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3-D Printing: A New Method to Investigate the Effect of Deformation on Remanent Magnetization

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1. Introduction

A fundamental assumption in paleomagnetism is that a sediment or rock retains the direction of the Earth's magnetic field over its geologic history. Sedimentary compaction or tectonic deformation can lead to the realignment of minerals, which could deflect the direction of the original natural remanent magnetization. Sedimentary compaction and tectonic deformation involve a number of geological processes, making it difficult to reproduce these processes on a laboratory scale. Redepositional experiments have been carried out to examine how remanent magnetization is affected by sedimentary compaction, but little experimental data is available for the deformation of rocks. Previous experiments have used deformation rigs to subject rocks to compactional or torsional deformation; however, the remanent magnetization of the rocks was often reset, due to strong magnetic fields associated with the rigs. 3-D printing opens new possibilities to create analogue rocks that can be subjected to deformation. In a proof-of-concept study, we have examined two designs to explore the applicability of the March model for simple compaction.

2. Experimental Method

Two approaches were taken to produce analogue rocks with a 3-D printer. In the first case 23.5 mm cubes with different pore geometries were printed using non-magnetic filament with an Object Connex3 printer (Fig. 1). The samples were then submerged in a ferrofluid and left to dry. An anhysteretic remanent magnetization (ARM) was imparted along the axis of compression in a 50 µT DC field superimposed on a 100 mT alternating field and measured using a 2G cryogenic magnetometer. Low-field anisotropy of magnetic susceptibility (AMS) was measured on an Agico MFK1-FA susceptibility bridge initially and after the last stage of compression. A sample holder was constructed to allow incremental, uniaxial compaction of the sample (Fig. 1), whereby the magnetization was measured after each step.

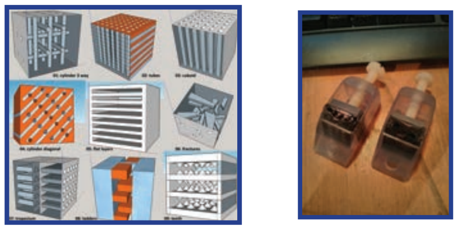

Fig. 1. Cube design for Case 1. Left: cube designs produced with the SketchUp CAD program. Cubes 02, 04,08 and 09 were printed with two materials of differing rheology. Right: Holder used to compress cubes while mounted on sample track of the magnetometer. Compression was vertical with respect to figure on the left in all samples except 8, where it was horizontal.

In a second set of experiments, cubes with 1 cm edge were printed with filament prepared with either 0.5 or 1 weight-% concentration (wt %) of 32 nm particles of magnetite/maghemite (Alfa Aesar NanoArc) mixed with PLA and extruded into the print filament. AMS and NRM were measured in the initial state and after the cubes were subjected to incremental compaction (Fig. 2).

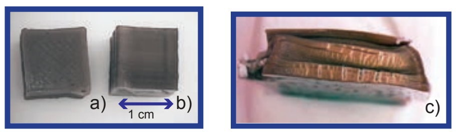

Fig. 2. Cube design for Case 2. Left: undeformed cubes showing a) print layers and b) top. c) Example of a cube that has undergone compressional compaction.

3. Case 1

The low-field AMS of the samples before the application of ferrofluid showed negligible anisotropy. After application of the ferrofluid a significant AMS was determined in every sample. k_{min} was initially approximately normal to the print plane in all samples, except for sample 9 (teeth) (Fig. 3). Samples were subsequently incrementally compressed, and the AMS was remeasured after the last compression step. The degree of foliation increased or remained approximately the same in most samples; it decreased, however, in samples 3 (cuboid) and 9 (teeth).

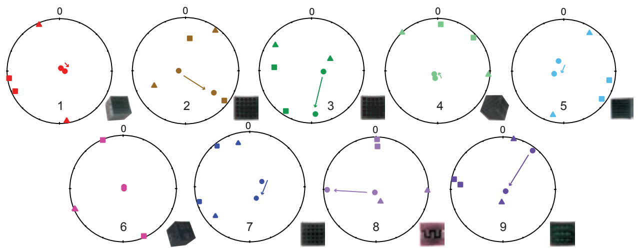

Fig. 3. Low-field AMS of cubes before and after deformation.

The initial direction of the ARM was vertical, i.e., in the direction of compression, for all samples. Samples were subjected to incremental shortening, and the magnetization was remeasured after each step. The maximum amount of compression was dependent on the sample material and geometry, and was between 25% to 60%. Although all samples show a decrease in inclination, the maximum deflection is generally less than 5° except for samples 3 and 9, where it reaches 7° to 10° (Fig. 4).

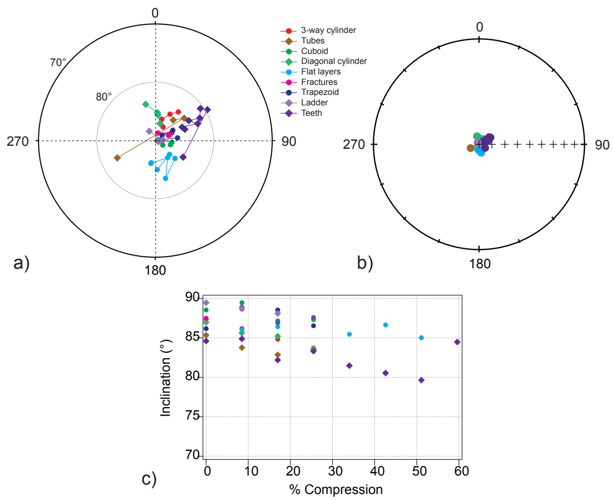

Fig. 4. Change in inclination with progressive compression. a) Lower hemisphere, equal-area net for inclinations above 70°, showing the change in direction during incremental compaction; b) full inclination range; c) inclination as a function of degree of compression.

4. Case 2

A better analogy for natural rocks is to have the magnetic particles embedded in the print material, because the particles can then act as rigid particles within the deforming matrix. In our first preliminary results, we have printed a series of cubes to test the homogeneity of the starting product. The print medium itself is diamagnetic, but with the addition of 1% ferromagnetic material, susceptibility is between 1.24 - 1.55 x 10^{-2} for samples with 1 wt% magnetite/maghemite and 7.28 to 10.1 x 10^{-2} for samples with 0.5 wt % samples. The AMS is near-perfectly oblate with k_{min} normal to the print plane (Fig. 5a). One sample with 1 wt % was subjected to three increments of compaction. The principal axes of the AMS ellipsoid do not change and the shape remains near-perfectly oblate. Only the degree of foliation increases with increasing compaction.

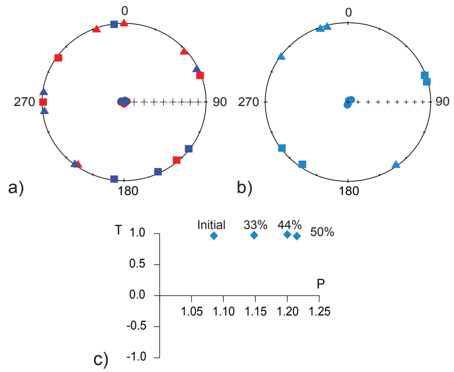

Fig. 5. a) Initial low-field AMS of the printed cubes with 1 wt % magnetite/maghemite (red) and 0.5 wt % (blue). b) Example of change in AMS during progressive compaction. c) Jelinek plot showing the change in the degree of anisotropy (P) with % compaction.

The NRM has similar direction in all samples for a print series. In the case of the 1 wt % samples, inclination is between 50° to 60°. In the first compaction test, the remanent magnetization shows an initial steepening of inclination after the first stage of compaction, and a further increase with the final compaction step. This unexpected results may be due to buckling of the layers during compaction (Fig. 2c), or to a magnetization induced by the steel vise used for compaction. Further tests are necessary to better understand the change in remanence.

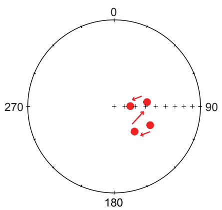

Fig. 6. Example showing the change in NRM direction with the incremental compaction.

Conclusions: This preliminary study illustrates how using 3-D printed materials can be used to examine how magnetic particles realign in a deformed material. Samples in Case 1 demonstrate that simple compaction does not lead to a large change in inclination in samples that are the more realistic rock analogs. Future experiments will further explore compaction, i.e. pure strain, but also simple shear, and its effect on both the AMS and remanent magnetization. Furthermore, advances in print technology will allow for more realistic analogs for natural rocks, by using materials with multiple rheologies.