Graphite in an Apollo 17 Impact Melt Breccia

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Although condensed organic phases coating lunar fines have been previously reported (*1*), studies of carbon in lunar rocks could not identify discrete carbon phases, except for carbides and solar wind implanted carbon [e.g., (*2*)]. Here, we report on the detection of discrete multiple micrometer-sized graphite phases within an Apollo 17 impact breccia.

This sample (72255) was collected from landslide material at Taurus-Littrow. It is an aphanitic impact-melt breccia (*3*, *4*) with a dark, fine-grained equigranular crystalline matrix containing larger clasts. The youngest material contained in the sample is dated to ~3.84×10^9 years ago, which is the age assigned to the Serenitatis impact basin.

We conducted two- and three-dimensional confocal Raman imaging spectroscopy (CRIS) on a thin section and on fresh fracture surfaces of sample 72255 (*5*) (fig. S1). Figure 1 shows a dark area of aphanitic matrix (DAAM) with a border to the surrounding lighter material (Fig. 1A). There is a greater concentration of 2- to 8-µm dark blebs within the darker area (Fig. 1B). Graphite spectra from 72255 exhibit a range of G to D band ratios (~1585 and ~1345 cm^{-1}, respectively) (Fig. 1C); however, the G band peak center positions and full width at half maximum (FWHM) measurements confirm that these phases are all crystalline graphite. The ratio of the 2D (~2690 cm^{-1}) to D band peaks increases between the three spectra (from I to III), showing the presence of graphite and rolled graphene sheets and graphite whiskers (GWs). The Raman spectrum of a GW is unique among carbon allotropes, and it is identified by an unusually intense 2D overtone mode (~2690 cm^{-1}) (*6*, *7*).

In all, we imaged an ~0.5-mm^2 area of thin section 72255,89, with over 68 occurrences of subsurface (2 to 8 µm within the surface) graphite blebs between ~2 to 6 µm in diameter (i.e., Fig. 1, D and E). Seven occurrences of subsurface GWs, one of which was mapped in three dimensions, occur between 3 and 8 µm within the section (Fig. 1I). All instances of graphitic carbon were restricted to the 0.1-mm^2 area analyzed around the DAAM pocket (I). The majority of blackened blebs in this area are ilmenite. Most occurrences of graphite appear to be within fused grain boundaries in the matrix (Fig. 1H), although some appear to occur within single discrete grains (Fig. 1H, white and yellow areas). No graphite phases are found in the 0.4-mm^2 area of lighter material that we have analyzed, although common carbon contamination phases occur all across the thin section (fig. S2).

Several lines of reasoning confirm that the observed graphite and GWs are indigenous to the sample (*5*). In particular, all known GW synthesis methods involve deposition from a carbon-containing gas at relatively high temperatures ranging from 1273 to ~3900 K (*6*, *7*). Thus, the GWs identified in 72255 cannot have been synthesized as a result of sample handling and preparation. Moreover, they could not have been implanted by solar wind, because this carbon is typically too small to identify structurally at the magnifications used (*1*, *2*). The crystalline graphite grains detected here are likely either intact remnants of graphite and GWs from the Serentatis impactor, or they could have formed from condensation of carbon-rich gas released during impact. This study indicates that impact may be another process by which GWs can form in our solar system. Furthermore, it appears carbonaceous material from impacts at the time of the Late Heavy Bombardment (LHB), and at a time when life may have been emerging on Earth, does survive on the Moon.

References and Notes

1. Y. Dikov, A. V. Ivanov, F. Wlotzka, E. M. Galimov, G. Wanke, *Sol. Syst. Res.* **36**, 1 (2002).
2. C. T. Pillinger, G. Eglinton, *Philos. Trans. R. Soc. London Ser. A* **285**, 369 (1977).
3. G. Ryder, "Catalog of Apollo 17 rocks: Stations 2 and 3 Johnson Space Center," JSC publication number 26088 (Johnson Space Center, Houston, TX, 1993).
4. C. Meyer, "The lunar sample compendium" (Johnson Space Center, Houston, TX, 2009).
5. Materials and methods are available as supporting material on *Science* Online.
6. M. Fries, A. Steele, *Science* **320**, 91 (2008); published online 28 February 2008 (10.1126/science.1153578).
7. P. H. Tan, S. Dimovski, Y. Gogotsi, *Philos. Trans. R. Soc. London Ser. A* **362**, 2289 (2004).

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Supporting Online Material

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Materials and Methods
Fig. S1
References

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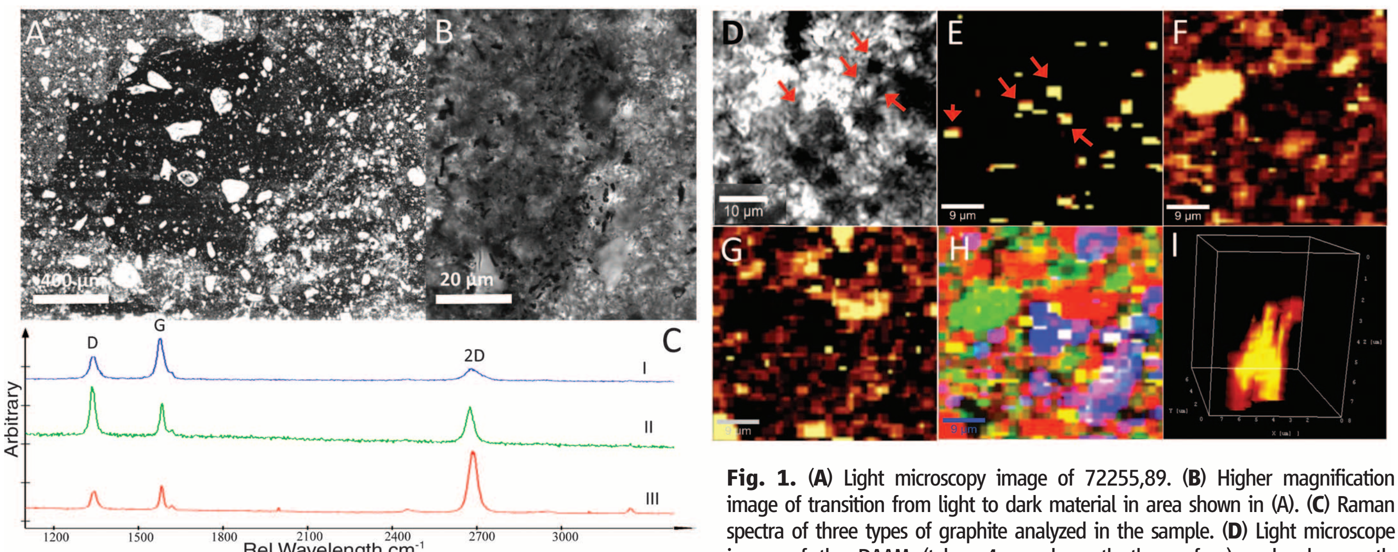

Fig. 1. (**A**) Light microscopy image of 72255,89. (**B**) Higher magnification image of transition from light to dark material in area shown in (A). (**C**) Raman spectra of three types of graphite analyzed in the sample. (**D**) Light microscope image of the DAAM (taken 4 µm beneath the surface) and subsequently analyzed by CRIS. (**E** to **H**) CRIS maps of (E) graphite 2D (~2650 cm^{-1}) band map. Red arrows correspond to dark blebs indicated by similar arrows in (D). (Color scale is thermal; lighter areas represent higher signal intensity.) (F) Feldspar, (G) pyroxene, and (H) four-color map with green indicating feldspar; red, pyroxene; blue, olivine; and yellow, graphite. (**I**) Three-dimensional depth profile of the graphite 2D band from the surface to 8 µm beneath the surface of the sample (2-µm ticks).