnetic signal, the glass plates were gravitationally separated, by settling the coarser fraction in ~10 cm of distilled water over ~30 min, under the assumption that, as observed for the glass beads, the larger particles would contain the most Fe impurities. This assumption proved correct and although hysteresis measurements were still very noisy, the saturation magnetization of the larger particles was roughly double the measurement performed on the VFTB for a specimen containing the entire grain size spectrum. To obtain interpretable

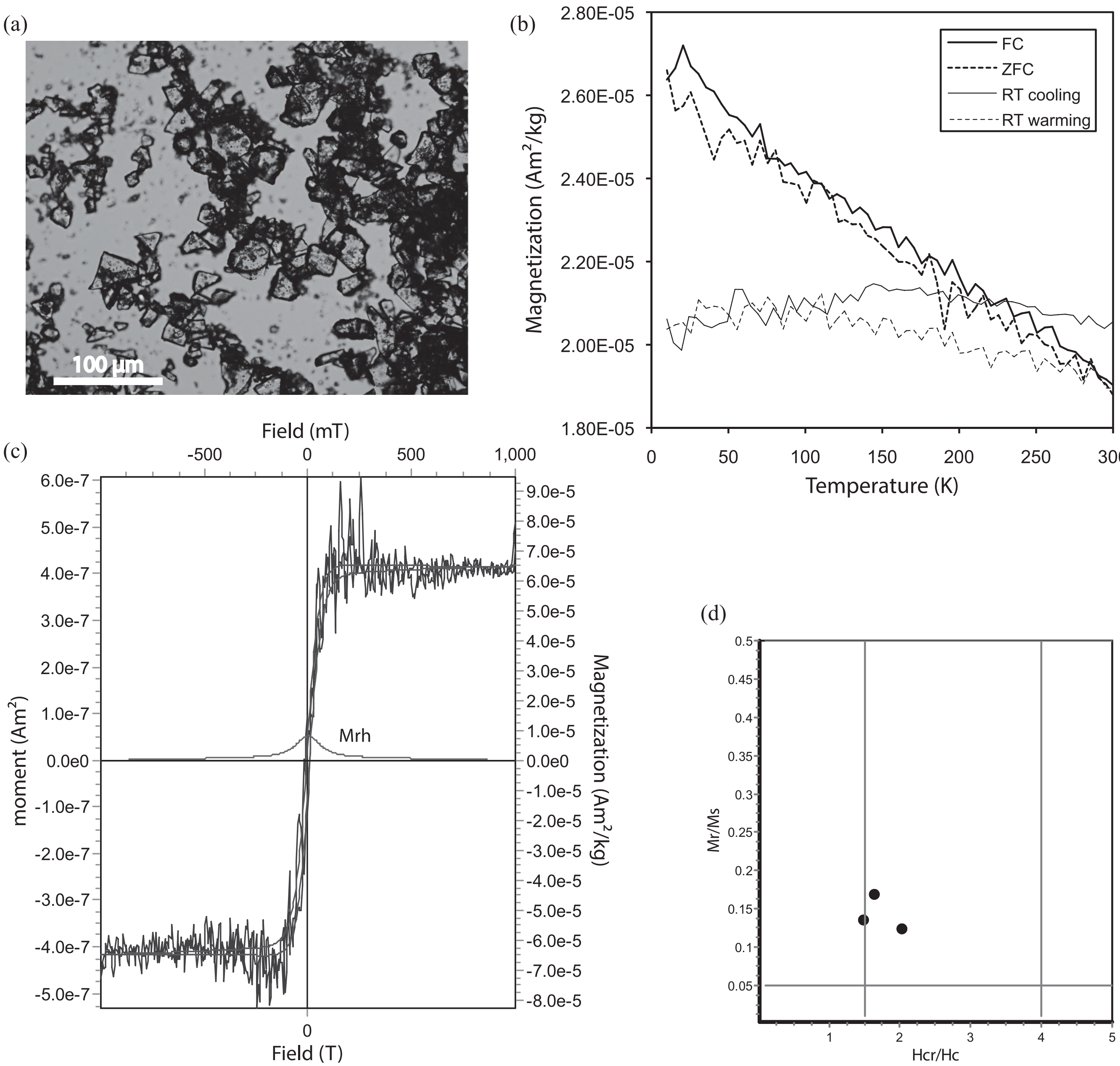

Figure 1. Rock-magnetic results for the glass plates: (a) micrograph of the particles; (b) Low-temperature experiments (FC/ZFC, field cooled/zero field-cooled magnetization; RT cooling/warming, room temperature cooling and warming). (c) Hysteresis loop showing diamagnetic/paramagnetic corrected data and fitted data (see text for details), M_{rh} curve is symmetry of the loop across the M-axis. (d) Day plot (Day *et al.* 1977) of measured hysteresis parameters.

results, data were fitted using hyperbolic functions using software developed at UMN (Jackson & Solheid 2010). *F*-tests support the validity of the non-linear fit of the data. Fitted hysteresis parameters are saturation magnetization (M_s): 6.49 × 10^{-5} Am^2 kg^{-1}, saturation remanent magnetization (M_{rs}): 8.15 × 10^{-6} Am^2 kg^{-1}, bulk coercive force (Hc): 7.67 mT (instrument settings: field range 1 T; moment range 50 × 10^{-6} Am^2; averaging time 0.2 s), and a backfield remanence paramater is coercivity of remanence (H_{cr}): 19.67 mT (instrument settings: field range 300 mT; moment range 200 × 10^{-9} Am^2; averaging time 5 s). Results are summarized in Figs 1c and d where a hysteresis loop and a Day *et al.* (1977) plot are shown.

Measurements performed on the MPMS (Fig. 1b), also show the very low remanence carried by the particles. A specimen was cooled from 300 to 10 K in the presence of a 2.5 T field and the remanence was measured upon warming back to 300 K (FC curve in Fig. 1b). The specimen was cooled again to 10 K in the absence of a magnetic field, given a low-temperature saturating isothermal remanent magnetization (SIRM) of 2.5 T and the remanence was measured upon heating again to 300 K (ZFC curve in Fig. 1b). At 300 K, a 2.5 T SIRM was imparted to the specimen and the remanence was measured again while cooling and subsequent warming (RT-cooling and RT-warming curves in Fig. 1b, respectively). The RT cooling/warming curves merge at ∼110 K, supporting the presence of some magnetite.

Bilardello *et al.* (2013) had reported the presence of both magnetite and pure iron in the glass spheres used in their experiments. Assuming such impurities to be common in glass-producing processes it is likely that a mixture of magnetite and pure iron is also present in the glass plates.

2.2 Experimental set-up

Particles were imparted a strong IRM to enhance their magnetization. In order to magnetize the particles along the basal plane, small amounts of sediment were allowed to settle in a beaker within the magnetically shielded room so that they would lie flat on the bottom of the beaker. The beaker was then placed in an electromagnet and a ∼0.7 T field was applied horizontally. The procedure was repeated until all the available sediment was magnetized (∼90 g). The rationale is that magnetizing the inclusions parallel to the basal plane of the glass plates makes the particles behave like homogeneous single-domain particles. The sediment was placed in a flat-bottomed borosilicate glass tube of 3.6 cm diameter and the tube was filled with double distilled water to form a water plus sediment column of 20 cm. The wet sediment height within the tube was 43.9 mm (the mean value measured after all the experimental runs described below). The measurement area of the LMU magnetometer used to make the measurements has its most sensitive region extending over 4 cm. The centre of the measurement tube coincided with the centre of the sediment.

Experiments using spherical particles were also conducted in parallel. The spherical particles are produced by Potters Industries LLC (www.pottersbeads.com); the physical characteristics, including detailed magnetic properties, are described in detail by Bilardello *et al.* (2013), who used the same particles for their deposition experiments. While Bilardello *et al.* (2013) had acid-rinsed the particles prior to drying and weighing them; in the current study the particles were first weighed and subsequently acid-rinsed. Following this procedure the drying step was avoided, which limits the possibility of particles sticking to each other and remaining attached as flocs. After the preparation of the tubes (and also after every experiment of the duration of 3 d or longer), tubes were placed in an ultrasonic bath to help separate particles thoroughly and break-up possible flocs. For the spheres, two different settling tubes of diameters of 2 and 3.6 cm were used, containing 15 g of beads each. Both tubes, as for the one containing platy particles, were filled up to form a 20 cm sediment plus water column. The ratios of sediment to total (water plus sediment) volume are therefore 0.22, 0.20 and 0.06 for the plates, the spheres in the small tube and the spheres in the large tube respectively. The plates and the spheres in the small tube thus have similar concentrations, which are ∼3.5 times greater than that of the spheres in the large tube.

Deposition experiments were conducted at the LMU. A stable magnetic environment was generated by Helmholtz coils ∼1 m on each side. A fluxgate magnetometer probe fixed within the coils constantly monitored the field, which was uniform over the volume in which the experiments were performed. Experiments were conducted while immersing the settling tubes in a 32 °C temperature-controlled water tank to minimize the effects of temperature fluctuations that could potentially change the water viscosity, in turn affecting the settling time of the sediment in the tubes (see Bilardello *et al.* (2013) for more details). Experiments were performed by shaking the settling tubes vigorously to achieve full separation and suspension of the sediment and then placing the tubes in the Helmholtz coils. After the established duration of the specific experiment was reached (see experiment description below), the tubes were carefully removed from the Helmholtz coils and placed in a vertically oriented 2G cryogenic magnetometer for measurement. After each magnetic measurement, the thickness of the sediment on the bottom of the tubes was measured using a digital caliper, to determine the volume of deposited sediment, allowing correlation to the accumulated magnetic moment. This measurement also quantifies sediment packing and monitors the consistency of the experiments.

2.3 Experiment description

Two different kinds of experiments were run. The first experiment set involved deposition in a100 μT field inclined at 0°, 30°, 60° and 90° over an uninterrupted 24-hr period. Each deposition run was repeated three times, allowing calculation of standard deviations. The main goal of this kind of experiment is to assess the repeatability of the measurements and behaviour of the different particle shapes and concentrations. Bilardello *et al.* (2013) showed that ∼100 min is enough time for the remanence of spherical particles to reach a stable maximum. Assuming that a similar amount of time would be necessary to stabilize the moment carried by plates (confirmed by the acquisition experiment described below), 24 hr were deemed a reasonable amount of time for a meaningful comparison. Magnetic moment, inclination and the thickness of the deposited sediment where measured for each run. These experiments will be referred to throughout the paper as '24-hr experiments'.

The second experiment is a DRM acquisition up to 10 d in a 100 μT field inclined at 60°. Measurements where performed after 0.5, 1, 3, 6, 24, 120 and 240 hr of continuous deposition, as in the experiments of Bilardello *et al.* (2013) involving beads, to which the new results are compared. After each measurement step, the tubes were vigorously shaken and placed back into the Helmholtz coils for the next settling time step. Individual measurements are used to construct curves for continuous DRM acquisition, allowing monitoring the acquisition of the magnetization over longer timescales, possible pDRM behaviour and/or eventual compaction. These experiments will be referred to throughout the paper as 'acquisition experiments'.

3 RESULTS

3.1 24-hr experiments

Results of the 24-hr experiments are summarized in Figs 2–4 and Table 1. Results of Tauxe & Kent (1984) are also included for comparison. It must be noted, however, that Tauxe & Kent's (1984) experiments employed natural disaggregated sediment containing both hematite and magnetite, at a concentration comparable to the 3.6 cm diameter tubes used in this study. The total sediment plus water height of their experiments (the settling depth) was 15 cm and their experiments were run for approximately 5 hr. Thus, although their experimental conditions are by no means identical to those employed here, their results provide an interesting comparison.

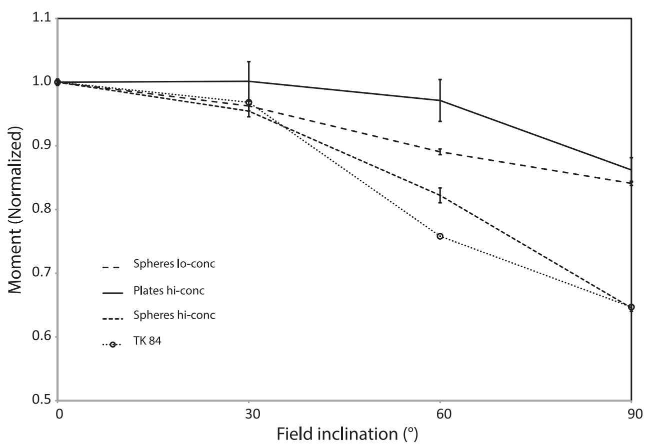

Figure 2. Moment data of 24-hr experiments for different applied field inclinations, means of three measurements are shown. Solid, dashed and smaller dashed curves are for plates, spheres in low and high concentrations, respectively. Error bars are one standard deviation. Dotted curve and open circles are data from Tauxe & Kent (1984).

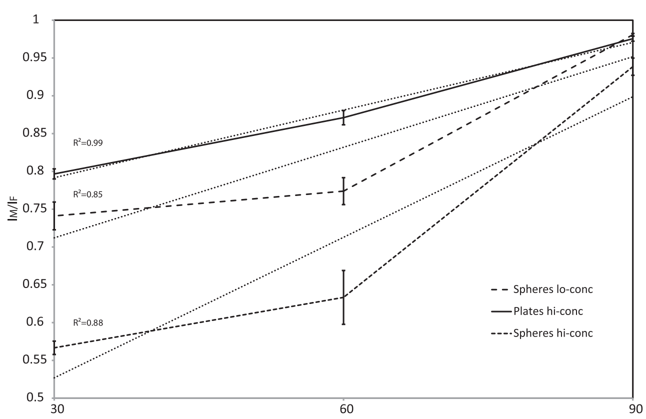

Figure 3. Fractional inclination error data of 24-hr experiments, means of three measurements are shown. Solid, dashed and smaller dashed curves are for plates, spheres in low and high concentrations, respectively. Error bars are one standard deviation. Dotted lines are linear regressions through the data with respective R^2 values.

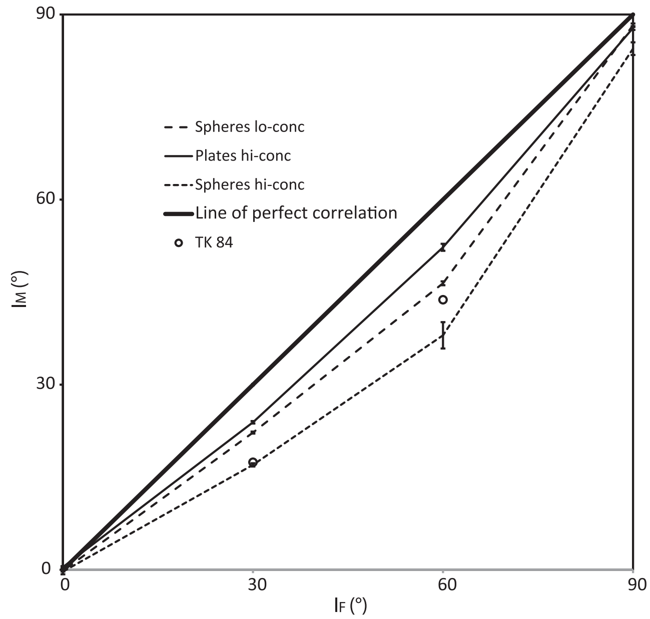

Figure 4. Measured inclinations over field inclinations. Means of three measurements are shown. Solid, dashed and smaller dashed curves are for plates, spheres in low and high concentrations, respectively. Error bars are one standard deviation. Open circles are data from Tauxe & Kent (1984). The thick solid line represents perfect correlation (no inclination error).

3.1.1 Magnetic moment

Fig. 2 shows a summary of magnetic moments measured in 100 μT fields with inclinations ranging from horizontal to vertical. Mean results of the three experimental runs are plotted with 1 *SD* error bars. For a direct comparison of magnetizations of different magnitudes, results have been normalized to the horizontal field-average for each tube. The moment recorded in horizontal fields is always the highest, except for one of the three measurements performed for the platy particles after settling in 30° field inclinations, which gives this point a higher magnetization.

After normalization, plates show the overall highest magnetizations, followed by the spheres at low concentrations and then at high concentrations. The curve obtained for the platy particles is the most non-linear, with a coefficient of determination (R^2) of 0.76 from a least squares linear fit, however the difference between highest and lowest magnetization, delta, is the smallest (0.14). The spheres in low concentrations in contrast have the most linear fit of all particles, $R^2 = 0.99$, and the second-smallest delta of 0.16. In higher concentrations, spheres exhibit $R^2 = 0.94$ and the largest delta of 0.35. Results of Tauxe & Kent (1984) overlap with those obtained in this study using both sphere concentrations (see Fig. 2 and Table 1). Over the range of settling field-inclinations, their R^2 is 0.94 with a delta of 0.35.

Probably the most striking observation is the dependence of the magnetization on field inclination. Tauxe & Kent (1984) had observed such a clear dependence, with magnetizations becoming progressively stronger from vertical to horizontal fields. Bilardello *et al.* (2013), however, did not observe such a clear pattern (*cf.* their fig. 5).

3.1.2 Magnetic inclination

Magnetic inclination data from the 24-hr experiments are summarized in Figs 3 and 4 and Table 1. Tauxe & Kent (1984) had defined

Table 1. Summary of results of the 24-hr experiments. Results for the platy particles, spheres in high and low concentrations and selected results from Tauxe & Kent (1984) are presented. Values presented are the arithmetic means of three measurements: Field Inc. is settling field; *M Norm.* is normalized magnetization; Meas. Inc. is measured inclination; I_M/I_f is the fractional inclination error; Delta *M* is the difference between strongest and weakest measured magnetizations; *f* is the shallowing factor (King 1955; bold is mean value); *R* is the ration of magnetizations measured in vertical over horizontal fields; *SD*'s are one standard deviation values.

Experiment	Field Inc.	M Norm.	*SD*	Meas. Inc.	*SD*	I_M/I_F	*SD*	Delta M	Delta I_M/I_F	*f*	*R*
24-hr deposition experiments in 100 μT fields and varying inclinations											
Plates hi-conc	90	0.86	0.02	87.80	0.30	0.98	0.00	0.14	0.18	0.00	
Plates hi-conc	60	0.97	0.03	52.27	0.57	0.87	0.01			0.75	
Plates hi-conc	30	1.00	0.03	23.90	0.20	0.80	0.01			0.77	
Plates hi-conc	0	1.00	0.00	0.43	0.15	0.00				**0.76**	0.86
Spheres lo-conc	90	0.84	0.00	88.27	0.28	0.98	0.00	0.16	0.24	0.00	
Spheres lo-conc	60	0.89	0.00	46.43	0.31	0.77	0.02			0.61	
Spheres lo-conc	30	0.96	0.01	22.23	0.16	0.74	0.02			0.71	
Spheres lo-conc	0	1.00	0.00	−0.17	0.12	0.00				**0.66**	0.84
Spheres hi-conc	90	0.65	0.01	84.47	1.03	0.94	0.01	0.35	0.37	0.00	
Spheres hi-conc	60	0.82	0.01	38.00	2.14	0.63	0.04			0.45	
Spheres hi-conc	30	0.95	0.01	17.00	0.26	0.57	0.01			0.53	
Spheres hi-conc	0	1.00	0.01	−0.30	0.44	0.00				**0.49**	0.65
∼5 hr results from Tauxe & Kent (1984) in 100 μT fields and varying inclinations											
TK84	90	0.65		–		–		0.35		–	
TK84	60	0.76		43.77		0.73				0.54	
TK84	30	0.97		17.43		0.58				0.55	
TK84	0	1.00		–		–				**0.55**	0.76

the fractional inclination error as the measured remanent inclination (I_M)/field inclination (I_F). This is plotted in Fig. 3 for the different settling field-inclinations; larger values correspond to less inclination shallowing. Plates exhibit the smallest inclination error of all particles and also the most linear fit, with delta and R^2 values of 0.18 and 0.99, respectively. Spheres in low concentration follow, with the second smallest inclination error but lowest $R^2 = 0.85$. The delta for the inclination error is also the second smallest (0.24). Highly concentrated spheres, instead, show the largest inclination error. The range of inclination error for the different settling field inclinations is also the largest, with a delta of 0.37. R^2 has a value of 0.88.

Fig. 4 plots the inclination error as I_M over I_F. The particle concentration and field inclination dependence of the inclination error described above are also apparent. Results of Tauxe & Kent (1984) are also plotted here for field inclinations of 30° and 60°. These data plot in between those for spheres in high and low concentrations although for the settling field inclined at 30°, they plot almost on the data for highly concentrated spheres. From Fig. 4 it is also apparent that the greatest inclination error (I_F–I_M) occurs at 60° field inclinations.

The most striking observation is the field inclination dependence of the inclination error, for all particles. The ratio of remanent to field inclination (I_M/I_F) is always the smallest in settling fields inclined at 30° and the largest at 90°. Similar results were observed by both Tauxe & Kent (1984) and Bilardello *et al.* (2013).

3.2 Acquisition experiments

The DRM acquisition experiment conducted at constant field intensity of 100 μT and field inclination of 60° up to 10 continuous days of deposition allowed a comparison between the different particles and concentrations. Results for the spherical particles are from Bilardello *et al.* (2013). They measured three tubes for each field intensity, inclination, and concentration experiment: here, the mean measurements of the three tubes for both sediment concentrations, deposited in the same field conditions (100 μT and 60°), are shown

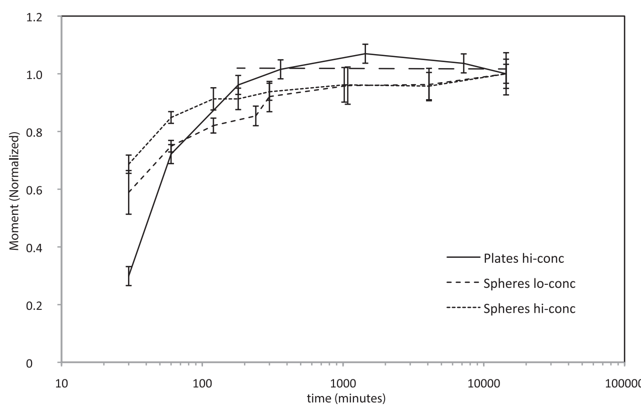

Figure 5. Acquisition of DRM for the 10-d experiments conducted in a 100 μT field inclined at 60°. Solid curve is from the platy particles (this study); the error bars are from the 24-hr experiments ($H = 100$ μT, $I_F = 60°$). Long-dashed line is a trend line fitted trough the measurement steps of 180 min and higher (see text for details). Dashed and smaller dashed curves are the mean results reported by Bilardello *et al.* (2013) for spheres in deposited in low and high concentrations, respectively, in the same experimental conditions. Error bars are one standard deviation.

together with their one standard deviation error bar. Because time allowed only one experimental run using the platy particles, the error bars for moment, inclination and sediment thickness are taken from the 24-hr experiments conducted in the same field conditions and are repeated for each of the time steps. While it is of little statistical significance to utilize error bars from a different experiment, given that only the time constant changes (except for the 24-hr step), it serves as a useful term of comparison. Results are summarized in Figs 5–7 and Table 2, and described in terms of magnetic moment, inclination and deposited sediment thickness.

3.2.1 Magnetic moment

For comparison among tubes, magnetization results for the three tubes are normalized to the last, 10-d, measurement (Fig. 5).

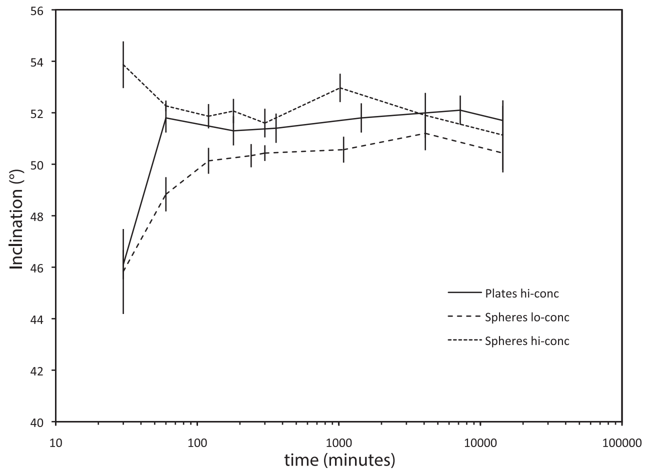

Figure 6. DRM Inclination data for the 10-d experiments conducted in a 100 μT field inclined at 60°. Solid curve is from the platy particles (this study); the error bars are from the 24-hr experiments ($H = 100$ μT, $I_F = 60°$). Dashed and smaller dashed curves are the mean results reported by Bilardello *et al.* (2013) for spheres in deposited in low and high concentrations, respectively, in the same experimental conditions. Error bars are one standard deviation.

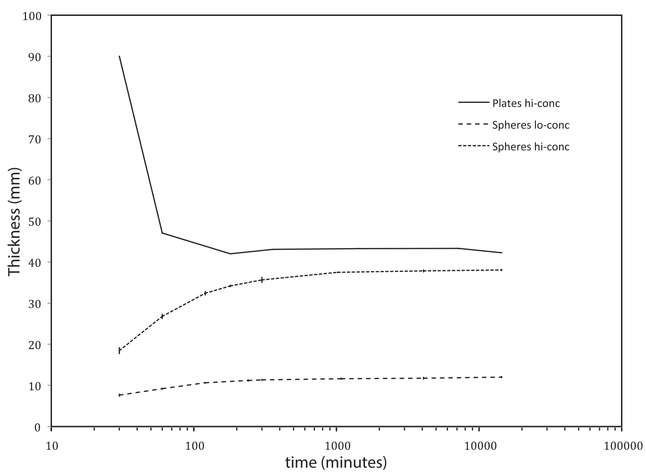

Figure 7. Accumulation of sediment thickness data for the 10-d experiments conducted in a 100 μT field inclined at 60°. Solid curve is from the platy particles (this study); the error bars (not visible at this scale) are from the 24-hr experiments ($H = 100$ μT, $I_F = 60°$). Dashed and smaller dashed curves are the mean results reported by Bilardello *et al.* (2013) for spheres in deposited in low and high concentrations, respectively, in the same experimental conditions. Error bars are one standard deviation.

Accumulation of magnetic moment follows a steeper initial trend for plates than for spheres. The highest magnetization reached by the plates occurs at the 24-hr step (1440 min) after which the moment declines again. A trend-line through the magnetic moments recorded after 180 min highlights the departure of the data from a constant, saturated magnetization. The moment acquisition curves of spherical particles, instead, remain more constant after reaching a plateau after 100–300 min.

3.2.2 Inclination

Magnetic inclination data are more constant than the magnetization data. All different particles appear to gain alignment already within 30 min after deposition. However, it is after approximately 1 hr that the inclination saturates and remains constant, within confidence intervals. Plates and spheres at low concentrations exhibit an initial increase in inclination, whereas that of spheres in high concentrations appears to decrease slightly. Unlike the 24-hr experiments, in the DRM acquisition experiment both plates and spheres in high concentrations gain approximately the same, and smaller, inclination error (∼8°), while the spheres in low concentrations possess ∼10° of error, although they have the smallest error bars.

Table 2. Summary of results of the 10-d DRM acquisition experiments conducted in field intensity and inclination of 100 μT and 60°. Values presented are the arithmetic means of three measurements: hours is the measurement step (in hours); M Norm. is normalized magnetization; Meas. Inc. is measured inclination; mm is the sediment thickness (in mm); *SD*'s are one standard deviation values.

DRM acquisition of particles, settling field: 100 μT, 60° inclination						
hours	M Norm.	*SD*	Meas. Inc.	*SD*	mm	*SD*
Plates, high concentration						
0.5	0.30	0.03	46.10	0.57	90	0.12
1	0.72	0.03	51.80	0.57	47.04	0.12
3	0.96	0.03	51.30	0.57	42	0.12
6	1.02	0.03	51.40	0.57	43.08	0.12
24	1.07	0.03	51.80	0.57	43.25	0.12
120	1.04	0.03	52.10	0.57	43.31	0.12
240	1.00	0.03	51.70	0.57	42.25	0.12
Spheres, low concentration						
0.5	0.59	0.08	45.83	1.65	7.64	0.36
1	0.75	0.02	48.83	0.67	9.21	0.24
2	0.82	0.03	50.13	0.50	10.65	0.18
4	0.85	0.03	50.33	0.45	11.20	0.27
5	0.92	0.05	50.43	0.31	11.34	0.22
18	0.96	0.06	50.57	0.50	11.63	0.26
68	0.96	0.06	51.20	0.66	11.75	0.33
240	1.00	0.07	50.43	0.75	12.02	0.24
Spheres, high concentration						
0.5	0.69	0.03	53.87	0.91	18.46	0.84
1	0.85	0.02	52.27	0.21	26.78	0.62
2	0.91	0.04	51.87	0.47	32.40	0.53
3	0.91	0.04	52.07	0.47	34.18	0.29
5	0.94	0.03	51.60	0.56	35.64	0.73
17	0.96	0.06	52.97	0.55	37.50	0.18
68	0.96	0.05	51.90	0.87	37.84	0.36
240	1.00	0.05	51.13	1.35	38.06	0.25

3.2.3 Sediment thickness

Accumulation of sediment on the bottom of the tubes was also measured after every depositing step. The curves for the spherical particles are very similar in shape, although the scale is very different. Spheres exhibit a continuous accumulation curve, which rises steeply and then flattens out. The most constant thicknesses are reached after approximately 1000 min for spheres in both concentrations.

The curve for plates, instead, has a different shape. After 30 min of deposition most of the particles have reached the bottom of the tube forming a dense slurry with a measurable height, without however having come to complete rest. After approximately 1 hr the height of the slurry is almost halved and then remains approximately constant over the subsequent measurement steps, indicating that the plates have completely settled.

4 DISCUSSION

4.1 24-hr experiments

The results presented from both the 24-hr and the acquisition experiments allow an interesting comparison of the depositional behaviour of platy and spherical particles. First-order observations are the field inclination dependence of the magnetization and the field inclination dependence of the inclination error for all particles (Figs 2 and 3). Somewhat counter-intuitively, smaller inclination errors are observed for the plates than for the spheres. The mean shallowing factor, *f*, calculated for plates is 0.76, whereas for the spheres in low and high concentrations, respectively, they are 0.66 and 0.49. The mean *f* factor calculated here for Tauxe & Kent's (1984) 30° and 60° inclination data at 100 μT is 0.55 (Table 2).

Comparing compilations of inclination shallowing data for natural rocks, Bilardello & Kodama (2010) did observe that hematite on average leads to higher inclination shallowing (smaller *f*) than magnetite (for which plates and spheres may be reasonable proxies). However, they also observed a greater variability for hematite than for magnetite, with hematite *f* factors ranging between 0.4 and 0.83. In this light, the *f* factor of 0.76 measured for plates is not that surprising.

An outstanding observation is that, for all settling field inclinations, platy particles exhibit much higher variability in moment acquisition than they do for inclination, compared to spherical particles (Figs 2 and 3). This behaviour may be explained by the overall particle alignment. On each deposition run, while mean orientation and inclination of particles remains constant, small variations in alignment may cause the total magnetic vector to be longer or shorter, resulting in the observed variability of magnetization but not of inclination. This hypothesis may be tested in the future by preparing discrete samples from deposited sediment and measuring magnetic anisotropy. Lower anisotropy values should correlate to weaker magnetizations.

The very weak magnetization of the platy particles used in these experiments of course enhances misaligning effects on the particles' trajectories. Magnetic alignment is counteracted by the hydrodynamic trajectory of the particles and randomizing effects such as thermofluctuations and Brownian motions. To quantify both the aligning magnetic torque and the misaligning forces for ellipsoidal particles is not trivial (see Jezek & Gilder 2006). Tauxe & Kent (1984) utilized the expressions derived by Collinson (1965) to estimate the aligning time for magnetic particles settling through a column of still water. In conjunction with the settling velocities calculated for oblate particles (Komar 1980) it is possible to further estimate the settling distance over which the magnetic particle will align with the applied field. Using a mean particle diameter of 15 μm and thickness to diameter ratios of 0.1, 0.2 and 0.75, the mean particle magnetic moments calculated from the measured M_s for volumes corresponding to the three thickness to diameter ratios above (2.13×10^{-17}, 4.25×10^{-17} and 1.60×10^{-16} Am^2), the applied field intensity (100 μT) and reasonable values for particle density (2500 kg m^{-3}) water density and viscosity (995.7 kg m^{-3} and 1×10^{-3} Pa s) and gravitational acceleration (9.8 m s^2), always yields aligning distances that by far exceed the water column in the settling tubes. By virtue of these calculations the experiments described should not show net alignment of particles, which, on the contrary, is unquestionably obtained. This highlights the non-strict validity of Collinson's (1965) expression, which in truth, was derived for spherical particles; Tauxe & Kent (1984) did however obtain 'realistic' results for the calculation of alignment distances of hematite particles (less than 1 mm to 2 cm).

The qualitative result of the calculations above is that the weakly magnetized particles employed align over long settling distances. This also implies that these must be subject to strong misaligning forces coming from hydrodynamic torques, mutual impingement of particles as they settle and Brownian motions.

Other objection to the results presented here may be that the magnetic moment of the plates may not lie exactly within the basal plane of the particles and that the glass flakes may not be an ideal proxy for hematite. Care was taken to impart IRMs parallel to the basal plane of the particles, however small deviations may still exist.

Undoubtedly, the platy particles used are not ideal, but given the weak moment of the particles and the effects of other misaligning factors, a non-exactly parallel magnetization in the basal plane may be considered negligible.

In contrast, the purely spherical particles used record large inclination errors and the strong repeatability of the results obtained strongly support the data presented. It follows that rolling of spherical particles is without question a great contributor to inclination shallowing.

For an ideal comparison between particle shapes, confining conditions should be identical, including particle magnetization. Unfortunately this is seldom the case because the 'ideal' material is impossible to come by. A strictly quantitative analysis is therefore ruled out, however, the data still allows extrapolation of significant trends.

Tauxe & Kent (1984) tried to use their results to test the 'rolling ball' model of Griffiths *et al.* (1960) against the 'plates and spheres' model of King (1955). Tauxe & Kent (1984) stated that, following the model of Griffiths *et al.* (1960), one would expect no dependence of the remanent intensity on the orientation of the applied field since the rolling is a response to microtopography and is independent of the orientation of the applied magnetic field. Therefore, the ratio *R* of the remanent intensity acquired in a vertical field to the remanent intensity acquired in a horizontal field of equal magnitude should be unity. The work of Bilardello *et al.* (2013) did not disprove this statement, however the results obtained here clearly do. Rolling of spherical particles must therefore be influenced by field orientation.

Rolling occurs around horizontal axes, therefore it makes sense that the closer the magnetic vector is to horizontal, the stronger the total moment that will remain. As a simple example, one may consider an assemblage of four particles depositing together and fully aligned towards the north and horizontal. Let each particle roll by equal amounts towards the closest cardinal point, N, E, S and W: the two opposing particles rolling towards N and S will each steepen their vector, thus cancelling each other's moment out when a 90° rotation is reached. Rolling of the remaining two particles to the E and W will leave their vectors unaffected no matter the degree of rotation. The total magnetic vector will thus be diminished by an amount in between 0 and 0.5.

Now let the same assemblage of particles settle in a vertical field. Rolling towards the four directions by the same amount will lead every particle to shallow its magnetization. The decrease of the total magnetic moment will be proportional to the amount of rotation experienced by all particles, decreasing by 100 per cent if the four particles of this idealized system all rotate 90° (their moments mutually cancel each other out). Upon uniform rotation, the total vector of particles deposited in fields with intermediate inclinations will experience a decrease in total moment in between 0 and 100 per cent, the shallower the depositing field inclination the smaller the decrease in moment, no matter the amount of rolling of the particles. Of course, multiparticle systems possessing a range of grain sizes will show complex behaviour, with the smaller particles undergoing higher rotations than the larger and surface topography also affecting the directions in which particles rotate. Some particles may also rotate by angles greater than 90°. However, in both a natural scenario and our experiments, where billions of particles are involved, these effects should smooth out, as the results presented here and by Tauxe & Kent (1984) demonstrate.

Tauxe & Kent (1984) also stated that the 'plates and spheres' model predicts a dependence of the remanent intensity on the orientation of the magnetic field. When the field is horizontal, all the magnetic grains can contribute to the remanence, whereas in vertical fields only the spheres contribute, resulting in a lower net remanence. For this reason the 'plates and spheres' model provided a better explanation for the cause of the inclination error in their experiments. The current study involving experiments with only plates or spheres disproves this statement, showing that both rolling (spheres) and flattening (plates) are dependent on field orientation.

Moreover, Tauxe & Kent (1984) also suggested that the value of f should be equal to the ratio R (remanent intensity acquired in a vertical field (spheres) over the remanent intensity acquired in horizontal fields (plates and spheres), as already predicted by models that treat the DRM as a tensor: $\bar{M}_{\mathrm{DRM}} = [K_{\mathrm{DRM}}]\bar{H}_{\mathrm{dep}}$, where $\bar{M}_{\mathrm{DRM}}$ is the DRM vector, K_{DRM} is the anisotropic detrital remanence tensor and $\bar{H}_{\mathrm{DRM}}$ is the depositional field vector (see Verosub 1977). We now know the equation $f = R$ is inaccurate; it is nevertheless interesting to verify whether a correlation exists between f and R (Table 1). For the new data presented here and Tauxe & Kent's (1984) data for 30° and 60°, the ratios R are systematically larger than the f values, however the two quantities do not vary coherently. Plotting R versus f (not shown) does not result in a linear correlation.

4.2 Acquisition experiments

Data from the acquisition experiments is somewhat less informative than data from the 24-hr experiments. While the 24-hr data were collected simultaneously for all particle shapes and confining conditions were therefore identical, data for the acquisition experiments of the beads are approximately a year older. The spheres used for the acquisition and the 24-hr experiments are of the same type and total mass, but come from different batches. Moreover, as mentioned in the methods section, beads for the 24-hr experiments were prepared differently, avoiding the drying step after the acid rinse. These factors may contribute to slight differences in the results.

A trend-line through the magnetic moments measured for the plates for time >180 min shows small departures from a constant value, but overall the magnetization may be considered saturated (Fig. 5). The decay of intensity observed over the last three time steps may appear to be caused by compaction/gravitational flattening. If this were the case, though, it would be accompanied by a decrease in both inclination and sediment thickness. This is not observed (Figs 6 and 7); therefore it is most probable that it is solely an effect of the uncertainty in the measurement of magnetization. It is thus possible to state with some confidence that the moment may be considered saturated after ∼180 min. The accumulation of moment up to this point is steeper for the plates than for spheres, which is not exclusively a function of concentration, since this is similar to that of the beads in the small tubes. From the moment acquisition and sediment thickness plots, it is possible to extrapolate that the steepness of the initial moment slope is attributable to the narrower grain size distribution of the magnetic plates and the larger mean grain size. This results in the faster deposition of the particles, at more homogeneous velocity (and consequent faster accumulation of magnetic moment). Depositing plates form a dense slurry which possesses measurable height, which then settles more slowly over time because of its increased viscosity. In other words, while for the spheres a measured sediment thickness is observed at the bottom of the tube, which grows as more spheres settle and the suspension thins, the plates quickly form a measurable dense cloud of sediment above which the water in the tube is completely clear. This cloud then diminishes in thickness over time, generating the inverted thickness pattern observed in Fig. 7.

It is also interesting to note that the inclination errors for plates and spheres in high concentrations are similar, and they are smaller than that of spheres in low concentration. This observation somewhat contradicts that from the 24-hr experiments where it is the spheres in high concentrations that possess the largest inclination error, but this is most likely an effect of the different spherical particles used between the two sets of experiments. As previously explained, the acquisition experiment results on spherical particles are from Bilardello *et al.* (2013), who had dried the particles after acid-rinsing. The drying process may promote sticking of some particles as flocs. Bilardello *et al.* (2013) had modelled the settling of particles in their experiments and indeed could not exclude the presence of flocs during the first few minutes of deposition. Numerical modelling showed a better fit of the data allowing the presence of small flocs (5 μm) during the first 10–20 min of deposition. While flocs themselves lead to inclination shallowing (e.g. Tauxe *et al.* 2006), they do not roll on the substrate like individual spheres. It is thus possible that a DRM resulting entirely from spherical particles will be more shallow than one containing a number of flocs. In the absence of flocculation, increasing particle concentration enhances particle interactions in the water column, leading to more pronounced inclination shallowing. However, if flocs are present, their larger composite diameter enhances the deposition rate, leading to faster locking-in of the particles. In highly concentrated slurries, such mechanical blocking of the particles could limit inclination shallowing. This process may help explain the different results obtained for the spherical particles in the two sets of experiments ('24-hr experiments' and 'acquisition experiments') and a rigorous comparison may thus be invalidated.

For all particles, the time evolution of the inclination error is similar, with shallowing occurring virtually instantaneously, whereas the accumulation of magnetic moment follows the deposition of the particles, measured as the evolution of sediment thickness. Jezek *et al.* (2012) and Bilardello *et al.* (2013) had demonstrated with numerical simulations that, despite the short alignment times, spherical particles already begin to acquire an inclination error in the water column. This effect is due to particle-particle interactions, and more specifically the 'rolling' of a slower particle around a faster-settling particle descending above it. Spherical particles thus reach the substrate already with a shallowed inclination, after which further rolling occurs.

In the experiments presented here, the inclination of the spheres in high concentration appears to be locked-in and does not change significantly from the beginning to the end of the experiment, whereas spheres in low concentrations regain ∼4° of inclination error during the first 180 min of deposition (Fig. 7).

Platy particles cannot 'roll', neither on the substrate nor in the water column. However, because of their weak magnetization (at least the ones used in this study) and their high potential of being affected by hydrodynamic torques and randomizing Brownian motions, it is very likely that misalignment also occurs due to particle-particle interactions in the water column. As shown in Fig. 7, a $\sim 5^\circ$ recovery of the inclination error then occurs between 30 and 60 min of deposition.

4.3 'Rolling ball' or 'plates and spheres'?

The data presented and discussed here allow for the first time to fully discriminate between the different models proposed. Bilardello *et al.* (2013) were able to validate and improve on the 'rolling ball' model of Griffiths *et al.* (1960), however, could not rule out the 'plates and spheres' model of King (1955). These new data do allow for this. It is clear that platy particles do not align in the horizontal plane irrespective of field inclination but rather flatten to variable degrees (and most probably along different orientations) depending on settling field inclination and the downdip azimuth of the particles. The magnetization and inclination error dependence on the applied field intensity still remains to be tested for platy particles.

5 CONCLUSIONS

A comparison of experiments run simultaneously with synthetic spherical and platy particles alone were conducted to determine which particle shape is the largest contributor to inclination shallowing in sediments. Two different concentrations of spherical particles and one (higher) concentration of platy particles were used.

Experiments of the duration of 24 hr were run in field intensities ($\mu_0 H$) of 100 µT, and field inclinations of 0°, 30°, 60° and 90°. All particles exhibit a field inclination dependence of the magnetization, with intensities increasing from 90° to 0° field inclinations. Spherical particles yield more repeatable magnetic moment measurements than plates. Spheres in lower concentrations also display the most linear field inclination-dependence of moment acquisition, while plates are the farthest from linearity.

The opposite is observed for inclination: platy particles yield more repeatable results and also the most linear relationship of inclination error to field inclination. Surprisingly, plates also yield smaller inclination error than spheres (mean flattening values, f, of 0.76, 0.66 and 0.49 for plates, low-concentration and high-concentration spheres, respectively). For all experiments, a clear field inclination dependency of the inclination error exists. The fractional inclination errors (I_M/I_F) approach unity through field inclinations of 30°, 60° and 90°. This progression is more linear ($R^2 = 0.99$) for plates than it is for spheres in both concentrations ($R^2 = 0.85$–0.88, low and high, respectively). Both the variance of the error and the error itself (difference between I_F and I_M) are always greater at field inclinations of $I_F = 60^\circ$ for both plates and spheres, as one might expect from the $\tan(I_M) = f \tan(I_F)$ relationship.

A continuous acquisition experiment involving plates was also run up to 10 d of deposition in $\mu_0 H = 100\,\mu$T and $I_F = 60^\circ$. The acquisition curves for moment, inclination and thickness of depositing sediment are compared to the mean curves measured for spheres by Bilardello *et al.* (2013) under the same field conditions.

The data presented do not support depositional compaction as the sole cause for inclination shallowing in plates.

These preliminary results contradict the widespread belief that inclination shallowing is more prominent for platy particles (e.g. hematite) than it is for more spherical ones (magnetite). Results undoubtedly confirm the relevance of rolling of spherical particles to the inclination error. It is true that compared to magnetite-bearing rocks, larger amounts of inclination shallowing have typically been observed in hematite-bearing sediments, but the range of observed amounts of shallowing is also larger. These considerations raise the interesting question whether it is the environment of deposition, such as a current in a flood plain, or later compaction during dewatering, which cause the high variation of inclination shallowing in natural red beds.

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