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THE CRACKING HISTORY OF *SERRANIA DE VARAS:* AN ALTERNATIVE VIEW

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Buchwald's (1975) theory of thermally induced cracking in Serrania de Varas *is critically examined from the standpoint of elementary stress analysis. New metallographic observations are presented. It is suggested that thermal cracking is unlikely to have been operating in this material.*

INTRODUCTION

The *IV* A chemical group of siderites embraces compositions in the range Ni 7.3-9.5%; P 0.02-0.18%; Ir 3.5-0.12 p.p.m. and, according to the self consistent Ni, Ir values of Wasson (1974) there is a hiatus at 8.5% Ni; 0.1% P; 1.25 p.p.m. Ir separating 27 "low-P" from 10 "high-P" irons. These designations are relative; all *IV* A's are of low phosphorus content compared with other siderites.

The 27 sub-group includes the *Gibeon* shower, where different fragments display microstructures ranging from Neumann bands to shock hardened ε to reheated metal. A similar structural range occurs in the other *IV* A meteorites in both subgroups.

Excluding Gibeon the average mass of the "low-P" group is 44 kg against 8 kg for "high-P."

Although *Serrania de Varas* is unambiguously "low-P" *IV* A it is unusual in its small size (1.5 kg), aerodynamically sculpted shape and impressive but variable (0.1 mm-7.0 mm) depth of visible heat alteration zone (h.a.z.). The pre-terrestrial structure below the h.a.z. shows evidence of non-uniform strain, viz:

(i) distinct adiabatic shear displacements that trans-sect the whole mass;

(ii) approximately equal proportions of monocrystal and polycrystal (= recrystallised) kamacite.

PREVIOUS INVESTIGATION

The main mass in the British Museum was briefly described by Fletcher (1889) but there was no detailed metallographic investigation until Buchwald's (1975) report. He recognised no artificial reheating nor hammering; hence the shear deformation and partial recrystallisation are of cosmic origin. Buchwald paid particular attention to the macroscopic crack distribution, Figure 1, and suggested that "the longest extend to the inner edge of the h.a.z., but only occasionally continue to the surface," from which he concluded that the cracks were "associated with the atmospheric flight [and were] . . . due to tension in the interior which is caused by tensile forces set up in the exterior part of the mass. Such a situation may be assumed quite normal for an iron penetrating the atmosphere, but will only . . . lead to fissuring when [the h.a.z.] constitutes a significant portion of the whole mass, as is the case with *Serrania de Varas*." He further described the cracks as "narrow, (1-15 μm), and partially filled with terrestrial corrosion products."

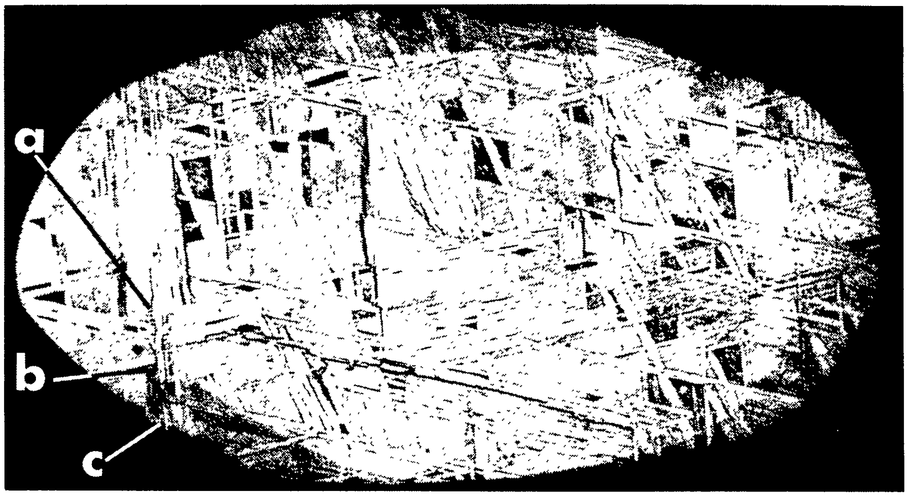

Fig. 1 **Slice from the flight-oriented main mass of *Serrania de Varas* B.M. 53323. Typical *IV* A structure plus cracking and h.a.z. The location of this slice is such that only 10% of its periphery intersects the frontal ablation surface of the meteorite. Location of Figures 2a, b, c indicated. Nital etch. Mosaic.**

PRESENT REINVESTIGATION

The approximate dimensions of Buchwald's section, Figure 1, are 5.7 × 3 cm and the maximum visible depth of h.a.z. is 0.7 cm at the acute ends of the ellipse, but decreasing greatly elsewhere. Buchwald argued that the cracking was induced by triaxial tension set up in the interior of the meteorite when the outer layers were flash-heated and quenched. However, to investigate the position further, we have analysed a very simple model in an attempt to quantify the internal stresses that might result from surface heating. The results of this analysis cast some doubts on Buchwald's theory. Consequently, we conducted a more detailed microscopic examination of the distribution of cracks in the specimen.

Stress Analysis

Let us consider the flash-heating of a sphere of material, and assume that there is a step discontinuity in temperature at the interface between the flash-heated layer and the material in the sphere interior. The circumferential strain at this interface will be $\varepsilon_{CIRC} \sim \sigma^*/E$ where E is the Young's modulus of the material and σ^* is the flow stress of the material in the flash-heated layer.

Now for a purely radial displacement situation as in the present simple model, classic elasticity theory easily shows that, for the material within the sphere interor, the stresses and strains are uniform (i.e. do not depend on position) and that the radial tensile stress is everywhere equal to $E\varepsilon_{CIRC}/(1\text{-}2\nu) \sim \sigma^*/(1\text{-}2\nu) \sim 2.5\sigma^*$ with Poisson's ratio (ν) equal to 0.3. Since it is hard to imagine that the fracture stress of the interior material will be as low as this value, remembering that σ^* is the flow stress of the flash-heated material, Buchwald's view that the cracking is due to the stresses generated within the interior of the meteorite when the outer layers are flash-heated, is not easy to sustain, at least on the basis of this very simple analysis.

Metallographic Examination

Through the courtesy of the British Museum we have reprepared and reexamined Buchwald's section. We confirm his observations on

(i) non-uniform strain and consequent patchy recrystallisation of kamacite,
(ii) local accumulations of ablation melt product at the thickest h.a.z. and
(iii) the distribution of visible h.a.z.

Terrestrial corrosion complicates the discussion; not only does it alter the outline of pre-existing sharp fracture surfaces, it may also extend existing cracks by the volume jacking stresses that accompany the more voluminous products of corrosion. Hence some of the smaller corrosion filled cracks may be of secondary-terrestrial corrosion-origin. Our present discussion is restricted to corrosion-free cracks.

Figures 2a, b, c are a sequence taken from the same, corrosion-free, crack system. It progresses from (a) the unheated interior to (b) midway in the thick h.a.z. and (c) the edge of h.a.z. The background structure changes from (a) monocrystalline kamacite with minor cosmic recrystallisation and Neumann bands to (b) and (c) α_2 reheated metal. The cracks tend to run along $\alpha-\gamma$ or $\alpha-\alpha$ phase boundaries of the unheated material, Figure 2a. As we follow the crack from (a) to (b) its originally sharp form becomes thermally rounded and at (c) it progressively welds up, leaving only a pattern of globular holes to mark the original path of the crack. This and other partly healed cracks in the h.a.z. do not have their dimensions enhanced by the intrusion of corrosion product. If the rounding and welding effects of heat are also allowed for, it appears that the crack population density is similar in the h.a.z. and interior regions. Thus the gradual change of crack morphology through the h.a.z. is consistent with an initially uniform population of cracks being subject to progressive annealing.

DISCUSSION

The microstructure of *Serrania de Varas* is complex, but within the compass of known *IV* A structures. The complexity arises in part from inhomogeneous strain and heating applied pre-terrestrially to the original Widmanstätten structure. Macroscopic and microscopic cracks in other *IV* A meteorites have been reported extensively by Buchwald (1975) and ascribed to preterrestrial fragmentation events.

In the available section of *Serrania de Varas* the h.a.z. is very impressive. However the analysis of *Stress Analysis* casts doubts on the generation of internal cracks by thermal stressing of the h.a.z. type. Furthermore, the progressive healing of cracks in the thick h.a.z. indicates that they were present whilst the h.a.z. was being formed. The thick h.a.z. is overlain by layers of ablation melt product and thus qualifies as a region of ablative *build-up* rather than ablative loss. Thus the cracks in the thick h.a.z. are not an early generation of thermal cracks that have been healed by the later encroachment of an inward moving ablation front. The progressive healing of cracks within the thick h.a.z. also implies plastic (creep) adjustment of metal at the high temperature part of the thermal cycle. Subsequent cooling of the plastically adjusted h.a.z. would produce tension in the rim and compression in the core of the body. This is the opposite condition to that required by the thermal cracking history.

We conclude that the cracking pattern in *Serrania de Varas* arose from pre-terrestrial impact events and it is not necessary to invoke thermal stresses generated by atmospheric burn up. The internal stress distribution in irons is not easy to determine in detail but an

Fig. 2 Micrographs of the crack system Figure 1.

a) Unheated portion of crack in kamacite, typical of impact fracture.

b) Same crack in h.a.z. showing rounding and partial healing of crack in α_2.

c) Same crack near back surface of meteorite, showing progressive welding of the original crack with increasing temperature in the h.a.z.

Nital etch. Scale bar 0.2 mm.

attempt would be worth considering in suitable cases. Antarctic siderites might be acceptable alternatives to fresh falls for such work.

REFERENCES

Buchwald, V.F., 1975. Handbook of Iron Meteorites. Center for Meteorite Studies, Arizona State University and University California Press, Berkeley.

Fletcher, L., 1889. On the meteorites, which have been found in the desert of Atacama and its neighborhood. *Mineralog. Mag.* **8**, 223-264.

Wasson, J.T., 1974. Meteorites. Springer-Verlag, New York.

APPENDIX

We are grateful to Vagn Buchwald for a helpful review. We acknowledge that the ablation process is complex. It involves moving temperature gradients. Our very simple analysis of potential stress systems is based on the highly simplified but mathematically convenient model of an unheated interior in static equilibrium with a uniformly heated h.a.z. and with a temperature step discontinuity between the two parts. The crux of the argument is that the low (σ^*) flow stress of the flash heated outer zone is capable of generating only $2.5\sigma^*$ internal stress in the cold interior and this is too low to produce fracture in the unheated material, because of the very high temperatures in the heated zone.

It might also be helpful to record that the Section shown in Figure 1 represents the first thin vertical slice cut through the edge of the oriented cone shaped mass with its base uppermost in the picture. The conical surface of the whole mass shows regmaglypts and has been subject to ablation. The rear surface is smoothly rounded and covered with ablation deposit. The unusually broad h.a.z. in Figure 1 corresponds to the rear surface of the oriented mass and to the girdle at which the flat rear surface meets the conical ablation surface. It would be instructive to have a more deep seated section for study.

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