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Unraveling the micromechanical response to mudstone compaction: A combined approach of nanoindentation mapping and machine learning data analysis

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Mudstones and similar fine-grained lithologies serve as key elements in various geoenergy applications, e.g., as source rocks for conventional oil and gas deposits, as unconventional reservoirs, or as top seals in geological storage complexes. Understanding compaction processes in these rocks therefore is crucial for energy transition initiatives. This study investigates the compaction processes in mudstone samples from varying depths (723.5 to 3213.5 m) in the Vienna Basin, focusing on micromechanical properties and porosity changes in the clay-rich, fine-grained fraction (“clay matrix”). A novel approach combining nanoindentation mapping with machine learning data analysis was developed to capture compaction-depth trends, efficiently extracting representative mechanical values semi-automatically. Results indicate a significant arithmetic mean increase in mechanical strength of the clay matrix with depth, with an increase of the reduced elastic modulus (E_r) and hardness (H) from 6.8 ± 3.4 to 22.6 ± 7.5 GPa and from 0.2 ± 0.2 to 0.9 ± 0.2 GPa, respectively. Additionally, a strong correlation between depth and porosity (3.3–26.4% Φ_{MICP}, Pearson correlation coefficient r = -0.94) and consequently micromechanical properties of the clay matrix (r = 0.94) was observed. Broad ion beam-scanning electron microscopy (BIB-SEM) analysis showed that porosity reduction mainly resulted from mechanical compaction rather than mineral diagenesis. The correlation coefficient matrix between multiscale porosity and nanoindentation measurements confirmed that porosity loss was closely linked to enhanced mechanical properties of the clay matrix. Empirical equations were derived to describe mechanical properties as functions of depth and porosity. This study offers a promising approach to study compaction processes across various burial depths at microscale, yielding information that may later be used to understand geomechanical behavior at macroscale. The obtained porosity data and mechanical values contribute to the understanding of burial history, porosity evolution, and associated mechanical changes, representing a potential avenue for assessing mechanical seal parameters in future geological storage applications.

Session: *Pangeo workshop: Mineral Raw Materials, and Energy Transition*
Keywords: *Nanoindentation, Compaction, Mudstone, Vienna Basin, Geoenergy*