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New materials for analogue experiments: Preliminary tests of magnetorheological fluids

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ABSTRACT

New materials and related apparatuses are welcome to advance analogue modelling techniques. In this contribution, we report on a first attempt to use magnetorheological (MR) fluids as analogue materials for simulating the mechanical behavior of mobile décollement layers that change their mechanical properties during deformation. For this purpose, a specific sandbox was designed to include the possibility of quickly applying and removing a magnetic field below a MR fluid layer, in order to induce an instantaneous change from a frictional to a viscous behavior in the basal décollement material. The simulation of gravitational gliding and sediment progradation above a basal mobile shale layer provided results that compare well with analogue models produced with other experimental techniques, and with natural structures like those developed in the Niger delta region. This pilot study thus encourages further research for optimizing the applicability of MR fluids to the analogue simulation of geological processes.

1. Introduction

Analogue modelling includes well-established laboratory techniques providing support and inspiration to structural geology, tectonics and geodynamics interpretations (e.g., Bonini et al., 2012; Brun and Fort, 2011; Cadell, 1890; Corti, 2012; Dooley and Schreurs, 2012; Graveleau et al., 2012). Applicability of analogue models to nature requires appropriate scaling of material properties, stress fields, and kinematic pathways (Hubbert, 1937; Ramberg, 1981). Scaling is a function of both experimental technique and analogue materials. In normal gravity experiments simulating crustal deformations, loose sand and sand-silicone multilayers are by far the most used materials (Brun, 2002; Davis et al., 1984; Davy and Cobbold, 1988; Rosenau et al., 2009). Glass microspheres (Schellart, 2000), hollow aluminum microspheres (Rossi and Storti, 2003), and muscovite interlayers (McClay, 1990), are some of the solutions that have been used to vary the frictional properties of granular matter. Wet clay (Cooke and van der Elst, 2012; Withjack and William, 1986) and plaster (Fossen and Gabrielsen, 1996) have also been used as analogue materials, as well as rock slices (Chester et al., 1991). An alternative experimental technique developed to overcome possible scaling problems is centrifuge modelling, which is able to produce gravity fields up to hundreds g, thus allowing the use of cohesive materials like plasticine (Corti, 2004; Dixon and Summers, 1985; Ramberg, 1981).

A common feature of all techniques listed above is the intrinsic difficulty to vary the rheological properties of analogue materials during experimental runs. A possibility may be provided by thermomechanical modelling, where temperature is used to control the rheology of paraffin vax (Cobbold and Jackson, 1992; Grujic and Mancktelow, 1998). In this technique, however, a temperature gradient is used to impose the vertical variability of the rheological behavior of the analogue material and remains typically unchanged during model runs (Rossetti et al., 2000). A technical solution that allows the effective frictional properties of décollement materials to be varied during deformation involves the use of pressurized air injected at the bottom of experimental multilayers undergoing deformation (Cobbold et al., 2001; Mourgues et al., 2009).

In this work, we present the preliminary results of the attempt to use magnetorheological (MR) fluids as analogues of natural materials affected by significant rheological changes during deformation. MR fluids are suspensions of micron-sized magnetic particles in carrier oil, which can exhibit dramatic changes in its rheological properties after the application of a magnetic field (Fig. 1). They switch instantaneously from a fluid state (viscous regime) to a solid state (frictional regime) without changing chemical properties by a process that is reversible in the order of milliseconds (Rosenfeld et al., 2002). We explored the design of a basic experimental apparatus suitable to exploit the potential of using MR fluids for simulating mobile upper crustal rocks in analogue modelling experiments under natural gravity conditions. To ensure effective testing of the suitability of MR fluids as analogue materials in physical experiments, we replicated: a) gravitational gliding in a sloping sandpack, following

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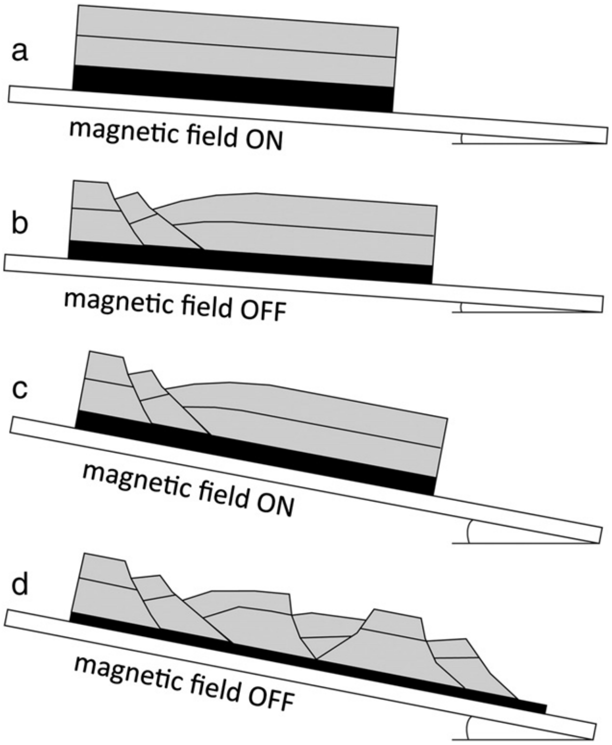

Fig. 1. Cartoon illustrating the effects of a magnetorheological fluid (black) at the base of a sand multilayer (gray), in the presence or absence of a magnetic field, respectively. a) The multilayer is gently inclined under a magnetic field: no deformation occurs. b) When the magnetic field is removed, the sand suddenly undergoes gravitational gliding. c) Remagnetization halts deformation also when the multilayer tilt is increased. d) Removal of the magnetic field causes instantaneous resuming of gravitational gliding.

the work of Mourgues and Cobbold (2003), who used pressurized air to produce a basal décollement layer; b) the experimental strategy in model 2 of Mourgues et al. (2009), who used a forelandward migrating area of pressurized air at the base of the sand multilayer to simulate the effects of delta progradation above shales, which is commonly assumed to behave as a viscoplastic Bingham material (e.g., Bingham, 1922; Ings and Beaumont, 2010) Comparison of experimental results obtained by the two different techniques is briefly discussed.

2. Materials and experimental apparatus

We tested the magnetorheological fluid Basonetic® 2040, produced by BASF Chemical Company, which contains 24% in volume of carbonyl iron powder as magnetizable material, and poly-α-olefin as base fluid. The density is 2.47 g/cm^3 at 25 °C, and the operating temperature range is from -40 °C to 120 °C, respectively. The producer provides details of the physical properties of this MR fluid and of its rheological behavior as a function of temperature and of the absence or presence of a magnetic field (BASF, 2010). The relations between shear stress and strain rate at room temperature and different intensities of the magnetic field are illustrated in Fig. 2, as well as the associated changes in viscosity. The graphs show that in the absence of a magnetic field, the strain rate increases non-linearly with the shear stress. This dependence decreases with increasing the magnetic field intensity and becomes almost negligible for values higher than 300 mT. Accordingly, for high values of the magnetic field the shear stress value is high and remains quasi-constant regardless of the applied shear strain.

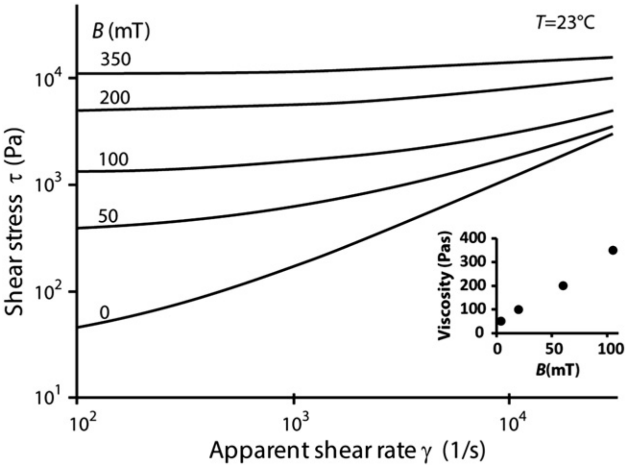

Fig. 2. Graph of the shear stress versus apparent shear rate for the MR fluid Basonetic® 2040 at different intensities of the magnetic field B (after BASF, 2010). The inset shows the computed viscosity of the MR Fluid for intensities of B ranging from 0 to 350 mT.

The experimental apparatus consists of a Plexiglas box with an array of removable magnets located below the rigid basal plate (Fig. 3a). When necessary, the mobile lateral walls can be connected to computer-controlled stepping motors to impose contractional, extensional, or transcurrent motions. Model surface topography evolution is recorded by a structured-light 3D scanner and by time-lapse photographing. The simplest experimental multilayer consists of a basal layer of MR fluid overlain by a multicolored sand pack (Fig. 3; Table 1).

3. Type 1 experiments: gravitational gliding

In this experimental program, the Plexiglas sandbox was located above an array of 18 removable magnetic stripes. A 3 mm-thick basal layer of MR fluid was deposited above the Plexiglas in the absence of the magnetic field. After magnetization, three 5-mm-thick pre-kinematic sand layers were sieved on top of the MR fluid. The sand was not in contact with the side walls to prevent lateral friction. The

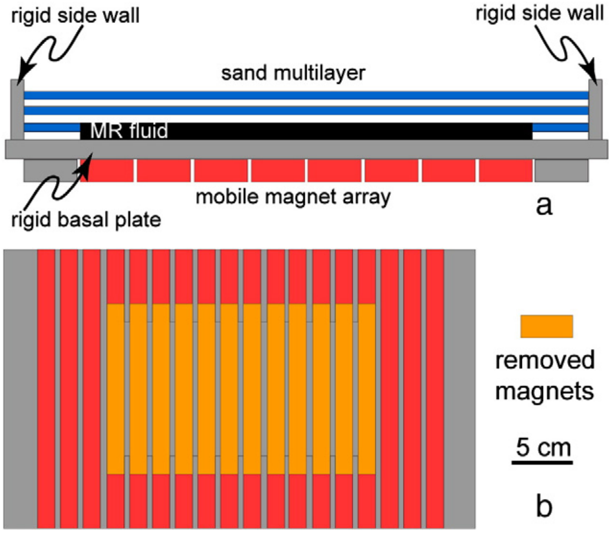

Fig. 3. a) Conceptual sketch of the experimental apparatus designed for the use of magnetorheological fluids. b) Map view of the basal magnetic array used in the Type 1 experiments, after construction of the experimental multilayer and before tilting the sandbox. The central area from which the magnets were removed is indicated in orange. See text for details.