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Temperature Gradients and Atmospheric Ablation Rates for the Barwell Meteorite

WE have been studying the fusion crust of the Barwell meteorite (an olivine-hypersthene chondrite[1]) in order to quantify the way meteorites behave in the atmosphere. We have found that systematic differences occur in the temperature gradients associated with specimens derived from various faces of the original stone. We have also determined the corresponding ablation rates (which seem to be the first to be reported for any stony meteorite), the mass loss and the effective heating time for this meteorite.

Tschermak[2] described the fusion crust as consisting of zones of fusion, absorption and impregnation. The third zone was said by Borgstrom[3] to be troilite-rich. We have confirmed this for Barwell by point counting: four specimens of fusion crust showed an average volume % of non-stoichiometric FeS and non-stoichiometric FeS/Ni-Fe eutectic near 25%, compared with 5% for the bulk matrix. Departures from stoichiometry in the FeS are being investigated with the electron probe.

More recently, Ramdohr[4] has studied the mineralogical changes that occur in the fusion crust. From these he was able to define six zones and estimate the temperatures at four of the zone boundaries (Fig. 1). The outer zone contains two phases—skeletal magnetite in a black opaque glass. All surface morphology occurs in this zone and it is assumed to have been wholly molten and isothermal. It ends abruptly at boundary *a*, after which a zone of opaque glass with no inclusions occurs. At boundary *b* there begins a zone of fragmented crystals which have melted around the edges and are surrounded by darker glass. Boundary *c* marks the start of a zone of unaltered material into which the metal and sulphide has flowed, and finally the original matrix of the meteorite is reached at *d*.

Table 1 Parameters of Heat Flow in Barwell Meteorite

Specimen	Face type	Temp. gradient at boundary *c* (°C/μm) From ablation theory	From Fig. 2	Ablation rate (cm s^{-1})
BM 1966, 59	Front, close	12	5.0	0.35
BM 1966, 65	Front/side, close	7.6	3.9	0.27
BM 1966, 57	Lateral, striated	6.1	3.3	0.22
BM 1966, 57	Rear, warty	3.5	2.3	0.18

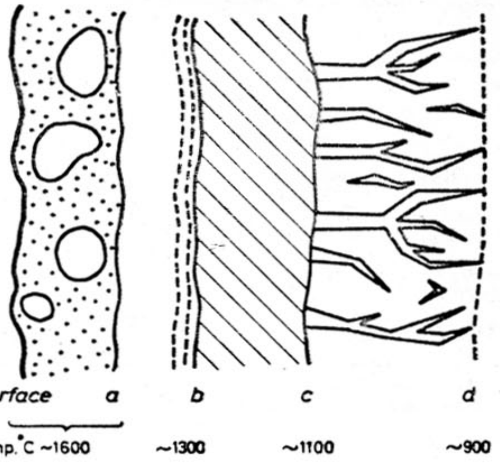

Fig. 1 Schematic representation of the fusion crust. The total depth represented would be about 0.4–0.8 mm, depending on orientation of the face.

We have examined the surface morphology of specimens of the Barwell meteorite and assigned face-type classifications as defined by Krinov[5]. This is a descriptive classification relating flow structures to the orientation of the face from which the specimen came (for example, front, lateral or rear). The Barwell fall was chosen because it is plentiful and contains representatives of all face-types found on stony meteorites. Polished sections were prepared of chips taken from faces of assigned type, and the distances of all four boundaries from the outer surface measured ten times at representative locations. Local differences were numerous but readily identified. The percentage standard deviations were: *a*, 75%; *b*, 29%; *c*, 20%; and *d*, 22%. Except for boundary *a* these values reflect the relative clarity of the boundary. Boundary *a* is very distinct, and the high standard deviation arises because the outer surface from which it is measured is very uneven the irregularities often representing a major proportion of this first zone. The value for boundary *d* is the least meaningful, because it depends as much on the amount of metal and sulphide initially present as on the temperature gradient. Temperatures associated with these boundaries are plotted against distance from the molten-solid boundary *a* in Fig. 2.

It is possible to determine the temperature gradient at any point in the fusion crust from these curves. Unfortunately the errors in such values may be considerable, arising chiefly from the assigned temperatures. An alternative approach involves taking the most reliable temperature/distance data—those for non-stoichiometric FeS melting at boundary *c*—and applying the theory of Bethe and Adams[6] for the ablation of glassy materials. In that case the ablation rate (v_w cm s^{-1}) is given by

$$v_w = -(k/y)\ln(T/T_1)$$

where k is the thermal diffusivity (a typical stony meteorite value is 8.4×10^{-3} cm^2 s^{-1}), T_1 is the temperature at the surface (1,600° C assumed), and T is the temperature at distance y from that surface. With the ablation rate determined, the temperature gradient can then be found from

$$\partial T/\partial y = v_w T_1 k^{-1} \exp(-y v_w k^{-1})$$

Values obtained by this method for the ablation rate and the thermal gradient across boundary *c* are given in Table 1. Eye-estimates of the gradient from Fig. 2 are also given for comparison.

Because the temperature gradients across the fusion crust of a meteorite are controlled by ablation, we expect them to be greater where the rate of ablation is greater. All the thermal gradients determined here show this trend. We believe this is

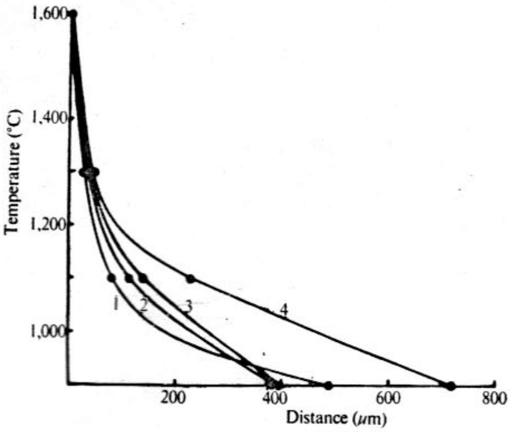

Fig. 2 Temperature as a function of distance from boundary *a* for four types of surface on the Barwell meteorite. 1, Front, BM 1966, 59; 2, front/side, BM 1966, 65; 3 (side) and 4 (rear), BM 1966, 57.

the first instance of stony meteorite ablation rates being determined: irons have already received some attention because of the more readily applicable metallurgical techniques. Their ablation rates are typically about 0.2 cm s^{-1} (ref. 7) which is surprisingly similar to the figures obtained here. It seems that a lower melting point is balanced by a higher thermal conductivity.

The mass loss experienced by the Barwell meteoroid may be estimated by taking the mean ablation rate of 0.25 cm s^{-1} and assuming this was sustained throughout a luminous flight time of 10 s, thereby removing 2.5 cm of material. No direct observation of the luminous flight time of Barwell is available, so we have been guided chiefly by the figure of 9 s quoted for the Lost City meteorite[8]. The ground track and beginning height of the latter are very similar to those of Barwell[9], although the velocity may well have been different. Total reconstruction of the Barwell meteorite from the 47 kg of fragments was not possible, and it is thought that only about one half has been recovered. The actual mass of about 100 kg would be equivalent to a spherical body of radius 19.0 cm. Replacing the material removed by ablation gives an original radius of 21.5 cm and a mass loss of 31%. This is an underestimate, because ablation is greater at altitudes higher than that at which the terminal fusion crust was formed. This figure may be compared with a fossil track estimate of 25% mass loss for the St Severin meteorite[10].

The "effective heating time" of any meteorite may be defined as the period required to form the terminal fusion crust and observable thermal gradients. Both Nininger[11] and Krinov[5] arrive at periods of the order of one second for this parameter. The method we explored to find this figure required measuring the enrichment of "troilite" in the innermost zone by point counting, and applying a knowledge of its rate of flow into this zone. When the latter was assigned a maximum value equal to the ablation rate, our result also was close to one second. It seems that only at the very end of luminous flight does the heat wave penetrate a meteorite to a depth greater than a few tens of micrometres: prior to that ablation must remove material faster than heat penetrates. It also seems that during this final second the Barwell meteorite did not significantly alter its orientation; if it had done so the observed differences would have been smoothed out.

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