Gas-Rich Meteorites: Possible Evidence for Origin on a Regolith

Abstract. *The asymmetry of irradiation features of grains in the Kapoeta and Fayetteville meteorites suggests irradiation on a regolith before meteorite formation. Chondrules and broken grains require approximately* 10^4 *years of irradiation time between formation or fracturing and compaction into the meteorite. Shock erasure of tracks from irradiated Kapoeta feldspars requires a severe shock event during or after meteorite formation.*

Gas-rich meteorites contain large amounts of rare gases (*1*) which have abundance ratios similar to those in the sun (*2*). Controlled etching experiments have shown that the "solar" gas resides in the outer few micrometers of individual grains and have led to the suggestion that the gases resulted from a low-energy particle irradiation (*3*) similar to an irradiation by present-day solar flare nuclei. This theory was corroborated by the discovery that a fraction of the grains in several gas-rich meteorites have high densities of particle tracks and steep track density gradients (*4*). Such track features could only have been produced by a low-energy particle irradiation of these grains as individuals with negligible shielding and could not result from cosmic-ray nuclei stopping in them at their present sites within the meteorite. Crystals that exhibit high track densities have been termed "track-rich" grains.

Irradiation geometry features of these grains provide evidence about the environment at the time of their irradiation. In particular, the discoverers of the track-rich grains reported that the irradiation features are apparently symmetrical (that is, the irradiation dose is the same at all faces of a given grain) and inferred that the grains were probably irradiated in free space (*4*). We report here several new features of track-rich grains observed during a detailed investigation of two well-known gas-rich meteorites, Kapoeta and Fayetteville. High-resolution electron microscope methods, described elsewhere (*5–7*), have increased our capability to resolve tracks at densities an order of magnitude or more higher than was previously possible. Here we outline briefly the new observations and their implications; a more detailed treatment has been presented elsewhere (*7*).

Figures 1, 2, and 3 show examples of the features described in this report. Figure 1 is a scanning electron microscope photograph of a track-rich chondrule-like olivine grain in situ in a section of Fayetteville chemically etched to reveal tracks in olivine. Although we have observed several intact irradiated chondrules in this meteorite, the importance of this particular observation is that this object has been broken and a track density gradient exists at the broken edge (inset), an indication that the low-energy particle irradiation took place after fragmentation. If the flux of low-energy particles which irradiated the track-rich chondrules in Fayetteville was similar to the present-day flux from solar flares, the observed track densities require $\sim 10^4$ years of irradiation time. Similar times were suggested previously (*4*) for track-rich grains from several gas-rich meteorites. The similarity of solar conditions at the time of irradiation and the present cannot be checked directly. Under the assumption, however, 10^4 years is a lower limit on the time between chondrule formation and meteorite compaction. Furthermore, the track density gradients are so steep (*7*) that the thickness of gas or solid matter between the sun and the irradiated chondrules (and grains) could not have exceeded $\sim 10^{-3}$ g/cm^2.

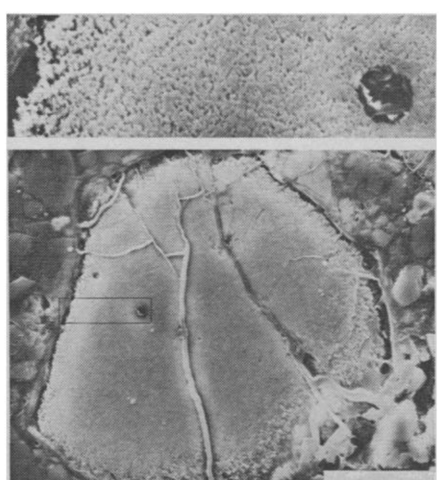

Fig. 1. Scanning electron microscope photograph of a track-rich olivine grain in a Fayetteville section. This broken olivine chondrule was irradiated after fracturing as shown by the track gradient at the broken edge. The area in the box is shown above the main illustration at $\times$ 5.1 greater magnification. The track density at the broken edge is $\sim 10^{10}$ tracks per square centimeter. The scale bar is 20 μm for the main photograph.

Figure 2 shows a track-rich feldspar grain in situ in a section of Kapoeta. The grain exhibits a feature which we have observed frequently in both Fayetteville and Kapoeta, namely, nonuniform track density around the grain borders. The variation is regular, with the highest density along one edge decreasing smoothly toward an opposite edge. The highest and lowest edge densities differ by approximately a factor of 3. Most track-rich grains in Fayetteville exhibit a similar nonuniformity (*7*).

The track densities at grain edges ($\sim 10^9$ tracks per square centimeter in Kapoeta and $\sim 10^{10}$ in Fayetteville) are much too high to resolve by optical microscopy and require very light etching combined with high-resolution techniques for their measurement. Thus it is not surprising that the nonuniformity was overlooked in the original descriptions of track-rich grains (*4*) which were, for the most part, based on optical microscopy. About 90 percent of the grains we observed have higher track densities at all edges than at their centers. This is in contrast to the case of lunar soil grains of similar size, which commonly have high track densities on only one side (*8, 9*).

The nonuniform irradiation features provide an important point for speculation about the environment of gas-rich meteorite formation, although the implications are not immediately obvious. It seems clear that such features could not be a *primary* result of "free space" irradiation of individual grains. Postirradiation erosion, or attrition during meteorite compaction, could result in nonuniform irradiation features, although it is difficult to see how this could explain the observed regular change in track density around the grain periphery. Arrhenius (*10*) has suggested irradiation in space in a loose agglomeration of small grains. The features in Kapoeta and Fayetteville are reminiscent of irradiated lunar fines, although, as pointed out above, the lunar grains commonly have high track densities on only one side. This suggests a higher "gardening" rate and possibly a lower gravitational field in the case of the meteorites, which would be compatible with earlier suggestions that the surfaces of small bodies are the sites of gas-rich meteorite formation [for example, see (*11*)].

Figure 3 is a micrograph of a shad-

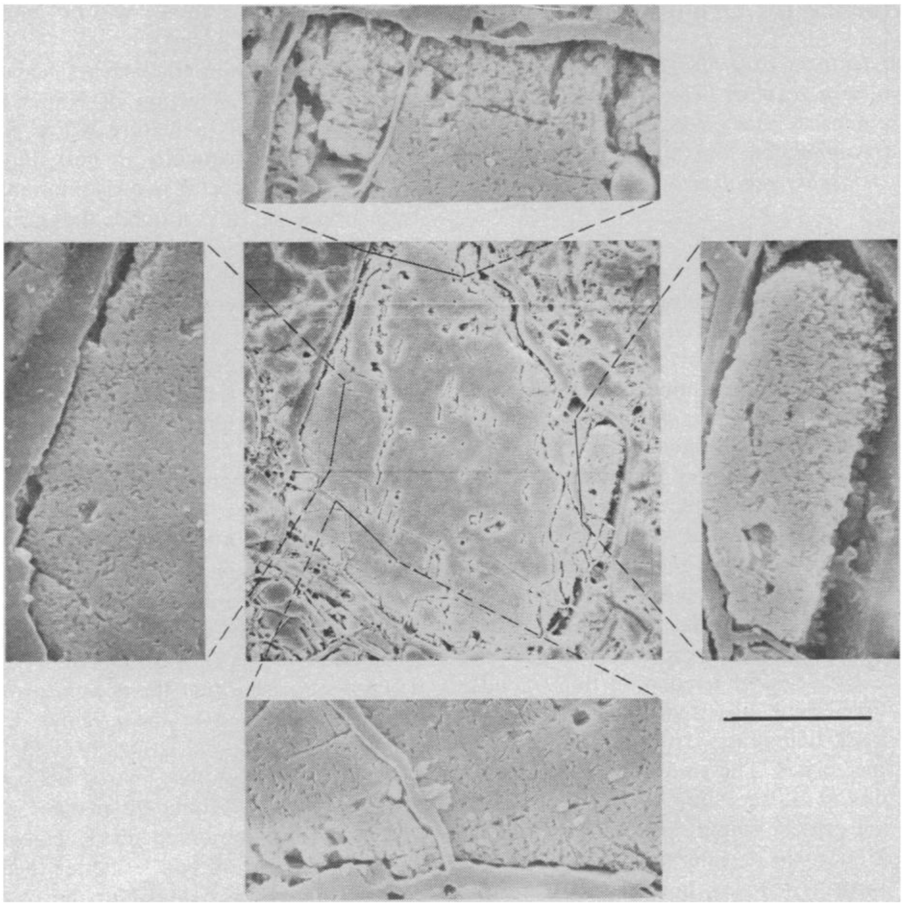

Fig. 2. Track-rich feldspar grain in a Kapoeta section, seen with the scanning electron microscope. Edges are shown at × 3.8 the magnification of the central grain to show the anisotropic irradiation effects. The scale bar is 60 μm for the central photograph. The track density is highest at the top and right side of the grain, lowest on the left side.

owed carbon replica (*5*) of an etched feldspar grain in a section of Kapoeta. Near the center of this elongate grain are areas where the tracks are short and the track density is lower than in adjacent regions. These areas are also characterized by narrowly spaced parallel markings which appear to be slip planes of the type described by Fleischer *et al.* (*12*). Thus this grain preserves a record of a shock event which occurred after its irradiation, since all tracks in the deformed areas are shortened. Evidence for extensive shock has been observed in Kapoeta by others (*13*); however, we had previously assumed that particle tracks would not survive the shocking and used the presence of track-rich grains as evidence for an absence of shock events during or after the compaction of Kapoeta (*8*). The results presented here indicate that a shock event affected Kapoeta components after irradiation of the track-rich grains, possibly during compaction of the meteorite. The event partially erased tracks in some grains and may have entirely removed them from others. This may partly explain the observed low abundance of track-rich grains in Kapoeta ($\sim$ 8 percent) as compared with Fayetteville ($\sim$ 30 percent).

Particle track features reported here, in addition to the steepness of the observed track density gradients in Fayetteville grains (*7*), can be used to place some limits on conditions during the history of Kapoeta and Fayetteville.

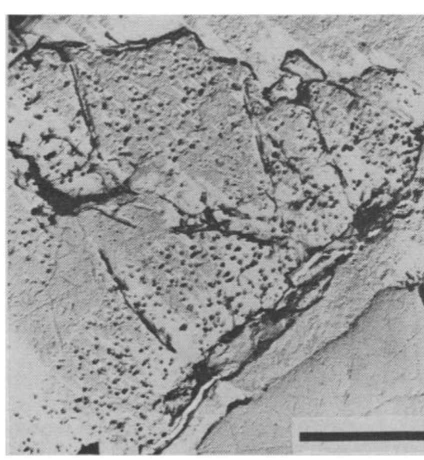

Fig. 3. Transmission electron microscope photograph of a shadowed carbon replica of an irradiated Kapoeta feldspar showing shock features as explained in the text. The scale bar is 4 μm. Tracks in this photograph appear as black, projecting objects with white shadows.

Irradiation on a small body would require a negligible atmosphere of $\lesssim 10^{-3}$ g/cm^2. If one postulates that these meteorites were formed in a jet stream of the type envisioned by Alfvén and Arrhenius (*14*), then gas pressure in the swarm must have been less than $\sim 10^{-9}$ atm. Either prior to or during the irradiation process, relative grain velocities must have been high enough to fragment chondrules. Although it has been previously mentioned that there are track-rich chrondrules in Weston (*4*), it has not been emphasized that this finding requires chondrule formation (and, as reported here, chondrule fracturing) $\gtrsim 10^4$ years before meteorite compaction. Finally, nonuniform irradiation effects must be a result of any model for gas-rich meteorite formation.

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