SPACE WEATHERING OF PHYLLOSILICATES BY HYPERVELOCITY IMPACT: EXPERIMENTAL INSIGHTS INTO SERPENTINE AMORPHIZATION BY NON-HYDROSTATIC STRESSES. D. Harries[1], D. Schmidt[1], A. Fazio[1], P. Wild[1], H.-P. Liermann[2] and F. Langenhorst[1], [1]Friedrich Schiller University Jena, Institut für Geowissenschaften, Carl-Zeiss-Promenade 10, 07745 Jena, Germany (dennis.harries@uni-jena.de), [2]Deutsches Elektronen-Synchrotron (DESY), FS-PE, P02, Notkestraße 85, 22607 Hamburg, Germany.

Introduction: Phyllosilicates of the serpentine-group are common water-bearing minerals in carbonaceous chondrites and hydrous interplanetary dust particles (IDPs). They are thought to have formed through the reaction of ferromagnesian silicates, mainly olivine and pyroxenes, with hydrous fluids at low to moderate temperatures. Samples to be returned from the C-group near-Earth asteroids 162173 Ryugu and 101955 Bennu by the Hayabusa2 and OSIRIS-REx spacecrafts will shed light on the behavior of these minerals during space weathering induced by solar irradiation and impacts of hypervelocity meteoroids. This understanding is crucial for assessing the properties of asteroid regoliths with remote sensing. The physical state of dust within planetary debris disks around stars other than the Sun provides additional, important insights into planetary evolution but requires well-understood material models.

Because serpentine minerals can be altered by a variety of physicochemical processes, such as thermal metamorphism, solar-wind irradiation, and impact-generated shock loading, it is important to understand how their structural and spectroscopic properties change in response. Here, we focus on the pressure-induced changes by applying rapid compression in membrane-driven diamond anvil cells (mDACs) to tens of GPa at rapid compression (e.g., [1-3]).

Methods: Starting material was natural aluminous lizardite of the composition $(Mg_{2.70},Fe_{0.16},Al_{0.12})(Si_{1.89},Al_{0.12})O_5(OH)_4$, collected from the Totalp serpentinite (Davos, Switzerland). It was either gently powdered in ethanol or scraped off using a sharp steel razor blade. The latter method was used to minimize amorphization during the preparation step. Matrix-rich portions of the Murchison CM2 meteorite containing Fe-rich cronstedtite were prepared in a similar fashion.

The powders were mixed with powdered gold to serve as an internal pressure standard and loaded into steel gaskets carrying a ~100 µm diameter hole. No pressure transmitting medium was added so that the subsequent compression in the diamond anvil cell occurred under non-hydrostatic conditions. mDACs were dynamically compressed using a gas-driven steel-membrane at synchrotron beamline P02.2 of PETRA III at DESY, Hamburg, Germany. Mean compression rates during the experiments ranged between 0.05 to 1.4 GPa/s. During the rate-controlled, continuous compression X-ray diffraction (XRD) patterns were recorded in fast succession at 25.6 keV X-ray energy using a Perkin-Elmer XRD 1621 fast flat panel detector (Fig. 1). Raw diffraction patterns were 2θ-calibrated employing a CeO_2 standard (NIST 674b) and radially integrated using the Dioptas software [4]. Background removal, pressure calibration, peak fitting and data analysis was done using R scripts.

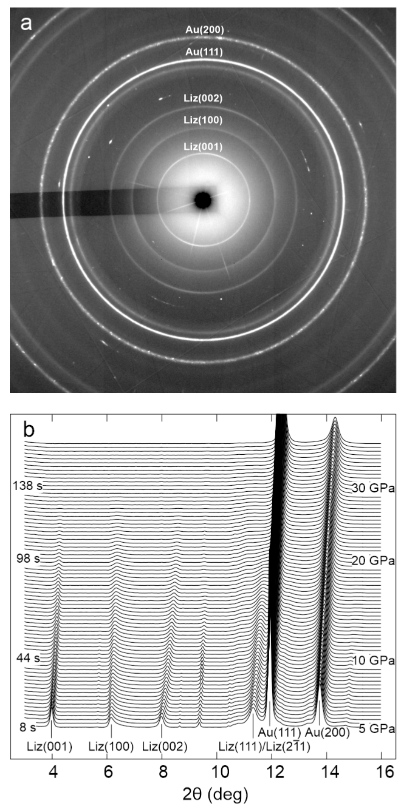

Fig. 1: (a) Single synchrotron XRD pattern of lizardite in the mDAC. (b) Shift of Bragg peaks and eventual loss of diffraction intensity during compression in the mDAC.

Results: The intensities of the serpentine (001), (002) and (100) diffraction peaks gradually decrease with increasing pressure indicated by the gold internal standard. Diffraction peaks typically disappear at pressures of about 25 to 30 GPa (signal-to-noise ratio <10), indicating nearly complete amorphization at these pressures. The onset of intensity loss occurs either immediately after the start of the compression cycle or after a short induction period of a few GPa.

Step-wise compression using mDACs with a methanol–ethanol–water mixture as pressure medium has demonstrated that lizardite can be compressed hydrostatically to at least 10 GPa without significant amorphization [5]. Without pressure medium the stress state within the mDAC comprises a significant non-isotropic stress component in addition to the hydrostatic component. This non-isotropic, deviatoric stress appears to be responsible for the rapid onset of amorphization observed.

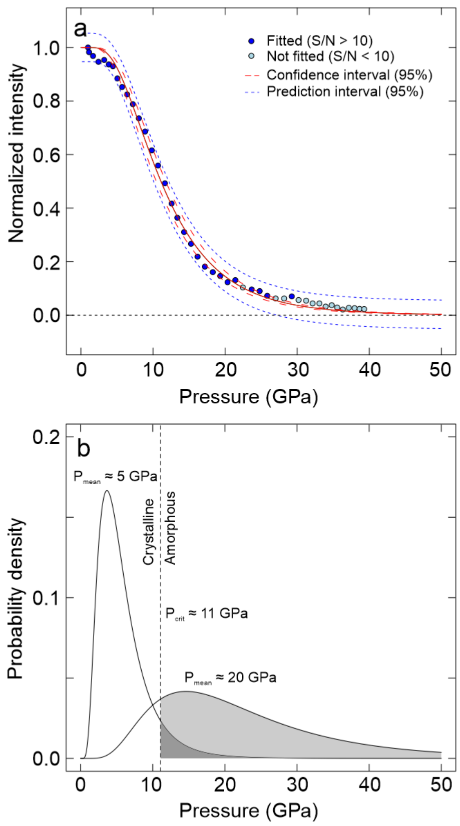

Fig. 2: (a) Fit of a lognormal model to the normalized intensity of lizardite (002) measured during compression in the mDAC. (b) Modelled probability density of the pressure distribution (in lieu of stress) within the mDAC for two mean pressures (5 and 20 GPa). Above P(crit) crystal domains become amorphous. Increasing mean pressures shift the population towards higher fractions of amorphous domains.

Statistical model. As a conceptual model we assume that the amorphization of a lizardite crystal requires the overstepping of a critical deviatoric stress in analogy to a von Mises criterion. If the second invariant of the deviatoric stress tensor (i.e., the von Mises stress) exceeds a material-specific critical limit, strongly enhanced crystal-plastic deformation, such as emission of dislocations and/or shear along susceptible crystallographic planes, sets in and leads to rapid amorphization.

In our statistical model we assume that the von Mises stress within the mDAC volume sampled by the X-ray beam is heterogeneously distributed. At any given pressure measured by the shift of the gold diffraction peaks, some grains or crystal domains experience higher von Mises stresses than others. Some domains exceed the critical limit and become amorphous. In terms of a statistical distribution, the critical limit equates to a quantile of the distribution, the corresponding probability yields the fraction of crystalline domains in the volume sampled by the beam. The distribution is characterized by a center and a dispersion (e.g., standard deviation) and both change with increasing pressure measured by the gold. In particular the mean von Mises stress increases with increasing compression such that successively more domains exceed the critical limit and turn amorphous.

At present the relations between the measured pressure and the mean von Mises stress and its spread within the sampled volume are not known. Analogous to earlier work [3] we assume that the mean von Mises stress is identical to the measured pressure (Fig. 2). Using non-linear least squares fitting we find that a lognormal distribution represents the pressure dependence of the normalized intensities well. The fit provides two parameters: A critical pressure and a standard deviation on the log pressure scale. The critical pressures range between 7 to 16 GPa and provide a measure of the critical stress required for amorphization with the caveat of the above assumptions. We did not observe an obvious dependence of the critical pressures on the compression rates used.

Murchison cronstedtite behaves very similar to the terrestrial lizardite. The results demonstrate that serpentine requires relatively little shear stress to become amorphous, although complete amorphization of complex grain aggregates likely requires extensive stress regimes. Shock loading by the impact of micrometeoroides could thus potentially contribute to serpentine destruction on asteroid surfaces, but other processes such as thermal input might be more effective.

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