NANO-CHEMO-MECHANICAL BEHAVIOR OF THE CARBONACEOUS CHONDRITE METEORITE TARDA (C2-UNG): IMPLICATIONS FOR PLANETARY DEFENSE. S. Bhatt\textsuperscript{1}, T. Davis\textsuperscript{1}, D. Cotto-Figueroa\textsuperscript{2}, E. Asphaug\textsuperscript{3}, L. A.J. Garvie\textsuperscript{4,5}, and C. G. Hoover\textsuperscript{1},\textsuperscript{*} School of Sustainable Engineering and the Built Environment, Ira A. Fulton Schools of Engineering, ASU, Tempe AZ 85287 (sbhatt88@asu.edu), \textsuperscript{2}Department of Physics and Electronics, University of Puerto Rico at Humacao, Call Box 860, Humacao, PR 00792, Puerto Rico, \textsuperscript{3}Lunar and Planetary Laboratory, U of A, Tucson, AZ 85721, \textsuperscript{4}Buseck Center for Meteorite Studies, \textsuperscript{5}School of Earth and Space Exploration, ASU, AZ 85287-6004.

Introduction: Clay-rich carbonaceous chondrites (CC’s), constituting 20-50\% of Near-Earth Objects (NEOs) [1], are of interest due to their impact risks. When two bodies come into contact, they exert a force on each other, and mechanical properties become important. Physical properties are also important for understanding a range of phenomena such as ablation, energy transfer during impacts, crater formation, fragmentation and friability. These properties can also help when deciding on asteroid deflection strategies. CC’s typically have an abundant clay matrix with a low hardness, likely necessitating a different asteroid deflection strategy than Dimorphos, which was impacted in NASA’s DART [2] mission. CC’s are multiscale and multiphase materials with heterogeneity in their mineralogy, textures, and mechanical properties from the nano- to millimeter scale necessitating advanced testing methodologies. Nanoindentation (NI) measures mechanical properties and energy-dispersive X-ray spectroscopy (EDX) yields elemental data, both on \( \mu \)m scales. A goal of this study is to use these techniques to determine the mechanical properties of the matrix in Tarda (C2-ung).

Samples & Testing Protocol: Tarda was prepared as a dry-polished epoxy potted button. Mechanical data were recorded using the Anton-Paar Ultra Nano Hardness Tester. Indents were acquired in a grid with a diamond Berkovich probe loaded in force-control up to 1.8 mN. The data output is a load vs. load point displacement curve at every indent. The modulus (\( M \)), which controls the elastically recoverable deformed material, and the hardness (\( H \)) which is force per unit area and has units of strength, were determined using the Oliver and Pharr model [3,4].

EDX maps were acquired at each grid location and the counts for \( Al, Mg, Si, S, Fe, \) and \( Ca \), were extracted from each indent location after subtracting the background counts. This data together with \( M&H \) at each indent location is input into a multivariate cluster algorithm [5] to get the number of statistical clusters in the dataset. This was done using just \( M&H \) and using \( M&H + \) elemental counts at each indent location. After obtaining the statistical phases, we try to determine which clusters are predominantly clay.

Results & Discussion: In Fig. 1 we display all data on \( M&H \) plots. Greater values of \( M/H \) indicate plastic deformation mechanisms, (increasing ductility) as \( M/H \) is the inverse of a yield strain [6]. With mechanical data only, we get 5 phases from \( \sim 3800 \) indents (Table 2, Fig. 1a). According to [7,8], the \( M&H \) for smectite and serpentine are approximately 40 and 2 GPa, respectively. Phase 3 has \( M&H \) values higher than expected for clays, so the mechanical response is likely dominated by magnetite and sulfides. \( M&H \) from phases 1, 2, 4, and 5 were used to calculate the average \( M&H \) of the clay, yielding 0.96 and 27.2 GPa (Table 1). When the elemental counts were included, 14 phases were obtained, though many overlapped (Fig. 1b). Phases 4, 6, & 10 likely belong to stiffer phases because their \( M&H \) were too large for most clays. From the remaining phases, the \( M&H \) of the clay matrix is 0.95 and 26.98 GPa, respectively, close to that determined from clustering just \( M&H \). Some points in phases 4, 6, & 10 could be clays (Fig. 1b) [7,8], but the elemental information contradicts this (Table 3). Specifically, phase 4 has a high \( Ca \) content, suggesting it could be carbonate or phosphate, and phase 10 has a high \( Fe \) content which could be magnetite [9]. These points were identified as something other than clays when the element counts were added to the clustering, thus demonstrating the value of including elemental information.

Conclusions: To safeguard Earth from potential impactors, a collaborative effort between scientific and engineering approaches to asteroid deflection strategies is crucial. The data shown by Tarda are significant because similar materials are present on asteroids Bennu and Ryugu. Thus, a detailed study of the CC’s provides the framework and points of comparison for the samples returned from hydrated, clay-rich asteroids, and provides necessary information to plan mitigation strategies.

Acknowledgement: The samples are from the BCMS at ASU. The authors are grateful for the support for this research, provided by the NASA YORPD program through grant 80NSSC22K0238.

Figure 1: Scatter plot generated using (a) $M$ and $H$ values from just the 3813 indents for which EDX analysis was done (b) $M$ and $H$ values from subfigure (a) with intensities of elements $Si$, $Al$, $Mg$, $Fe$, $S$, and $Ca$, (c) Same as for subfigure (b), but after removing phases 4, 6, and 10.

Table 3: Table with mean and standard deviation of $H$, $M$, and total number of points per cluster, and intensities of elements ($Si$, $Al$, $Mg$, $Fe$, $S$, and $Ca$) with respect to the phase for 3813 points.