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Perspective

Multi-field coupling mechanics of deep heterogeneous rocks: Progress and prospects

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Abstract:
The mechanical response of heterogeneous rock masses under multi-field coupling conditions is central to geo-energy development and underground storage. This study synthesizes key insights from Session 49 of the second “International Geo-Energy Frontier Forum”, entitled “Multi-field Coupled Mechanics of Deep Heterogeneous Rock Masses”. Twenty-two experts and scholars presented their recent advances in heterogeneous-structure characterization, laboratory testing, mechanical mechanisms, and engineering applications. The discussion was organized around the experimental characterization of deep heterogeneous rocks, mechanistic links between local damage and fracture-network development under coupled thermal-hydraulic-mechanical-chemical conditions, and implications for energy development and underground storage. Perspectives distilled from these themes may provide useful guidance for optimizing stimulation schemes, assessing containment safety, and evaluating long-term reliability in deep geo-energy operations.

1. Introduction

Deep earth engineering is increasingly being extended into rock masses characterized by high stress, temperature and pressure as well as strong production/chemical disturbances. The applications driving this field include deep shale gas and coalbed methane development, enhanced geothermal systems, CO_2 geological storage, underground hydrogen and gas storage, compressed-air energy storage, deep mining, and underground space utilization. These systems encompass multi-scale heterogeneous media, such as pores, minerals, bedding planes, joints, natural fractures, faults, caverns, and caprock interfaces, that control deformation, damage, seepage, heat transfer, chemical reactions, and instability. Rock heterogeneity is therefore not merely a geological detail but the structural basis through which stress, fluid flow, temperature, and chemical processes interact, with significant engineering consequences.

Understanding the mechanisms of rock mechanics governed by heterogeneous structures under multi-field coupling conditions has therefore become a central issue in deep energy and underground engineering. Progress in this area depends on linking structural characterization, laboratory testing, theoretical analysis, and numerical modeling. Computed tomography, scanning electron microscopy, mineral mapping, and digital rock methods are currently able to provide quantitative descriptions of heterogeneous structures. The controlled fabrication of rock-like materials and three-dimensional (3D)-printed rock analogues makes it possible to isolate the effects of pores, minerals, bedding, and fractures under repeatable conditions. Indentation and cuttings-based tests further extend parameter acquisition to small or incomplete deep rock sam-

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ples. Across these approaches, it is increasingly understood that the coupled thermal, hydraulic, mechanical, and chemical responses of highly heterogeneous rocks depend on their structural characteristics, especially under true-triaxial stress, injection-production disturbance, temperature variation, and fluid-rock reaction conditions.

At present, the main challenge is not simply to describe heterogeneity but to translate heterogeneous rock mechanics into engineering practice. Structural observations become mechanically useful only when they are converted into state variables, constitutive parameters or model constraints. Strength, brittleness or permeability measured in the laboratory under simplified paths may not represent rock behavior under cyclic injection-production, heating-cooling, unloading, pressure diffusion, and chemical disturbance. Furthermore, fracture-network complexity should not be treated as universally favorable, because stimulation, storage, sealing, and excavation stability require different structural outcomes. As introduced by Cai (2026), founder and Editor-in-Chief of *Advances in Geo-Energy Research* (*AGER*) and the Chair of the Organizing Committee of the International Geo-Energy Frontier Forum, the second such forum reflected *AGER*'s effort to build a high-level platform for academic exchange and interdisciplinary collaboration in geo-energy research. Within this forum, Session 49, called "Multi-field Coupled Mechanics of Deep Heterogeneous Rock Masses", further focused the discussion on the need to connect heterogeneous structures with coupled mechanical mechanisms and engineering constraints.

Based on the presentations and discussions in Session 49, this study summarizes research directions in the multi-field coupled mechanics of deep heterogeneous rock masses from three perspectives: (1) experimental characterization and reproduction of heterogeneous structures; (2) multi-field coupling mechanisms governed by heterogeneous structures; (3) engineering applications in energy development and underground storage.

2. Experimental characterization of deep heterogeneous rocks

The central purpose of experimental characterization is to clarify which heterogeneous features control coupled mechanical responses and how these features can be quantified for theoretical modeling and engineering analysis. From the micro- to nanoscale, pore-throat geometry, mineral assemblage, cementation state, and reactive surfaces influence fluid storage, transport pathways and local stress concentration. Meanwhile, at the millimeter- to centimeter-scale, bedding planes, microcracks, weak interlayers, and mineral-filled discontinuities govern crack initiation, fracture deflection, coalescence, and preferential seepage. At larger scales, natural fractures, faults and caprock interfaces control pressure diffusion, stress redistribution and system stability (Chen et al., 2025). Therefore, the key task of characterization is not only to describe pores, minerals, bedding and fractures but also to transform them into mechanically interpretable structural descriptors that can be incorporated into hydraulic, thermal, chemical and mechanical analyses.

A persistent challenge is that natural deep cores are difficult to obtain and often exhibit strong discreteness, poor repeatability and uncontrollable heterogeneity, making it difficult to separate the effects of individual structural factors using natural samples alone. In this way, controlled heterogeneous rock-like specimens provide an important complementary route for mechanism-oriented research (Yang et al., 2024). Instead of merely reproducing the appearance of natural rocks, analogue preparation should focus on reproducing the structural variables that dominate coupled responses, such as pore connectivity, mineral contrast, bedding anisotropy, weak-plane distribution, and fracture-network geometry. Through the controlled adjustment of matrix composition, fabric arrangement, prefabricated discontinuities, pore templates, and 3D-printing strategies, specimens with targeted heterogeneous structures can be prepared for repeatable mechanical testing.

The value of such controlled specimens becomes evident only when they are tested under realistic engineering processes. Deep-rock testing is moving beyond conventional single-scale triaxial compression toward an integrated framework that combines natural core testing, heterogeneous analogue simulation, digital rock modeling, and engineering-path loading. Multi-scale imaging provides structural constraints. Artificial specimens allow the systematic evaluation of how pore structure, mineral heterogeneity, bedding orientation, fissure density, and fracture connectivity affect strength, deformation, failure, and permeability. Experiments subjecting specimens to true-triaxial loading, unloading disturbance, cyclic injection-production, hydro-mechanical coupling, thermo-mechanical coupling, and fluid-rock reaction further reproduce the stress, temperature, pressure, and chemical conditions encountered in deep reservoirs (Cheng et al., 2023). In this sense, experimental characterization acts as a bridge between structural observation and coupled-mechanism interpretation.

In line with the above, a practical route for future experimental characterization is to identify dominant heterogeneous structures, reproduce selected controlling features in controllable specimens, load the specimens along representative engineering stress-temperature-pressure paths, and calibrate the measured parameters against natural cores and field observations. The main value of artificial analogues lies in isolating causal mechanisms that are difficult to distinguish in natural cores because of uncontrolled variability. When combined with natural samples, digital models and field monitoring data, controlled experiments can improve the reliability of elastic modulus, strength, permeability, and fracture parameters, and provide more defensible inputs for hydraulic fracturing design, wellbore stability analysis, in-situ stress inversion, fracability evaluation, as well as deep underground safety assessment.

3. Multi-field coupling mechanism of heterogeneous rocks

The deformation and failure of deep heterogeneous rocks under multi-field coupling should be understood not as a simple superposition of mechanical, hydraulic, thermal, and chemical effects but as a structure-controlled process in which local heterogeneity progressively evolves into macroscopic instability. Heterogeneous structures determine damage initiation, propagation, and evolution into connected fracture networks or localized failure zones. Thus, the essential mechanism is the transformation from initially discrete structural differences to spatially organized damage, fracture interaction, permeability evolution, and instability.

At the pore-mineral scale, heterogeneity provides the initial condition for coupled damage. Pore-mineral features create local contrasts in stiffness, strength, pore-pressure response, and chemical sensitivity. These contrasts make certain zones more prone to stress concentration, compaction, micro-crack initiation, and chemical weakening (Yi et al., 2026). For this reason, pore-mineral heterogeneity should not be interpreted only in terms of storage capacity or mineral composition. The more important mechanical significance of such heterogeneity lies in defining the initial damage field from which macroscopic deformation, permeability change and fracture development emerge.

As damage expands from the microscale to the bedding-fissure-fracture scale, the controlling issue shifts from damage initiation to fracture-path selection. Pre-existing structural discontinuities act as structural boundaries that guide, deflect, arrest, or connect propagating cracks. Fracture evolution in heterogeneous rocks is therefore inherently path-dependent. Analytical and experimental studies of kinked, intersecting and curved cracks have improved our understanding of crack-tip driving forces, mixed-mode failure, and crack deflection in anisotropic media (Saber et al., 2023). Hydro-mechanical tests and numerical simulations have further shown that bedding geometry, pore-pressure diffusion, stress redistribution, and fracture interaction jointly determine the final fracture pattern and hydraulic conductivity. Therefore, fracture-network formation should be regarded as an organized response controlled by structural hierarchy, rather than a random result of material heterogeneity.

Under deep in-situ conditions, multi-field coupling further strengthens the role of structural heterogeneity. Mechanical loading changes pore volume and fracture aperture; fluid pressure modifies effective stress and promotes hydraulic fracture propagation; temperature variation induces thermal fatigue and mineral-scale deformation chemical reactions alter cementation, pore geometry, fracture roughness, and long-term strength. Rather than acting independently, mechanical, hydraulic, thermal, and chemical effects interact through feedback. Damage may increase permeability and accelerate pressure diffusion, whereas stress redistribution and chemical alteration may either enhance or reduce fracture conductivity. Rough-fracture experiments have shown that normal stress and aperture closure can strongly reshape channelized flow (Wu et al., 2024), and thermal-hydraulic-mechanical-chemical (THMC) models further reveal coupled feedback among damage, pressure, temperature and reaction. These findings help explain why deep-rock stability and reservoir performance cannot be inferred from mechanical strength alone.

A useful conceptual understanding is that pore-mineral heterogeneity controls the origin of damage, bedding-fissure-fracture heterogeneity controls the path of failure, and THMC coupling controls the rate, mode and engineering consequence of instability. Such framework still leaves room for separate studies on pores, minerals, cracks, and fractures, while it places their engineering value in a broader context. Their relevance depends on whether they can be integrated into constitutive models and numerical frameworks that preserve the dominant structural controls while remaining applicable to field-scale analysis. Future research should therefore move from describing isolated heterogeneous features toward establishing structure-informed coupling mechanisms that can explain and predict deformation, fracture evolution, permeability change, and instability in deep heterogeneous rock masses.

4. Application in energy development and storage

The engineering value of multi-field coupled mechanics lies in translating structural and mechanistic understanding into operational criteria. In deep energy development, underground storage and underground space utilization, heterogeneous structures cannot be judged by a single standard. A fracture network that benefits reservoir stimulation may become a leakage pathway in storage projects or a weakness controlling excavation instability. Therefore, heterogeneous-rock mechanics should be applied according to the functional objective of the underground system: conductivity creation, sealing integrity, or deformation-failure control.

In unconventional oil and gas development and enhanced geothermal systems, the aim is not to tackle fracture complexity itself but to achieve controllable connectivity and durable conductivity. Structural heterogeneity help identify intervals where damage can be initiated and propagated efficiently. However, stimulation effectiveness is controlled not only by brittleness (Zhao et al., 2023) but also by geostress, bedding anisotropy, pore-pressure diffusion, fracture interaction, and coupled THMC processes (Xu et al., 2024). Therefore, stimulation design should shift from simply pursuing complex fractures to regulating fracture networks that remain connected and conductive under deep in-situ conditions.

In storage-oriented projects, including CO_2 storage, hydrogen storage and gas storage, the engineering logic is reversed, with the key objective being containment rather than fracture connectivity. Injection-induced pressure buildup and cyclic injection-withdrawal may reduce effective stress, reactivate faults, damage caprock, alter fracture apertures, and create leakage pathways (Ramesh Kumar et al., 2023). Multi-field coupled mechanics is therefore needed to define the allowable operating windows, including injection pressure, injection rate, pressure-buildup strategy, leakage-risk zoning, and monitoring indicators. Structures favorable for stimulation must be re-evaluated as potential risks for containment.

For deep mining, underground caverns and space projects, stability control is a central issue. High in-situ stress, excavation unloading, blasting disturbance, groundwater infiltration, and temperature variation may activate bedding planes, joints, faults and pre-existing cracks, causing spalling, rock bursts, fault slip, or surrounding-rock collapse. In these settings, heterogeneous structures control damage accumulation, energy release, crack propagation, and crack arrest around excavations. The engineering task is to translate this structural understanding into excavation layout, support timing, achieve a proper reinforcement design, conduct destress measures and apply crack-arrest strategies.

Overall, heterogeneous-rock mechanics should move beyond a universal favorable-or-unfavorable index. Its practical role is to link structure identification, coupled-mechanism modelling, field monitoring, and parameter updating with project-specific objectives. Future applications should therefore shift from the static evaluation of heterogeneity toward a function-oriented regulation of coupled rock-mass behavior.

5. Conclusions

Deep heterogeneous rocks should be understood as structure-controlled and multi-field coupled systems, wherein heterogeneity is not merely a descriptive geological feature but a governing condition that affects damage initiation, fracture-path selection, permeability evolution, and engineering risk. The studies presented at the forum collectively demonstrate that the key scientific issue is to establish a clearer connection between structure and mechanism: pore-mineral heterogeneity defines the initial damage field, bedding-fissure-fracture heterogeneity controls the propagation and interaction of fractures, and THMC coupling determines whether local damage evolves into permeability enhancement, fracture-network reorganization, or instability.

As indicated by the discussions in this forum session, future work should focus on converting structural descriptors obtained from imaging and digital rock analysis into constitutive variables and upscaled parameters, reproducing realistic engineering loading paths in laboratory tests, and developing mechanism-informed operating windows for engineering design. These directions require scholars to focus not only on cyclic injection-production, unloading, heating-cooling, pressure diffusion, and chemical reaction, but also on the balance among stimulation efficiency, durable conductivity, storage containment, induced-seismicity control, and long-term stability. Emphasizing heterogeneity does not mean the addition of unlimited model complexity. The practical task is to identify which structural variables matter and under which engineering paths, as well as how they can be measured, modeled, monitored, and regulated. Progress in these directions will provide a stronger theoretical and experimental basis for several fields, including deep oil and gas production, geothermal exploitation, CO_2 and hydrogen storage, underground energy reserves, deep resource extraction, and safe underground space utilization.

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Conflict of interest

The authors declare no competing interest.

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