Quantifying how earthquakes and impacts are magnetically recorded by rocks and meteorites

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The magnetic field recorded by rocks and meteorites is central to understanding many key events in the history and evolution of the Earth and Solar System, e.g., Tarduno *et al.* (2015) obtained the first ancient field intensity estimates from the Hadean (~4.2 Ga), which pushes back by nearly 1 Gyrs the age the Earth is argued to be habitable. Notwithstanding the many great successes of palaeomagnetic methods in the Earth Sciences and beyond, **magnetic studies have largely avoided problems which involve 'low' levels of stress (<1 GPa)**, even though there are many examples, where stressed rocks have associated magnetic anomalies, for example, near seismically active faults (Elhanati *et al.*, 2020).

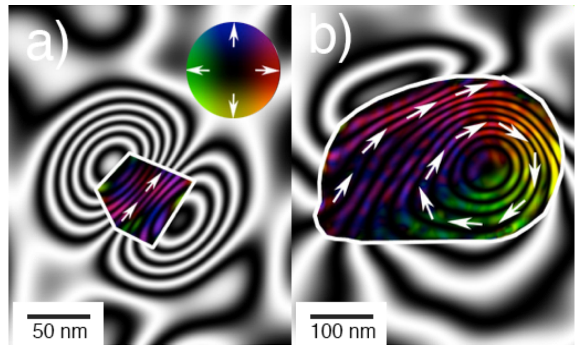

Figure 1. Nanometric magnetic images for magnetite particles at 300 K and 0 MPa: a) magnetic phase map for a uniform (single domain, SD) magnetisation, and b) a magnetic phase map for a slightly larger particle showing a non-uniform (single vortex, SV) structure. The colour wheel shows the magnetic direction. Unpublished from Muxworthy's group.

Why have low stresses been ignored? Since the work of Nobel-prizing winning Néel (1949), it has been assumed that on geological timescales the grains carrying the magnetic remanence are magnetically uniform, so-called single domain (SD, i.e., < ~80 nm for magnetite, Fig. 2a).) SD particles were thought to be the main carriers of "stable" magnetic remanence in rocks and meteorites; larger particles (80–10,000 nm) with vortex structures (single vortex (SV), Fig. 2b), although ubiquitous, were thought to be "unstable" on geological timescales and thus palaeomagnetically unimportant. However, the behaviour of these SV particles had been hard to quantify until recently due to their highly non-linear behaviour and small size. We now know that SV particles' magnetic remanences are very stable, even more stable than SD remanences and contribute significantly to the palaeomagnetic signal (Nagy *et al.,* 2022). Even larger particles (>10 µm), known as multidomain (MD), whose size makes them easier to directly observe, have been demonstrated as palaeomagnetically unreliable.

However, our understanding on the effect of stress on rocks is still based on SD theory. Theoretical calculations for SD particles, indicate that pressures > 1 GPa are needed to reset stable SD remanences; however, these calculations are not entirely supported by experimental work: Nagata's classic 1960s experiments – succinctly summarised in Nagata (1971) – demonstrated that magnetic remanences of rocks could be irreversibly altered by pressures of just tens of MPa, that is, **current SD theory does not explain experimental results.** To better understand this, we have recently conducted the first numerical micromagnetic model for the effect of stress on palaeomagnetic recorders (North *et al.*, 2024), and have shown that vortex structures can be remagnetized by compressional pressures as low at ~10 MPa. Such pressures are very common in nature, and rocks often experience such pressures during mountain building and/or burial. Although a ground-breaking study, this paper of North *et al.* (2023) has only scratched the surface on the effect of stress on non-uniform structures; for example, the largest grains considered were only 200 nm.

PhD Project: The aim of student project is to test and verify these numerical predictions experimentally. In particular, the student will experimentally explore the effects of strain-rate (think earthquakes) and temperature on the magnetic response to stress, using both the palaeomagnetic laboratory at Imperial and the rock deformation laboratory at UCL. It is also hoped to field test these experimental findings at well constrained faults, e.g., San Andreas fault. Candidates should have a degree in Earth Science, Material Science or Physics and a good background in laboratory-skills.

References

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