EXPERIMENTAL STUDY OF HIGH-ENERGY PROCESSING OF PROTOPLANETARY MATERIALS: IMPLICATIONS FOR THE POST-GIANT-IMPACT EARTH. M. I. Petaev[1,2], S. B. Jacobsen[1], J. L. Remo[1,2,3,4], R. G. Adams[3] and D. D Sasselov[2,4] [1]Department of Earth & Planetary Sciences, Harvard University, 20 Oxford St., Cambridge MA 02138, USA; [2]Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge MA 02138, USA; [3]Sandia National Laboratories, P.O. Box 5800, Albuquerque NM 87195, USA; [4]Department of Astronomy, Harvard University, 60 Garden St., Cambridge MA 02138, USA.

Introduction: Giant impacts are currently believed [e.g., 1] to have been rather common during accretion of terrestrial planets. For example, the very existence of the Earth-Moon system is apparently a direct result of a collision between an almost fully grown, differentiated, hot (~4000 K on the surface increasing to 20000 K internally) proto-Earth and a cooler Mars-size differentiated body (2000 – 4000 K), with peak shock pressure reaching ~ 300 GPa in 10-20 minutes [2]. Such high pressures and temperatures are currently beyond the limits of most experimental techniques, except for shock experiments involving high-energy output lasers [3-6]. The laser-induced shock loading of quartz and fused silica up to ~1000 GPa and 60000 K [3,4] led to the development of a new SiO_2 phase diagram that outlines high T-P stability fields of 'bonded liquid' and 'atomic fluid' in addition to different solid silica polymorphs. We recently reported preliminary results of the laboratory shock experiments [5,6] aimed at understanding metal-silicate interaction at very high temperatures and pressures, comparable to those that may have existed in the deep mantle during and after the putative Moon-forming giant impact [2]. Here we review these results in the light of new calculations of our experimental shock conditions [7]. We also discuss implications of our experiments to the magma ocean chemistry of post-giant impact Earth, paying special attention to the problem of W and Hf partitioning during metal-silicate equilibration [8] that still remains an unsettled issue in isotope geochemistry [9,10].

Summary of experimental results: Ni-free Fe metal crystals (20-50 μm) and powdered ALM-2 dunite (5-300 μm) were mixed together in varying proportions (10-50 wt.% metal) and pressed into disk-shaped pellets (6.3 mm in diameter, ~1-3 mm thick) at ~40 kPsi. The ALM-2 dunite consists of forsterite (Fo 93.1±0.5, NiO ~0.4 wt.%) with minute grains of clinopyroxene, orthopyroxene, Al-rich chlorite, and chromite. Targets sealed in a vacuum (<10^{-4} torr) chamber were irradiated with the 527 nm pulsed ZBL laser focused to ~1 mm spots, delivering ~140-400 J at 0.15-1 nsec. The measured shock transit time was ~500 nsec/mm, setting an upper limit of the experimental timescale to ~1 μsec for a typical 2 mm thick target. Real timescales of high T and P processing of the targets were probably closer to the laser pulse time of ~0.4 nsec. Shock pressures and temperatures at the target front surfaces (Fig. 1), calculated from known laser intensity and wavelength [7], are similar to those obtained for silica in laser shock measurements [4] and consistent with the Hugoniots and melting curves of forsterite and Fe metal [11].

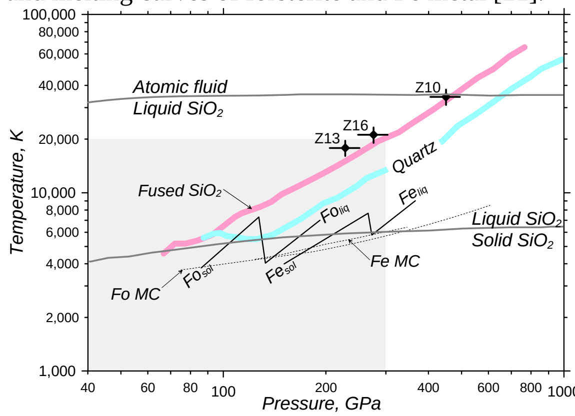

Fig 1: Experimental pressures and temperatures for the ZBL targets are shown by labeled circles with 10% error bars. Black solid lines show the Hugoniots for the solid and liquid forsterite, Fo, and Fe metal, Fe [11]. The dotted lines show the melting curves of Fe metal and forsterite [11]. The Hugoniots for the fused silica and quartz as well as the estimated phase boundaries for solid, liquid and atomic silica fluid are from [4]. The shaded box outlines the P-T space of the Earth-forming giant impact [2].

BSE images of cratered target fragments show rough crater surfaces with host metal and forsterite grains being bound together by thin films or pockets of silicate melt with varying amounts of dispersed metal beads. No traces of melt were found on crater surfaces. Melt apparently fills porous space, grain boundaries, and cracks and crevasses in forsterite grains. There is no evidence for incipient melting such as reaction relationships among metal-silicate melt and host metal and forsterite grains. Moreover, optical properties of forsterite grains surrounded by melt show no evidence of experiencing high temperatures and pressures. This implies that the metal-silicate melt in our targets represents a portion of the high P-T ablation melt driven into the cold target by the shock wave; the remaining melt along with the shocked and shattered target minerals was lost upon pressure release [7].

Chemistry of experimental melts: Chemical compositions of silicate melt and metal beads differ significantly from the host olivine and metal, respectively (Fig. 2). Silicate melt is enriched in Al_2O_3, Cr_2O_3, and FeO compared to the host forsterite. NiO concentrations in silicate melt depend upon the presence or lack of metal beads in it: silicate melt without metal beads has

NiO contents similar to that of the host forsterite, while silicate melt with abundant metal beads is depleted in NiO. Simultaneously, metal beads contain substantial amounts of Ni and Si, providing direct evidence for the extraction of Ni and Si from the silicate melt into the coexisting metal.

The substantial enrichment of the silicate melt in Fe (expressed as FeO in Fig. 2) is quite different from the results of lower-pressure shock experiments [12]. Although the nature of the Fe enrichment currently remains unknown it is possible that such enrichment independent of the lack or presence of metal beads hints for increasing miscibility of metal and silicate melts, with the Fe-enriched melt approaching the stability field of an 'atomic fluid' in the Fe-Mg-Si-O system.

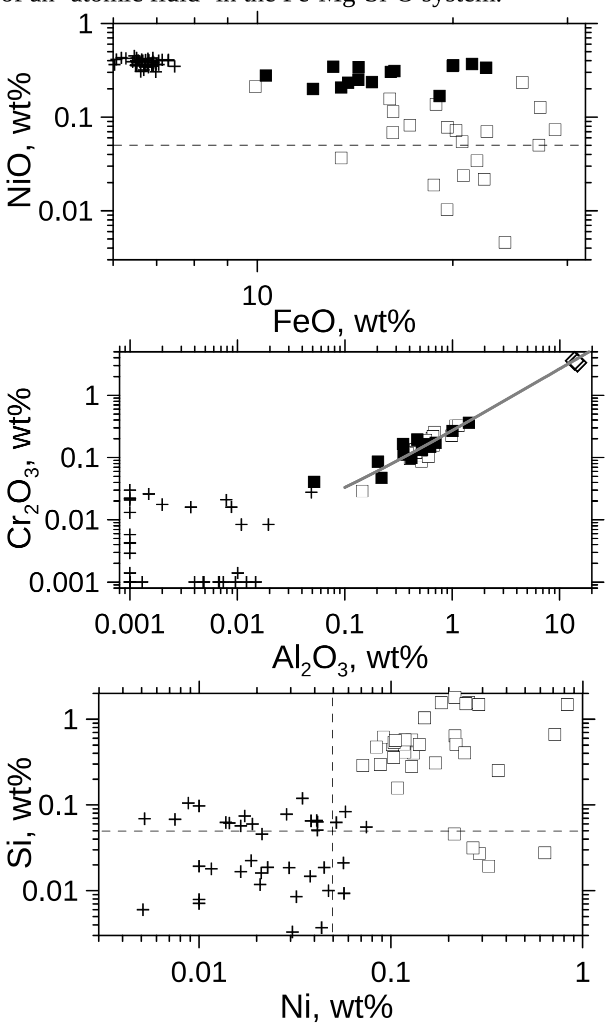

Fig 2: Concentrations of Al_2O_3, Cr_2O_3, FeO and NiO in forsterite and impact melt and Si and Ni in source metal and metal beads. Dashed lines show approximate detection limits. Heavy gray line is the least-square fit to the Al_2O_3 and Cr_2O_3 concentrations. Top and middle panels: Crosses – forsterite, filled squares – silicate melt without metal beads, open squares – silicate melt with embedded metal beads, open diamonds – chlorite. Bottom panel: Crosses – Si, Ni-free source metal, open squares – metal beads embedded in silicate melt.

Timescales of metal-silicate equilibration: High contents of Al_2O_3 and Cr_2O_3 in the silicate melt require a high degree of target homogenization most likely in the ablation melt layer at the target surface by incorporating Al_2O_3 and Cr_2O_3 from the minute grains of Al-rich chlorite (middle panel of Fig. 2). Given the short lifetime of the ablation melt (probably <<10nsec), the homogenization of target materials by thermal mixing in our experiments must be very rapid. Taking a conservative value of 10 nsec and ~ 1 mm target, approximation of thermal mixing by a diffusion equation yields an effective diffusion coefficient of ~200 m^2/s.

Implications to the post-giant impact Earth: Our experimental results have important implications to the final stages of Earth's accretion. First, scaling our experiments to predicted giant-impact conditions suggests that in just an hour a complete homogenization of projectile material would occur on a scale of ~2 km. Within this volume metal blobs up to 10 m in diameter are capable of nearly complete extraction of Ni from FeO-rich impact melts. Furthermore, reverberation shock experiment [12] suggests that Richtmayer-Meshkov instabilities during giant impact would lead to an effective mixing of the impactor's core with the terrestrial mantle.

Perhaps more important is the implication that the post-giant impact terrestrial magma ocean could have been much more ferrous (~15-25 wt.% FeO) than the current mantle (7.6 wt.%). This implies that more than half of FeO from the primary magma ocean must have been reduced to Fe to be transported into the Earth's core as metal droplets. The high efficiency of this process in metal-silicate equilibration has already been demonstrated [13,14].

Conclusion: Our experimental results provide strong evidence that the metal-silicate equilibration in the post-giant impact Earth was very rapid and effective. This validates the Hf-W system as the best tool for dating core formation in terrestrial planets.

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