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A metallographic study of the iron meteorite Verkhne Dnieprovsk (BM 51183)

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SUMMARY. The Verkhne Dnieprovsk material (BM 51183) in the collection of the British Museum (Nat. Hist.) is chemically group IIE and therefore distinct from Augustinovka. Structurally it is a finest octahedrite, with a kamacite band-width (0.05 mm) and bulk Ni content (Scott and Wasson, 1976) appropriate to a cooling rate of 830 K Myr^{-1}. Subsequent pre-terrestrial shock has produced localized deformation and shock-heating effects, which include mm-size globules of metal-phosphide melt product with a dendritic texture indicating resolidification at *c.*10 000 K sec^{-1}. It is suggested that the phosphides were already fissured at the time of shock-melting. The structure of Verkhne Dnieprovsk, although lacking silicates, is analogous to that of Kodaikanal.

THE iron meteorite Verkhne Dnieprovsk in the collection of the British Museum (Nat. Hist.) is listed by Hutchison *et al.* (1977) as a structurally anomalous member of chemical group IIE: an analysis by Scott and Wasson (1976) gives 8.78% Ni, with 22.8; 70; 6.1 μg/g of Ga; Ge; Ir respectively. However, Buchwald (1975) has shown that certain specimens labelled Verkhne Dnieprovsk in other museums are really fragments of the IIIB meteorite Augustinovka. The 24.5 g of Verkhne Dnieprovsk (BM 51183) were presented to the British Museum Collection in 1877 by Professor Kulibin of Leningrad and appear to be the only genuine material of Verkhne Dnieprovsk for which the location is known. The object of the present paper is to present a metallographic description of this material.

The confusion between Verkhne Dnieprovsk and Augustinovka arose because of incomplete or conflicting documentation on the rusty fragments that were reportedly found at Verkhne Dnieprovsk, in the Ekaterinoslav district, Ukrainian USSR, in 1869 or 1876, and the extensively weathered mass of about 400 kg that was dug up in 1890 at the village of Augustinovka, approximately 80 km from Verkhne Dnieprovsk. Yavnel (1976) has made a critical review of the early literature and has drawn attention to inaccuracies. In particular he has listed catalogue reports of Verkhne Dnieprovsk material in the collections: London 24.5 g; Calcutta 36.8 g; Vienna 8 g; Paris 3 g; Chicago 76.8 g; New York (A.M.N.H.), 77 g. He produced chemical evidence to show that the Chicago sample was a mislabelled fragment of Augustinovka and made a plea for the detailed examination of other material. Yavnel was instrumental in arranging the new analysis of the British Museum material by Scott and Wasson (1976) as reported above. It appears from Buchwald's report that the New York material is also Augustinovka. However, some of the Vienna material may be Verkhne Dnieprovsk and should be examined.

Metallography

The Verkhne Dnieprovsk material in the British Museum (Nat. Hist.) (BM 51183) consists of fourteen badly corroded, angular fragments totalling 24.5 g. The largest fragment (7.2 g) and one of the smaller (4.2 g) were cut in half and examined metallographically.

Fig. 1 shows the etched macrosection of the largest fragment. Scott and Wasson (1976) analysed a small portion from the blunt end of the section facing that shown in fig. 1, which avoided the areas with a dendritic texture visible in figs. 1 and 2. The smaller fragment, which is more extensively cracked and corroded, is not illustrated here but visual examination showed it to contain all the features present in the largest fragment.

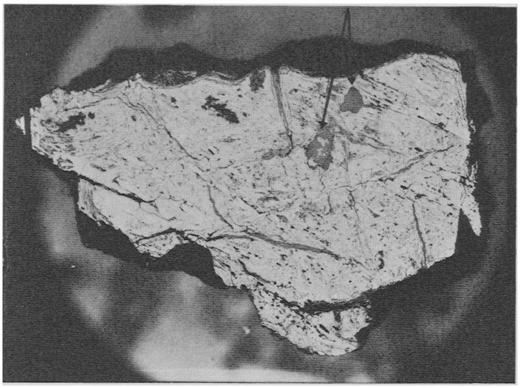


FIG. 1. Macrostructure of the largest (7.2 g) fragment of Verkhne Dnieprovsk (BM 51183) showing finest Widmanstätten structure, cracked and corroded. Two dark etching globules of dendritic melt product are visible near the long edge of the fragment (arrowed). Troilite is present along the long edge. Nital etch. True length of specimen 2 cm. (See also fig. 3.)

The overall macrostructure (fig. 1) is cracked, mechanically deformed, and deeply penetrated by terrestrial corrosion at the boundaries between the kamacite, taenite, and schreibersite of the Widmanstätten structure. There is also cracking and corrosion penetration within the larger dendritic pool of fig. 2, indicating that the dendritic areas suffered terrestrial weathering and were not produced by human agency after recovery. Much of the cracking has been caused by corrosion while the material lay buried in the soil of the Dnieper basin, but from the deformed nature of the macrostructure it is probable that some fissures were already present in the material before the onset of corrosion, even before it entered the Earth's atmosphere. The alternative of damage due to Earth-impact seems less likely, in view of the absence of an associated crater-forming mass, and by comparison with the shock-damaged fragments of the main Cañon Diablo meteorite, which (albeit under different climatic conditions) tend to be free from deep corrosion penetration: the small 'plains' specimens that escaped the shock of impact, however, are deeply corroded (Axon and Couper, 1976).

In making a metallographic examination of Verkhne Dnieprovsk it is convenient to consider first the structure as it was before the effects of local mechanical deformation and terrestrial corrosion, and secondly the implications of the deformation and reheating events now superimposed on that original structure.

The undamaged structure of Verkhne Dnieprovsk consists of an anomalous and imperfectly developed finest octahedrite structure with kamacite band-widths approximately 0.05 mm. The Widmanstätten pattern is continuous throughout the $c.2 \times 1\frac{1}{2}$ cm section of the largest fragment studied, although much of the outer edge of the fragment is occupied by cracked and corroded particles of what appear to have been massive troilite. The kamacite occurs on a microstructural scale as broad swathing zones in contact with the relics of peripheral troilite; as irregular lamellae up to 5 mm long; as shorter stubby lamellae; and as areas of equiaxed grains up to 0.3 mm in diameter. Plessite occurs as net, spheroidal, cellular, and martensitic varieties. Taenite forms discontinuous strips up to 20 μm wide, which border the plessite fields, and blebs within some kamacite plates. The central regions of some of the larger taenite ribbons and spheroids have decomposed to martensitic transformation products. Schreibersite is abundant as 50–100 μm grains and platelets orientated centrally within the broader kamacite lamellae and as filaments substituting for taenite at kamacite boundaries. Rhabdites were not observed. In general, the phosphorus- and nickel-depleted kamacite adjacent to schreibersite is subject to corrosion. Neither cohenite nor graphite was observed.

Shock damage to Verkhne Dnieprovsk consists of local shock effects superimposed on the structure described above. Kamacite displays a profusion of straight, distorted, and degenerated Neumann bands. However, the outstanding features of the etched macrostructure of Verkhne Dnieprovsk are the globular areas with a dendritic texture (figs. 1 and 2), which may extend up to 2 mm in diameter. The spacing of the dendrite arms is $c.2$ μm which, according to Blau *et al.* (1973), indicates a cooling rate of $c.10\,000$ K sec^{-1} as the dendritic area solidified. A bulk analysis of the dendritic region was obtained using an AEI Stereoscan S180 with an energy-dispersive facility and showed 3.4% P, 84.7% Fe, and 11.9% Ni: no other elements were detected. Point analyses in the central spines of the dendrites showed 11.8% Ni, 1.7% P as against values in the interdendritic material of 11.9% Ni, 5.5% P, consistent with the rapid solidification of a phosphorus-enriched melt.

Kamacite well away from the dendritic areas contains only straight Neumann bands. However, at three locations in the specimen there are well-developed shear zones within which the metal is translated and recrystallized. One such shear zone interacts with a small phosphide grain to produce the duplex incipient melted phosphide structure described by Axon *et al.* (1977). This effect is located at X in fig. 3. Adjacent to this incipient melted phosphide the kamacite occurs in the shock-hardened ε form.

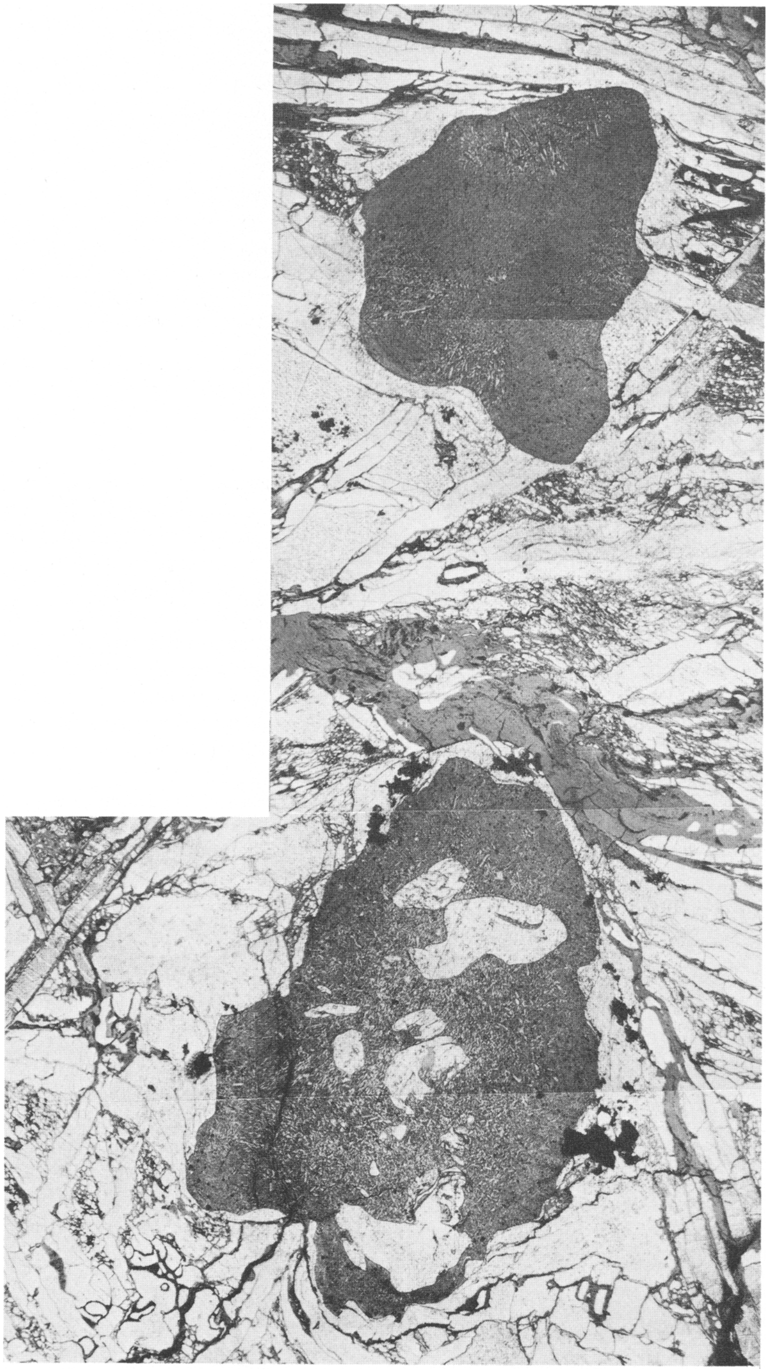
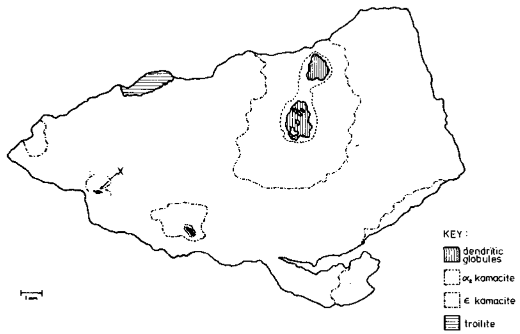


FIG. 2. Microstructure of the dendritic globules of fig. 1 and of the surrounding metal. Photo-mosaic, showing extensive corrosion, finest kamacite bands, and spheroidized plessite. Aureoles of reheated α_2 surround the dendritic globules but light etching does not clearly show the ε-kamacite. A corrosion filled crack runs through the larger globule. True length of this photo-mosaic field 3 mm. (See also fig. 3.)



FIGS. 3 and 4: FIG. 3 (*left*). Map of the distribution of dendritic material, α_2 kamacite, ε-kamacite, and troilite obtained by the microscopic examination of the section shown in fig. 1. FIG. 4 (*right*). Dendritic area in detail showing undissolved fragments of distorted and reheated metal. Field view 0.17 × 0.11 mm. Nital etch.

When the dendritic areas are examined in detail it is seen that they may contain undissolved fragments of distorted and reheated metal (fig. 4): their outer edges also have sharp interfaces with aureoles of unmelted but reheated metal, which may show intense circumferential flow. This is similar to the whirlpool deformation noted by Buchwald (1975) in Durango, Jamestown, Kalkaska, Sandtown, Seneca Township, and Wood's Mountain, which he interpreted as being due to atmospheric ablation: in Verkhne Dnieprovsk, however, it appears to be of pre-atmospheric origin.

The deformed and reheated aureole is surrounded by a zone of shock hardened ε-kamacite that merges into the essentially unshocked kamacite of the rest of the section. Fig. 3, which is a map of the section shown in fig. 1, shows the distribution of the ε-structure in relation to the dendritic pools and it is clear that the shock-hardened kamacite is causally related to the dendritic pools, which must have formed *in situ* by a shock process. Microhardness measurements of the kamacite were made at regular intervals from the dendritic areas outwards, and the results, shown in fig. 5, support the metallographic observations.

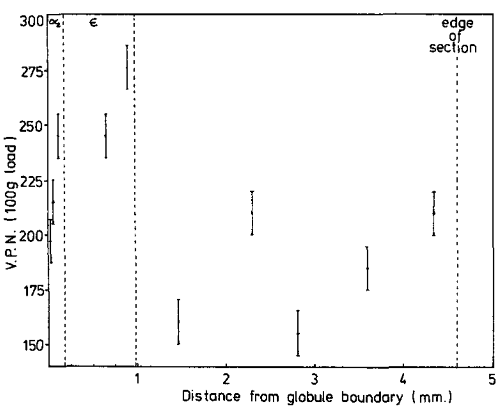


FIG. 5. Microhardness measurements in kamacite along a line outwards from the larger dendritic globule of fig. 1. Within the ε-kamacite the hardness is significantly greater than in the main mass of the kamacite. The over-all hardness is variable because of local distortions.

In both the specimens examined in the present work the dendritic pools are situated on zones of shear deformation. Shear zones in fragments of the terrestrially shocked (crater-forming) Cañon Diablo meteorite have been extensively studied, and a gradation of effects from incipient melting to complete melting of phosphide bodies has been reported by Axon and Couper (1976) and by Axon *et al.* (1977). Phosphide melting in Verkhne Dnieprovsk appears to have originated by a similar process of shock compression and shear, but it differs from Cañon Diablo in being of pre-terrestrial origin and occurring on a much coarser scale. The largest area of dendritic material has a diameter somewhat less than 2 mm but it contains inclusions of unmelted metal. The bulk Ni and P content of the dendritic material is consistent with a melt formed of one part of schreibersite and four parts of metal, which would imply for the largest schreibersite crystal an approximate size before melting somewhat less than 1 mm.

Discussion and comparison

The Verkhne Dnieprovsk structure is unusual both in the scale of its Widmanstätten structure and in the effects of shock on that structure. Using Wasson's (1971) equation relating cooling rate, band-width, and bulk Ni content, which is based on the data of Goldstein and Short (1967), a cooling rate of 830 K Myr^{-1} is obtained for the production

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