NANOINDENTATION OF LUNAR BASALTS: MECHANICAL PROPERTIES OF THE NWA 12008 METEORITE

P. Grèbol-Tomàs[1,2], J. M. Trigo-Rodríguez[1,2], J. Ibáñez-Insa[3], E. Peña-Asensio[1,4], R. Cuscó[3], I. Weber[5], J. Sort[4,6]; [1]Institut de Ciències de l'Espai (ICE-CSIC), Campus UAB, Cerdanyola del Vallès, Barcelona, Catalonia, Spain (grebol@ice.csic.es); [2]Institut d'Estudis Espacials de Catalunya (IEEC), Ed. Nexus, Barcelona, Catalonia, Spain; [3]Geociències Barcelona (GEO3BCN-CSIC), Barcelona, Catalonia, Spain; [4]Universitat Autònoma de Barcelona (UAB), Cerdanyola del Vallès, Barcelona, Catalonia, Spain; [5]Institut für Planetologie, Münster, Germany; [6]Institució Catalana de Recerca i Estudis Avançats (ICREA), Barcelona, Spain.

Introduction: A good knowledge of the mechanical properties of lunar meteorite samples and their analogs may be particularly relevant to design future lunar space missions (e.g. Artemis [1]). A proper classification of extraterrestrial materials is key when devising maneuvers where physical contact processes are crucial, especially for in-situ resource utilization (ISRU) and even impact-hazard defense missions (e.g. DART [2]).

Nanoindentation is a powerful technique applied to investigate minerals and advanced materials to extract their mechanical properties. One of its main advantages is that it is quasi-nondestructive because the studied material can be recycled for other analyses. The sample is indented with a nanometer-sized sharp end. The amount of displacement as a function of the applied load is the main vector to derive the material's mechanical properties.

We present a nanoindentation study of the major minerals in the NWA 12008 lunar meteorite. This is a highly-shocked lunar mare basalt with a rich mineralogy, which results from its igneous history. Olivine and pyroxene are the main minerals in this achondrite, which also features sizable amounts of plagioclase and ilmenite. Other minerals such as barite or troilite have also been reported [3]. Although it is a widely used technique, nanoindentation studies on meteorites are scarce [4, 5]. Here we determine the hardness, Young modulus, and the elastic and plastic works of different minerals of NWA 12008, which are compared with data from their terrestrial counterparts.

Technical procedure: A mosaic of a thin section from NWA 12008 (Figure 1) was made with a Zeiss Axio Scope A1 microscope. A grid was added to identify regions of interest (ROIs). Nanoindentation was conducted with an Anton-Paar nanoindenter (NHT2 model) with a Berkovich tip (diamond pyramidal-shaped). Each measurement comprised a 100 mN load at a 200 mN/min rate, followed by a steady pause of 2 s and an unload at the same rate. A total of 92 nanoindentations were performed in 5 ROIs. Minerals were identified by SEM-EDX using a Hitachi TM4000plus tabletop microscope equipped with a Bruker EDX detector. The presence of vitreous phases (glass, maskelinite) was checked by Raman spectroscopy, using a Jobin-Yvon T64000 Raman spectrometer. Given that NWA 12008 is a highly-shocked meteorite with numerous microfractures, around one third of the nanoindentations turned out to be too close to fractures. Data from those regions were not considered for the present study.

Figure 1: Mosaic of the NWA 12008 sample. Each grid separator corresponds to 1 mm in physical scale.

Results: Mineral mechanical properties were analyzed separately for different mineral groups and/or individual mineral species. The main minerals (and groups) identified in NWA 12008 were: forsterite (olivines); pigeonite and augite (pyroxenes); albite, anorthite, and maskelinite (plagioclases); and ilmenite (oxide). We report in Table 1 the mean values of the measurements for each mineral group as a whole.

Here we focus on the case of olivine, the mechan-

Table 1: Hardness (H) and reduced elastic modulus (E_r) for different mineral groups. Errors correspond to 1σ std. The number of nanoindentations for each species is also specified. Maskelinite is separated from plagioclase due to its non-crystalline nature.

Mineral	H (GPa)	E_r (GPa)	#
Olivine	7.6 ± 2.2	110 ± 32	33
Pyroxene	7.1 ± 1.3	91 ± 12	10
Ilmenite	8.4 ± 0.6	91 ± 13	2
Maskelinite	7.2 ± 2.8	86 ± 34	20
Plagioclase	6.9	74	1

ical properties of which have been widely investigated because it is the most abundant mineral in the Earth's mantle. We show in Figure 2 the mechanical properties of olivine as obtained in this work, compared to those obtained in terrestrial samples [6, 7] and in the Chelyabinsk meteorite [4]. The 33 nanoindentations performed here for olivine show a high standard deviation.

It is worth noticing that the average hardness measured in NWA 12008 olivines is only comparable to that from terrestrial amorphous olivine, while it is sizably lower than that measured in other types of terrestrial olivine crystals and also in the Chelyabinsk meteorite. Error bars for NWA 12008 do not overlap with those of crystalline (terrestrial and extraterrestrial) olivine samples. Similarly, olivine also appears to be more elastic (smaller elastic modulus) than in the Earth counterparts. However, the elastic modulus found for NWA 12008 is somewhat comparable to that of the Chelyabinsk meteorite.

Similar analyses have been performed for the rest of the minerals. They are not shown in Figure 2 due to the lack of bibliographical data for Earth materials. A preliminary analysis suggests that ilmenites and pyroxenes in NWA 12008, for example, are also more elastic than their terrestrial counterparts.

Discussion and conclusions: Nanoindentation is a valuable technique to investigate the mechanical properties of minerals. The tests performed on the main minerals of the NWA 12008 lunar breccia suggest that they tend to be slightly softer and more elastic than their crystalline terrestrial counterparts. The Chelyabinsk meteorite, which is a low-porosity ordinary chondrite, exhibits an olivine hardness comparable to that of Earth crystals. Based on this result, we hypothesize that the remarkable behavior of NWA 12008 may be attributed to a high porosity of this achondrite. Porosity in NWA 12008 might have originated from volatile compounds in the original magmas or might be the consequence of collisional processes and shocking. Future work is thus required to extend the experimental data of this work and confirm whether porosity is the main responsible for the anomalous mechanical behavior of NWA 12008.

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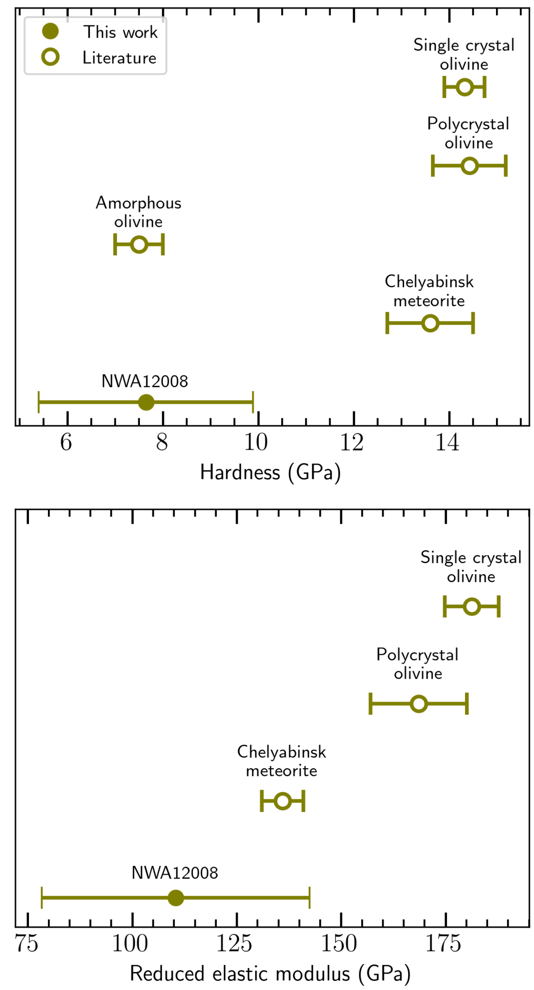

Figure 2: Measured hardness and reduced elastic modulus for olivines in NWA 12008. Values are compared with the corresponding values published in the literature for terrestrial olivines and for the Chelyabinsk meteorite.

References: **[1]** NASA (2020) *NASA's Plan for Sustained Lunar Exploration and Development*, Tech. rep. **[2]** Cheng A. F. et al. (2023) *Nature*, 616.7957, 457-460. **[3]** Gattacceca J. et al. (2020) *Meteoritics & Planet. Sci.*, 32, A74. **[4]** Moyano-Cambero, C. E. et al. (2017) *ApJ.* 835.2, 157. **[5]** Tanbakouei, S. et al. (2019) *A&A*, 629, A119. **[6]** Kranjc K et al. (2016) *Geoph. R.L.*, 43.1, 176-184. **[7]** Baral P. et al. (2021) *Acta Materialia*, 219, 117257.