SIMULATION OF SHORT-TERM HIGH-TEMPERATURE IMPACT PROCESSES BY USING A HIGH-ENERGY LASER BEAM

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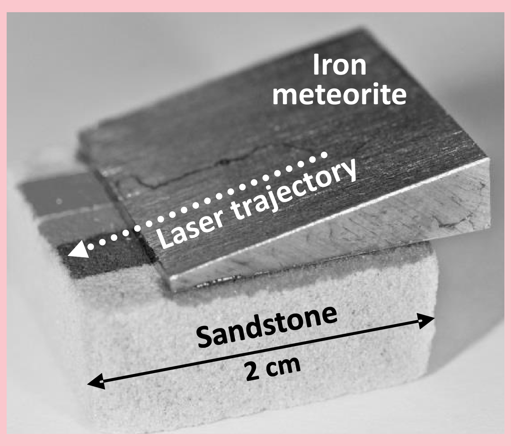
Introduction

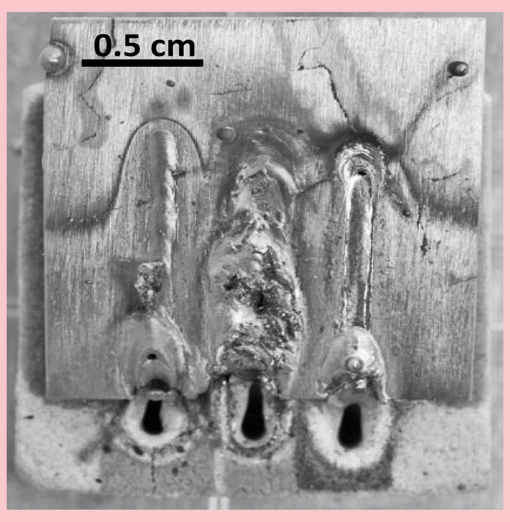
This study introduces an experimental approach that uses a high-energetic laser beam (Trumpf Haas HL 3006D; Nd:YAG-laser 1064 nm) simulating the virtually instantaneous melting taking place during meteorite impacts. High-speed imaging, time- and space-resolved temperature measurements, and detailed petrologic investigations of the irradiation target (sandstone) and projectile (iron meteorite, steel) materials, clearly show features very similar to those of impactites from meteorite craters and hypervelocity impact experiments, i.e., formation of lechatelierite, partially to completely molten sandstone, and injection of projectile droplets into the target melts. The target and projectile melts have experienced significant chemical modifications during interaction of these coexisting melts.

Experiment conditions

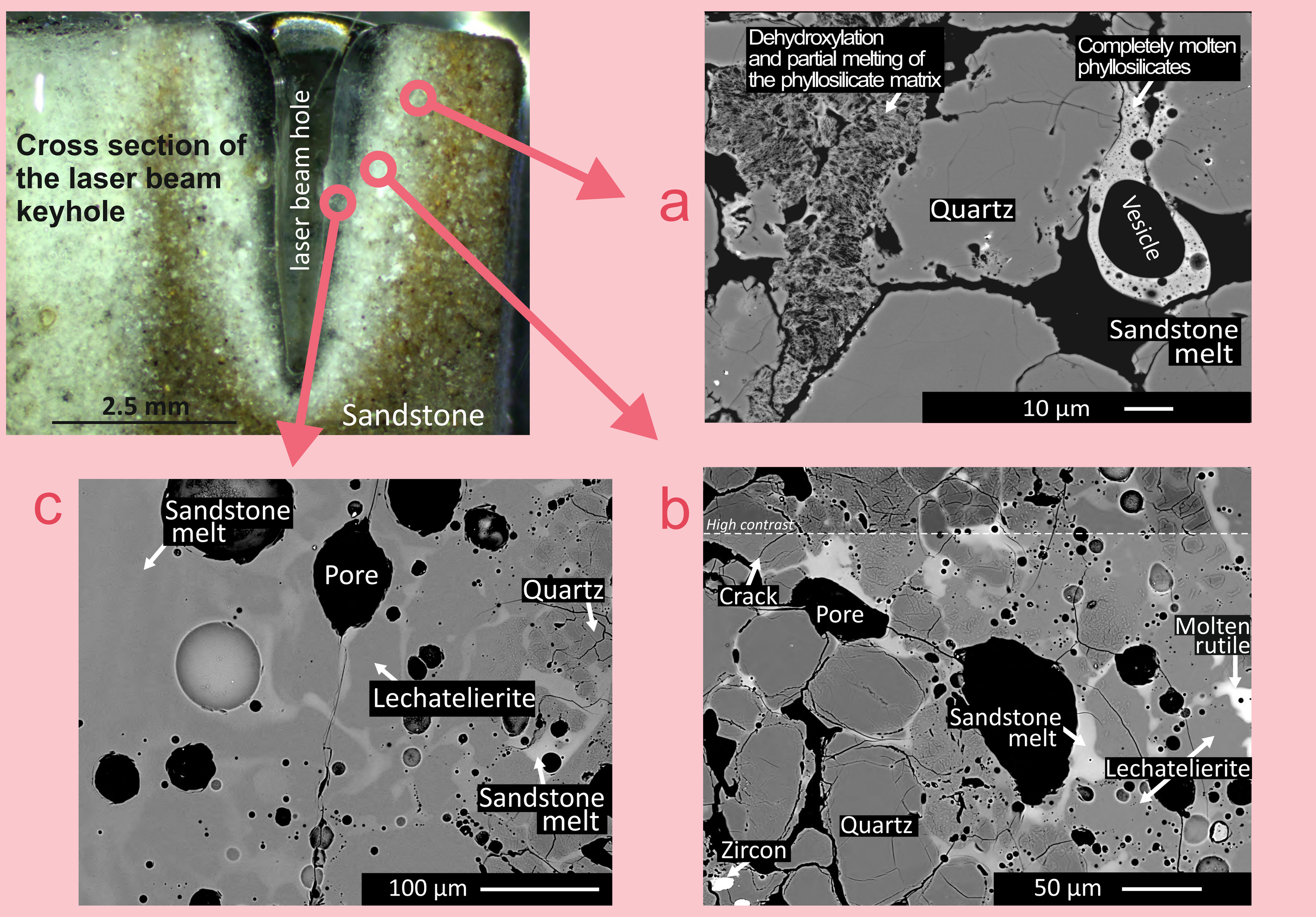
Name	Target material	Projectile material	Laser power	Duration of irradiation	Laser track length	Laser point diameter
LE-F	Sandstone	No Projectile	2.5×10^5 W cm^{-2}	0.5 s	Point	1 mm
LE-G	Sandstone	Steel	2.5×10^5 W cm^{-2}	1 s	1 cm line	1 mm
LE-H	Sandstone	Steel	2.5×10^5 W cm^{-2}	1 s	1 cm line	1 mm
LE-I	Sandstone	Iron meteorite	2.5×10^5 W cm^{-2}	1 s	1 cm line	1 mm
L887	Sandstone	Iron meteorite	5.3×10^4 W cm^{-2}	2 s	2 cm line	2.2 mm

Laser-induced partial melting



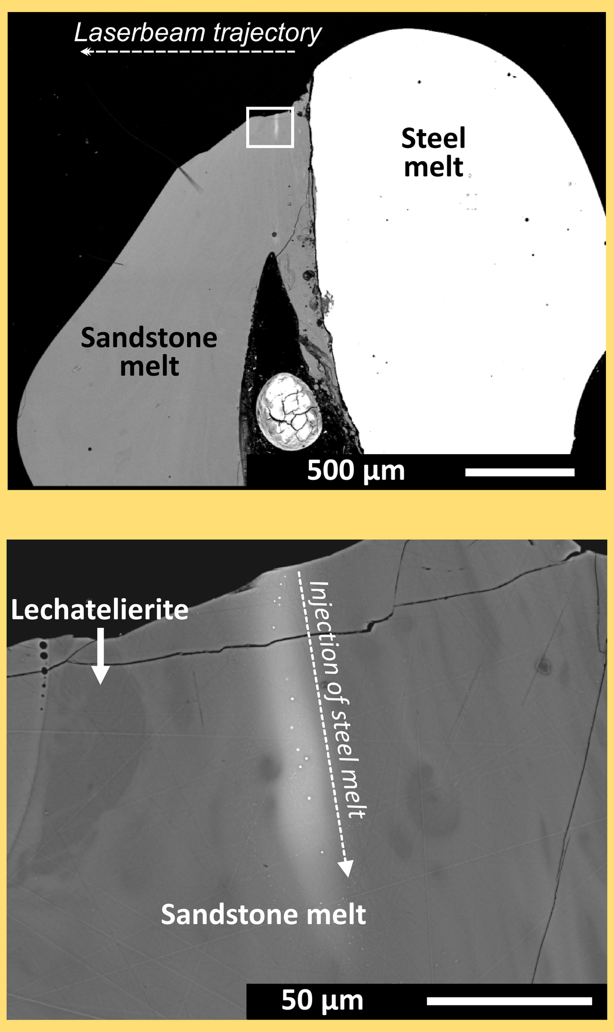


Experimental setup before (top) and after (bottom) laser beam irradiation. The laser beam was automatically rastered along 1cm lines across the two materials.

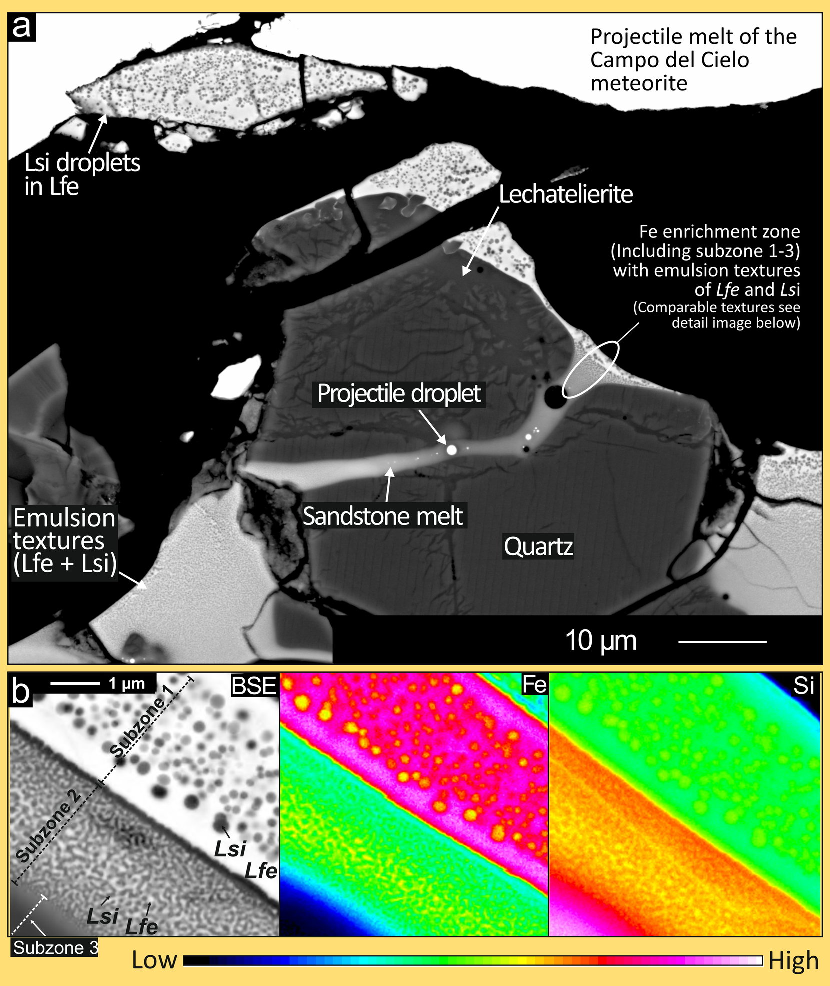


(a) Dehydroxylation and initial melting of the phyllosilicates (kaolinite, illite, muscovite)
(b) Initial formation of lechatelierite; melting of qtz starts at their margins and propagates inwards
(c) Complete melting and mixing of the sandstone minerals

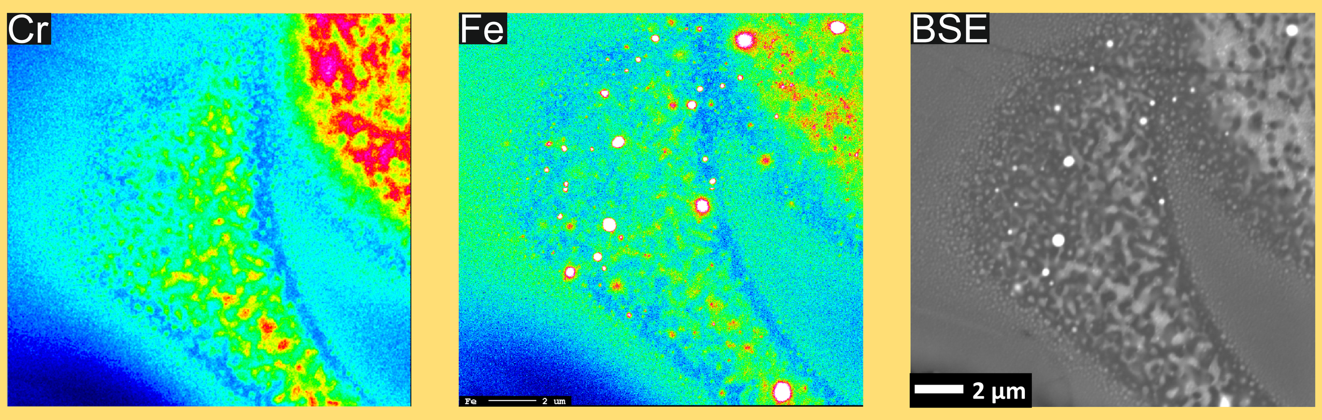
Mixing of target and projectile melts



(Top) molten contact between steel and sandstone; (bottom) completely molten sandstone with injection path of projectile melt. Melting of quartz indicates temperatures of 1996 K (melting point of quartz) and assuming melting took place at constant (i.e., atmospheric) pressure.

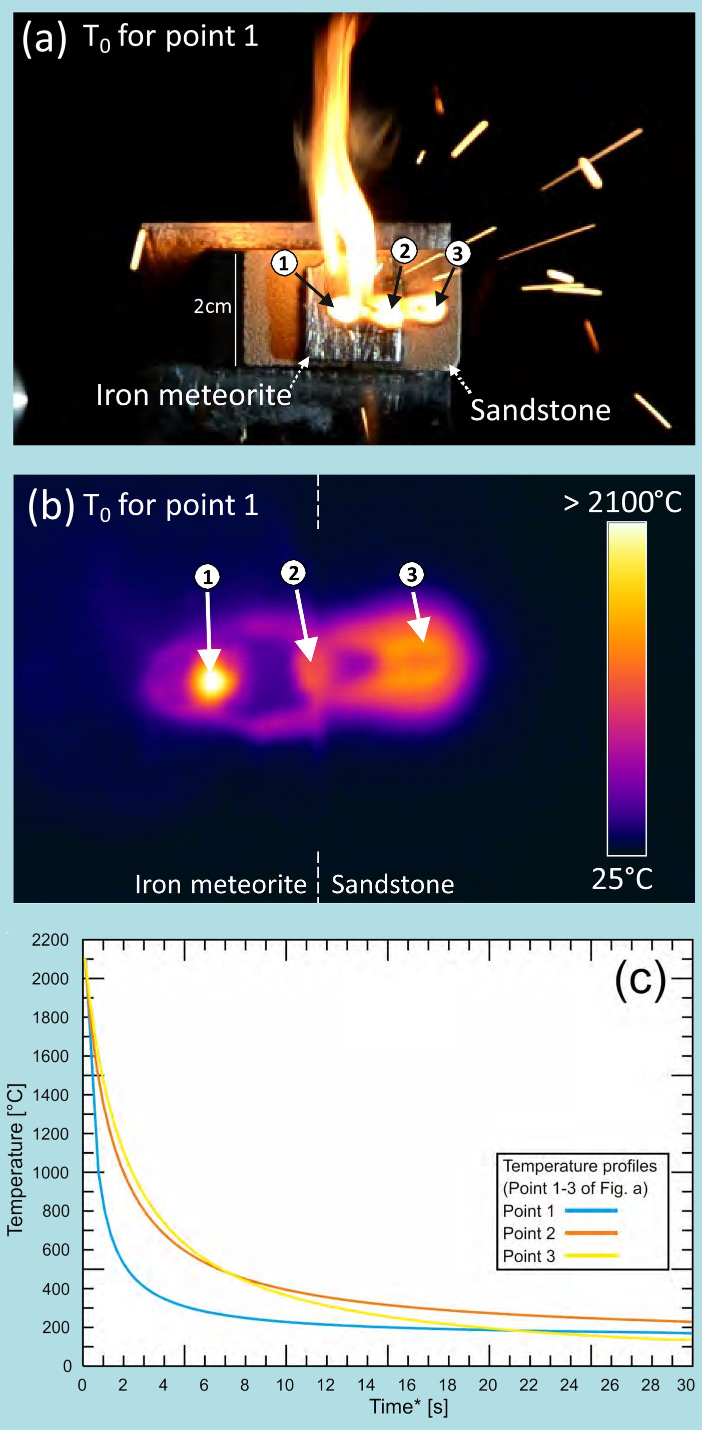


Projectile matter was transferred from completely fused Campo del Cielo meteorite into the sandstone target melt, particularly at the interface between the two source materials. The transition between molten projectile and molten sandstone target is defined by a compositional gradient that clearly shows unmixing of silicate melts (Fe-rich melt [Lfe] and Si-rich melt [Lsi]). In addition, small iron meteorite melt droplets were injected into the sandstone melt.



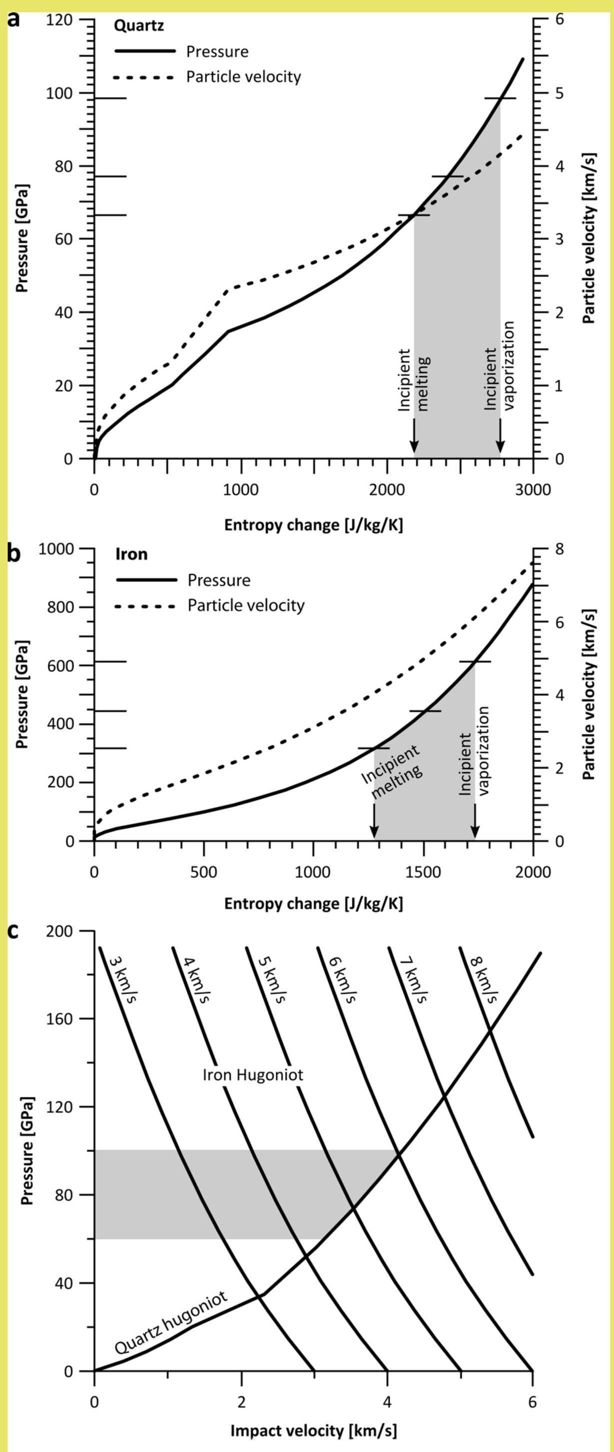
Qualitative element maps (iron and chromium) of emulsions of sandstone melt mixed with projectile melt droplets of steel (white spheres in BSE images).

Temperature measurements



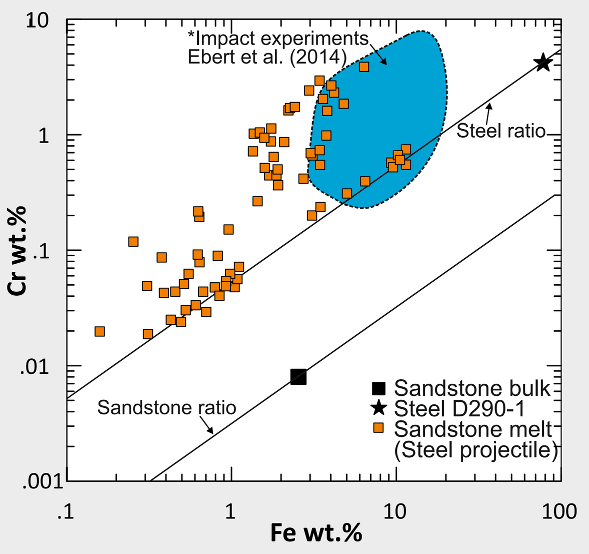
Time-resolved temperature measurements (a) High-speed framing camera image of experiment L887 (Campo del Cielo iron meteorite attachted onto sandstone cube). (b) Example infrared micro-bolometer image of experiment L887. (c) Cooling profiles over time for points 1, 2 and 3.

Calculation of entropy change

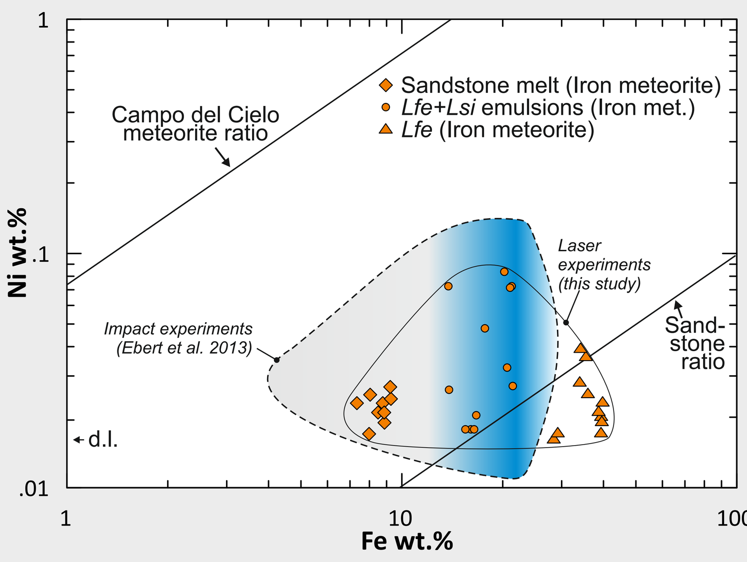


The grey fields denote the calculated entropy change of our experiments, the solid and dashed lines are Hugoniot data for quartz (a) and iron (b). (c) Planar impact approximation for an iron meteorite striking a quartz target at different velocities. At an impact velocity of ~6 km/s, peak shock pressures of ~100 GPa are induced in the target which give rise to successively decreasing shock pressures as the shock wave attenuates.

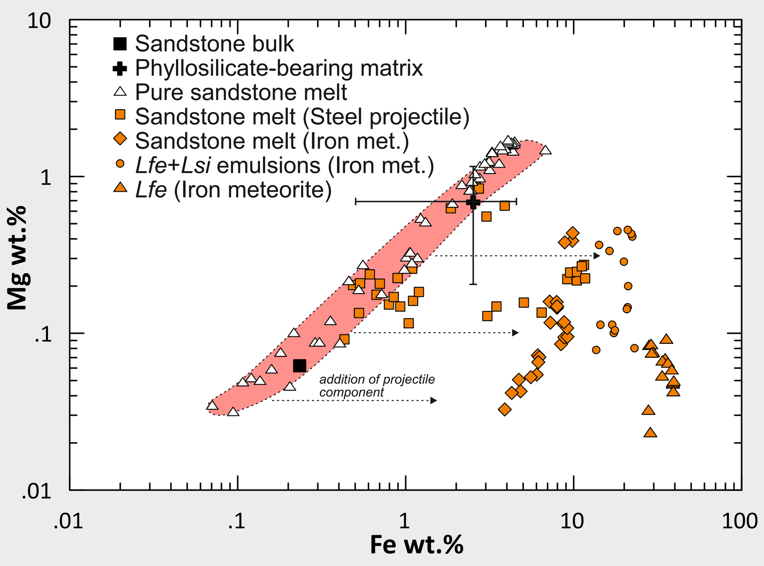
Geochemical signature of the projectile



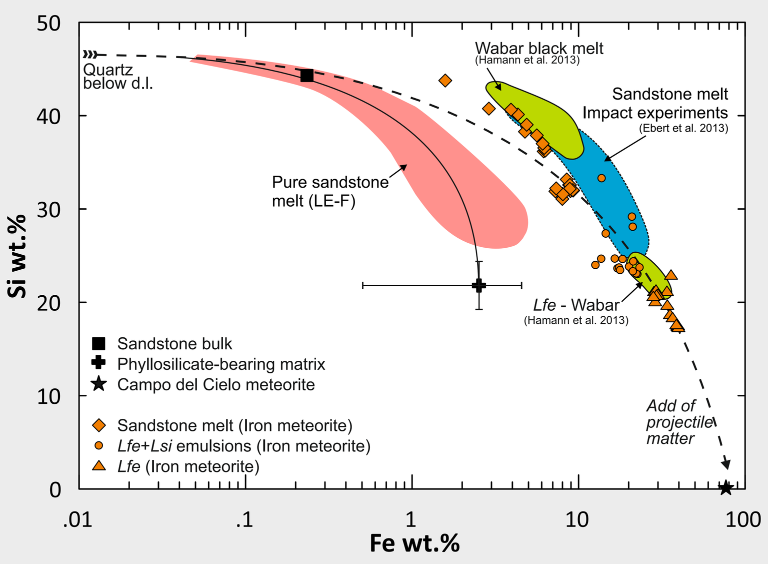
The sandstone melt show a distinct enrichment of Cr over Fe. The impact experiments show a higher degree of enrichment in Cr.



Ni is transferred from the molten meteorite into the adjacent sandstone melt. The highest degree of Ni enrichment occurs in the emulsions of Lfe and Lsi. Fe and Ni show roughly the same amount of enrichment in LE and HV experiments.

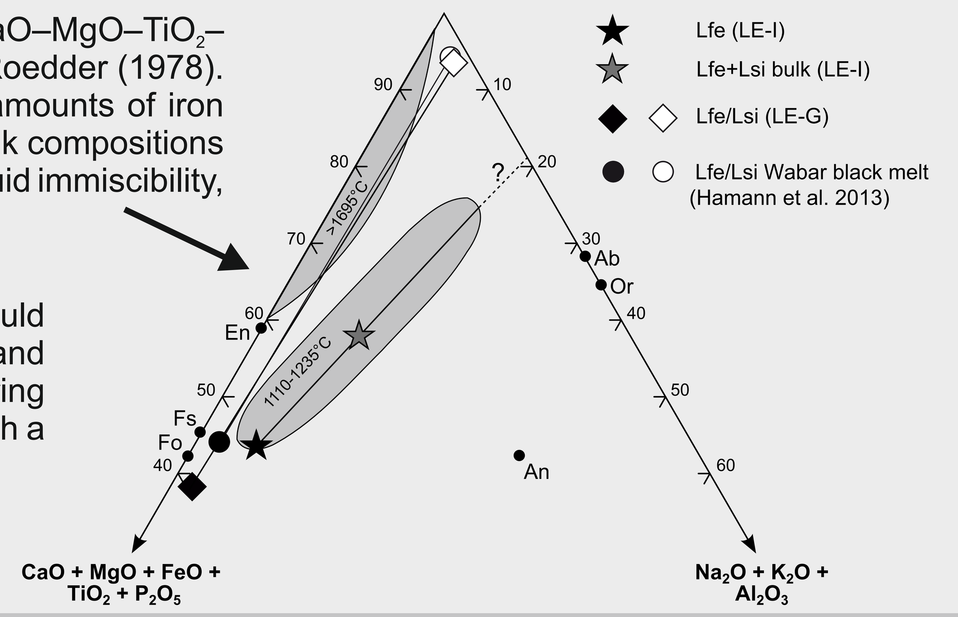


The pure sandstone melt shows a positive linear correlation of FeO and MgO. A deviation from this Mg/Fe ratio can be used to identify an addition of Fe, which has to originate from the molten projectile.



Hypervelocity impact experiments and natural impactites reveal more or less the same enrichment of meteoritic iron with the products of this study.

Pseudo-ternary system SiO_2–FeO–CaO–MgO–TiO_2–P_2O_5–Al_2O_3–K_2O–Na_2O modified after Roedder (1978). Heterogeneous admixture of various amounts of iron meteorite or steel matter resulted in bulk compositions that separated upon cooling through liquid immiscibility, forming Lfe/Lsi emulsions.



Reaction times of 0.6 to 1.4 seconds could be derived for element partitioning and phase-separation processes by measuring time-depended temperature profiles with a bolometric detector.

Conclusions

Laser experiments allow (i) separate high-temperature melting to better constrain primary melt heterogeneities before mixing of projectile and target, (ii) the quantification of element partitioning processes between coexisting projectile and target melts, (iii) the determination of cooling rates, and (iv) the estimation of reaction times. Processes of minor partial melting of single minerals up to complete melting and homogenization of target and projectile materials can be simulated with one laser-induced melting experiment. The entropy changes for laser-melting with sandstone and iron meteorite correspond to shock pressures and particle velocities produced during the impact of an iron projectile striking a quartz target at a minimum impact velocity of ~6 km s^{-1}, inducing peak shock pressures of ~100 GPa in the target.

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Roedder E. (1978) Geochimica et Cosmochimica Acta, 42:1597–1617.

This work is part of the MEMIN program supported by the German Science Foundation DFG. (Research Unit FOR-887; De 401/23-1, He-2893/8-1, He-2893/8-2. Ke-732/18-1). We wolud like to thank N. Artemieva for fruitful discussions and helpful comments on this study.