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Mineralogical alteration of artificial meteorites during atmospheric entry. The STONE-5 experiment

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Abstract

The generic concept of the artificial meteorite experiment STONE is to fix rock samples bearing microorganisms on the heat shield of a recoverable space capsule and to study their modifications during atmospheric re-entry. The STONE-5 experiment was performed mainly to answer astrobiological questions. The rock samples mounted on the heat shield were used (i) as a carrier for microorganisms and (ii) as internal control to verify whether physical conditions during atmospheric re-entry were comparable to those experienced by "real" meteorites. Samples of dolerite (an igneous rock), sandstone (a sedimentary rock), and gneiss impactite from Haughton Crater carrying endolithic cyanobacteria were fixed to the heat shield of the unmanned recoverable capsule FOTON-M2. Holes drilled on the back side of each rock sample were loaded with bacterial and fungal spores and with dried vegetative cryptoendoliths. The front of the gneissic sample was also soaked with cryptoendoliths.

The mineralogical differences between pre- and post-flight samples are detailed. Despite intense ablation resulting in deeply eroded samples, all rocks in part survived atmospheric re-entry. Temperatures attained during re-entry were high enough to melt dolerite, silica, and the gneiss impactite sample. The formation of fusion crusts in STONE-5 was a real novelty and strengthens the link with real meteorites. The exposed part of the dolerite is covered by a fusion crust consisting of silicate glass formed from the rock sample with an admixture of holder material (silica). Compositionally, the fusion crust varies from silica-rich areas (undissolved silica fibres of the holder material) to areas whose composition is "basaltic". Likewise, the fusion crust on the exposed gneiss surface was formed from gneiss with an admixture of holder material. The corresponding composition of the fusion crust varies from silica-rich areas to areas with "gneiss" composition (main component potassium-rich feldspar). The sandstone sample was retrieved intact and did not develop a fusion crust. Thermal decomposition of the calcite matrix followed by disintegration and liberation of the silicate grains prevented the formation of a melt.

Furthermore, the non-exposed surface of all samples experienced strong thermal alterations. Hot gases released during ablation pervaded the empty space between sample and sample holder leading to intense local heating. The intense heating below the protective sample holder led to surface melting of the dolerite rock and to the formation of calcium-silicate rims on quartz grains in the sandstone sample.

Keywords: Artificial meteorite; Atmospheric entry; Dolerite; Sandstone; Gneiss impactite; Fusion crust

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1. Introduction

The basic concept of the artificial meteorite experiment STONE is to fix rock samples on the heat shield of a recoverable space capsule and to study their modifications during atmospheric re-entry. The first experiment STONE-1 was performed in 1999 in order to address the question whether Martian meteoroids of sedimentary origin could survive atmospheric entry and thus could fall as "Martian" meteorites on Earth (Brack et al., 2002). Unfortunately, the succeeding experiments STONE-2 to STONE-4 were not successful for several reasons. STONE-2 samples were lost because of crash landing of the capsule, STONE-3 was never launched, and STONE-4 samples were lost due to explosion of the carrier rocket immediately after launch.

The STONE-5 experiment was performed mainly with astrobiological questions. The rock samples mounted on the capsule's heat shield were used (i) as a carrier for microorganisms and (ii) as internal control to verify whether physical conditions during atmospheric re-entry were comparable to those experienced by "real" meteorites. Samples of dolerite (an igneous rock), sandstone (a sedimentary rock), and gneiss impactite from Haughton carrying endolithic cyanobacteria were fixed to the heat shield of the unmanned recoverable capsule FOTON-M2. Holes drilled on the back side of each rock sample were loaded with bacterial (*Bacillus subtilis*) and fungal (*Ulocladium atrum*) spores and with dried vegetative cyanobacterium (*Chroococcidiopsis* sp.). The front of the gneissic rock was also soaked with *Chroococcidiopsis* sp. to simulate a natural endolithic community. Biological investigation of the gneiss impact sample showed that the heat of entry ablated and heated the original rock to a temperature well above the upper temperature limit for life to below the depth at which light levels are insufficient for photosynthetic organisms (~5 mm), thus killing all of its photosynthetic inhabitants. This study showed that atmospheric transit acts as a strong biogeographical dispersal filter to the interplanetary transfer of photosynthesis (Cockell et al., 2007).

Here we report on the results of the mineralogical investigations of the STONE-5 experiment based on the observed differences between pre- and post-flight samples. Special attention was dedicated to the fusion crust as a potential protective barrier for the microorganisms and as a specific mineralogical marker of the stone. The generation of significant fusion crusts in STONE-5 was a real novelty since they did not form in STONE-1, thus strengthening the link with real meteorites. For STONE-1 different sample materials were used including a basalt, which unfortunately was lost before the landing of the capsule.

Although the re-entry speed of 7.7 km/s of the capsule was considerably lower than the 12–20 km/s of typical meteoroids it was expected that frictional heat would be sufficient to form fusion crusts on the surfaces of samples. For re-entry speeds in the range of natural meteoroids one might expect higher peak temperatures and faster ablation rates during atmospheric passage. However, if formation of fusion crust on the samples occurs, thermal conditions during the experiment should be comparable to those experienced by meteoroids, although the peak temperatures attained by the latter were not reached.

2. Samples and flight details

Three samples were selected for the STONE-5 experiment:

(1) A dolerite (coarse-grained basaltic rock from Pauliberg, Burgenland, Austria) of Miocene age (Poultidis and Scharbert, 1986). Major mineral phases of the dolerite (Fig. 1) are ~3 mm to <1 cm-sized crystals of pyroxene (augite) and feldspar (plagioclase). Opaque phases are dominated by Fe–Ti oxides (ilmenite and magnetite). The dolerite has a texture similar to that of extraterrestrial basalts (eucrites and shergottites) and was chosen to serve as an in-flight control and to demonstrate that the frictional heat was sufficient to form a fusion crust during re-entry.

The modal composition (in vol%) of dolerite from the Pauliberg location (Piso, 1970) is 4.4% olivine, 19.5% augite, 45% plagioclase, 13.2% alkali-feldspar, 13% opaques, 3.9% apatite, 1.0% biotite. The corresponding chemical analysis (in wt%) is given as 50.2% SiO_2, 3.9% TiO_2, 18.5% Al_2O_3, 4.0% Fe_2O_3, 2.5% FeO, 0.15% MnO, 4.2% MgO, 8.9% CaO, 3.7% Na_2O, 2.6% K_2O, 0.43% P_2O_5, 0.45% H_2O^+, and 0.38% H_2O^-.

(2) A sedimentary rock (sandstone) from Wallsee, Lower Austria, Austria. The sandstone at Wallsee comprises the major part of the Upper Oligocene Molasse zone which is overlain by a thin layer (locally 3–5 m thickness) of glacial sediments. The basement of the sandstone is formed by granites of the Bohemian Massif (Schnabel, 2002). The sandstone consists mainly of sub-rounded to rounded

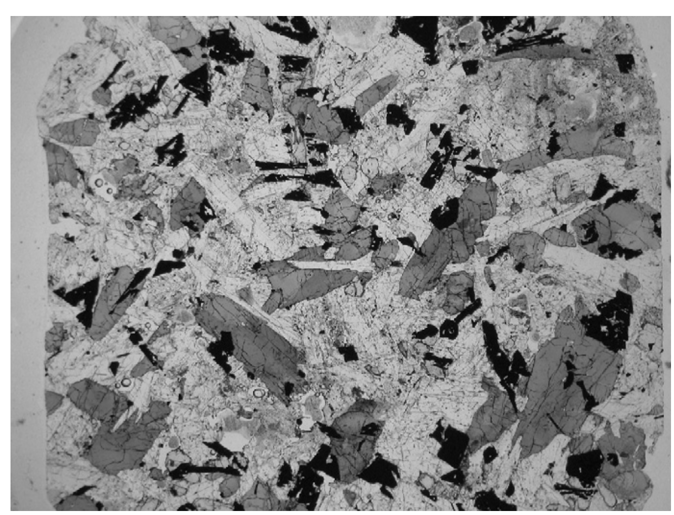

Fig. 1. Photomicrograph of the dolerite sample from Pauliberg, Burgenland, Austria, exhibiting a coarse-grained texture with crystals of augite (medium grey), feldspar (light grey), and Fe–Ti oxides (black). Width of image = 2 cm.