USING NUMERICAL MODELLING TO ASSESS BIOMARKER SURVIVAL IN TERRESTRIAL MATERIAL IMPACTING THE LUNAR SURFACE. S. H. Halim[1], I. A. Crawford[1], G. S. Collins[2], K. H. Joy[3]. [1]Birkbeck, University of London, UK (shalim03@mail.bbk.ac.uk). [2]Imperial College London, UK. [3]University of Manchester, UK.

Introduction: The Moon's rich impact history is exemplified by an epoch circa 3.9 Gyr ago when the terrestrial planets are thought to have experienced frequent, large-scale impact bombardment [1-4]. During this time, Earth would have experienced numerous giant, hypervelocity impacts [5], potentially ejecting terrestrial material into Moon-crossing orbits [6]. This has led to the proposal that such ejecta could be preserved on the lunar surface as terrestrial meteorites [7-10]. These could provide a geological record of terrestrial biomarkers predating the period for which the earliest evidence of life exists on Earth. Here, we have used the iSALE-2D shock-physics code [11-13] to determine the pressure and temperature regimes of simulated terrestrial meteorites impacting the lunar surface, in order to gauge the survivability of biomarkers in the projectiles. Previous impact modelling has used specific peak pressure thresholds as a proxy for survivability, with peak temperature from shock heating assumed to correlate with peak pressure. Here, we assess the additional influence of shear heating, which has been shown to be important, or even dominant, in raising temperatures within the projectile at lower impact velocities [14]. If this were the case, survivability of projectiles and their organic or hydrated mineral constituents would be less favourable than previously thought.

Methods: We simulated non-porous and porous sandstone and limestone projectiles (dia. = 0.5 m), vertically impacting a basalt target at 2.5 and 5 km/s, the most likely and upper limit of the vertical velocity component found via analytical methods by [7,8] for terrestrial meteorites impacting the Moon, respectively. Oblate and prolate projectiles were also investigated but without porosity. Initial porosity [13] of the target basalt layer was varied between 0-70%, based on various locations across the lunar surface [15,16] and the porosity of the impactor was varied between 0-40%, to investigate a variety of sedimentary materials. The strength of the materials was modelled using the method described in [12], important for resolving both shock and shear heating. Simulations used lunar gravity (1.62 m/s^2) and a surface temperature of 273 K. Each model used 100 cells per projectile radius (cppr), improving resolution on [10]. Tracer particles recorded pressure and temperature in the projectile material during the simulation. Pressure and temperature regimes were then compared to known thermal degradation parameters for some example biomarkers (arginine, valine, glutamine, tryptophan [17], and lignin [18]), using a modified version of the Arrhenius equation and the method described by [19]. Pressures and temperatures for which lycophyte megaspore microfossils have survived in metamorphosed rocks were also used for comparison [20]. To investigate the influence of shear heating, we compared simulations of a solid sandstone projectile impacting a solid basalt target at 2.5 and 5 km/s, both with a strength model and without (hydrodynamic).

Results: In each simulation, pressure and temperature regimes were taken from tracers in the materials to create survival contour maps for each projectile in the figures going forward.

The influence of material strength: Projectiles displayed very similar peak pressure contours across the projectile for simulations with and without strength at both impact velocities. The top of Fig. 1 shows this for the 2.5 km/s velocity projectile. However, there is a marked increase in the peak temperatures experienced (bottom, Fig. 1) when a strength model is included. This highlights the importance of a strength model that can resolve shear heating, which provides additional heating to the projectile material at these velocities.

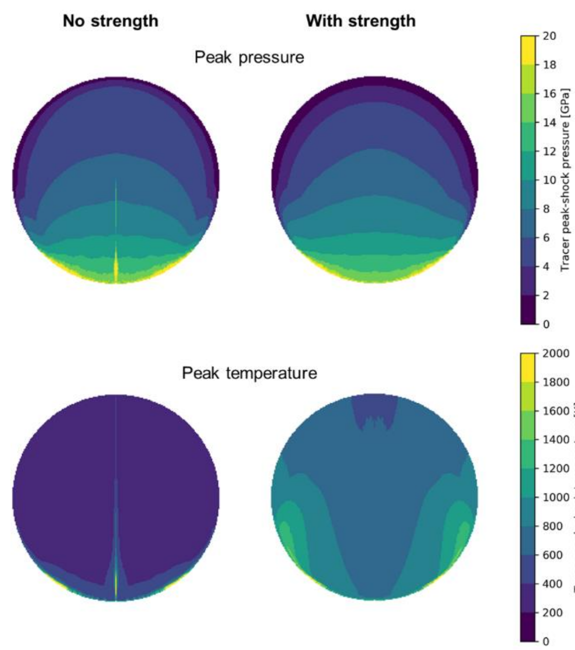

Fig. 1: *Contour maps of peak pressure (top) and temperature (bottom) for solid projectiles impacting a solid target at 2.5 km/s. Left projectile maps used no strength model (hydrodynamic), right projectile maps used a Collins strength model [12].*

Sandstone projectiles: Fig. 2 shows the most favourable conditions for survival of biomarkers, in the simulations we modelled. Maximum temperatures in

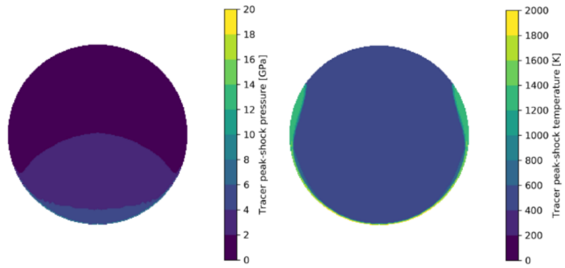

Fig. 2: *Contour maps of peak pressure (left) and temperature (right) for a solid (0% porosity) sandstone projectile impacting a 70% porous target at 2.5 km/s.*

most of the projectile reach only 600 K. In terms of thermal degradation of biomarkers, there is essentially no degradation on the timescale of shock and shear heating. Therefore, the severity of thermal degradation will depend on the post-shock temperature and cooling rates of projectile fragments. For plausible post-impact cooling rates of surviving projectile fragments, only minor thermal degradation is expected. This bodes well for biomarker survival, especially towards the rear of the projectile, where lycophyte megaspores would survive with little alteration, according to the survival pressures/temperatures (<1 GPa/630 K) of metamorphosed examples [20]. Fig. 3 shows the least favourable conditions for biomarker survival. In this case, temperatures are too high (>2000 K) for any substantial proportion of amino acids to survive for a significant period of time and pressures are too great for lycophytes to survive. Results for spherical projectiles between these extremes show a range of biomarker survival.

Limestone projectile comparison: Limestone projectiles showed comparable results for their sandstone counterparts. Peak-shock pressures in the limestone projectiles were almost identical to those in the sandstone projectiles, but peak-shock temperatures were reduced in the limestone projectiles relative to the sandstone projectiles, with the most noticeable difference in solid projectiles impacting solid targets at 2.5 km/s (Fig. 4).

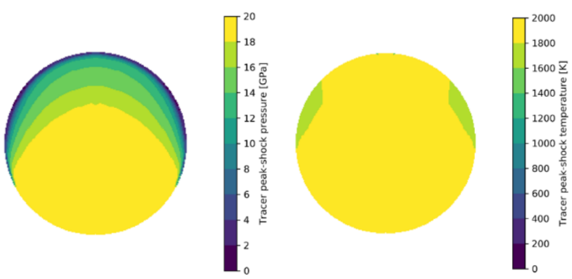

Fig. 3: *Contour maps of peak pressure (left) and temperature (right) for a 40% porous sandstone projectile impacting a solid (0% porosity) target at 5 km/s.*

Conclusions: With the aid of numerical modelling, we show that including strength in the simulation materials is important for accurately assessing the temperature in a projectile impacting at velocities expected for terrestrial meteorites. Nevertheless, in spite of the higher temperatures that result, we have shown that biomarkers within terrestrial meteorites can probably survive after impact with the Moon, especially at the lower end of the range of impact velocities. Increasing projectile porosity is detrimental to the survival of biomarkers, whereas increasing porosity in the target increases the chances of surviving projectile material. Comparing sandstone and limestone projectiles shows similar temperature and pressure profiles for the same simulation, with limestone providing slightly more favourable conditions for biomarker survival.

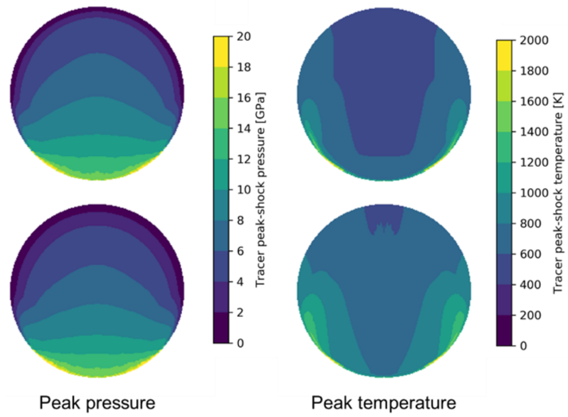

Fig. 4: *Contour plots comparing pressure and temperature regimes in limestone (top) and sandstone (bottom) projectiles. Both sets of plots are the result of a solid projectile impacting a solid target at 2.5 km/s.*

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References: [1] Turner G. (1973) *4th Lunar Sci. Con.* 1889–1914. [2] Hartmann W. (1975) *Icarus*, 24, 181-187. [3] Stöffler D. et al. (2006) *Rev. Min. Geochem.*, 60, 519-596. [4] Marchi S. et al. (2012) *EPSL*, 325-326, 27-38. [5] Marchi S. et al. (2014) *Nature*, 511, 578-582. [6] Beech M. et al. (2019) *American Journal of Astronomy & Astrophysics*, 7, 1-9. [7] Armstrong et al. (2002) *Icarus*, 160, 183-196. [8] Armstrong J. (2010) *Earth, Moon, & Planets*, 107, 43-54. [9] Gutiérrez J. L. (2002) *ESA SP-518*, 187-191. [10] Crawford I. A. (2008) *Astrobiology*, 8, 242-252. [11] Amsden A. et al. (1980) *LANL Report*, LA-8095. [12] Collins G. S. et al. (2004) *MAPS*, 38, 217-231. [13] Wünnemann K. et al. (2006) *Icarus*, 180, 514-527. [14] Kurosawa K. & Genda H. (2018) *GRL*, 45, 668-679. [15] Heiken G. H. et al. (1991) *Cambridge University Press*, ISBN 0-521-33444-6. [16] Schultz P. H. et al. (2010) *Science*, 330, 468-472. [17] Rodante F. (1992) *Thermochimica Acta*, 200, 47-61. [18] Brebu, M. & Vasile C. (2010) *Cellulose Chemistry and Technology*. 44. 353-363. [19] Pierazzo E. & Chyba C. (1999) *MAPS*, 34, 909-918. [20] Bernard S. et al. (2007) *EPSL*, 262, 257-272.