THE HETEROGENEOUS RESPONSE OF MARTIAN METEORITE ALLAN HILLS 84001 TO PLANAR SHOCK T. L. North[1*], G. S. Collins[1], A. R. Muxworthy[1], T. M. Davison[1], S. C. Steele[2], R. R. Fu[2], [1]Department of Earth Science and Engineering, Imperial College London, London, SW7 2AZ, UK, [2]Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, USA (*t.north18@imperial.ac.uk)

Introduction: Martian meteorite Allan Hills 84001 (ALH 84001) was ejected from the surface of Mars around 14 million years ago (Ma) [1]. Predominantly orthopyroxenite, the meteorite contains coarse-grained inclusions of chromites, carbonates and plagioclase feldspar in addition to fine-grained iron oxides and sulfides that host a heterogeneously oriented natural remanent magnetization (NRM) [2]–[5]. The meteorite contains several shock-induced textures and mineral thermometers indicative of one or more impact events.

Petrologic and paleomagnetic studies have shown shock metamorphism to be fundamental to the mineralogical development of ALH 84001 [6]. However, the strength of these impacts is poorly understood as there are contradictory interpretations of evidence for temperature excursions within the meteorite [6]–[9]. The NRM hosted in the iron oxides and sulfides embedded within chromites is understood to be a thermoremanent magnetization (TRM) and has two strongly magnetized components that do not share common alignment, in addition to several incoherent, weakly magnetized grains, indicative of an underlying mechanism capable of localized (~200 nm) heating [5].

To place new constraints on the shock pressures associated with multiple impacts suffered by the meteorite up to and including its ejection from Mars and attempt to reconcile independently reported thermal histories of the meteorite, we have simulated planar shock wave propagation through computational analogs of two samples of ALH 84001.

Modeling: Using the iSALE-2D shock physics code [10]–[12], we have performed a suite of ‘mesoscale’ simulations to quantify the effects of impact-induced shockwaves likely to have been experienced by the meteorite.

The initial simulation geometry is a ‘sandwich’ design whereby a 2D planar impactor with a given velocity collides with an initially stationary cover plate. A shock front is generated in the cover plate and travels into the sample, while a release wave forms at the rear of the impactor. After the shock front travels through the sample, it dissipates through a buffer plate at the bottom of the computational mesh. The simulation was run until the release wave had passed through the sample and the thermodynamic response of different components within the meteorite is recorded by Lagrangian tracers placed throughout the Eulerian mesh.

Material Models: The constituent materials that make up the meteorite are each described by an equation of state (EOS) and strength model. As the availability of accurate equations of state for meteoritic materials is limited, we used the closest analog materials possible. A main criterion when representing the meteorite was to maintain the natural heterogeneity of the system while eliminating the smallest inclusions (<<10 µm). Therefore, we divided ALH 84001 into four constituent parts: chromites, carbonates, plagioclase and orthopyroxene, which are described by material models for chromite (developed for this study), calcite [13], gabbroic anorthosite (gabbro) [14] and dunite [15, 16], respectively. The chromite and gabbro are described using a Tillotson EOS [17], while the calcite and dunite are represented with an ANEOS-derived tabular EOS. A pressure-, temperature- and strain-dependent strength model was used to describe the resistance of the geologic materials to shear deformation, while a pressure-independent ductile strength model was used to describe the shear strength of chromite [10].

Paleomagnetic studies have placed constraints on the thermal history of ALH 84001 based on measurements of iron sulfides and oxides present within the meteorite. We represented all these iron compounds using our material model for chromite. The Tillotson parameters (a, b, α, β, B) were fitted to shock data for magnetite, while other material constants were chosen to be appropriate for chromite.

Results: Following the passage of the shock wave, we find strong and complex material shear that causes intense and well-defined thermal gradients across the

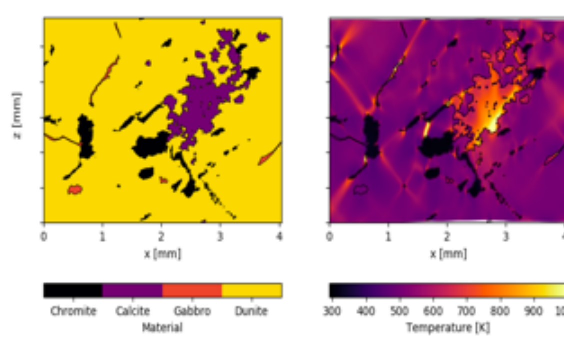

Figure 1: Temperature map of one of the cross-sections we examined of ALH 84001 immediately after the release wave has passed through the sample. The chromite remains cold immediately following an impact while reverberations between the calcite-dunite boundary heat the calcite. There is intense shear in the dunite as seen by the narrow high-temperature bands.

sample. The shear occurs predominantly in the dunite (orthopyroxene), with the inclusions of other (weaker) materials acting as nucleation points (Fig. 1). We see both intra- and inter-material variations in temperature on length scales of tens of microns.

Subsequent modeling of post-impact thermal equilibration reveals that the constituent materials reach equilibrium around ~3 seconds after the release wave has passed through the meteorite (Fig. 2). This has implications for paleomagnetism. Previous paleomagnetic studies have found evidence of remagnetization in the meteorite on the sub-millimeter scale, but the mechanism for such heterogeneous heating is unclear. We observe that portions of chromite grains close to shear zones will experience temperatures significantly higher than those elsewhere in the meteorite which only warm up to the equilibrium temperature (Fig. 2). This means that small fractions of the meteorite may be remagnetized in low-pressure impacts.

Constraints from Paleomagnetism: Paleomagnetic measurements have found a long-lived (~4 Ga) primary magnetization hosted in the iron oxides and sulfides, indicative of an event where most, or all, of the magnetic carriers in the meteorite were magnetized. This would require the thermal equilibrium temperature of the meteorite to exceed 320°C. There is also a younger (~3.9 Ga) TRM that is hosted in some magnetic grains. This suggests a second strong impact that heated some, but not all, of the carriers above ~320°C. Our simulations show that a bulk thermal equilibrium temperature of 320°C requires a bulk shock pressure of at least 45-50 GPa. Moreover, we find peak temperatures in some chromite grains exceed 320°C in all simulations with a bulk shock pressure ≥25 GPa. This implies that to achieve only partial remagnetization, the second impact likely involved a bulk shock pressure between 25-45 GPa.

Finally, to preserve "cold" paleomagnetic evidence [3], our modeling indicates that the meteorite cannot

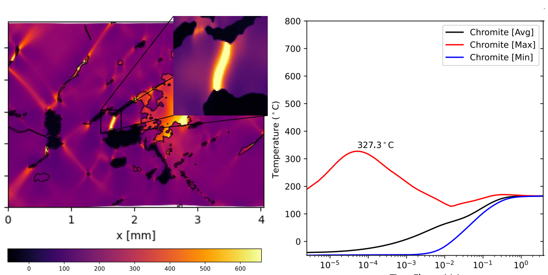

Figure 2: Thermal history of a subsection (highlighted in pop out) of the cross-section close to a shear zone in a 33 GPa impact. Time zero is immediately after the release wave passes through the sample. We see that some tracers in the chromite experience new maxima as the meteorite approaches thermal equilibrium.

have experienced a shock pressure greater than 16 GPa when ejected from Mars, as the whole meteorite would have been heated to a bulk temperature greater than 40°C. A 16 GPa impact is also consistent with a short-lived local peak temperatures of ~400°C [7].

Revised Shock History: The results from this study emphasize the utility of mesoscale modeling when investigating meteoritic samples; we have identified strong thermal gradients where peak temperatures can vary by two orders of magnitude on a length scale less than 100 µm. Our results are consistent with a strong shock (45-50 GPa) around 4 Ga where the entire meteorite would have been heated above 320°C, followed by a weaker shock (25-45 GPa) around 3.9 Ga, where some fraction of the magnetic carriers present in the meteorite were heated above 320°C. An important mechanism responsible for the heterogeneous response is intense material shear that occurs even at low pressures (<5 GPa). To preserve "cold" paleomagnetic evidence would require an average shock pressure upon ejection from Mars below 16 GPa.

Our results are inconsistent with any long-lived, high-temperature impact event since 3.9 Ga. Furthermore, we do not find evidence of an impact-induced scenario where peak temperatures in any of the constituent materials could be in excess of 1400°C [9] in an impact below 50-55 GPa.

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