EXPERIMENTAL STUDY OF HIGH-ENERGY PROCESSING OF PROTOPLANETRAY MATERIALS.

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Introduction: The metal-silicate fractionation in celestial bodies effectively separates siderophile dauther ^{182}W from lithophile parent ^{182}Hf into the core and mantle, respectively, making the Hf-W chronometer ideal for dating core-formation in differentiated planetary bodies [1]. It is generally believed that there was equilibration of the Hf-W system during primary metal-silicate fractionation of small, initially chondritic, parent bodies. However, the accretion of larger objects like Moon and terrestrial planets generally involves giant impacts, with both the target and projectile probably being differentiated. Because in large planetary objects only one reservoir – the silicate mantle – is usually available for sampling, the Hf-W dating of core-formation in such a case has to assume metal-silicate re-equilibration at high T and P while metal droplets rain through the magma ocean of a growing planet. If such equilibration has occurred ('fully equilibrative' accretion [1]), then the Hf-W system will date 'true' core-forming event, if not ('core-penetrative' accretion) then the W isotopic composition of the silicate mantle may 'remember' metal-silicate fractionations in the earlier generations of planetesimals accreted together to form a large planet. Recent modeling of a giant Moon-forming impact [2] predicts significant disruption of colliding bodies, followed by orbital re-assembly of binary Moon-Earth system, with the proto-Earth having an extensive hot (up to 10000 K) magma ocean in the deep (P>100 GPa) planetary interior. Currently no experimental data at such conditions exist. Recently we started experiments [3,4] aimed at studying partitioning of Fe and Ni (proxy for W) between metal and silicate melt formed at high P and T by laser shocks of powered mixtures of pure Fe metal and Ni-bearing ALM-2 dunite. The experimental details are described in the accompanying abstract [5]; here we report the results of petrologic and chemical studies of the recovered targets.

Samples and Experimental Conditions: The vapor-deposited Ni-free Fe metal (20-50 μm) and finely 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 – Fig. 1) at ~40 kPsi. The ALM-2 dunite consists of forsterite (Fo 93.1±0.5, NiO ~0.4 wt.%) with minute grains of clinopyroxene, chlorite, and chromite. The porosity of the targets evaluated from their BSE images was 20-35 vol.%.

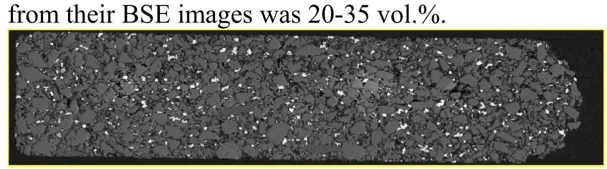

Fig. 1. Unshocked target: 90% dunite (gray) and 10% metal (white)

The targets were irradiated with the 527 nm ZBL laser (single pulse) focused to ~1 mm spots, delivering ~140-400 J per 0.15-1 nsec pulse. At lower pulse energies no melting was observed while at higher energies targets did not survive. The measured travel time of the shock wave was ~500 nsec/mm that sets the upper limit of the experimental timescale to ~ 1 μsec for a typical 2 mm thick target. The real timescales of high T and P processing of the targets were probably closer to the laser pulse time of ~1 nsec. The shock pressures at the front surfaces of the targets, estimated based on the known intensity and wavelength of a laser pulse [5], were in excess of 200 GPa for the experiments described below. As suggested by the measured shock wave and particle velocities, such pressures very rapidly dissipated to ~20 GPa upon traveling ~ 100 μm into the target, suggesting pressure gradients of ~ 1,000 GPa/mm. Temperatures experienced by the target surfaces are estimated to be in excess of 10^4 K, similar to those obtained for silica at similar pressures in laser shock measurements [6], which is consistent with shock melting phase diagrams of both forsterite and Fe metal [7].

The recovered targets were studied by SEM and EPMA using the JEOL SuperProbe typically operated at 15 KeV and 20 nA. The analytical standards were pure elements and well-characterized natural and synthetic minerals.

Results and Discussion: The recovered targets or their fragments show more or less rounded craters which have blackened appearance. The BSE images of the cratered target fragments (Fig. 2) show rather rough crater surfaces with the host metal and forsterite grains being bound together by thin films or pockets of silicate melt with varying amounts of metal beads dispersed in the silicate melt. The melt apparently fills porous space, grains boundaries, and cracks and crevasses in forsterite grains. No evidence for an incipient melting such as the reaction relationships among metal-silicate melt and the host metal and forsterite grains was found in the targets studied so far.

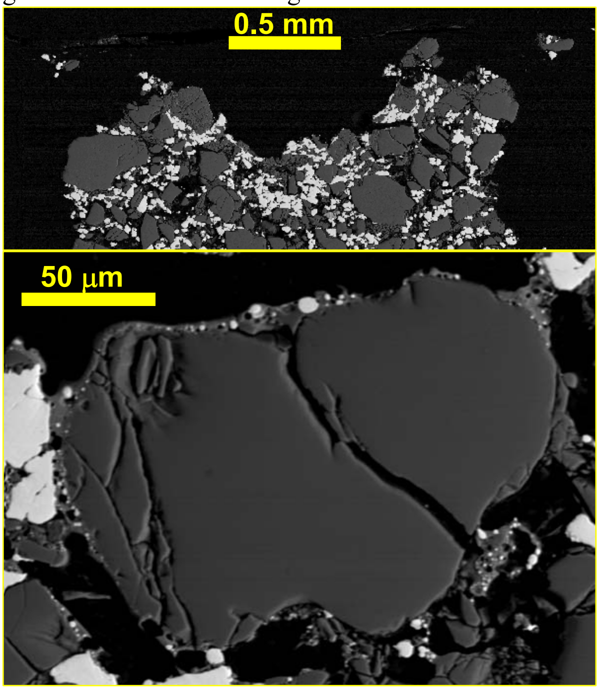

Fig. 2. Top: Cratered fragment of the ZBL-16 target. Bottom: Forsterite grain surrounded by thin films or pockets of silicate melt with or without metal beads. BSE images. White – metal, darker gray – forsterite, lighter gray – silicate melt.

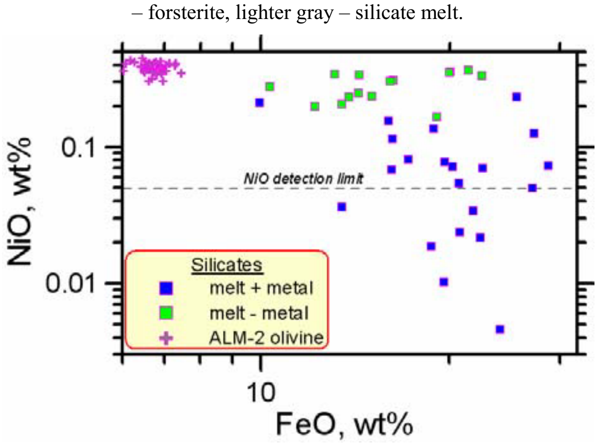

Fig. 3. Silicate melt is significantly enriched in FeO compared to the host forsterite (crosses). The melt without metal beads (green squares) has NiO contents similar to the host olivine, while melt with abundant beads (blue squares) is significantly depleted in NiO.

The chemical compositions of the silicate melt and metal beads differ significantly from the host olivine and metal, respectively. The silicate melt is enriched in Al_2O_3, Cr_2O_3, and FeO (Fig. 3) compared to the host forsterite. The NiO concentrations in the silicate melt depend upon the presence or lack of metal beads in it (Fig. 3): silicate melt without metal beads has NiO contents similar to that of the host forsterite, while the silicate melt with abundant metal beads is depleted in NiO. At the same time, metal beads contain substantial amounts of Ni and Si (Fig. 4), providing direct evidence for the extraction of Ni and Si from the silicate melt into the coexisting metal.

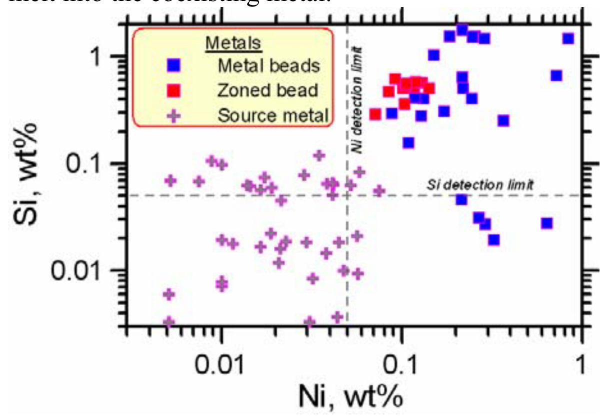

Fig. 4. The host metal (crosses) is essentially free of Ni and Si, white the metal beads enclosed in silicate melt consistently have rather high Ni and Si contents. Red squares show compositions of a large (~15 μm) zoned bead, providing strong evidence that high Si concentrations in this and other metal beads are real and not a result of X-ray fluorescence from the surrounding silicate melt.

Concluding Remarks: Both the lack of incipient melting of the targets studied and the rather high contents of Al_2O_3 and Cr_2O_3 in the silicate melt imply formation of the metal-silicate melt at high T and P at the very surface of the target from a plasma cloud that would effectively homogenize the target composition by incorporating Al_2O_3 and Cr_2O_3 which can only come from minute grains of Al-rich chlorite and chromite. Then the melt was injected into the porous space where it quenched rapidly, preserving the chemical compositions established at high T and P compared to those estimated for the post-giant impact proto-Earth. The partitioning of Ni between silicate and metal melts points to a rapid equilibration at a nanosecond-microsecond timescale in our experiments. Scaling this for simple physical models of the aftermath of the Moon-forming giant impact suggests that sufficient metal-silicate equilibration occurs to validate the Hf-W chronometry.

References: [1] Jacobsen S. B. (2005) *Ann. Rev. Earth Planet. Sci., 33,* 531-570. [2] Canup R. (2004) *Icarus, 168*, 433-456. [3] Remo J. L. et al. (2006) *AGU Fall 2006*, abstract#MR51B-0967. [4] Petaev M. I. et al. (2006) *AGU Fall 2006*, abstract#MR53D-05. [5] Remo J. L. et al. (2007) *this volume*. [6] Hicks D. G. et al. (2006) *PRL, 97,* 25502-1 to 25502-4. [7] Luo S.-N. and Ahrens T. J. (2004) *Phys. Earth Planet. Int., 143/144*, 369-386.