

AFM-Based Characterization of Thermally Activated Evolution of Surface Morphology and Nanomechanical Properties in Fault Gouge Materials

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Abstract

Atomic force microscopy (AFM) in novel Peakforce Quantitative Nanomechanical Mapping (PFQNM) mode was used to qualitatively investigate the morphology and nanoscale mechanical response of granite, shale, and sandstone over a temperature range of 80 - 450 °C. The height and modulus channels data, corrected for tilt, bowing, artifacts and distortions, revealed distinct mineralogical and structural dependent responses. Granite exhibited a progressive increase in surface roughness up to 250 °C, followed by partial smoothing at higher temperatures, along with relatively uniform modulus distributions, reflecting the inherent rigidity of its crystalline framework. Sandstone exhibited a similar roughness trend, along with a progressive increase in modulus with temperature, likely resulting from microstructural transformations driven by mechanisms such as phase boundary stiffening, viscous flow and lattice diffusion. For shale surface roughness decreased significantly at higher temperatures, indicating dehydration and compaction, but exhibited pronounced heterogeneity and locally elevated modulus values, influenced by its foliated structure, mineral transformation and microstructural anisotropy. These findings reveal that thermally induced microstructural transformations strongly influence how stress is distributed and released within geomaterials and can lead to the development of localized stress concentrations that act as initiation points for thermally driven seismic events. The study also demonstrates the effectiveness of AFM in capturing nanoscale mechanical responses and estimating elastic properties under varying temperature conditions. Nevertheless, meaningful interpretation requires rigorous calibration, tip characterization, and model-based corrections to account for mineral heterogeneity and anisotropy. By linking nanoscale mechanical behavior to macroscopic stress evolution, this research advances understanding of how thermal processes in geothermal reservoirs can initiate or intensify induced seismicity.