N92-10932

Impact and Collisional Processes in the Solar System.

Thomas J. Ahrens[a], C. Gazis[a], R. Pepin[b], R. Becker[b], R. Cronin[c], J. Tyburczy[c], T. Tingle[d], T. Duffy[a], and L. Rowan[a], [a]California Institute of Technology, [b]University of Minnesota, [c]Arizona State University, [d]University of California, Davis.

As impact cratered terranes have been successively recognized on the Moon, Mars, Mercury, and Venus, as well as on the satelllites of Jupiter, Saturn, Uranus, and Neptune, and are inferred to have existed on the Hadean earth, it has become clear that impact processes are important to the understanding of the accretion and evolution of all solid planets. The noble gases (Ne, Ar, Kr, and Xe) in the normalized atmospheric inventories of the planets (Earth, Mars, and Venus), and the normalized gas content of meteorites are grossly similar, but demonstrate differences from each other which are not understood. In order to study shock devolatilization of the candidate carrier phases which are principally thought to be carbonaceous or hydrocarbons in planetesimals (Swindle, 1988), we conducted experiments on noble gas implantation in various carbons--carbon black, activated charcoal, graphite, and carbon glass. These were candidate starting materials for impact devolatilization experiments.

Initial experiments[1] were conducted on vitreous amorphous carbon samples which were synthesized under vapor-saturated conditions using argon as the pressurizing medium. Solubility of Ar in carbon data were obtained for temperatures of 500 to 800°C and pressures of 250 to 1500 bars. Up to 7 wt% Ar was dissolved in the carbon. Initial shock experiments showed that 28% of the total argon in amorphous carbon was released by driving 4 GPa shocks into the argon-rich carbon. We demonstrated that shock-induced argon loss is not simply caused by the impact-induced diminution of grain size. The present value of shock pressure required for partial impact devolatilization of Ar from carbon is below the range (5 to 30 GPa) at which H_2O is released from phyllosilicates, e.g. serpentine[2].

In collaboration with Professor R. Pepin and Dr. Richard Becker of the University of Minnesota, we have during the last year, conducted the first successful noble gas impact devolatilization experiment. We obtained an initial experimental result at ~6 GPa. Contrary to initial expectations, noble gases are in more retentative sites in Murchison than water! We found that while ~10% of the water was driven off in our initial experiment, only ~1% of the He was devolatilized.

Carbonaceous chondrites contain amino acids and hydrocarbons that were created early in the evolution of the solar system[3]. We have performed one amino acid and Surface Analysis by Laser Ionization (SALI) analyses of three samples of shocked Murchison meteorite. Peak shock pressures of ~19 to 36 GPa were achieved. Analyses for over 24 amino acids and simple amines were carried out both on hot-water extracted and acid hydrolyzed material. Several interesting and unanticipated results were evident. For a number of amino acids, including α-amino isobutyric acid (α-AIB) and isovaline, the extraterrestrial amino acids found in K-T sediments by Zhao and Bada (1989), the shocked material has a lower concentration that has the unshocked Murchison. However, for several amino acids (glycine, β-alanine), the post-shock content is greater than in unshocked Murchison. Several amines that may represent breakdown products of amino acids (for example, methyl amine, ethyl amine, and isopropylamine), are also present in greater abundance in shocked versus unshocked Murchison. For glutamic acid, alanine, and α-amino butyric acid, the post-shock content is approximately the same as in the unshocked material. Detailed interpretation of these preliminary results is currently in progress.

In order to tie shock recovery experiments to infall velocity and construct thermodynamic models for various porosity regoliths, knowledge of the Hugoniot and release isentrope equation of state is required. Serpentine is a key model of phyllosilicate material which we assume was present in the planetesimals which accreted to form the planets and brought to them a large fraction of their H_2O inventory. Laboratory shock pressures can be related to planetesimal impact velocities by assuming uniform, homogeneous accretion. For impact between two bodies of the same material ("symmetric" impact), the impact velocity required to generate a given shock pressure is twice the particle velocity of the shocked state. Minimum impact velocities onto a planetary surface are equal to the body's escape velocity. Thus, assuming constant density, the radius of the planet is a linear function of impact velocity:

$$r = V_p(8\pi G\bar{\rho} / 3)^{-1/2} = 2u_p(8\pi G\bar{\rho} / 3)^{-1/2} \quad (1)$$

The release adiabat data strongly suggest that a high pressure phase forms. If serpentine forms a high pressure hydrous phase, it appears possible to have a substantial H_2O reservoir within a terrestrial planetary mantle, as, for example, is speculated to be the case for the early Earth[5]. To further examine this issue, we have conducted a series of Hugoniot and release isentrope experiments for brucite, $Mg(OH)_2$[6]. For brucite, the effect of water on the equation of state is more clear-cut, as MgO by itself appears not to undergo any phase changes upon shock compression to at least 100 GPa.

It was Phillips *et al.*[7] who showed there was a significant negative Bouguer gravity anomaly above a wide size range of impact craters on the Earth and Moon. Moreover, seismic refraction studies of terrestrial impact and explosion craters (e.g. Meteor crater, Oak explosion crater, Ries Crater) show that very marked seismic velocity deficits are incurred in an annular region around crater rims. Both the Bouguer gravity anomalies and P-wave (and presumed S wave) velocity deficits produced by cracks are not yet predicted by current physical or numerical models, because of the lack of an experimental basis for describing tensile wave induced cracking. However, it appears likely that with an understanding of the mechanisms of rock tensile failure via cracking, a constraint on the physical parameters of the impact event, e.g., energy and impact velocity, can be obtained from observed velocity deficits and Bouguer anomalies.

We recently completed a first study in which a series of shock loading experiments on a porous limestone and a non-porous gabbro in one and three dimensions were performed[8]. These demonstrated large (factors of ~2) decreases in compressional wave velocity within target blocks of rock within two crater radii. We have combined one-dimensional dynamic tensile (spall) study with a series of sample assemblies to test crack-induced failure models, and their time dependence, in a less complex geometry.

We have also conducted a series of recovery experiments in which shocked molten basalt at 1700°C is encapsulated in molybdenum containers and shock recovered from up to 6 GPa pressures. Post-shock temperatures are at least ~2000°C. The results (Fig. 1) are striking in that the basalt and Mo have strongly reacted in the ~1 sec or so (required for cooling) during and after the impact experiment which is conducted at low f_{O_2} in vacuum. By comparing apparent partitioning of elements between basalt and metal (Rowan and Ahrens 1991), it appears that the f_{O_2} is very low and controlled by the Mo-MoO_2 buffer. We envision these experiments represent a model of reaction which may occur upon planetary accretion upon infall of metallic planetesimals into a magma ocean.

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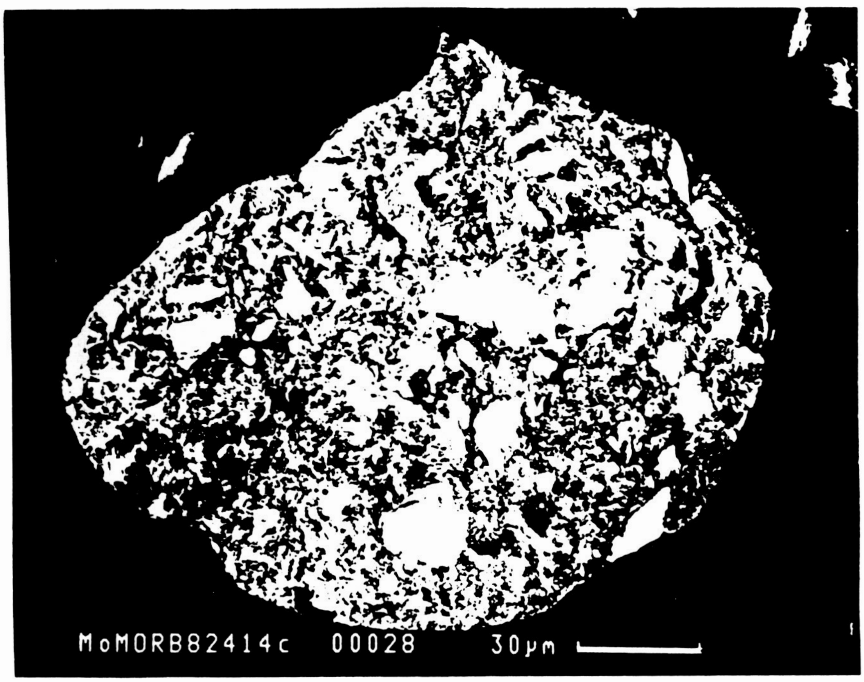

Fig. 1: Back-scattered electron photograph of a cross-section of a recovered fragment taken on the scanning electron microscope. The bright white region is the molybdenum metal and the dark gray region is the basaltic glass. This fragment was shocked to 6 GPa and shows intimate intermixing and reaction between the molybdenum and the basalt.

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