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THERMOMECHANICAL FRACTURING OF METEORITES DURING ATMOSPHERIC PASSAGE

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Thermal attack is the basic process that dominates the atmospheric passage of a meteorite. The severity of heating by shocked air (with temperature ranging from 10,000^{o} K to 25,000^{o} K) depends upon pre-atmospheric velocity and angle of entry. It can produce eventually a destructive thermal stress pulse inside the body. While gross fragmentation at higher altitudes seems to have mainly a thermal origin, at lower altitudes the destruction (with occasionally its remarkable abundance of fragments) is likely to be attributed to the combined effect of high temperature and increased pressure. If it is assumed that these conditions control both the number and size distribution of fragments, then much can be learned of the comminution process by studying the fragment distribution in existing meteorite falls.

Aerodynamic heating of those large dense cohesive cosmic bodies that traverse the earth's atmosphere with meteoric velocities, is capable not only of destroying the body surface through ablation, but also of generating destructive pulses that can penetrate them in depth, possibly to their core. An attempt is made below to outline the circumstances under which high-intensity stress pulses of thermal origin contribute to rupture a cosmic body (Jones and Kaiser 1966; McCrosky and Ceplecha 1970).

At heights over 90 km the peculiar erosive action on the surface of a body, resulting from free molecular flow (Bodry 1973), can be regarded as a relatively limited pre-heating. The transition to an entirely turbulent flow regime takes place below about 80 km, which is characterized by the formation of a ballistic shock wave (Korobeinikov, Chushkin and Shurshalov 1973); there, the heating becomes remarkably powerful and efficient. For example, according to the approximate semi-empirical formula of Perini (1975), the rate of heat transfer at the convective stagnation point in front of a non-ablating body with a spherical head of ~13 cm dia., flying with a velocity of 14 km/s at a height of 40 km, is about 4.3 kW/cm^2. However, for an ablating body that injects the ablation products into the gas phase, the actual value would be much lower (Hurwicz and Rogan 1973).

The shocked air also heats the body. At the stagnation point of a spherical body, the simplified procedure of Krosnov (1964) gives approximate temperatures ranging from ~10,000^{o} to ~25,000^{o} K, for velocities at atmospheric entry

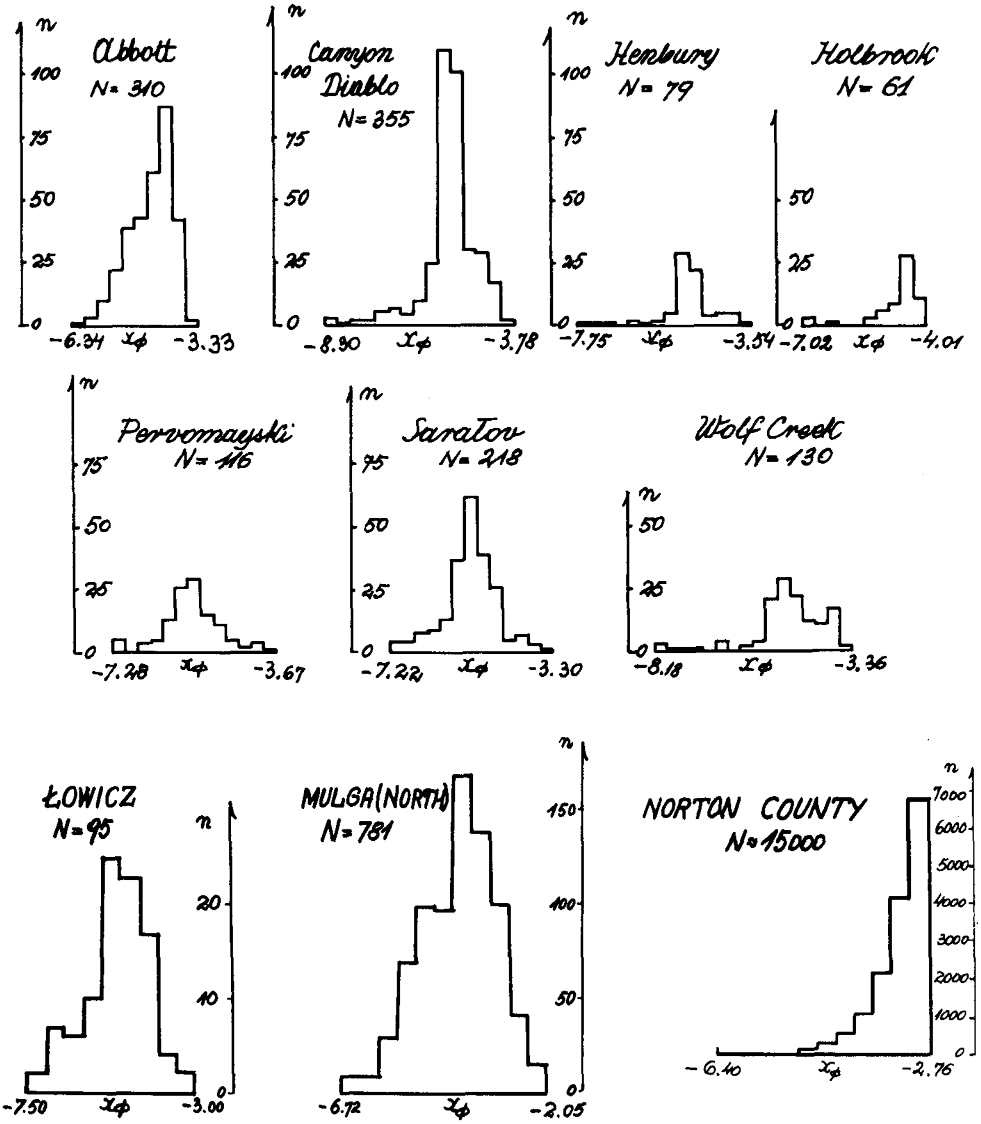

Figure 1a. *Frequency histograms for meteorite fragment populations: abscissae: fragment sizes in logarithmic Krumbein units, ordinates: frequencies.*

Figure 1b. *Examples of near to normal populations.*

Figure 1c. *Example of size distribution corresponding to Pearson Type I J-shaped distribution.*

between 11.2 and 22 km/s. The same procedure gives for the initial pressure (H ~ 80 km) of the stagnation point, an estimate of ~0.1 atm. With increasing air density in the lower atmosphere, this pressure of a decelerating body gradually rises to a level of several tens of atmospheres at heights 40 - 30 km. Compared to the possible rate of change of temperature along the trajectory, the rise of the pressure is slow and delayed. Compared with the compressive strength of 1770 kg/cm^2 and the tensile strength of 230 kg/cm^2 for stony meteorites (Baldwin and Sheaffer 1971) the pressure alone, neglecting high-temperature heat attack, can hardly be regarded as an efficient destruction factor.

The breakup of cosmic bodies before reaching the ground occurs at least one in every four falls. For about one in twenty falls the number of fragments is high enough to be statistically significant. A record of the fragmentation process is stored in the size distribution of the meteorite fragments. For some of these cases, we have converted mass values into logarithmic phi units (Krumbein 1936; Frost 1969), and plotted size distributions in the frequency histograms of Fig. 1. The moments, used for analysis of these distributions have been calculated according to standard procedure (Mitropolskij 1971). The analysis covers all fragments from available published data.

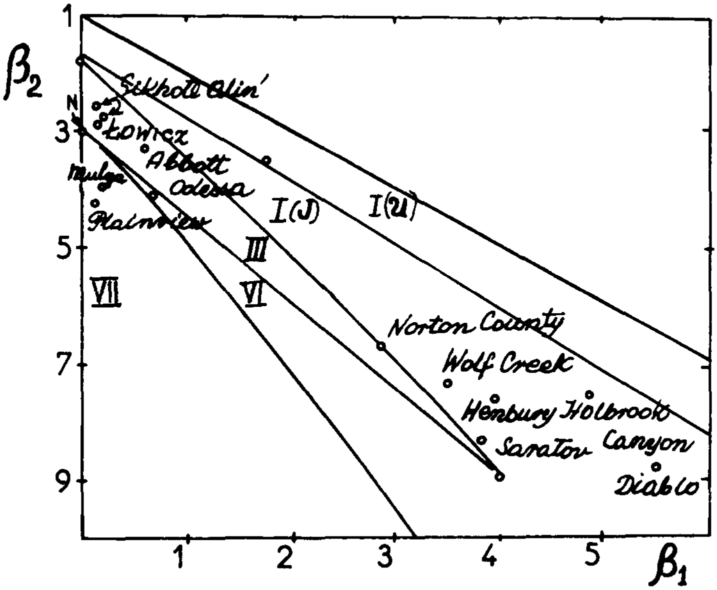

Figure 2. Pearson chart with mapped points representing meteorite fragments populations analyzed statistically. The Roman figures represent the different Pearson types of frequency distribution; the two subclasses in type I are distinguished by J and V to separate the J-shaped and the U-shaped distributions. Point N(0,3) is the normal distribution. Fragment populations clearly cluster in two groups, one near point N, another one far away in the J-shape distribution.

The calculated moments β_1 and β_2 corresponding to particular meteorite fragment populations were mapped on the β_1,β_2-plane of the Pearson chart of frequency distributions (Fig. 2). There appear to be two groups: the first being near normal (0,3), the second belonging to Pearson Type I J-shaped distribution (Elderton and Johnson 1969; Hahn and Shapiro 1967).

The normal (lognormal for natural mass units) distribution suggests classical Kolmogorov chain mechanism of comminution (Kolmogorov 1941; Aitchison and Brown 1957; Lang 1972). This mechanism seems to be compatible with a prompt, smooth transition from a purely thermal destructive action, to that due to the coupling of high temperature with increased pressure.

The Pearson Type I J-shaped distribution seems to record these as two distinct events. In the first event, thermal attack prevails and yields large fragments. The second event seems to be an impact-like, eventually highly efficient, coupling of high temperature and increased pressure, responsible for the abundance of small and very small fragments. The tailing towards larger fragments (more negative values for phi units) in J-shaped distributions seems to be due to relicts from gross fragmentation (Lang and Liszewska 1973).

An acceptable explanation of meteorite fragmentation cannot be given without an answer to the question of why the majority of meteorites are single non-fragmented bodies. The severity of the thermal attack in relation to the spallability property of the body seems to play here a most important role. The temperature behind the front of the shock wave and the subsequent heat transfer rate to the body are primarily functions of the intensity of the shock wave. While the latter depends upon the velocity of flight and the air density, the integral effect of heat transfer, equal to the rate of decrease in kinetic energy, is determined by deceleration and air density gradient along the trajectory as imposed by the angle at atmospheric entry. One can speculate, that apart from differences in mechanical properties, including spallability, size, shape, surface structure, thermal properties, etc., for given admissible pre-atmospheric velocities, meteorite fragmentations occur within a defined interval of angle values at atmospheric entry. Such an interval possibly offers an array of conditions, controlling both the number of fragments and their mass and size distribution.

A contribution of other factors of destruction is not to be excluded either. Gross fragmentation of the body can produce a transient space configuration of fragments of very short duration, channeling the hot plasma-like air to form some kind of piercing jets.

The abundance of fragments can be increased by a possible destructive thermal shock from a rapid cooling of the body, after decay of the shock wave.

The above suggestions may be supported in two ways. The first is offered by the advances in exploration of thermal rock fracturing (Lauriello and Chen 1973). Particularly encouraging is the work of Thirumalai and co-workers (1974), who report the computed stress distribution inside a solid sphere under local heating, resembling heat transfer to the body during its atmospheric passage. The authors also explain why fracture initiation critically depends upon tensile strength.

The second way comes from the incorporation of the relevant advances in space technology into meteor study. With its present status, a successful prediction of the two most important aspects, flow field and material ablation, can be expected.

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DISCUSSION

MCINTOSH: In some work we are doing at Ottawa on ablation of meteorites, D. O. Revelle finds that in the low atmosphere region (30 - 40 km) radiation heating dominates convective heating by a factor of about 5. Therefore heating rates are much higher than predicted by convective heating only. Have you taken radiation heating into account?

LANG: No. Only the convective part of the heat flux was accounted. The detailed computation must include contribution of radiation to the heat transferred to the body.

A REFEREE: The fragmentation process may also be considerably influenced by the occurrence of stresses, fracture planes, etc., induced by the prehistory of the body, perhaps in the heating and cooling regimes of its origin, or in shock effects at its later collisional breakup.

THE EDITOR: Although the relevance of Lang's interesting contribution to the major theme of the book was not directly apparent, it represents a valuable paper, taking largely into account the work done in Central and Eastern Europe on the thermodynamics of meteorite passage through the atmosphere; however, if it has been kept here, it is mainly because of the previous remark of a referee: When we understand the fragmentation process better, we may indeed recognize further clues on the shock history of the meteorite bodies, connected to their origin and evolution in the early solar system.