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Role of spherical particles on magnetic field recording in sediments: Experimental and numerical results

Dario Bilardello [a,*], Josef Jezek [b], Stuart A. Gilder [a]

[a] Department of Earth and Environmental Sciences, LMU, Theresienstrasse 41, 80333 Munich, Germany

[b] Institute of Applied Mathematics and Information Technologies, Faculty of Science, Charles University in Prague, Albertov 6, 128 43 Praha 2, Czech Republic

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ABSTRACT

We report deposition experiments using spherical glass beads that possess remanent magnetizations stemming from iron impurities. 15 g of glass beads with a well-characterized size distribution were loaded in two different sets of tubes with diameters of 2.0 and 3.6 cm. Each tube contains identical column heights of de-ionized water, thereby allowing us to assess the effect of sediment concentration on the results (352 versus 90 kg/m^3 [g/l], respectively). The tubes were placed in magnetic fields of variable inclination and intensity in a temperature-controlled environment. The full vector magnetization and sediment accumulation rates were measured upon deposition times ranging from 10 min to 10 days. Experiments were run in triplicate to evaluate data reproducibility. Together with the lack of magnetic interaction and the absence of clumping, the experiments elucidate an end-member scenario of how sediments acquire remanent magnetizations in the absence of flocculation. Our results show that inclination shallowing, in the range of 7–20° for field inclinations of 30° and 60°, is indeed possible with solely spherical particles. More importantly, we observe a field dependence on the inclination error. Field dependence on the moment acquisition and inclination error both exhibit non-linearity, which may complicate interpretations of relative paleointensity data in paleomagnetic records. A newly developed numerical model, whereby particle collision during settling combined with both rolling and slipping (translation) on the substrate, is consistent with the experimental results.

1. Introduction

Acquisition of remanent magnetization in sediments, called a depositional remanent magnetization (DRM), is typically described by spherical magnetic particles falling through a stagnant water column (Rees, 1961; Collinson, 1965; King and Rees, 1966; Stacey, 1972; Tauxe and Kent, 1984; Shive, 1985; von Dobeneck, 1996; Katari et al., 2000). Viewed in this way, the particle is subject to balanced inertial, viscous and magnetic torques, and spherical magnetic particles attain perfect alignment with the ambient field within seconds (Nagata, 1961; Collinson, 1965). The situation is much more complicated in nature, where the sedimentation process spans a vast parameter space regarding particle size and shape distributions, viscosity, pH and Eh of the fluid, etc. (Verosub, 1977). Contact forces between particles and Brownian motion also play a role. Eventually the particles encounter the substrate, leading to mechanical interaction and possibly experiencing shear from bottom currents. Within the sediment column, bioturbation, dewatering, diagenesis and compaction can modify the magnetization, which is known as a post-depositional remanent magnetization (pDRM) (see Tarling and Turner, 1999 and references therein).

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 were parallel) (e.g., Barton et al., 1980; Tauxe and Kent, 1984). Several experiments demonstrate that the net effect of a depositional remanent magnetization is to shallow the remanent inclination in the rock (I_R) with respect to the applied field inclination (I_B) such that $\tan(I_R) = f \times \tan(I_B)$, where f is the flattening factor (King, 1955; Løvlie and Torsvik, 1984; Tauxe and Kent, 1984). Misalignment of declination is negligible. Two basic models are used to explain inclination shallowing. In that of King (1955), sediments are composed of spherical and platy particles: shallowing depends on the relative contribution of the latter. Griffiths et al. (1960) explained inclination shallowing by equal-sized spherical particles rolling into depressions between grains lying on the sedimentation plane. On the other hand, however, instances of natural sediments yielding inclinations compatible with those predicted from apparent polar wander paths and possessing the same inclinations as lava flows, which are mostly immune to inclination shallowing have also been reported (e.g., Opdyke, 1961).

* Corresponding author. Current address: Instituto de Geociências, University of São Paulo, Rua do Lago 562, 05508-080 São Paulo, Brazil.

E-mail address: dario.bilardello@gmail.com (D. Bilardello).

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Several experimental and theoretical studies on DRM acquisition have focused on particle aggregation (flocculation) during settling, which affects the magnetic intensity and inclination recorded by sediments based on the clay content, clay mineralogy and fluid conductivity (Ellwood, 1979; Shcherbakov and Shcherbakova, 1983; Lu et al., 1990; Deamer and Kodama, 1990; Sun and Kodama, 1992). For example, Sun and Kodama (1992) found that magnetic grains attach to clay minerals by either electrostatic or van der Waals forces. The magnetic grains become incorporated into the clay fabric of the sedimentary rock and rotate with the clay particles during post-depositional compaction (Arason and Levi, 1990; Katari and Bloxhamm, 2001). Van Vreumingen, 1993a,b) showed that flocculation varies as a function of salinity of the sediment suspension, and Tauxe et al. (2006) found a non-linear field dependence on remanence for certain floc sizes. Mitra and Tauxe (2009) explored remanence acquisition as a function of applied field and floc size distributions. Their work helped explain discrepancies in relative paleointensity and inclination data, highlighting the complex nature of DRM acquisition with respect to different sedimentary environments (variable salinity, mineralogy, organic matter content, etc. (see also Katari and Tauxe, 2000). Shcherbakov and Sycheva (2008, 2010) recognized that more than seven parameters are needed to describe the magnetization acquisition of sediments. This multi-parametric control on DRM hinders relative paleofield intensity estimates by redeposition methods since laboratory conditions do not reproduce the natural environment.

Other workers have addressed the question of lock-in depth of the magnetic signal in sediments (Kent, 1973; Tucker, 1980; Bleil and von Dobeneck, 1999; Roberts and Winklhofer, 2004). For example, Løvlie (1974, 1976) attributed the lag between changes in ambient field and lock-in of the magnetization to post-depositional alignment of the magnetic grains, with consolidation-rate significantly influencing a sediment's magnetic intensity. Irving and Major (1964) showed that sediments first deposited in a null field, and then subjected to an applied field, accurately recorded the field direction. While post-depositional effects seem to play a role in influencing the final orientation of the magnetic vector, other laboratory experiments and numerical models find a limited influence (Verosub et al., 1979; Shcherbakov and Shcherbakova, 1987; Katari et al., 2000).

Despite significant efforts to understand the genesis of a detrital remanent magnetization, complete knowledge of the underlying principles are still lacking. We thus initiated a series of experiments to focus on a particular aspect of the problem—namely the contribution of solely spherical grains in the absence of flocculation. Our experiments do not intend to simulate a natural detrital remanent magnetization acquisition, rather to unravel one specific factor that contributes to it. Hence, we carried out deposition experiments with synthetic spherical magnetic particles whose size distribution is well known. Numerical simulations are developed to explain the results. We are particularly interested whether spherical particles can produce inclination shallowing by rolling on the substrate when they settle. This necessitates a re-evaluation of the classical rolling spheres model of Griffiths et al. (1960). Our experimental results and numerical models contradict the idea of King (1955) that spherical particles accurately record the ambient field direction,

2. Materials and methods

2.1. Glass beads

Fig. 1a shows a scanning electron microscope image of the solid glass spheres (Potters Europe, spheriglass 5000) used in this study. The image attests that almost all the particles are spherical in shape. Laser particle analysis (Coulter) was used to measure the grain-size spectra of the beads (Fig. 1b). Five independent runs, made without using dispersing agents or ultrasound, are highly reproducible and reveal no evidence for clumping or clustering of the particles. Particle radii range between a fraction of a micrometer to 11.4 μm, showing a sharp peak for the smallest grain sizes, then decreases almost exponentially with increasing radii. Overall, 10% of the particles have radii <0.48 μm, 25% are <1 μm, 50% are <3 μm, 75% are <6.8 μm and 90% are <7.7 μm. Company specifications list a median radius of 1.7–3.5 μm, with 90% of the spheres having radii between 0.3 and 9.7 μm. We accepted the company's reported density of 2.5 g/cm^3 without independent verification.

Experiments on the beads indicate they contain impurities that carry a magnetic remanence. Hysteresis loops, backfield curves and magnetization versus temperature curves were measured with a Petersen Instruments, variable field translation balance (dwell field 30 mT, dwell time 1 s, ramp slope [heating and cooling] 40 °C/min). The magnetic moment upon heating undergoes a change in slope at 580 °C followed by a major drop around 770 °C, suggesting the presence of both magnetite and iron, respectively (Fig. 2a). Magnetic intensities during cooling lie systematically below those of heating, signifying a net loss of magnetic moment during heating. Repeat heating–cooling cycles in 100 °C intervals indicate that already below 400 °C the cooling curve is lower than the heating curve. Our interpretation is that the glass contains only pure Fe as a remanence carrier, but that Fe partly oxidizes into magnetite during heating. Acid rinsed, non-annealed glass beads were used in the experiments.

Fig. 2b shows a typical hysteresis loop of the material measured at room temperature. Hysteresis loops determined on four independent samples exhibit a high degree of reproducibility, with hysteresis parameters lying within the pseudo-single domain field on

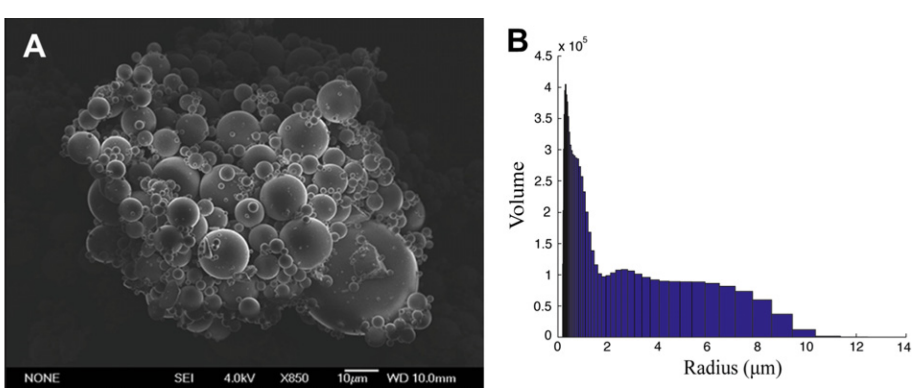

Fig. 1. (A) SEM image of the glass beads used in the deposition experiments highlighting the size distribution and the predominantly spherical shape of the particles. (B) Grain-size distribution of the particles measured with a laser counter (no de-flocculants or ultrasound used). The grain-size bins sum to ∼100%.