(*Reprinted from Nature, Vol.* 208, *No.* 5011, *pp.* 636–638, *November* 13, 1965)

ORIGIN OF ATYPICAL METEORITES FROM THE ARIZONA METEORITE CRATER

By PROF MICHAEL E. LIPSCHUTZ
Department of Chemistry, Purdue University, Lafayette, Indiana

THE well-known Arizona Meteorite Crater is an impact feature having a diameter of nearly 1 km. Estimates of the mass of the meteoroid which produced it have ranged from 30,000 (ref. 1) to 2·6 million[2] metric tons. The (spherical) diameters corresponding to these estimates are 20 m and 86 m. The main mass of this meteoroid has never been located. Inasmuch as most of the meteoroid probably vaporized or mixed with the surrounding rock during the explosion, it seems rather unlikely that much of the mass will ever be found. However, a fraction did survive the explosion in the form of many thousands of fragments ranging up to 640 kg in weight. The overwhelming preponderance of these have been 'normal' coarse octahedrites with kamacite band-widths ranging up to 4–5 mm. Less than 12 of the recovered fragments had structures corresponding to those of medium octahedrites. These atypical meteorites have been called Canyon Diablo No. 2, Canyon Diablo No. 3 and Monument Rock[3]. There is no doubt that these three types differ significantly both from the normal Canyon Diablo meteorites and among themselves[4] in structure and chemical composition.

Four explanations have been offered which can account for the atypical samples. The first of these is that the meteoroid was not a solid mass on impact with the Earth but consisted of a swarm of much smaller objects[5]. The possibility of such a swarm seems rather remote[3], and will not be considered further here. A second possibility is that the meteoroid consisted of a main mass of coarse octahedrite structure and several satellites with the medium octahedrite structures[3]. A third explanation is that there were four distinct falls: a large crater-forming coarse octahedrite mass, followed by three separate medium octahedrite falls[3]. The fourth possibility is that all were part of the same mass which had varying physical structures and minor element contents[6,7].

Until recently, no definitive results had been obtained as to which of these explanations was correct. On the basis of cosmogenic rare-gas measurements[6], Heymann was able to show that Canyon Diablo No. 2 was probably buried in the main mass of the meteoroid and exposed to cosmic-ray bombardment for 540 ± 100 million years at a pre-atmospheric depth of 50 cm. The remote possibility, however, existed that it was a distinct fall with a cosmic-ray exposure age of 64 ± 12 million years. The results of the rare-gas measurements on Canyon Diablo No. 3 were rather less conclusive. Either this meteoroid was part of the main mass and had an exposure age of about 1,000 million years or it was originally in a 10^5 kg object having an exposure age of 540 ± 100 million years (either a protuberance on the main mass or as a separate 10^5 kg mass). Similar alternatives[7] were proposed in order to explain the observed rare-gas contents of sample 24, a normal Canyon Diablo. However, a subsequent $^{40}K/^{41}K$ measurement by Voshage[8] of sample 24 yielded a value in substantial agreement with the exposure age of 540 million years. This result casts considerable doubt on the validity of the exposure age of 1,000 million years for Canyon Diablo No. 3. Most of the known measured medium octahedrites have exposure ages in the 500–600 million year range[8,9] and it is therefore not possible from Heymann's measurements to decide whether Canyon Diablo No. 3 was located in a 10^5 kg projection from the infinite mass ($\gg 2 \times 10^5$ kg) meteoroid or was a separate fall. A number of recent investigations[3,7,10] have established the fact that all known normal Canyon Diablo meteorites found on the Crater rim have been shocked to at least 130 kb. Since all three atypical types were recovered from the north-east rim[11] it seemed reasonable to examine them for shock effects in an attempt to resolve the question of their origin.

With the help of Prof. C. B. Moore, curator of the Nininger Meteorite Collection, I obtained samples of Canyon Diablo No. 2 (371.3), Canyon Diablo No. 3 (586.1), and Monument Rock (587.1x). The first two of these are shown in Fig. 1. Monument Rock is illustrated

Fig. 1. Comparison between the apparently normal, undeformed Widmannstätten pattern of the moderately shocked Canyon Diablo No. 3 sample (left) with the faint deformed pattern of the heavily shocked Canyon Diablo No. 2 (right). The white areas on the polished surface of the Canyon Diablo No. 3 are ε iron

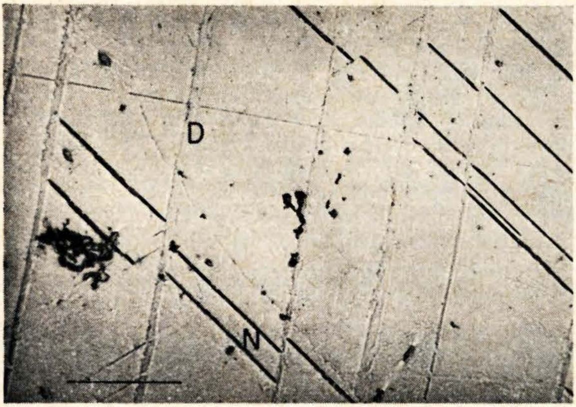

Fig. 2. Microstructure of the lightly shocked Monument Rock meteorite showing deformation bands (*D*) and Neumann bands (*N*). The bar in these figures is 0·1 mm

in Plate 22, Fig. 2*E* of ref. 3. These samples were polished and examined by standard metallographic techniques. The detailed interpretation of shock-induced metallographic changes in meteoritic iron have been described previously[7,10] and need not be repeated here.

Monument Rock. This meteorite falls into the lightly shocked category ($<$ 130 kb) of Heymann *et al.*[7]. The large number of Neumann bonds (shock twins) in it has previously been noted by Nininger[3]. The only evidence for any unusual shock is the presence of small deformation bands (Fig. 2) in the kamacite (α-iron). There were no inclusions in the exposed surface which could be studied crystallographically for shock effects.

Canyon Diablo No. 2. This meteorite falls into the heavily shocked category ($>$ 750 kb) of Heymann *et al.*[7]. The Widmannstätten pattern is indistinct (Fig. 1) and the kamacite is entirely recrystallized (Fig. 3). The cohenite (Fe_3C) grains show diffusion borders of pearlite. Some ledeburite-like eutectic is present and the rhabdites (Fe_3P) in the hotter end of the sample are redissolving. The taenite (γ) and plessite ($\gamma + \alpha$) grains are partially or completely clear and there is a secondary kamacite precipitate in some of them. That these thermal effects are due to shock and not to contact with hot ejecta or artificial heating is proved by the crystallographic character of the cohenite, which has been shocked to about 1,000 kb[12].

Canyon Diablo No. 3. This meteorite falls into the moderately shocked category (130–750 kb) of Heymann *et al.*[7]. The Widmanstätten pattern is quite distinct and undeformed although the macrostructure shows areas of ε iron (Fig. 1). Pressure gradients are very common. Some kamacite areas show normal Neumann bands, while others show regions of finely recrystallized kamacite around inclusions, or areas of completely recrystallized kamacite. Some of the patches of ε iron are normal, while others are in the process of conversion to polycrystalline kamacite (Fig. 4). The rhabdite and schreibersite (Fe_3P) grains are apparently thermally unaltered. Some cohenite grains show borders of martensite, but most exhibit no carbon diffusion zones. The taenite and plessite regions are clearing and there is a secondary kamacite precipitate in some taenite bands. The exposed troilite (FeS) nodule of the coarse type 2 variety. A systematic crystallographic study of the cohenite grains in this sample is not yet complete. Those specimens studied thus far fall into the 400–500 kb range so that there seems

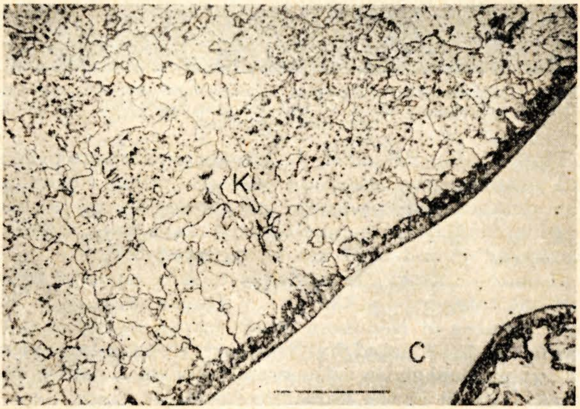

Fig. 3. Microstructure of the heavily shocked Canyon Diablo No. 2 sample showing polycrystalline kamacite (*K*) and pearlite diffusion border around the cohenite (*C*)

Fig. 4. Microstructure of the moderately shocked Canyon Diablo No. 3 showing ε iron beginning to recrystallize, particularly on the left at the interface between the cohenite grain and the iron

little doubt that portions of this meteorite were shocked to pressures of at least 500 kb.

It is regrettable that the results from the Monument Rock sample permit no absolute conclusion regarding the origin of this meteorite. It could have been part of the main mass, a satellite of it, or a separate fall. However, it should be pointed out that it is indeed a unique sample. Not only is it the only known specimen of its type found at the Crater site but it is also the only known exception to the observation that rim samples (whether of the normal or atypical varieties) have been moderately to strongly shocked.

An unambiguous conclusion can be reached, however, regarding the origin of both Canyon Diablo No. 2 and Canyon Diablo No. 3. These meteorites were involved in a catastrophic explosion during which they were shocked and therefore heated. The narrow widths of the carbon diffusion borders around the cohenite grains indicate that the duration of reheating was short, at most a few minutes, and that the meteorites cooled quickly to below the $\gamma-\alpha$ transformation temperature. Thus, their immediate post-shock mass was not considerably larger than their recovered mass. These characteristics are the same as those of the normal shocked Canyon Diablo meteorites. It seems very highly probable, therefore, that both Canyon Diablo No. 2 and Canyon Diablo No. 3 were located in the interior of the meteoroid during the instant of its explosion and were therefore neither satellites of the main mass nor separate later falls. It seems, therefore, reasonable to regard as proved the earlier suggestion[6,7] that chemical and structural variations do exist in iron meteorites over distances of less than 100 metres.

This work was supported by grants from the Advanced Research Projects Agency and the National Aeronautics and Space Administration.

[1] Bjork, R. L., *J. Geophys. Res.*, **66**, 3379 (1961).

[2] Öpik, E. J., *Irish Astron. J.*, **5**, 14 (1958).

[3] Nininger, H. H., *Arizona's Meteorite Crater* (American Meteorite Museum, Sedona, Arizona, 1956).

[4] Goldberg, E. A., Uchiyama, A., and Brown, H., *Geochim. et Cosmochim. Acta*, **2**, 1 (1951).

[5] Barringer, D. M., *Meteor Crater in Northern Central Arizona* (privately published, 1909).

[6] Heymann, D., *Nature*, **204**, 819 (1964).

[7] Heymann, D., Lipschutz, M. E., Nielsen, B. N., and Anders, E., *J. Geophys. Res.* (in the press).

[8] Voshage, H. (personal communication).

[9] Vilcsek, E., and Wänke, H., *Proc. Symp. Radioactive Dating, Athens*, 1962, 381 (I.A.E.A., Vienna, 1963). Voshage, H., and Hintenberger, H., *ibid.*, 367.

[10] Lipschutz, M. E., and Anders, E., *Geochim. et Cosmochim. Acta*, **24**, 83 (1961).

[11] Nininger, H. H., *Out of the Sky*, 234 (Dover, New York, 1952).

[12] Lipschutz, M. E. (in preparation)

Printed in Great Britain by Fisher, Knight & Co., Ltd., St. Albans.