EXPERIMENTAL SHOCK METAMORPHISM OF TERRESTRIAL BASALTS INDUCED BY SHOCK WAVES UP TO 115 GPA: AGGLUTINATE-LIKE PARTICLES' FORMATION, PETROLOGY AND MAGNETISM.

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Introduction Micrometeoroid bombardment represents an agent responsible for the soil formation on surfaces of airless solid solar system bodies. The bombardment of micrometeoroids - particles with size ranging from a few μm to a few cm and having the velocities around a few km/s and higher - forms particles with specific lithology and new physical properties [1, 2]. Magnetic characterization of such particles is very important for better understanding and interpretation of magnetism of extraterrestrial materials as well as planetary magnetic anomalies [3]. The aim of this work was to investigate both petrology and chemistry of particles, experimentally produced by impacts of high-velocity copper projectiles with basalt targets, and to combine it with the full magnetic characterization of these particles.

Methods and Results: We used in this work materials recovered from shock experiments, which were carried out using a two-stage light-gas gun at the Institute of Mechanics (M.V. Lomonosov Moscow State University, Russia) [4]. During experiments, spherical copper projectiles 5-mm in diameter were launched at velocities of about 6 km/s (see Table 1). Our targets represented basalt blocks ~10 cm in size. Each block was fixed in a sample's cell that prevented spreading of target debris outward into the gun expansion chamber. During the shots, the expansion chamber was evacuated to an air pressure ranged from 2 to 45 torrs. Four types of basalt rocks were used as targets. Middle Atlantic Ocean Ridge fine-grained basalt had a variolotic texture and consisted of rare olivine (Fa$_{15-20}$), augite (Fs$_{22-27}$Woll$_{43-45}$), and glass between plagioclase (An$_{65-75}$) laths. Titanomagnetite formed sub- and euhedral 0.5 -3 μm in size grains scattered in the rock, the crystal sizes prevented accurate microprobe analyses. Olivine basalt (Kamchatka, Russia) consisted of olivine (Fa$_{16-20}$), plagioclase (An$_{70-75}$), and pyroxene (Fs$_{10}$Woll$_{46}$) microphenocrysts in a matrix with an intersertal texture. The matrix consisted of laths of plagioclase (An$_{65-75}$) with sub- and euhedral pigeonite (Fs$_{25}$Woll$_{6}$) and augite (Fs$_{8-14}$Woll$_{39-44}$) crystals and interstitial glass rich in tiny pyroxene grains. Two types of magnetite grains were found: i) relatively large crystals of about 15–50 μm in size; ii) 1 -3 μm in size grains, which bordered matrix pyroxene. Aluminous basalt with a porphritic texture consisted of zoned plagioclase (An$_{42-71}$) and olivine (Fs$_{25-27}$) phenocrysts in an intergranular matrix. The matrix consisted of plagioclase (An$_{55-73}$) and pyroxenes (Fs$_{27-29}$Woll$_{10}$ and Fs$_{14-16}$Woll$_{53-61}$), the later contained sometimes olivine inclusions. Titanomagnetite formed both 5–40 μm euhedral grains and sub-micron crystals, disseminated in the matrix. Basalt from the Putorana (East Siberia, Russia) trap formation had a doleritic structure and consisted of plagioclase (An$_{66-78}$), pigeonite (Fs$_{30-33}$Woll$_{9-13}$), augite (Fs$_{14-16}$Woll$_{39-43}$) with some quartz. Magnetic phases were titanomagnetite and ilmenite with needle-like precipitates of rutile. The minerals often formed aggregates 20-60 μm in size. Titanomagnetites from all basalt samples had 15-17% of TiO$_2$ and some Al$_2$O$_3$, MgO, CaO, SiO$_2$, and V$_2$O$_3$. The rocks did not have any traces of hydrothermal alteration or weathering.

Table 1.

Shot#	Projectile velocity (km/s)	Peak shock pressure (GPa)	Cu metal content*, average (vol. %)	Plagioclase phase in unmelted basalt clasts
9	6.02	107.6	6.5	dia.glass[&]
12	5.42	90.6	10.0	dia.glass
13	5.94	105.0	4.5	dia.glass, pl[&]
18	5.83	101.9	11.0	dia.glass
25	6.30	115.5	16.5	dia.glass
26	5.82	101.6	22.0	pl

*relatively whole silicate fraction only, without taking into consideration the porosity

[&] dia.glass is diaplectic glass;pl is plagioclase

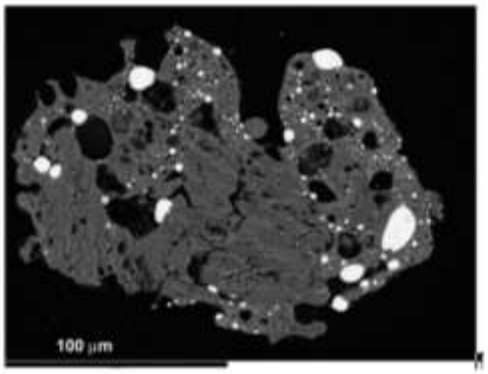

Fig. BSE image of an agglutinate-like particle from shot 9 (see Table 1). The particle is composed of unmelted or partially melted basalt clasts (e.g., to the left and in the center) and polymineral glass (to the right of the central largest basalt clast) cemented by glass with disseminated copper droplets and nuggets (white).

Basalt blocks after the shock experiments were comminuted to fragments ranged in size from a few cm to a few μm or less. Small (obviously <1 mm) agglutinate-like particles were found among the debris. The particles stand out against black basalt fragments due to their reddish color. They were picked out, sectioned, and were studied using ASEM and

EPMA. The agglutinate-like particles consist of fragments of target materials cemented by glass (Fig.).

Two types of the glasses could be distinguished. The first glass type contained numerous copper spheres and droplets disseminated in a porous silicate matrix. The glass was chemically homogeneous and glass compositions were close to compositions of the initial basalts. The second glass type was in form of heterogeneous glass having a flow-banded structure. Compositions of glass bands were similar to compositions of plagioclase and pyroxene. Areas or fragments of the glass of this type were often cemented by the homogeneous glass of the first type. The particles sometimes contained relatively large nuggets of copper. Most basalt fragments, included into the particles, showed prominent shock-induced features. Plagioclase was converted to diaplectic glass but rare plagioclase laths were converted to diaplectic glass partially and PDF were present in the birefringed areas (Table 1). Plagioclase from shot 26 did not show any shock features. Practically all pyroxene grains have polysynthetic mechanical twins.

All shocked samples were characterized magnetically at CEREGE (Aix en Provence, France). We measured magnetic susceptibility vs. temperature in order to determine the Curie temperature of samples and confirmed that all the samples were either magnetite or titanomagnetite-bearing (with different titanium content). We also measured hysteresis properties and magnetic remanence for all samples and roughly determined the size of their magnetic grains. Shock-induced magnetic hardening (increase in a coercivity of remanence B_{cr}) of samples and some other changes in intrinsic magnetic properties were also found.

Discussion: *Formation of the agglutinate-like particles*. Using a model of crater growth [5], we suggest that the "whole rock" homogeneous glass was formed in the crater cavity at the projectile-target contact surface during an early stage of excavation. The contact motion leads to homogenization of the target silicate melt and dissemination of the copper projectile in the melt. Subsequently, the melt impregnates adjacent target material including unmelted fragments as well as portions of total and partial melted basalt and the separate particles are formed during low-velocity ejection or recoi according to the state of plagioclase phases l. During their formation the particles included material that had experienced different stages of shock metamorphism – from unshocked to shock melted. However, most of the included unmelted basalt clasts from all but one shot were shocked at ~ 30–45 GPa according to the state of plagioclase phases and only the particles from shot 26 contain clasts shocked at less than ~ 12 GPa, if at all.

Comparison to lunar agglutinates. According to description of lunar regolith components, agglutinates are individual particles composed of crystalline grains and glasses and fragments of older agglutinates bonded together by vesicular glass [2,6]. Although texturally the experimental particles are similar to lunar agglutinates, they differ from them due to i) presence of copper projectile droplets in the homogeneous glass and ii) relatively low glass content comparing with lunar agglutinates. It is accepted that lunar agglutinates were formed by processes of melting and mixing of the melts during impacts of micrometeoroids. The micrometeorite flux is composed almost entirely of chondritic material [7] (mainly CM-like), and, hence, it has to be dissolved in target melt by dissemination. Containing in the micrometeoroids carbonaceous matter can reduce FeO in the melt and such the process could be responsible for formation of tiny numerous iron droplets in lunar agglutinates. Lunar agglutinates contain much more glasses comparing with the experimentally produced agglutinate-like particles. The reasons for this are widespread different glasses in regolith and its porosity, the later has to result in higher post-shock temperatures than in the case of non-porous basalt.

Based on the observed similarity between the experimentally produced agglutinate-like particles and lunar agglutinates we suppose that chondrite contents in agglutinates lie in range from a few percent to 50% and are grouped around 10%. Hence, taking into account the I_r content in chondrites (500 ng/g) we estimate a mean I_r content in agglutinates in 50 ng/g.

Magnetic results of our shock experiments have important implications in meteoritics and planetary science as the basaltic material is a terrestrial analogue of crustal material of solid solar system bodies such as Moon or Mars. That is why shock-induced changes in intrinsic magnetic properties of basalts (e.g., increase in samples' coercivity of remanence B_{cr}, which roughly reflects the samples' magnetic hardness) can be directly interpretable on natural impact processes taking place in our solar system.

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