EARLY FRACTURING AND IMPACT RESIDUE EMPLACEMENT: CAN MODELING HELP TO PREDICT THEIR LOCATION IN MAJOR CRATERS? A. T. Kearsley[1], G. A. Graham[2], J. A. M. McDonnell[3], P. A. Bland[4], R. M. Hough[5] and P. A. Helps[6]. [1] Space Science Research, BMS, Oxford Brookes University, Oxford, OX3 0BP, UK, ***atkearsley@brookes.ac.uk***; [2] IGPP, LLNL, Livermore, California, USA; [3] Planetary and Space Sciences Research Institute, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK; [4] Department of Earth Science and Engineering, Exhibition Road, Imperial College of London, South Kensington Campus, London SW7 2AZ, UK; [5] Museum of Western Australia, Francis St, Perth, WA 6000, Australia; [6] School of Earth Sciences and Geography,Kingston University, Kingston-upon-Thames, Surrey, KT1 2EE, UK.

Introduction: In a field investigation of a crater, where are the most effective places to look for material that could reveal the nature of object responsible for the impact? Can numerical modeling of impact processes help to predict locations in which recognisable residue of the bolide could be found?

Locations of Residue Preservation: The nature of an extraterrestrial body whose hypervelocity impact has created a terrestrial impact crater can sometimes be determined by collection of disrupted and shocked impactor fragments as loose fragments or within small bodies of impact melt from the ground surface in and around the crater: e.g. iron meteorites from the vicinity of Barringer Crater, (USA); Henbury (Australia); Sikhote Alin (Siberia), meteoritic debris and impact glasses from Lonar (India), Wabar (Saudi Arabia) and Monturaqui (Chile); and even meteoritic debris from the Eltanin impact (SE Pacific), sampled from the deep sea [1]. If a major melt component is still preserved at the crater e.g. glass bombs within the suevites at Ries (Germany) or as a substantial discrete melt body as at Popigai (Siberia), materials suitable for bulk trace-element or isotopic analysis may also be relatively easy to collect. When an impact feature has been substantially modified by subsequent erosion (e.g. Sierra Madera, Texas), it may prove more difficult, or impossible, to find chemical residue from the bolide for analysis. Characteristic large-scale impact-related structures, (e.g. central uplifts and ring-synclinoria) may remain, with diagnostic shock indicators (e.g. shatter cones, planar deformation features and high pressure mineral polymorphs), yet the ejecta-blanket and any impact melt body are lost.

Residues and Fractures: Some eroded structures do retain extraterrestrial residues and debris derived from higher structural levels, emplaced within fractures, e.g. 'Granophyre Dykes' into granulite facies basement at Vredefort (R. of South Africa) [2], and breccias in rim rocks at Roter Kamm (Namibia) [3]. For residue to penetrate along these fissures, is it not likely that fracturing must occur very early in the crater-forming process? In some craters there is also substantial outward motion of target debris along major radial fractures, such as the 'Offset Dykes' at Sudbury [4]. Outward compressive motion has been seen in the reverse faults of the Chicxulub [5] and Silverpit [6] craters, also implying an early origin for these planes of movement. How often are major fractures created during early phases of crater growth? How widespread is residue emplacement into fractures?

Metallic residues, in melts and fractures: Distinctive, fine-scale siderophile segregations occur at a number of smaller (km scale) craters. At Lonar, Wabar, Monturaqui and Barringer, metallic residue is intimately associated with impact products, within silicate glass, vesicles, and brecciated rock fragments, or as thin coatings on target rock clasts. Residual metal may have a typical meteoritic Fe:Ni ratio, but often shows substantial modification of composition during and after impact. In a single small impactite specimen there may be metallic grains of widely differing texture and composition, with local enrichment of nickel and cobalt, and loss of iron to silicate-rich melt (Figure 1).

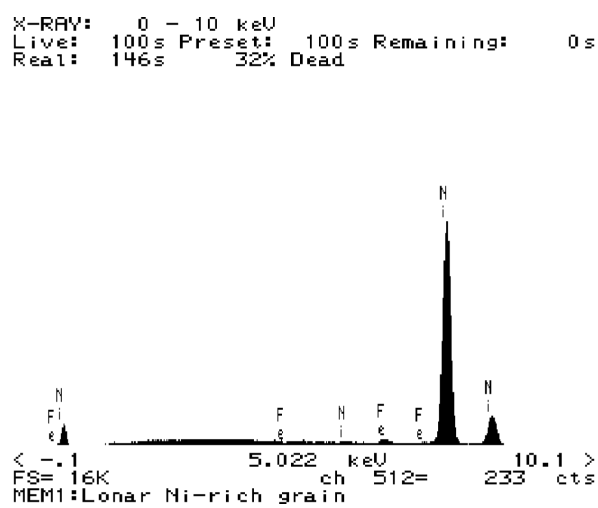

Fig. 1. Energy dispersive X-ray spectrum of Nickel grain from Lonar impactite.

Where iron-bearing oxides, such as ilmenite, occur in the target rocks, as in the basalts of the Lonar crater, metal may also be generated by mineral dissociation. The characteristic titanium content and the close proximity of melt droplets to remnant titanium oxides distinguish this metal from true impactor residue.

At the Ries crater, brecciated and foliated granitic igneous basement rocks, cored in the Nördlingen 1973 borehole, contain dispersed tiny nickel grains, perhaps similar to [7], and whose abundance can reach levels equivalent to 660 ppm in the whole rock. Occurrence of these distinctive grains implies that modified impactor components were emplaced into deep target rock, subsequently uplifted during crater modification.

Evidence from small impact craters: As part of a separate study [8], we have made an extensive survey of millimeter-scale impact craters on brittle, laminated glass solar cells exposed to hypervelocity collision (typical velocity 25 km s^{-1}) during exposure in low Earth orbit on the Hubble Space Telescope. Craters may contain particulate impactor residue in fractures, as well as in a thin melt sheet. The fractures have previously been considered late-stage features, and due to extensional failure (spallation) close to the glass surface, following passage of a shock wave through the laminate structure. However, the presence of included micrometeoroid fragments suggests that the fractures must be formed early. Our laboratory experiments, utilising a range of mineral and metal grain projectiles accelerated to c. 5 km s^{-1} in a light gas gun (LGG), have revealed that delicate, volatile-rich residues can be emplaced into fractures around small craters on a variety of brittle substrates such as glasses and rocks.

Numerical modeling of crater formation: Modeling of small impacts [9], using AUTODYN 2D, has revealed that fractures can be generated at a surprisingly early stage in the impact process, prior to rebound of the crater floor and ejection of the bulk of remnants of the impacting body (Figure 2).

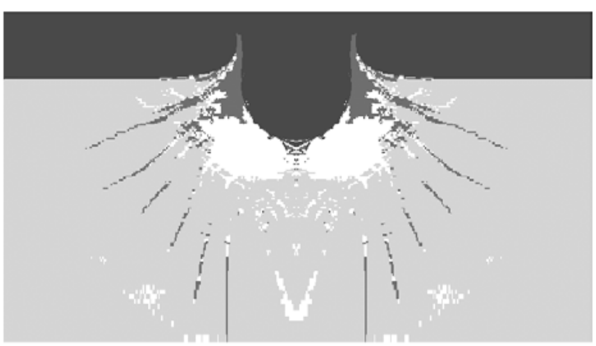

Fig. 2. AUTODYN 2D simulation of hypervelocity impact of a small metal sphere onto a glass target. Dark grey areas indicate failure, including fractures.

The model fractures correspond in position and orientation to locations in which we have observed residue in both space-exposed craters and laboratory light gas gun impacts. Numerous authors have shown that numerical modeling can be remarkably successful in simulation of larger features of crater development, and can account for many structures recognized during field examination of larger terrestrial craters. The significance of small (metre-scale) brittle structures in and around terrestrial impact craters is also becoming apparent from both modeling and field studies [10]. Important questions that have not yet been fully addressed include the timing and location of major fracture development in relation to the availability and possible pathways of bolide residue material. Tracing 'tagged' projectile material throughout the duration of the modeling process might prove rewarding. The potential role of early-formed fractures in outward transport, thickening of the pre-impact stratigraphic sequence, and localisation of structural weaknesses that permit subsequent inward crater collapse may also prove worthy of further investigation.

Conclusions: We believe that distinctive nickel-enriched residues can be used to track the presence of processed meteoritic metal. Small grains and melt droplets can be emplaced within silicate impact melts, within vesicles and within fractures in both impact clasts and deeper into basement. These observations imply that the fractures must have been present at a stage when bolide remnants were still abundant. Evidence from both space-exposed and laboratory-simulated hypervelocity impacts of small projectiles suggests that small craters can develop extensive fracturing at an early stage, when impactor residue is still available to be emplaced. Although we do not suggest that the results of simulation from a mm-size should be scaled to km-size craters, our intriguing results suggest that modeling the early brittle responses of geological materials in larger, lithified, stratified target sequences may help to explain the distribution of fracturing and residue emplacement in and around major craters. Such models may help to constrain the optimum sites for sampling around eroded craters.

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