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LDEF IMPACT CRATERS FORMED BY CARBON-RICH IMPACTORS: A PRELIMINARY REPORT

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SUMMARY

Two impact craters found in Al from LDEF experiment tray A11E00F have residues concentrated in the bottoms, along the walls, and on the top of overturned rims. Analyses indicate a "chondritic" compositional signature (Si, S, Ca, Fe, Mg, and Ni) for the bulk residue. In one crater (# 74) round to irregular silicate grains (crystalline in appearance) are overlain by carbon. In addition, carbon also partially covers the crater walls, the top of the raised/overturned rim and extends outwards from the crater. The second crater (# 31) also contains carbon with similiar distribution in and about the crater, although the silicate residue appears to be glassy. Silver, I, K and F (possibly some of the Ca, S, and Cl) appear to be contaminates as well as analyzed aromatic carbonaceous species associated with the raised rim and the area surrounding the crater. The origin of the impactors is assumed to be extraterrestrial. The existence of impactor residue in the two craters implies impact velocities of ≤ 6 km based on experimental hypervelocity impact studies.

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INTRODUCTION

Cursory examination of LDEF by the Post Retrieval Examination Team (ref. 1) showed the existence of thousands of impact craters but a low percentage of craters with impactor debris or ejecta sprays. While the study of this debris is of interest to many science disciplines, it is of particular interest to exobiology in terms of residual carbonaceous and biogenic element contents. Moreover, a comprehensive study of impactor residue could provide information concerning IDP (interplanetary dust particle) impactor source (cometary, asteroidal, or lunar) and the characteristics of IDP carbonaceous materials. We report here the preliminary morphological and compositional study of two impact craters with carbonaceous impactor residues.

ANALYTICAL TECHNIQUES, SAMPLES, AND METHODOLOGY

Aluminium panels from LDEF experiment tray A11E00F (F. Hörz, P. I.) were scanned with a microscope for crater identification. Craters with possible partially intact impactor debris were "punched out" from the main piece to a sample size of 7 mm. These craters were further scanned with an SEM (scanning electron microscope) in order to study crater morphology and to confirm the existence of impactor residue. Of the hundreds of observed craters < 10% were found to have residues and of these only a few percent (e. g., #31 and #74) had significant intact residues. SEM/EDX (energy dispersive X-ray spectroscopy) analyses indicate that both of the residues have a "chondritic" compositional signature, i. e., presence of Si, Al, Ca, Mg, Fe, and Ni, among other elements, which strongly suggests extraterrestrial origin.

These samples were then subjected to an imagery and analytical protocol that included FESEM (field emission scanning electron microscopy), AES/SAM (Auger electron spectrometry/scanning Auger microscopy, and TOF/SIMS (time-of-flight secondary ion mass spectrometry). AES/SAM was performed using a Perkin-Elmer PHI 660 instrument operated at 10kV. Beam diameter and hence, imaging resolution is ≈ 1000 Å. Both point analysis and multielement mapping were performed. TOF/SIMS analyses were performed using the CHARLES EVANS & ASSOCIATES instrument (ref. 2). The instrument was operated in the ion microprobe mode using a microfocused Ga^+ beam as the sputtering source. After completion of these analyses, a molecular identification study of carbonaceous materials will be accomplished by LIMS (laser ionization mass spectrometry) and, finally, the residues will be excavated, microtomed into ultrathin wafers and studied for phase identification and crystal structure by TEM (transmission electron micoscopy) methods.

CRATER AND IMPACTOR MORPHOLOGY

Crater #74 Morphology

Crater #74 is 119 micrometers in diameter, measured from the points in the crater walls where the plane of the unraised surface intersects the crater (not measured from points on the raised rim walls). The depth/diameter ratio is 0.59 consistent with the average value of 0.6 for other LDEF craters (ref. 1). Figure 1 shows vertical and slighlty tilted views of the crater. Impactor residue is concentrated in the bottom with impact melt "splash" lining the crater walls. The overturned raised rim shows irregular patches of dark to light material that consist mostly of carbon with lower amounts of Fe, Mg, Na, K, Ca, Cl, Ag, I, and F (see next section). Figure 2 shows two views from the crater edge to the bottom. Impactor debris is mostly covered by an unknown thickness of carbon. The frozen impact melt splash seen on the walls in Fig. 2b consists mostly of the Al target admixed with minor amounts of "chondritic" elements which are thinly covered by carbon. Detailed resolution of splash morphology is shown in Fig. 3. Possible intact silicate grains are shown in Fig. 4 where rounded to irregular shaped material (which may be only slightly disturbed from impact) is covered by carbon and very small (hundreds of nanometers), dark blobs.

Crater # 31 Morphology

This crater is 158 μm in diameter with a depth/diameter ratio of 0.8. Whereas crater #74 contains partially intact material, the impactor residue in #31 was completely melted (Figs. 5 and 6). The impactor appears to have melted on impact, thus, lining the crater bottom and walls with glassy impact melt. Twisted glass is present in the bottom where the morphology suggests freezing of viscous, molten material during splash rebound after impact. Small glassy beads line the upper walls of the crater (Fig. 6). Even though the impactor appears to have completely melted, a "chondritic" compositional signature remains together with a rather large amount of carbon, at least on the residue surface (see the next section).

ANALYTICAL RESULTS

Auger Electron Spectrometry/Scanning Auger Microscopy

Auger survey analyses of crater # 31 were performed in the bottom of the crater, 25μm and 1 mm away from the edge of the crater, respectively. Table 1 gives examples of some elemental concentrations, which were calculated by using nominal sensitivity factors, for three locations Carbon concentration varies from ≈ 40 at.% at the crater bottom to 6 at. % 1 mm from the crater. Similar concentrations were found for crater #74. In addition, the partially intact impactor debris in the bottom of crater 74 has surface C concentrations ranging from 72 to 54 at. %. Figure 7 is a 3-element map of crater 31 and the surrounding area in which the distribution of Al, C, and F is shown. Each image contains 128 x128 pixels. Carbon-rich areas are observed inside and outside the crater. The F-rich area outside the crater is likely to represent cross contamination from adjoining experiment trays.

Time-Of-Flight/Secondary Ion Mass Spectrometry

The resulting mass spectra and images are shown in Figures 8 through 13. Figure 8(a & b) shows negative and positive ion mass spectra of crater 31 and Figure 9(a & b) shows negative and positive ion mass spectra for crater 74. They were acquired from a rastered region 200 x 200 μm in size, which covers the craters and surrounding Al surface. The intense signals of Ag^+, I^- and AgI_2^-observed in the positive and negative ion mass spectra indicate the presence of silver iodide contamination. Organic fragment ions such as $C_8H_5O_3^+$ (m/z 149) are also likely surface contamination products.

Figures 10-13 are examples of mass separated images from crater 74. Species such as Mg^+ (Fig.10) and Na^+ , which are concentrated within the crater, appear to be intrinsic to the impactor. Iodine (Fig. 11), K^+ (Fig. 12), and some of the Ca^{2+} (Fig. 13), which are concentrated on the raised rim, are probably contaminates. Hence, the ability to map the distribution of species is a powerful aid in the interpretation of a mass spectrum.

INTERPRETATION

From this limited crater/impactor preliminary study, no conclusions can be made regarding extraterrestrial impactor sources, impactor bulk compositions, grain crystal structures (of apparent intact grains), and the character of carbonaceous molecular species, if any. On-going laser ionization mass spectrometry, isotopic ratio imaging, and TEM studies may produce more significant and quantitative information. However, a few important aspects of this study are evident:

(1) The "chondritic" signatures of both impactors strongly indicate an unspecified extraterrestrial source.

(3) The apparent high carbon content of both impactors would seem to be, at this time, unusual with regard to an asteroidal (meteoritic) source. Known carbonaceous chondrites have nominal C contents lower than what we have tentatively assumed for the two impactors. Some cometary particles (CHONs) are higher in C content, compared with known meteorites, but little is known about their overall quantitative compositions and characteristics (e. g., ref. 3).

(3) Organic/non-organic contaminations are abundant and care should be taken in interpreting impactor compositions (see also ref. 4, these Proceedings).

(4) The characteristics and amounts of residual impactors in both craters imply impact velocities of ≤ 6 km/s based on experimental impact studies (ref. 5).

ACKNOWLEDGEMENTS

We thank M. Laurance for assistance in sample preparation and SEM-EDX analyses and the NASA OSSA Exobiology 199-52-12 and OAET 506-48 Programs for partially supporting this work.

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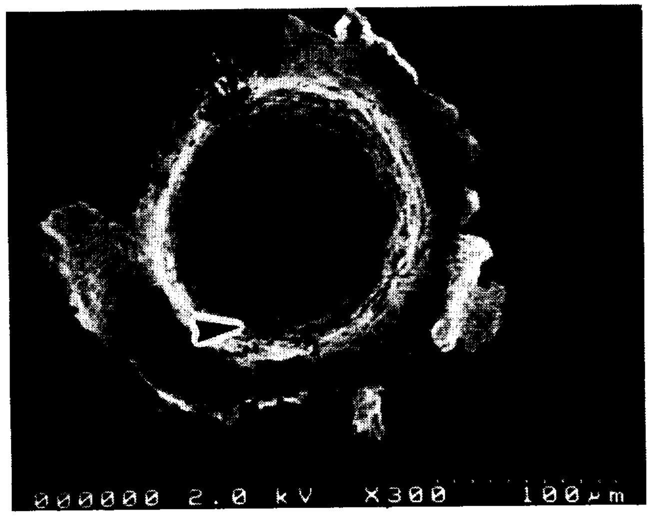
Table 1. Auger survey surface analyses of LDEF Crater 31 and surrounding areas (expressed as atomic %).

Element	Crater bottom	25 microns away	1 mm away
O	34.4	51.3	34.4
Si	2.0	5.7	5.4
F	1.12	1.12	1.0
S	0.24	1.02	1.0
C	39.6	12.7	6.1
Mg	1.9	1.0	n.d.
Na	n.d.	0.83	n.d.

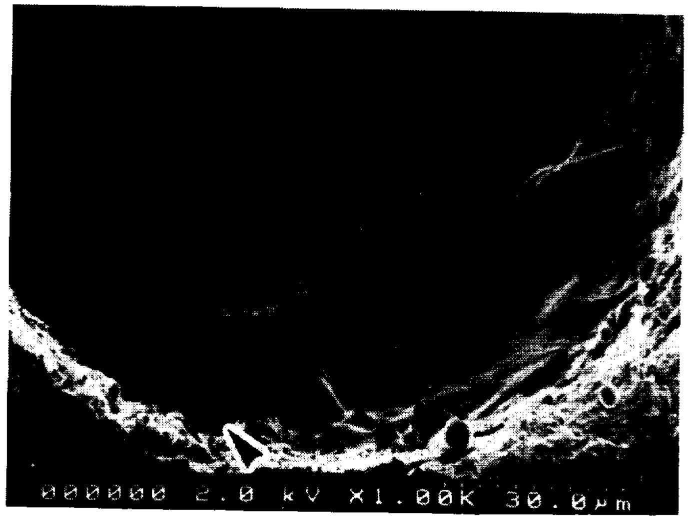
These are surface/near surface analyses only and do not imply bulk analyses. AES depth resolution is 2-30 nm, thus if C covers silicate materials (in this case, glasses) their elemental signals are greatly surpressed or are completely missing.



a

b

Figure 1. **(a)** FESEM BSE (backscattered electron) image of crater #74. Arrow points to round residual grain which is used as a reference in other figures. Fractures in Al that radiate away from the crater (NW direction), probably resulted from ductile/brittle fracturing during uplifting of the rim. Carbonaceous material (dark; curved arrow) is shown on the top of the overturned, raised rim. **(b)** Same crater as in (a) (slightly tilted and rotated 180°). FESEM BSE image. Note partially intact residual impactor in the crater bottom. 10 division scale is given in microns in the lower right corner of all FESEM images.



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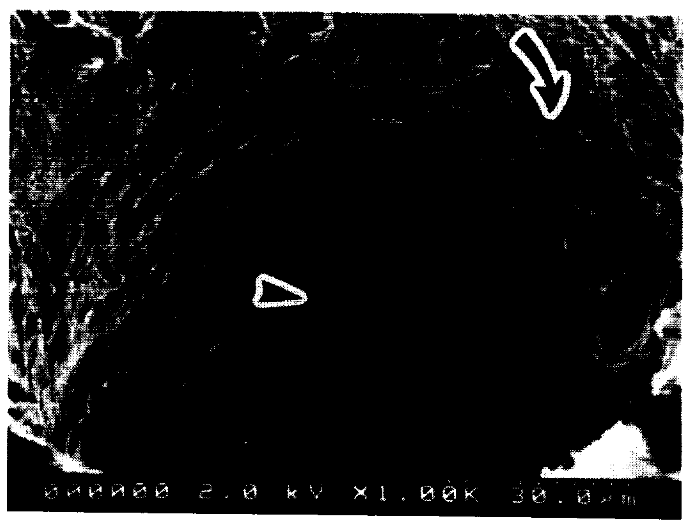

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Figure 2. (**a**) A view (FESEM BSE image) from the top of the rim into the bottom of crater #74. Note irregular lumps (partially intact impactor) and melt/splash material. The area is mostly dark due to carbon which coats most of the debris. (**b**) Similar view but opposite the rim in (a). Curved arrow points to upward moving frozen melt.

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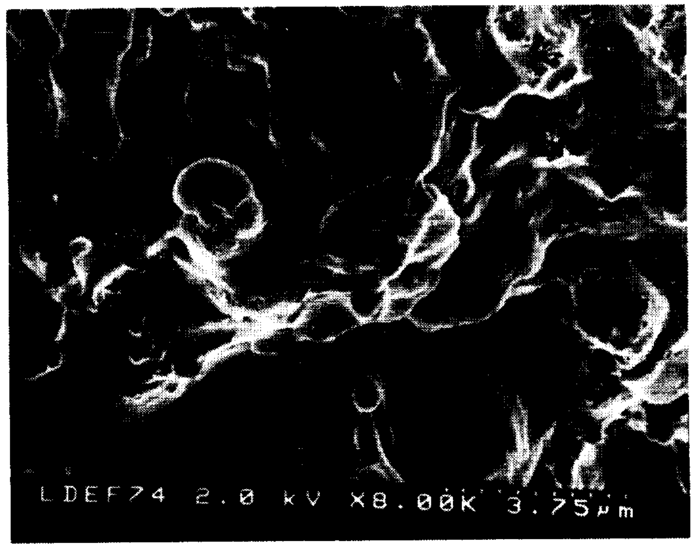

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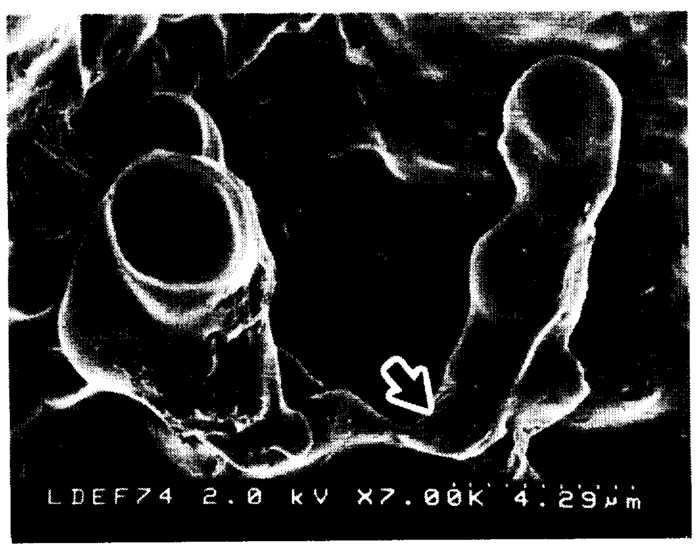

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Figure 3. (**a**) Melt splash on the wall of crater #74. (**b**) Partially melted impactor grains that are coated with glass. Arrow points to twisted, pinched glass. (FESEM BSE image).

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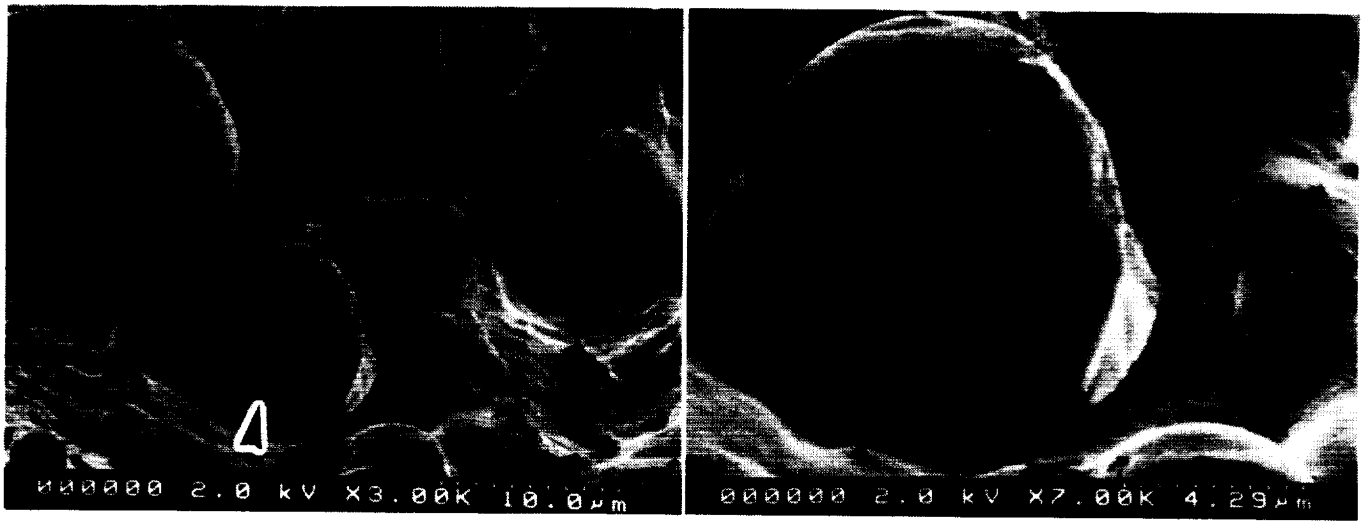
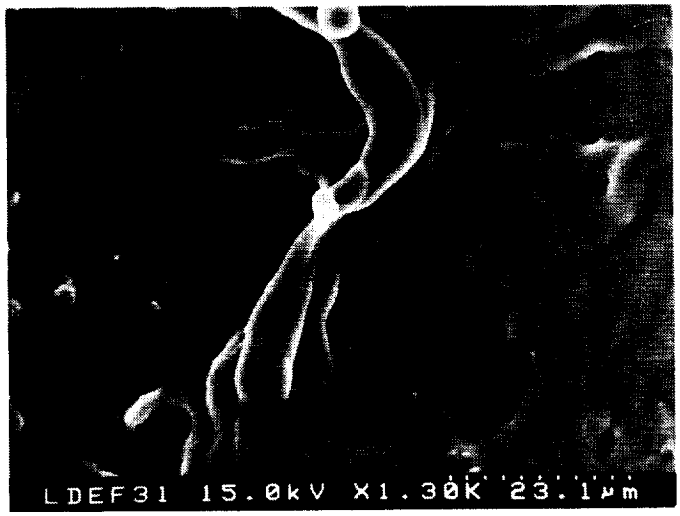


a b

Figure 4. (**a**) Round to irregular shaped impactor debris coated with carbon. Because of the morphology and qualitative composition of Mg and Si, the rounded grain may be olivine. (**b**) Enlarged view of (a). (FESEM BSE image).

Figure 5. Crater #31. Impactor residue is probably all glass. (FESEM BSE image).



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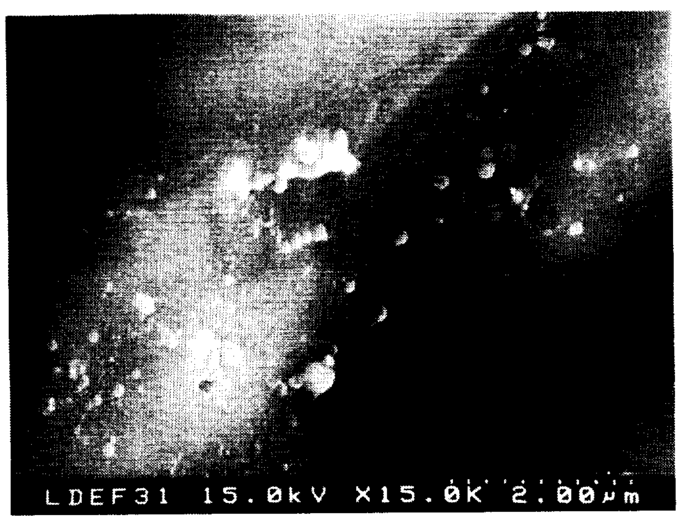

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Figure 6. (a) Enlarged view of crater bottom glassy impactor debris which is mixed with melted Al. (b) Small glassy droplets near the top of the crater wall. The light droplets may be metal or sulfides. (FESEM BSE image).

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Figure 7. Three-element SAM map (Al = blue; carbon = green; F = red) of crater 31.

(See color photograph, p. 601.)

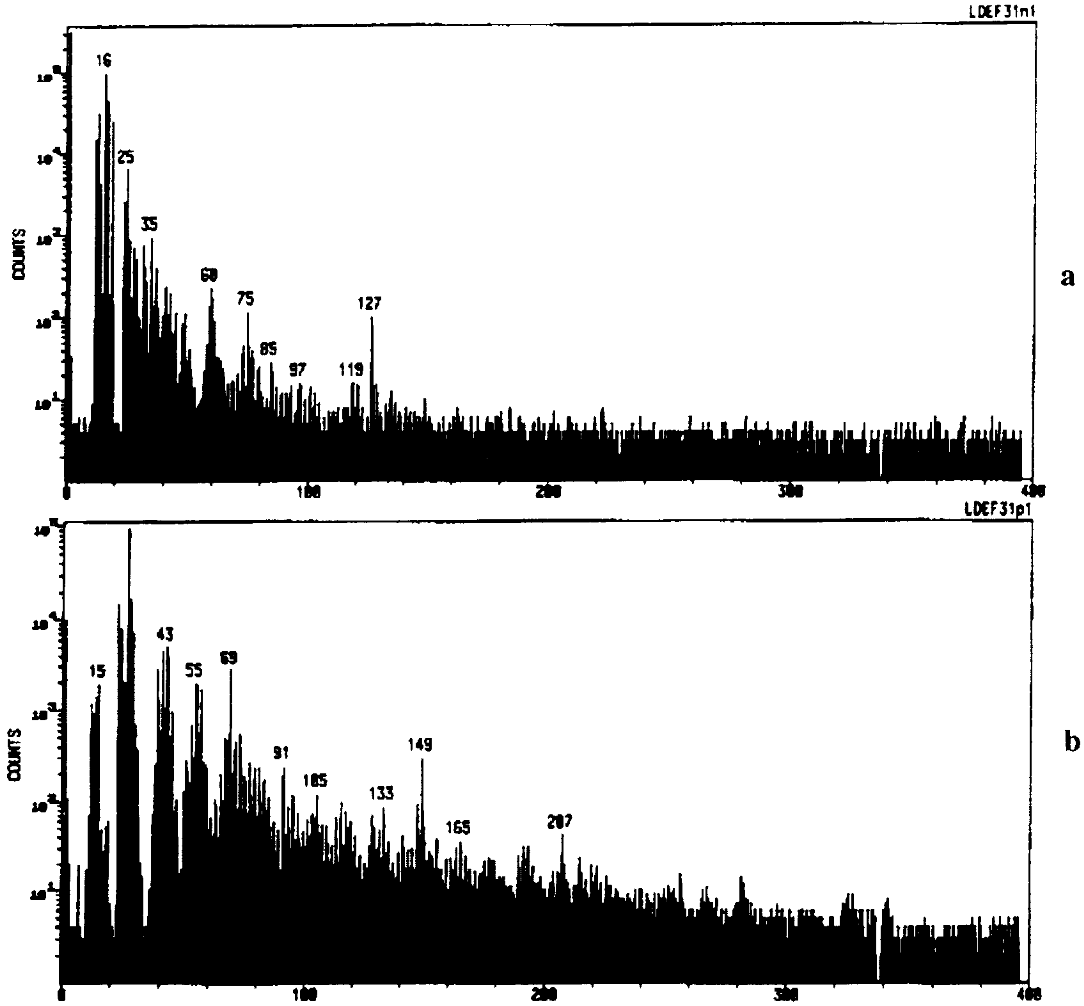

Figure 8. TOF/SIMS negative (a) and positive (b) spectra of crater 31.

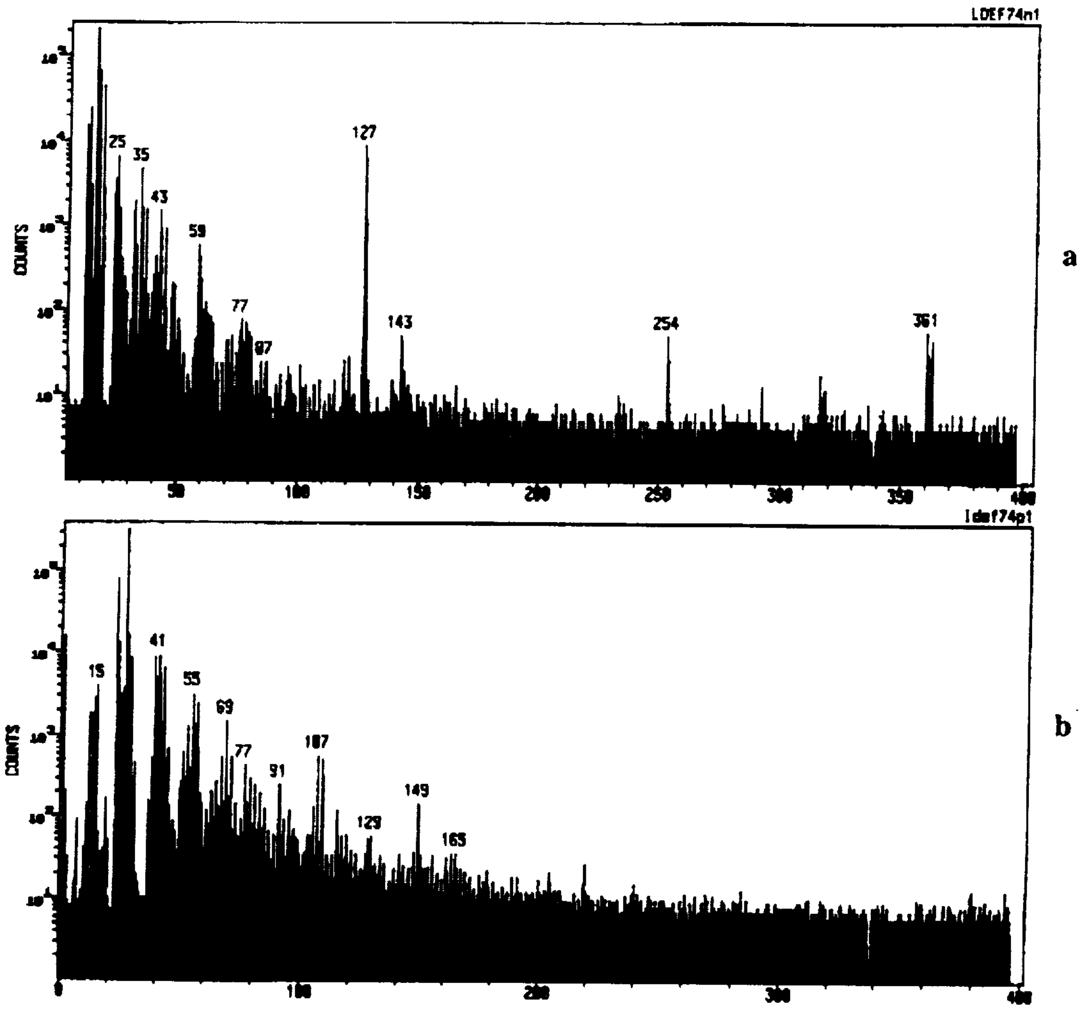

Figure 9. TOF/SIMS negative (**a**) and positive (**b**) spectra of crater 74.

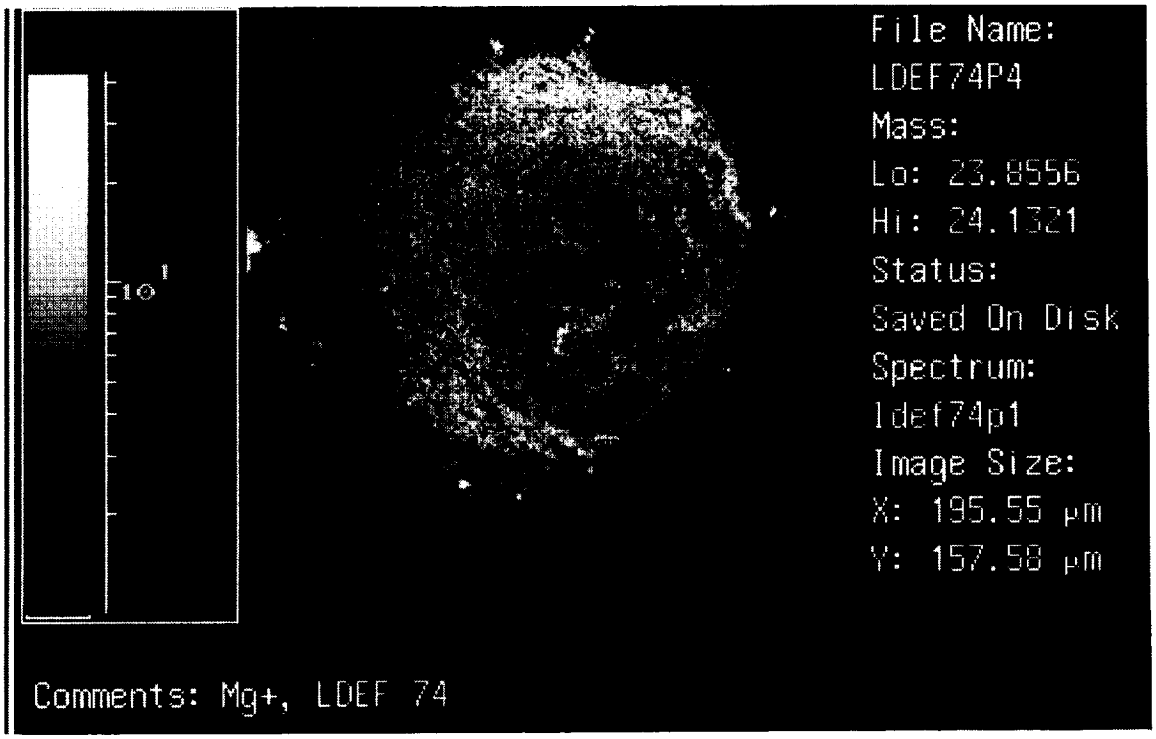

Figure 10. Mass separated image of Mg^+; crater 74.

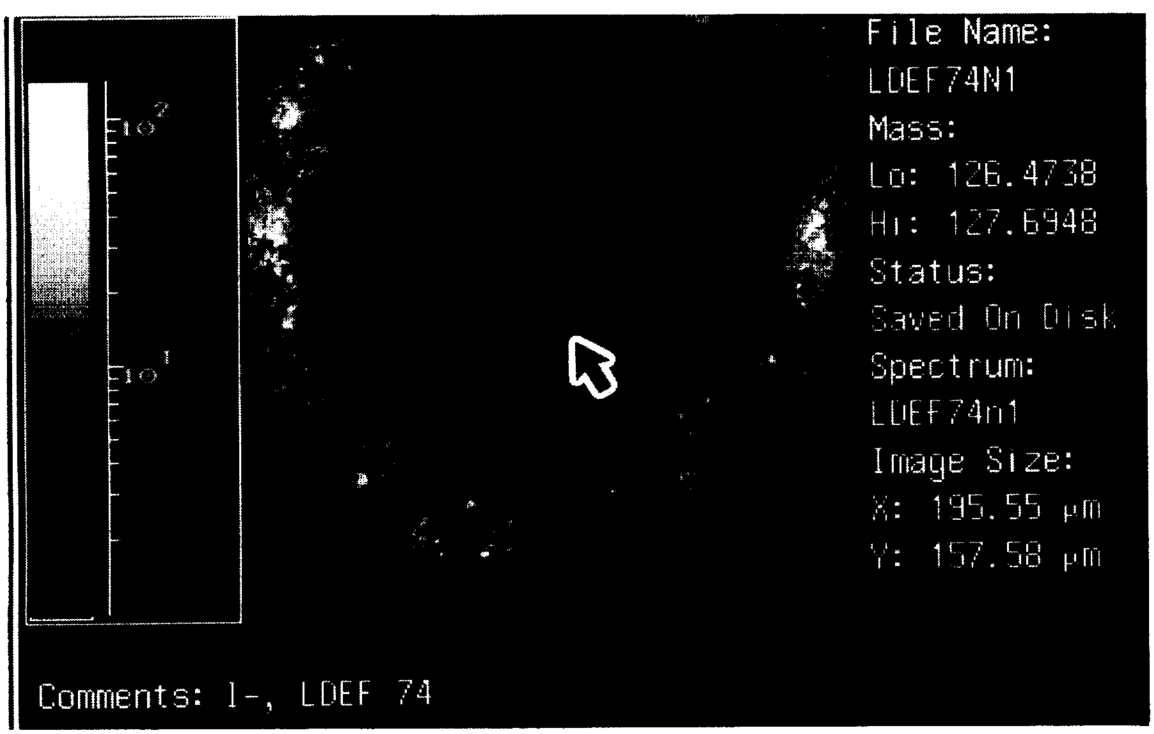

Figure 11. Mass separated image of I^-; crater 74.

(See color photographs, p. 602.)

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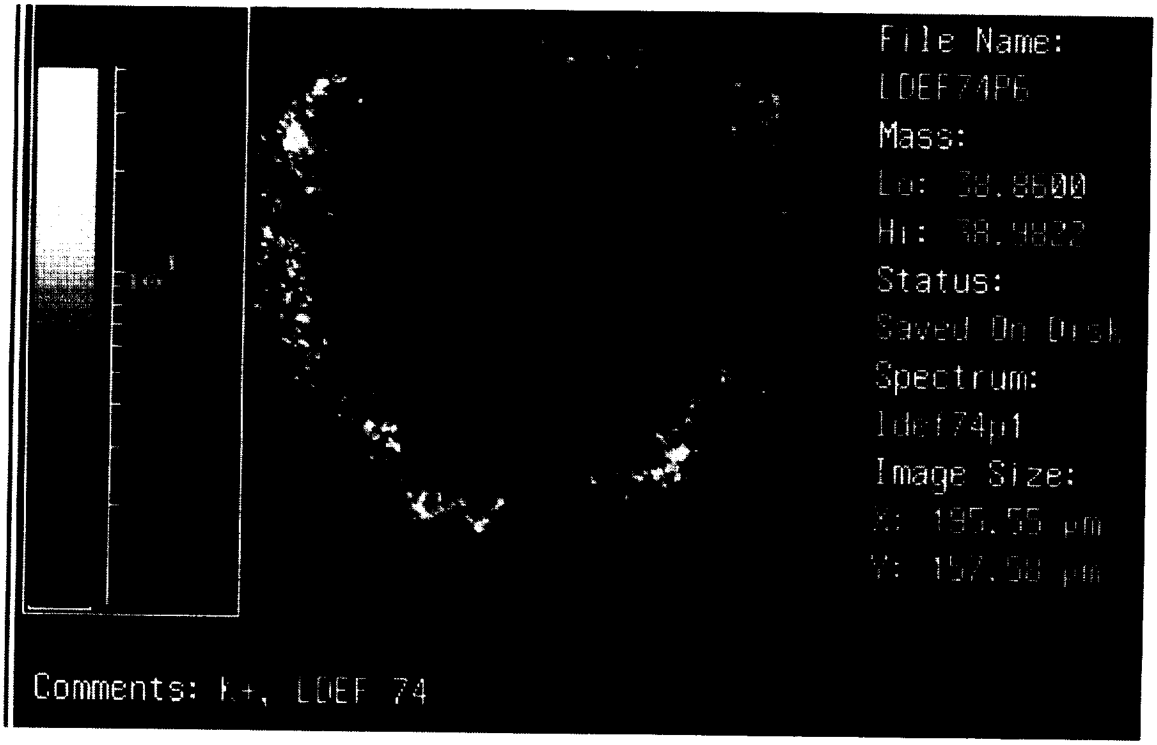

Figure 12. Mass separated image of K^+; crater 74.

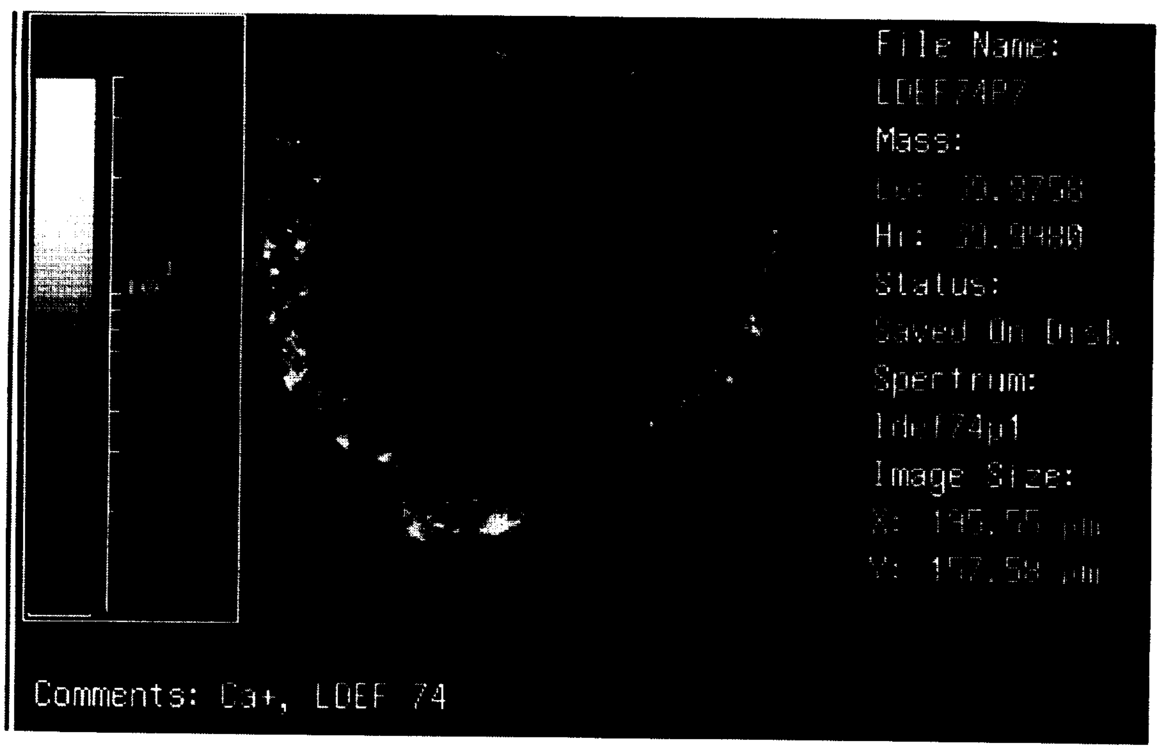

Figure 13. Mass separated image of Ca^+; crater 74.

(See color photographs, p. 603.)