

*The metallographic structure of the  
Kodaikanal meteorite*

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*Summary.* From a metallographic study the thermo-mechanical history of Kodaikanal is proposed as a slow structure-forming cool, followed by mechanical damage, then mild reheating, and finally entry to earth.

THROUGH the courtesy of the Keeper of Minerals and Dr. Max Hey it has been possible to examine the macro- and micro-structures of the British Museum specimen of the meteorite Kodaikanal, which is reported (Hey, 1966) as a brecciated octahedrite with silicate inclusions.

Kodaikanal was found in 1898 in the Madura district, Madras, India and was suspected to have fallen about eight years previously. The mass as found weighed about 35 lb. and specimen B.M. 85485 weighs 2325 g. There does not appear to be a published value for the bulk nickel or cobalt content of the metal phase of this meteorite. According to Olsen and Mueller (1964) Kodaikanal contains about 10 % by volume of two types of silicate nodules, which are embedded in the metal; one type consists of glass up to 8 mm across while the other type consists of glass, devitrified glass, and several recognizable silicates and has a size range from 3 to 15 mm across. These authors gave a detailed description of the silicate and glass phases, which they reported to be not fractured and the individual crystals not granulated; they contrasted this situation with the severe deformation that appeared to be present in the metal phase, and they suggested that a pre-terrestrial shock event may have melted the silicates without significantly reheating the metal phase. Deformation and mild reheating of the metal was diagnosed by Buri and Orsini (1966) as a result of their optical and electron microscope study of a 17 g sample from Rome Mineral Museum; they drew attention to the fact that irrespective of whether the term *brecciated* is truly appropriate to this meteorite it certainly shows *granulation* on both the macroscopic and microscopic scale.

The specimen B.M. 85485 is an end-piece with an etched flat surface of some 65 cm<sup>2</sup>. The surface is deeply etched and was prepared some considerable time ago but the preparation is still good enough to confirm the proportion of approximately 10 % silicate nodules and it seems very probable that there is no significant swathing kamacite around the silicates. The macro-structure of the metal consists of large equiaxed grains, approximately 1 in. in diameter, which appear to show no macroscopically visible kamacite along the grain boundaries and within each large grain there is an extremely fine Widmanstätten pattern, the orientation of which varies from one grain to another. There is occasional local deformation and bending of the Widmanstätten pattern.

The outer surfaces of the mass have an irregular corroded appearance with no unambiguous evidence of fusion crust or ablation deposit but it is not certain to what extent the present condition of the surface is due to natural weathering and to what extent it may have been attacked by etching agents when the etched flat was being prepared.

From B.M. 85485 a specimen of 82 g was cut to provide an area of nearly ten square cm. for micro-examination. This micro-specimen was unfortunately free of silicate inclusions so that it was not possible to examine the nature of the silicate-metal interface or investigate the existence of swathing kamacite. However, the Rome specimen would appear to be suitable for such investigation. Apart from the absence of silicate the 82 g specimen showed most of the macroscopic features that have previously been noted, but in addition showed a zone of heat penetration extending inwards from the surface and indicating that the shape and size of the meteorite as recovered was not the result of terrestrial weathering to any major extent. Microscopic examination revealed the usual signs of heat penetration that accompany atmospheric entry, namely ragged  $\alpha_2$  granulation of the kamacite, removal of Neumann bands, melting of phosphides. Low-power magnification of the macro-structure revealed that most of the macroscopic grain boundaries were invested with corrosion product and such boundaries also showed signs of severe local displacement parallel to the boundary interface and were accompanied by macroscopically visible deformation bands in the metal and by elongated distributions of partly remelted troilite, which was smeared out along the deformed boundaries. The small amount of uncracked and undeformed grain boundary that was available for examination showed a pattern of microscopic schreibersite precipitates centrally within a continuous microscopic boundary zone of kamacite. The total width of the kamacite boundary zone is about 0.4 mm whereas

the schreibersites are about 0.1 mm wide and of variable length from one to several millimetres, and are strung out along the grain boundary and occupy approximately three-fifths of its total length. Such a structure would be particularly liable to cracking, displacement, and corrosion penetration along the grain boundaries and the structure of most grain boundaries in the present specimen is consistent with severe mechanical deformation along boundaries that were originally of the type described above.

The structure of the metal within the macroscopic grains and away from the sites of local deformation was a finest octahedral distribution of 0.1 mm kamacite bands, many of which contained centrally placed laths or small particles of schreibersite and a range of plessite structures that, in order of increasing size, showed morphologies that could be described as martensitic, granular, globular, and, in the largest instances, hollow fields of kamacite bounded by a continuous wall of taenite. The plessites had a morphology similar to that encountered in Bacubirito [B.M. 84235], which meteorite has also been reported to contain considerable distortion of kamacite lamellae although no distortion was observed in a small micro-specimen from B.M. 84235.

Some of the micro-structural indications of a low-temperature reheating at about 400° C have been noted by Buri and Orsini (1966) as kamacite polygonization and partial annealing of Neumann lines without visible effect upon the schreibersite and to this may now be added the darkening by precipitation of the deformation bands and the recrystallization of kamacite to micron-size crystals within the deep-seated deformation bands.

The intensity of deformation indicated by the deformation bands is appropriate to a cosmic event rather than to terrestrial damage by man but the pre-terrestrial origin of the deformation bands was proved beyond doubt by the fortunate presence of a deformation band approximately perpendicular to the outer surface of the 82 g specimen and running into the zone of heat penetration. In this instance careful examination revealed grains of ragged  $\alpha_2$  growing across the partly obliterated, and hence earlier, deformation band.

Thus the metallurgical history of Kodaikanal must involve at least a relatively slow cool to produce a finest octahedrite structure within an original austenite grain size of about one inch diameter. Such indications as are available suggest that this cooling rate, although relatively slow, may have been considerably more rapid than is usually encountered in meteorites. This was followed by a drastic pre-terrestrial

deformation, which induced cracking and mutual sliding at grain boundaries, the bending of the Widmanstätten structure and the introduction of deformation bands along surfaces of intense shear deformation. Simultaneous or subsequent mild reheating allowed alteration of the more deformed regions of metal without significant general alteration and the superposition of atmospheric heating effects upon the deformation bands gives a clear indication that the deformation was of a pre-terrestrial origin. It would be desirable to pursue these investigations on a sample that also contained silicate inclusions.

*References*

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