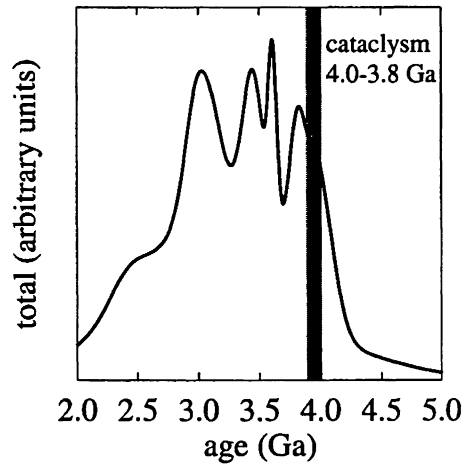

Fig. 1. Each clast age is represented by a Gaussian curve with a unit area. The ideogram is the addition of all impact-melt-clast Gaussians.

impact events are represented. Though the young ages of some clasts preclude their formation in basin-forming events, their crystalline and clast-free nature imply that they were created in large craters. A similar age distribution is seen in the oldest lunar spherules [8]

Implications: The lack of impact melt >3.9 Ga in lunar meteorite samples supports a cataclysm in the Earth-Moon system. On the Moon, this produced more than a thousand large (>20-km-diameter) craters, including basins and swarms of secondary craters [9]. The number of impacts occurring on Earth would have been an order of magnitude larger, implying >10,000 large impact events in a brief time. The largest of these probably produced immense quantities of ejecta, temporarily charged the atmosphere with silicate vapor, and boiled away large quantities of surface water [10]. Interestingly, the earliest isotopic evidence of life on Earth comes from this same period of time [11]. Impact events of these sizes on Earth would have affected the environment and most likely any life that had arisen [e.g., 12].

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MAGNETIC PROPERTIES OF HEMATITE IMPACT BOMBS AND ASSOCIATED IRONSTONES FROM THE ARAGUAINHA ASTROBLEME, CENTRAL BRAZIL.

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The 40-km-diameter Araguainha astrobleme is located in the Guimarães highland at the border between the states of Mato Grosso and Goiás (16°47'S; 52°59'W [1]). The target rocks affected by the impact event are principally Paleozoic siltstones, claystones, and red sandstones. The astrobleme is a well-defined circular structure, with a raised rim and a central uplift characteristic of a complex impact crater [2].

The hematite-rich impact bombs occur within some domains of the suevitic breccias in a radius of a few kilometers from the uplifted core. The bombs display a variety of shapes and sizes (5–50 cm) and commonly show an asymmetric geometry with concave and convex sides. The bombs present a gradual increase in porosity from the concave to the convex side, and a noticeable internal linear fabric of hematite crystals (in the form of conical aggregates), suggesting a mechanism of aerial crystallization and aerodynamic sculpturing during their development [3].

The permanent magnetization (natural remanent magnetization, or NRM) of different hematite-rich materials from this astrobleme (porous hematite bombs, massive hematite bombs, and undeformed ironstones) has been investigated for evidence of their origin and evolution.

The investigated ironstones, forming part of the country rock, were probably not affected by the impact. This material possesses a relatively weak NRM that is extremely stable against alternating field demagnetization but has an anomalously low blocking temperature (120°C). This NRM appears to be the result of moderate heating and subsequent cooling in the Earth's magnetic field. Samples of the porous hematite bombs are very strongly magnetized with high stability and a blocking temperature near the hematite Curie point (680°C). The NRM could have been acquired by cooling in the Earth's magnetic field after heating to high temperature. The NRM of the massive hematite bombs lies between that of the parent rock, and the porous hematite bombs also display high stability and high blocking temperature. However, laboratory experiments show that this NRM cannot be explained by cooling in the Earth's field as proposed for the porous material.

The different basic magnetic properties of the porous and massive hematite bombs suggest different thermal histories, although both are believed to have originated as molten ejecta from the impact site. Various genetic scenarios will be described in this paper, including the possible importance of shock in contributing to the observed magnetic properties.

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ON THE REMELTING OF TYPE B CALCIUM-ALUMINUM-RICH INCLUSIONS.

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We have shown [1–3] that the variation in the minor-element concentration of spinels ($MgAl_2O_4$) and their relationship to host silicate chemistry from type B CAIs is a powerful tool in constraining the igneous history of these objects. We conducted electron microprobe studies of the minor-element distributions among spinels from three type B1 CAIs: Allende TS-34, Allende TS-23, and Leoville 3537-2. By maintaining the petrologic context (edge, middle, and center of the inclusion plus their host silicate phase), four populations of spinels are resolvable based on their positive Ti to V correlation. Grains from the middle and center areas define trends that are divided into three populations: spinels enclosed by melilite, fassaite, and anorthite. These grains also show important Ti, V, and Cr correlations with their host silicate chemistries. The other population resides within the edge area (mainly mantle melilite) and is characterized by the highest V contents with little chemical relationship to their host silicates.

If these objects formed from a single-stage fractional crystallization event the overall range in Ti and V concentrations should be at most a factor of 2 [3]. The observed range is, however, considerably larger (up to a factor of 8 in Ti and an order of magnitude in V for TS-34). Thus even if we regard partition coefficients as a free parameter, a single-stage fractional crystallization model (SSFCM) cannot explain type B CAI formation.

A nearly bimodal distribution exist between the Ti, V, and Cr contents of spinels to the host melilite X_{Ak} contents, separated at ~X_{Ak} of 0.4 for each inclusion. At $X_{Ak} > 0.4$ an overall negative trend is observed in each case, suggesting that spinels enclosed within melilites with a $X_{Ak} < 0.4$ formed differently than those enclosed in melilite with $X_{Ak} > 0.4$. Such trends are not predicted in a SSFCM.

A positive relationship exists between the Ti and V of spinel grains to the Ti and V concentration of host fassaites. Such a relationship suggests a possible contribution from subsolidus reactions and cannot be completely ruled out yet [1,3]. This relationship, however, is also not a prediction of a SSFCM.

The simplest explanation for the observed trends is that that these objects experienced at least one additional melting event after their initial formation.

This event heated these object to ~1250°–1350°C, partially melting them. Much of the core of these inclusions melted (anorthite, fassaite, melilite with $X_{Ak} > 0.4$, and possibly some spinel), producing a new liquid rich in Ti and V. Upon cooling, spinel + fassaite crystallized first. Titanium and V are more compatible in fassaite than spinel and thus the liquid composition trend was impressed on the co-crystallizing spinels, explaining the positive correlation between Ti and V of spinel to Ti and V of fassaite. The absence of Ti-rich spinels in melilite shows that it crystallized after spinel and fassaite in the last melting event.

It is clear from our data that type B CAIs have experienced multiple-melting events, possibly including many episodes of alteration and are thus not pristine. Thus their thermal histories are more like chondrules than previously discussed: They have both experienced epochs of multiple melting. Any model that realistically could have produced these objects *must account for their remelting*. Perhaps a potentially more important source of pristine early solar system derived materials is a compact type A (CTA) inclusion. Our understanding of the formation of CTAs is in its infancy and requires exploration in greater detail.

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LITHIFICATION SCENARIOS FOR ORDINARY CHONDRITES.

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Introduction: An ordinary chondrite is the lithified accumulation of chondrules and dust. Porosity studies and inspection of thin sections [1] suggest that the average 10% porosity of ordinary chondrites can be accounted for by post-lithification cracks, and probably does not represent void spaces between chondrules and dust grains. Lithification was complete.

When, where, and how did this lithification take place? Was the lithification process rapid or slow? Is it related to subsequent episodes of metamorphism? Is it related to the processes that lithify breccias? Did it depend on conditions present only in the early solar system? To understand how to go about answering such questions, it is useful to start with a range of possible lithification scenarios.

Terrestrial rocks such as sandstones lithify from the application of pressure, heat, solvents, and time. A deficit of one of these ingredients can be compensated by a surplus of another. With this in mind, we can suggest possible events in the history of the meteorites where lithification could have taken place.

Collision Scenarios: Collisions provide an obvious source of pressure and heat. However, many meteorites show no evidence of shock metamorphism and yet still are well lithified. And collisions are also the most likely source of the cracking, fragmentation, and destruction of meteorites. But lithification might occur in low-speed collisions, or far from the point of impact.

Low-speed impacts are possible in the early solar nebula. The presence of a gas would result in materials of different sizes and densities orbiting at slightly different speeds; collisions between such objects could conceivably take place with enough energy to lithify, but slowly enough to prevent shock metamorphism. The absence of a perturbing planet like Jupiter would also prevent collisions from being too violent. In this scenario, the initial lithification of meteorites would occur quickly, and would depend on conditions present only in the early solar system.

Impacts into a parent body produce shock waves that may destroy material at the point of impact, but that could merely cause compression at sufficiently large distances from the point of impact. Such a scenario could account for the lithification of breccias in present-day asteroids. However, the first round of lithification must have taken place between relatively large unlithified parent bodies. The transmission of shock waves in such an originally highly porous (unlithified) planet body needs to be better understood.

Slow Lithification Scenarios: In the absence of high pressures or heat, lithification reactions proceed slowly, but much longer timescales than on Earth may be available for meteorite lithification.

Early parent bodies might have been much larger than present-day asteroids; the material in the asteroid belt today represents only a tiny fraction of that originally present. Terrestrial sandstones lose their porosity at pressures higher than a few hundred kilopascals. But parent bodies large enough to have internal pressures and temperatures sufficient to lithify chondrules and dust would have to be larger than Ceres. Dynamical models suggest such large bodies should have remained intact to this day.

Pressure solution in terrestrial rocks allows lithification to proceed more quickly, with less pressure, if a solvent such as water or CO_2 is present. But the low oxidation state of ordinary chondrites argues against such a solvent. On the other hand, more time may be available for meteorite lithification. And the absence of an oxidizing atmosphere may mean that fresh surfaces in contact can coalesce ("cold welding") more readily in space than on Earth. The rate of such welding under space conditions deserves further study.

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LICHTENBERG, BENZENBERG, BRANDES, AND THEIR METEOR HEIGHT DETERMINATION IN 1798–1800: AN EMPIRICAL APPROACH TO SOLVE THE METEORITE ENIGMA.

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"Lichtenberg sprach am letzten Morgen seines Lebens irre und sprach viel von den Dämpfen, von den Sternschnuppen und Gotha, von der Bestimmung der Deklination der Magnetnadel..." Benzenberg to Brandes [1].

The last words of G. C. Lichtenberg (1749–1799) have come down to us by a letter from Benzenberg to Brandes, from one pupil to another, telling us from the scientific projects Lichtenberg managed in his last years: inter alia about meteors ("Sternschnuppen") and about the first scientific congress ("Gotha") in which small planetary bodies were one of the topics. J. F. Benzenberg (1777–1846) as well as H. W. Brandes (1777–1834) were strongly involved in both of Lichtenberg's projects.

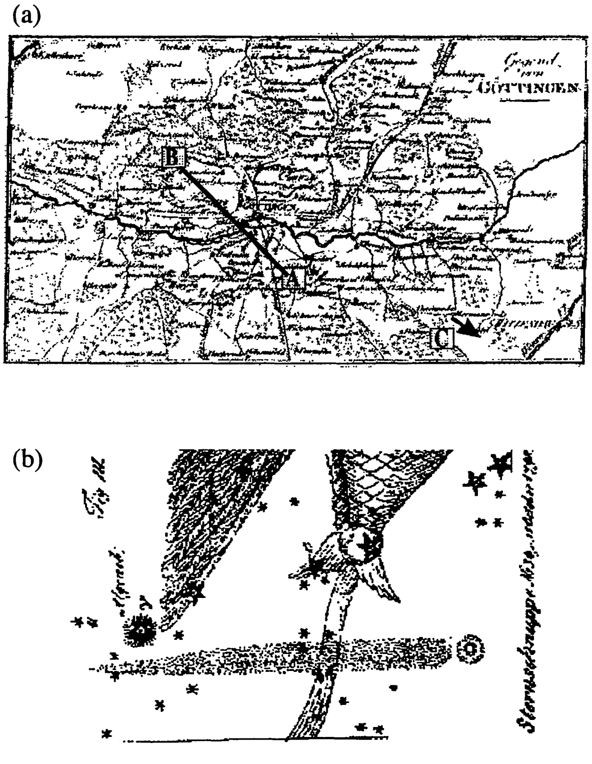

Fig. 1. **(a)** The baseline at Benzenberg's and Brandes' first three observation days was between Ellershausen (A) and Clausberg (B) about 8791 m away. Afterwards, it was prolonged to Sesebühl near Dransfeld (C, outside map) up to 15,615 m. **(b)** Sketch of meteor No. 34 from October 14, 1798.