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INTERPLANETARY METEOROID DEBRIS IN LDEF METAL CRATERS

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SUMMARY

We have examined craters in Al and Au LDEF surfaces to determine the nature of meteoroid residue in the rare cases where projectile material is abundantly preserved in the crater floor. Typical craters contain only small amounts of residue and we find that less than 10% of the craters in Al have retained abundant residue consistent with survival of a significant fraction (>20%) of the projectile mass. The residue-rich craters can usually be distinguished optically because their interiors are darker than ones with little or no apparent projectile debris. The character of the meteoroid debris in these craters ranges from thin glass liners, to thick vesicular glass containing unmelted mineral fragments, to debris dominated by unmelted mineral fragments. In the best cases of meteoroid survival, unmelted mineral fragments preserve both information on projectile mineralogy as well as other properties such as nuclear tracks caused by solar flare irradiation. The wide range of the observed abundance and alteration state of projectile residue is most probably due to differences in impact velocity. The crater liners are being studied to determine the composition of meteoroids reaching the Earth. The compositional types most commonly seen in the craters are: A) chondritic (Mg,Si,S,Fe in approximately solar proportions), B) Mg silicate and C) iron sulfide. These are also the most common compositional types for extraterrestrial particle types collected in the stratosphere. The correlation between these compositions indicates that

vapor fractionation was not a major process influencing residue composition in these craters. Although the biases involved with finding analyzable meteoroid debris in metal craters differ from those for extraterrestrial particles collected in and below the atmosphere, there is a common bias favoring particles with low entry velocity. For craters this is very strong and probably all of the metal craters with abundant residue were caused by asteroidal dust impacting at minimum velocities.

INTRODUCTION

The systematic study by Bernhard et al., 1993 has demonstrated that approximately half of the craters in pure Al and Au contain detectable projectile residue. In our SEM study of >200 craters in pure Al we have found that in the majority of cases the residue consists of small patchy deposits representing at most only a few percent of the projectile mass. In the majority of cases the projectile is either almost entirely vaporized or ejected from the crater. In rare craters however, large amounts of residue survive in the crater. These craters are easily identified in the SEM and in most cases they can be identified optically because their interiors are darker than the typical craters that have smooth walls and are nearly devoid of residual projectile. In this study we have concentrated on the craters with abundant residue because they can be studied in detail to provide information on composition, mineralogy and other projectile properties. Because a significant fraction of the projectile remains in the crater it is expected that the surviving residue is a reasonably representative projectile sample. In the more common case where only trace amounts of the projectile survive, the residue may not be representative. Laboratory studies of collected interplanetary dust samples have shown them to be highly heterogeneous at the micron scale. The sparse distribution of residue in typical craters also complicates the general analysis problem due to the combined effects of crater geometry and dilution of the small signal from the residue with the substrate material.

RESIDUE TYPES

The extraterrestrial meteoroid residue found lining craters in LDEF aluminum is highly variable in both quantity and type. We observed the following sequence of natural meteoroid residue types that in broad terms represents decreasing modification of original projectile properties. The frequency of occurrence of the types decreases downwards in the list but the relative amount of residue retained in a crater tends to increase.

- No residue
- Thin glass
- Thicker glass sometimes vesicular with metal beads
- Vesicular glass with some unmelted mineral fragments
- Unmelted mineral fragments on crater bottom

The most common craters are smooth bottomed and contain either no or only trace amounts of residue detectable by SEM-EDX techniques. Figure 1 shows a SEM photo of a 150 μm crater in Al that contains moderate to trace amounts of chondritic composition projectile material. In approximately 10% of the craters, residue occurs that is both common on the crater floor or wall and thick enough (>0.5μm) to give reasonably strong EDX spectra. Usually this material is a mixture of glass and either Fe metal or sulfide beads. In some cases the glass is highly vesicular but there is a complete range in porosity. The degree of vesicularity is presumably determined by heating and the abundance of volatile compounds in the projectiles.

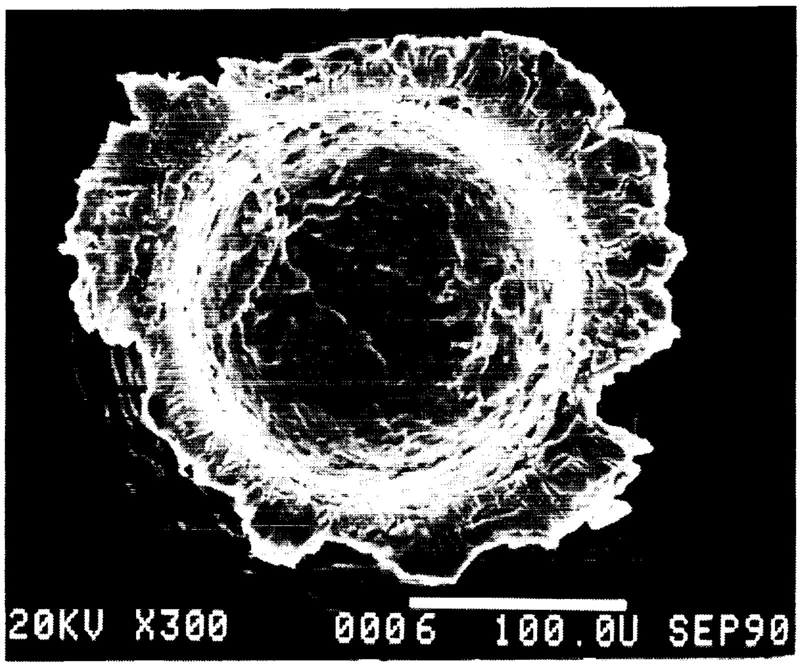

Figure 1 SEM photo of a 150μm crater that contains a moderate to trace amount of melted chondritic meteoroid lining the crater floor.

By direct SEM analysis of a crater it is usually not possible to quantitatively determine the amount or composition of the residue. Major complications with quantitative EDX analysis are the unknown thickness of the residue and its relationship with the substrate metal. Correction for absorption and other effects to quantify the x-ray spectra requires knowledge of the geometry and mixing of the projectile and target. For several craters we have made 0.1 μm microtome sections through the glass/metal interface and in these cases the sample geometry does allow accurate analysis but only for the regions within the section. EDX analysis of the sections in the transmission electron microscope can give excellent analyses using standard thin film correction techniques. This works well for some craters but for those where the liner is inhomogenous and sparsely distributed, a truly representative analysis is not practical even with microtome sections. A representative analysis would require an impractically large number of sections.

Metallic spherules. In the glass-bearing craters that were sectioned, the projectile melt was a discrete liner composed of a mixture of silicate projectile melt and substrate aluminum. (Figures 2 and 3). These crater liners are dominated by a Mg,Fe silicate glass that contains high but variable amounts of Al from the substrate. For Al to enter the silicate glass it must oxidize and it is apparent that redox reactions occur during the impacts in-spite of the short time scales involved. Metallic Fe and FeNi beads are commonly seen in the glass (Figure 2) and it is likely that some of these were formed by reduction. FeS beads are observed in some craters. Analogous to thermite reactions it appears that some of the aluminum target oxidized during the impact while some of the FeO in the projectile was reduced to form metal beads ranging in size from 10 nm to 1 µm . There are two populations of metal beads, one that has meteoritic Ni levels and one that appears to be Ni free. The Ni-bearing metal may be original metal melted and shock dispersed while the pure Fe droplets may be formed by in-situ reduction. The FeNi metal beads are amorphous presumably to very rapid quenching rates.

Figure 2 SEM photo of vesicular silicate glass liner that contains numerous FeNi and FeS beads.

Unmelted Meteoroid Fragments. In rare cases we observed large amounts of unmelted mineral grains in the crater floors (Figures 4 and 5). Although our data set on these craters is not large it appears that an abnormally high fraction of these craters were produced by projectiles dominated by forsterite (Mg_2SiO_4) and enstatite ($MgSiO_3$). These phases have melting points of 1890 C and 1557 C, respectively, and it is likely that their high melting points played a role in their preservation. High melting point is not an exclusive requirement for survival of unmelted mineral fragments because relatively large iron sulfide grains are seen in some craters (Figure 4). It is extraordinary that unmelted mineral grains survive in some of the hypervelocity impacts into solid Al and Au targets. Although fragmented to micron size during the impact, they contain many of their original properties. Solar flare tracks have been seen in fragments in some of the craters (Figure 6). These linear defects caused by Fe group cosmic rays provide information on the cosmic ray lifetimes of the projectiles and also provide insight into shock and thermal modification during cratering. Tracks usually anneal and are erased when samples are heated to temperatures above 600 C. The survival of tracks suggests that noble gasses are probably also retained in the fragments.

THE ORIGIN OF METEOROIDS PRODUCING RESIDUE-RICH CRATERS

The survival of unmelted mineral fragments and the general retention of significant amounts of residual projectile material are most probably the results of low velocity impact. Calculations by Bernhard et al., 1993 indicate that plausibly low impact velocities on LDEF can limit shock heating effects to the pressure regime where some solid mineral grains can survive intact. The craters with abundant natural meteoroid residue and particularly those with unmelted mineral grains are a highly selected subset of meteoroids that approach the Earth at minimal velocity and with favorable orbital parameters to minimize impact velocity. Because asteroidal particles approach the Earth with relatively low velocity (Flynn, 1990) it is likely that all of the craters with abundant residue are exclusively asteroidal in origin.

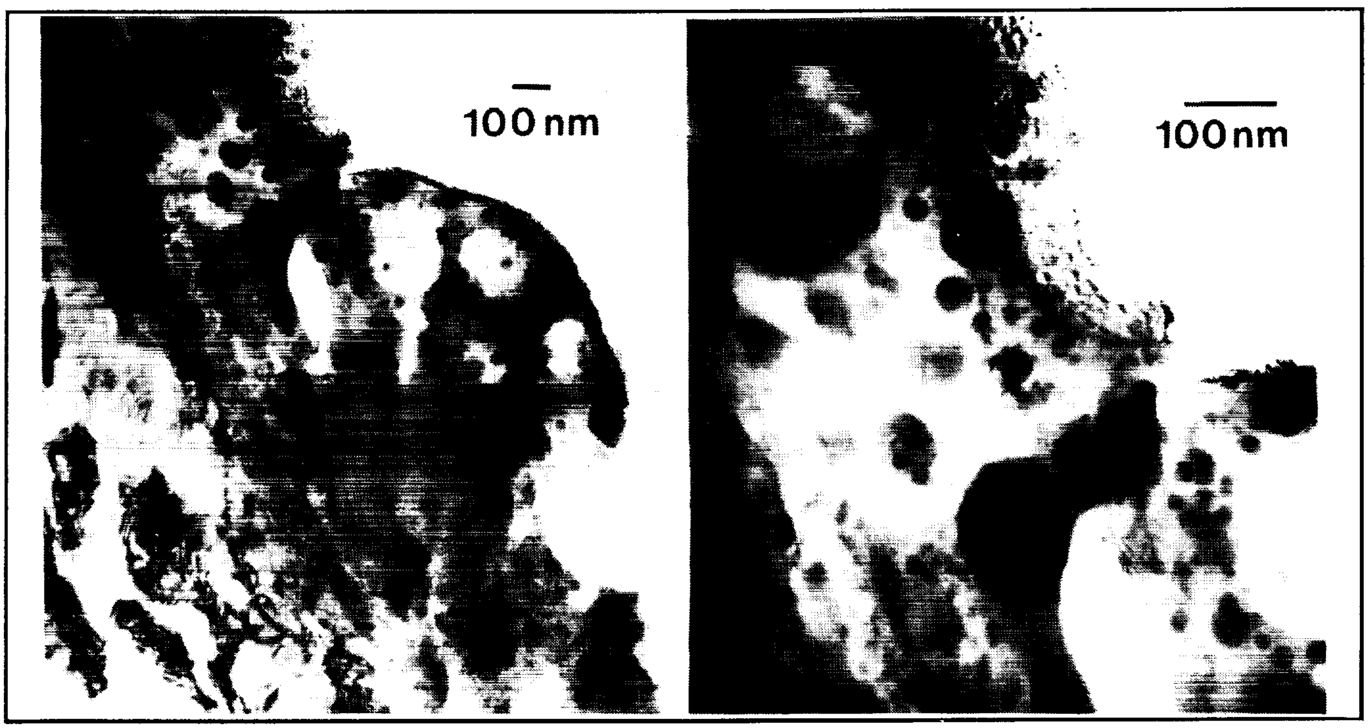

Figure 3 Transmission image of 0.1μm microtome section of chondritic meteoroid residue on pure aluminum from experiment A0187-1. The lower magnification image on the left shows the vesicular silicate glass with imbedded FeNi spherules. The contact between the glass and the underlying aluminum is only 0.1μm thick and is seen as a diagonal line from the upper left to the bottom center of the image. The higher magnification image on the right shows details of the 5nm to 100nm amorphous metal beads inside the glass projectile residue.

CONCLUSIONS

Rare craters in pure aluminum and gold on LDEF contain substantial amounts of projectile material occurring as melted and unmelted debris. These samples provide excellent material for determining the nature of the natural meteoroids impacting LDEF. If residue retention is strongly dependent on impact velocity, then these residue-rich craters were made by a highly selected subset of meteoroids whose orbital parameters yielded low encounter velocities with LDEF probably in the 5-10 km s^{-1} range. Even though the collection is selective, the LDEF metal craters show that it is possible to collect natural meteoroids from Earth orbiting platforms. Only a small fraction of the LDEF metal craters contain abundant residue but the results are highly suggestive that other materials specifically designed to reduce the shock pressure during impact could provide effective capture over a broad velocity range. Silica aerogel and other such low density capture media may provide extraordinary capabilities for future direct capture of hypervelocity meteoroids.

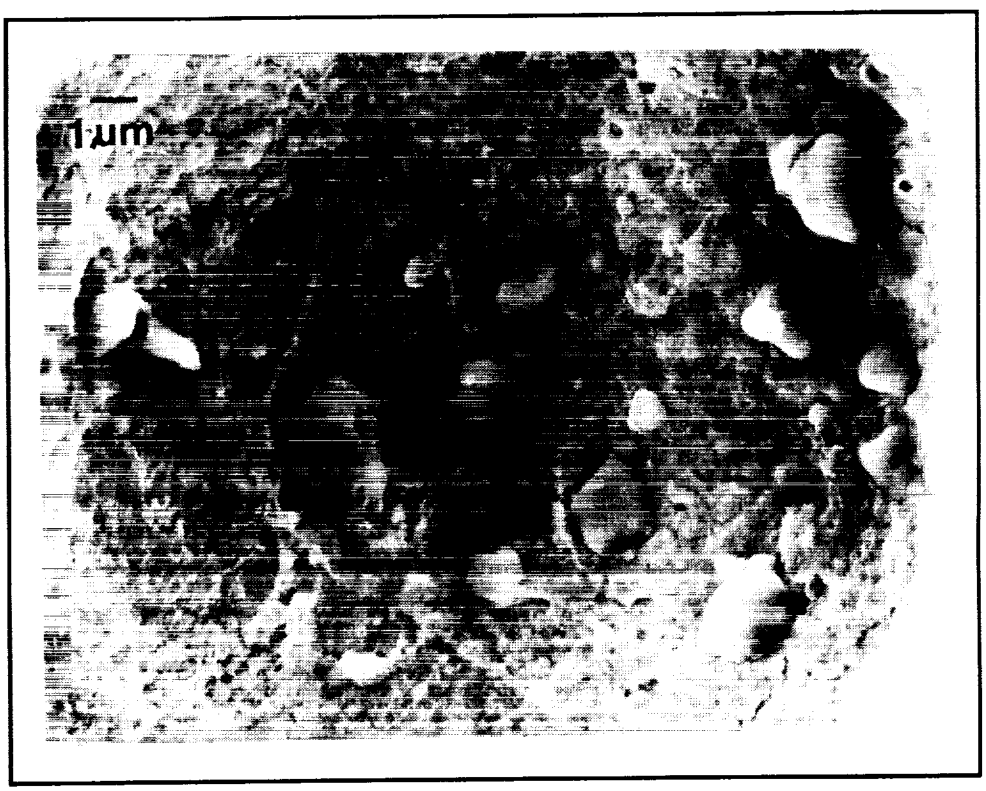

Figure 4 Glass and micron-sized unmelted FeS grains lining the base of a crater in pure Au.

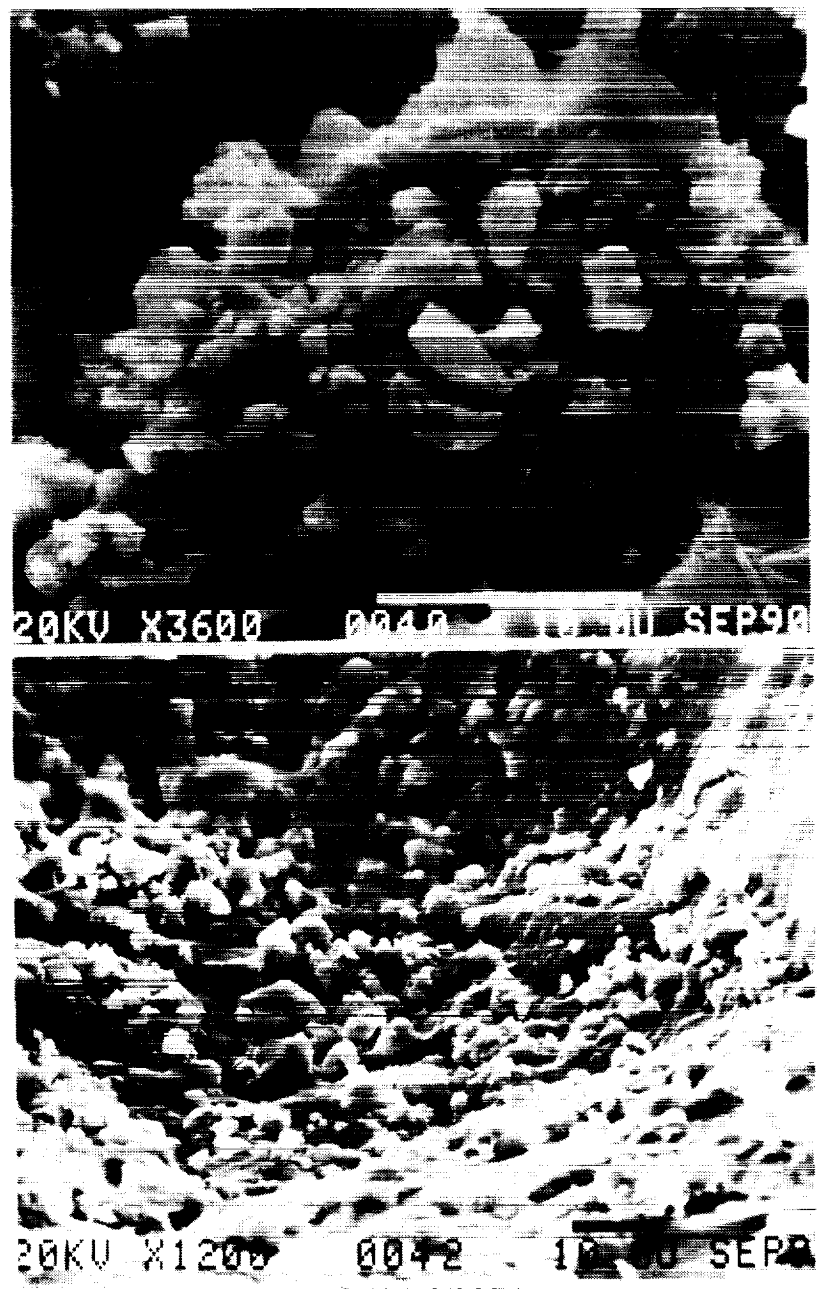

Figure 5 Micron-sized fragments of $MgSi0_3$ and Mg_2SiO_4 lining the walls of crater .in pure LDEF aluminum (Exp A0187-1). Some glass, sulfides and other materials exist in these craters.

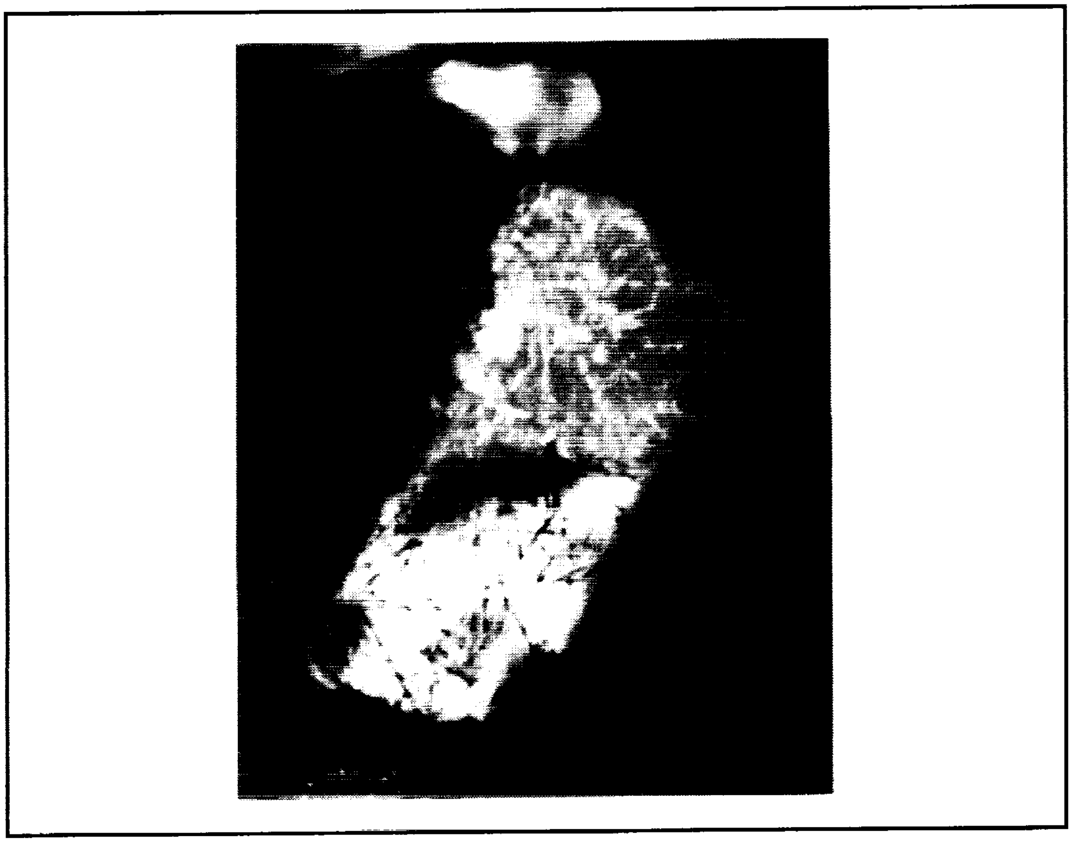

Figure 6 Solar flare tracks in a 0.3μm long anorthite grain extracted from the bottom crater in Figure 5. The tracks are imaged in both darkfield and bright field conditions in the transmission electron microscope. Many of the grains extracted from this crater are track-rich indicating an unshielded exposure to solar cosmic rays for >10,000 years. The preservation of tracks implies only moderate alteration during the cratering event with peak heating not significantly above the track erasure temperature of 600 C.

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