

The Role of Rock Mechanics in the 21st Century



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Abstract Rocks and rock masses pose very complex problems that must be addressed by the engineering and scientific communities if the challenges of the 21st century are to be met. New societal demands for improved infrastructure, clean water, sustainable energy, and climate change, all call for an improved understanding of the multi-physics phenomena involving rock and all require a multi-disciplinary approach. The chapter identifies five topics that, among others, limit further developments in the field or are critical to societal demands: (1) Underground construction, geology and geotechnical risks; (2) Microstructure-enriched damage and healing mechanics; (3) Damage detection inside rock; (4) Coupled processes for energy extraction; and (5) Sustainable recovery of subsurface energy resources.

Keywords Rock mechanics · Coupled processes · Efficient mining · Environmental impact · Induced seismicity · Transparent earth · Underground construction

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1 Introduction

The National Academy of Engineering has identified fourteen Grand Challenges for the 21st Century. Of those, four directly involve rock mechanics and rock engineering: Restore and Improve Urban Infrastructure, Provide Access to Clean Water, Develop Carbon Sequestration Methods, and Engineer the Tools for Scientific Discovery. All call for an improved understanding of the multi-physics phenomena involving rock and all require a multi-disciplinary approach.

Rocks and rock masses are highly heterogeneous, with complex behavior that it is not only stress and time dependent, but also, and this is most important, scale dependent. It can be argued that the behavior at different scales is due to the “defects” that exist in the rock. These defects can be found at the atomic scale, where atom lattices may have irregularities; at the grain scale, where cracks are pervasive at the grain contacts and inside crystals, and up to the regional or continental scale because of different geological formations or due to discontinuities or faults that can range from microns to hundreds of kilometers in size, e.g. the North Anatolian or the San Andreas faults (see Fig. 1).

The complexities that the rock mechanics/geomechanics profession face are many. Rocks are formed from many different minerals, each with different chemo-mechanical properties, and defects (joints) that make the materials highly heterogeneous, anisotropic, and stress, time and scale dependent. The minerals in the rock may weather with time under different environments, joints may propagate due to subcritical crack growth or due to anthropogenic activities, which all change the behavior of the rock mass. Rocks, at great depth, are subject to large temperature and stress gradients and to different fluids such as formation fluids, oil, gas. Fluids in the rock mass originate from either geological processes or anthropogenic interventions such as carbon-dioxide sequestration or leakage from nuclear waste disposal. The stresses in the rock as well as the fluid environment may be engineered, e.g. for oil and gas extraction, for geothermal energy or for energy or waste storage including carbon sequestration.

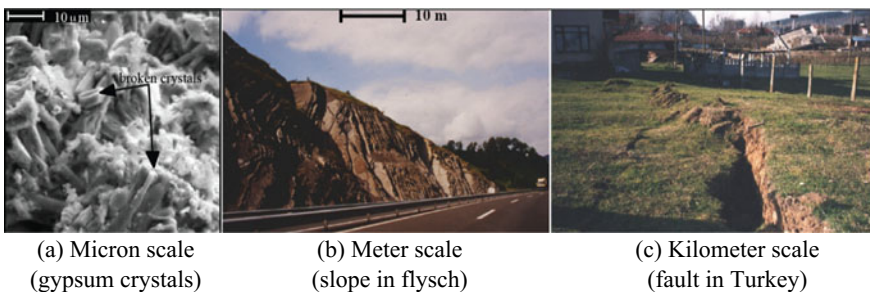


Fig. 1 Rock discontinuities at different scales

The challenges for rock mechanics and rock engineering in the 21st century stem out of society's continuous demand for improved levels of comfort and access to sustainable, safe and renewable resources. Sustainability calls for safe and economic technologies for waste disposal, CO₂ sequestration and new sources of clean energy. The science required to face these problems is inherently interdisciplinary, but not yet available. Finding solutions for these questions is a great challenge but also a great opportunity.

It is not possible to discuss in a single chapter the state of knowledge in rock mechanics/geomechanics, nor the specific research needs for the entire subject. What is done is focus on a few particular aspects that, in the authors' opinions, limit further developments in the field or are critical to societal demands. The topics chosen align with the challenges identified in Chapter 1 "[The Role of Geotechnics in Addressing New World Problems](#)", and revolve around the following themes:

- Underground construction, geology and geotechnical risk
- Microstructure-enriched damage and healing rock mechanics
- Damage detection inside rock
- Coupled processes for energy extraction
- Sustainable recovery of subsurface energy resources.

The following sections address the themes and provide insights into fundamental aspects of rock behavior such as damage and healing across the micro-, macro- and time-scales, coupled-processes to e.g., extract geothermal energy, as well as into practical aspects such as the central role that rock mechanics plays on energy resources, waste storage and anthropogenic effects associated to the utilization of the underground space, the pressing need for volumetric imaging of the subsurface, and on the interplay that exists between geology, design, construction and risk associated through all the stages of the infrastructure process, from conception to implementation.

2 Underground Construction, Geology and Geotechnical Risk

The underground construction industry has consistently provided the nation with needed infrastructure, meeting schedule, cost and scope goals. Population growth will continue, and so will the growth of our cities—but not always in predictable ways. In the past, we have lived through urban migration and growth, followed by suburbanization, and now perhaps the concept of the compact city describes how our cities will change in the future. The compact city concept is intimately wedded to increasing and intensive planned use of underground space, but engineers and planners have challenges in preparing our old and new infrastructure for the future.

It is generally appreciated that the nation must invest in the rehabilitation of existing infrastructure, but there continues to be a lack of political and public will to

do so. The value of our underground infrastructure needs to be better communicated to the US population. If our systems become increasingly unreliable, then it is likely that more of the world's leading industries will relocate to countries with more reliable infrastructure.

As we create and use more underground space, particularly in urban environments, we may find ourselves working in ground conditions not experienced before. This means that much of our conventional and current wisdom based on experience in a city may not be applicable. For example, we anticipate increased use of deeper underground space for many purposes. Higher ground stresses and water pressures will likely be encountered, and soil and rock behavior may become more problematic. As new needs for underground space are identified, owners and the public will request larger and more complex 3-D complex geometry for underground space applications. This may require advanced design concepts for long-term performance and stability. And as our coastal cities grow, more of the new infrastructure must be placed into more challenging ground for which risks and costs may be higher. This may require new approaches to ground improvement and displacement control.

The infrastructure can no longer be considered as isolated systems. Our infrastructure networks are developing emergent interdependencies that affect system performance, reliability and expected life. More of our systems are becoming diversified with gridded, distributed and local components not necessarily working together seamlessly, and this threatens to lead to a loss in robustness and resilience of service delivery at a time when the population is growing increasingly risk averse. We must make our systems smarter and able to self-detect problems. We must also commit to developing an IIM (Infrastructure Information Model) for all major cities, analogous to a Building Information Model (BIM) increasingly used for high-rise building design and construction management. The functions of a city must be preserved, and advanced sensing and spatial and temporal registration and tracking of all facilities and functions will elevate our infrastructure to the reliable and resilient systems our society needs [84].

Significant impacts from extreme events, including climate change, earthquakes, tsunamis, floods, storms—are arguably becoming more frequent and costly. Our future global cities must support the population both through disasters and for daily living, perhaps analogous to the human body's resistance and resilience to a high-grade fever and also to manage a low-grade infection. With the growth of population and megacities, our society deserves and demands integrated planning for improved space utilization. The scale and definition of geologic variation are as important as political boundaries. Engineers and planners must realize that:

- Urban growth will extend infrastructure into deeper and more fragile and challenging geologic environments
- Sustainability, terrorism and security drive new constraints for retrofit and new infrastructure system design
- The experienced intensity, impact and frequency of extreme events have been and are expected to continue to increase (data shown in Fig. 2 for weather-related losses).

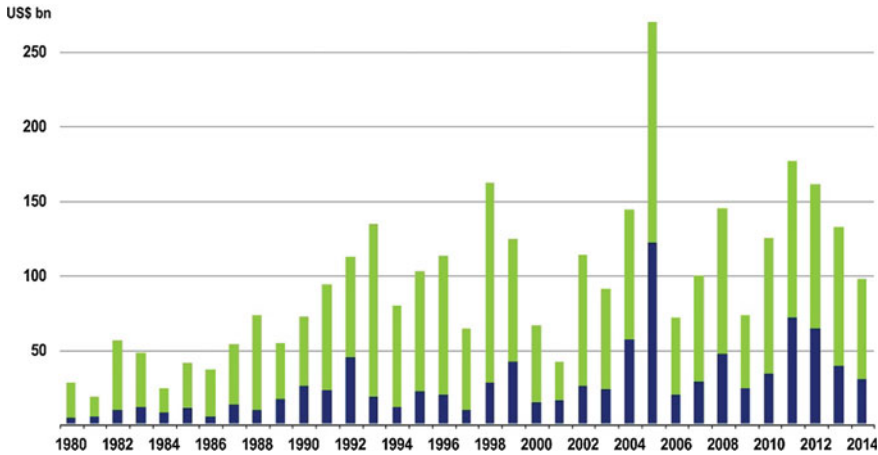


Fig. 2 Weather-related loss events worldwide 1980–2014. (green is overall losses and blue is insured losses, all in 2014 values) [55]

In many cases, the design loads used by engineers at the time of construction of our older infrastructure, may not be the loads we would use now. Our design and professional codes have always incorporated factors of safety against failure by such events, but the impacts of recent events have been more severe and complex with interdependent responses. Engineering professionals, construction contractors, and urban planners and managers must work together to identify new ways to retrofit and bolster our infrastructure against extreme event impacts. Underground engineering can be a part of effective design and solution of problems. Therefore, the underground is an important resource to enhance urban resilience, as is summarized in Table 1.

2.1 Reduction of Costs and Risks

Beyond the need for infrastructure services is the need to manage the budget. It is notable that infrastructure costs for construction and rehabilitation have only increased in recent time. Innovations are needed to reduce costs and support schedule reliability, and best decisions on investments can only be made with increased use of Life Cycle Engineering (LCE) which requires databases that by-and-large do not exist. With increased use of LCE, performance metrics can be established for integrated surface and underground infrastructure planning and design, and to support sustainable multi-hazard design and LCE trade-offs. This need may define a new profession of urban stewards—engineers who design and construct holistically integrating over x, y, z and time.

It is also imperative the physical facilities be made more durable, and the infrastructure performance be made more reliable. Cost increases are often driven by

Table 1 Advantages and disadvantages for underground infrastructure and extreme event impacts

| Type of event | Advantages or mitigations | Disadvantages or limitations |
|--|--|---|
| Earthquake | Ground motions reduce rapidly below surface | Fault displacements must be accommodated |
| | Well-built structures move with the geologic material | Instability in weak materials or poor construction |
| Hurricane, tornado | Wind loadings have minimal impact on fully buried structures | Damage to shallow utilities from toppling of surface structures such as trees and power lines |
| Flood, tsunami | Ground provides protection from surge and debris flow | Extensive restoration time and cost if entrances are flooded |
| Fire, blast | Ground provides effective protection, limit damage by compartmentalization | Entrances and exposed surfaces are weaknesses, confined space risk |
| Radiation, chemical/biological exposure/releases | Ground provides additional protection | Appropriate ventilation system protections required |
| | Limited exposure with compartmentalization | Confined space may increase personnel risk |

increased risks: Risk = Probability x Consequences (or Impact). For consequence evaluation, we need to know the value of underground space. We need an improved ability to quantify risks—including impacts and their probability of occurrence, as well as a framework for evaluation of mitigation strategy and assignment of responsibility. Once we better understand what problems drive risk increases, then we can contemplate where is the will to pay. A majority of the risk associated with underground infrastructure construction and performance is derived from the spatial variability and uncertainty associated with geologic conditions, including soil rock and water. Six areas of focus are discussed below:

- Risk avoidance
- New technologies and methods
- Better subsurface characterization
- Better management of water
- Risk awareness, assessment and management
- Risk communication and willingness to accept and share risk.

Risk Avoidance. Geologic conditions in the subsurface should be primarily managed by invoking the concept of underground zoning which provides spatial thinking and integrated planning to place above- and below-ground facilities in an optimized geologic setting. In New York City and other cities, such a consideration leads to vertical segregation of different infrastructure systems. However, much of the shallow infrastructure represents spatial chaos and project costs are strongly impacted by the need to manage the mayhem of aged near-surface systems.

The Japanese experience is a bit different. The 2001 Deep Underground Utilization Law established that land ownership rights in populated areas (e.g., Tokyo, Osaka) only extend to 40 m below ground, or 10 m below a deep foundation. In the case of public use of the underground space, no compensation to the land owner is required. The first projects using the law have included underground water mains in Kobe, and the Tokyo Gaikan Expressway.

New Technologies and Methods. In many areas of research, the pipeline from fundamental research to application has been thwarted. It is imperative that industry and owners commit to partner with universities to develop new technologies and methods, including new ways to excavate and support underground openings. The underground industry has many methods that can be applied including Tunnel Boring Machines (TBMs) and shields, and the newer slurry, earth pressure balance and hybrid pressure-face equipment, but more developments are needed to decrease costs, and improve safety (e.g., avoid hyperbaric cutter replacements and other interventions). The seemingly inexorable trend is for larger and larger diameters, and this by itself drives up project costs and expands project schedule.

In addition, it is important to incentivize the application of new technologies. For example, ground improvement techniques have come a long way in the past 30 years, and it is important that advances continue, and that techniques of ground improvement be proactively implemented before a project is started to change and remove identified geologic risks, rather than respond to the risks as encountered. Such postures often result in changed condition claims, litigation, increased costs and delays.

Many of our infrastructure projects are designed for low first cost and to comply with right-of-way limitations. Such systems are not necessarily designed for long-term sustainability and maintainability. Engineers must seek new materials and technologies to enhance performance and durability of our infrastructure systems, new and old. In addition, new technologies must not be just implemented—they must be assessed for short and long-term performance. Sober assessment of performance is very often forgotten in the cycle of innovation we seek for the underground industries.

Safety in the underground during construction and operation continues as a concern, and incident rates for heavy construction are considerably higher than for mining projects. Safety innovations continue to be needed, and include personal protective equipment during construction and also fire and explosion incident management, particularly when the public are involved in response.

Spatial and temporal variations in subsurface materials and conditions continue to be a risk, and a new look at integrating geophysical and remote sensing methods is warranted. Engineers should also rethink materials and methods in use. For example, development of new concrete, grout and shotcrete materials for application in the underground are needed, and engineers and contractors should revisit and dramatically improve our “old” or “conventional” technologies such as drill/blast operations.

Better subsurface characterization. Knowledge of the underground conditions has been improving over past decades, but the combination of continuing sore points and

arising new difficulties must be considered in planning. In many urban environments, previous underground works have demonstrated spatial and material property distributions to be expected, so our conventional site investigations should be confirmatory rather than exploratory.

But some geologic issues continue without full resolutions, as a low-grade infection on the industry. Examples include the following:

- Shallow cover, varying depth to rock
- Ground movements, subsidence
- Consolidation settlements
- Weathered rock and rock mass (including karst)
- Rock mass structure and variability
- Time dependency in materials behavior
- Muck abrasiveness and stickiness
- Aggregate reactions and concrete durability.

Geological and Geotechnical Engineers still wrestle with scale effects as well, extrapolating from laboratory behavior to full scale in the field. Many rock mass rating systems have been developed—too many. On a large number of projects, ratings applications have been uninformed and inconsistent, and there have been only limited attempts to validate their inference, or the use of a large number of empirical correlations. This observation also can be applied to the plethora of computational models available for subsurface design. We must make opportunities to validate design assumptions and performance prediction.

More urban infrastructure will necessarily be placed deeper, and the in situ stress state will likely become more important on more projects. Estimation of in situ stress is not easy without a clear geologic framework for interpretation, and most stress assessments are made as point measurements (interpretation of deformation measurements at a point). This can only be addressed by obtaining a better understanding of the spatial variability of rock mass structured which introduces uncertainty. The variety of excavation shapes and dimensions can be expected to vary in the future, with more gallery space rather than plane strain tunnels needed, making the predictions of stress redistribution around an underground opening increasingly important. We need to understand spatial and temporal variations that affect performance of existing facilities for sustainable design and operations.

Geologic material failure and time-dependent response of geologic materials are far more likely to be observed in an underground mine than in a civil works project. Mining engineers develop a strong geologic perspective on risk that would benefit in application to civil construction projects. Such a partnership or collaboration across industries brings an enhanced potential for real spatial understanding of rock mass and water inflow and pressures variability, and for better understanding of time effects, presenting the possibility to develop sustainability performance information. The two industries also have many environmental issues in common, as do they have a mutually beneficial potential for application of automation, robotics, and big data/information systems. This is the era of information: with an expansion in

sensing and measurement capabilities, how should the entire site investigation and construction process be re-thought, not to mention real-time data flows and their importance to effective management for resilience of urban infrastructure systems.

Better management of water. The presence of water in the subsurface changes the behavior of materials and strongly influences the long-term performance of underground facilities. Full consideration of the influence of water includes knowledge and understanding of volume, flow rate, quality, pressure, and changes over time.

Management of water is sometimes a matter of resource conservation, but environmental (bio-geo-chemical) and construction impacts can be profound. During construction, water management includes compressed air, and the use of pressure-faced shields. Microtunneling and trenchless methods are very flexible and work well for smaller diameter emplacements, which potentially can be efficiently and economically reamed to larger diameters.

Water inflows can complicate the construction process, and even compromise the capabilities of installed support. Some of the most active areas of new technology implementation have been the introduction of waterproofing into tunnel linings.

Operational impacts of seepage and inflows are incredibly important since water drives long term deterioration in the underground, and inflows can cause piping and ground loss that affects structures nearby. The long-term performance of waterproofing or drainage management technologies is not well known in most cases. Assessment is needed.

Risk awareness, assessment and management. Many underground construction projects now use the three-legged stool of a Disputes Review Board (DRB), requirement for bid documents to be escrowed, and the development of a Geotechnical Baseline Report (GBR) as a part of the contract documents explicitly developed for geologic risk management.

The GBR is thoughtfully written to present a geologic analysis of “geoproblem event” frequency (temporally and spatially) to be assumed during a project. To be done is the collection of project data to inform statistical probability and consequences of encountering major geotechnically-driven stoppages in underground excavations. The data and information needed include:

- Spatial frequency: km/event
- Typical event sources: excavation and equipment, ground control, water
- Temporal frequency: hours/event
- Response duration distribution
- Quality/performance of contractor.

Not everything about a specific project is “one-off”, and the framework of geologic inference and analysis opens the prospect for real predictability of geotechnical event with extreme impact on a project. And for this geologic effort, it is clear that mining and civil industries can share geodata.

An increasing number of projects continue into the project with risk registries which are living documents that characterize risks, assign responsibilities, and record mitigation plans. What is not developed to date is a broad consensus as to the method of risk analysis.

Risk communication and willingness to accept and share risk. The commitment for investment requires far more effective communication of the value of infrastructure and of underground space. The value of the nation's infrastructure may be estimated in several ways, but totals on the order of \$70–\$100 trillion can be suggested for the US. If this number is divided by the population of the US, the per capita investment in infrastructure is on the order of \$300,000, the price of a house in many areas. This \$300 K can be interpreted as a birthright for each person born in the US, a pre-investment upon which the economic engine runs, the quality of life is assured, and career potential of each individual is leveraged. Even as families reinvest in a house to retain value, so must the nation reinvest in its infrastructure. This is an example of a metric that can be meaningful to each citizen and politician.

3 Microstructure-Enriched Damage and Healing Rock Mechanics

Plasticity models and failure envelopes have been used in Earth Sciences and Rock Engineering for decades, with little emphasis on the scales and orientations of discontinuities that affect rock macroscopic properties. While thermodynamic equations of crack propagation and rebonding are formulated at the crystal scale, homogenization schemes are based on strong assumptions on microstructure topology. The gap between microscopic and macroscopic rock damage models makes it infeasible to uniquely characterize the pore- and crack- scale mechanisms that control deformation and flow regimes, predict percolation thresholds coupled to changes of rock stiffness, or relate crack rebonding time to stiffness and permeability healing time. A theory that couples rock microstructure descriptors (e.g. pore and crack sizes) and macroscopic thermodynamic variables (e.g. deformation and damage) is presented. Model predictions can be used to recommend the conditions of moisture and temperature necessary to minimize damage and/or enhance healing in rocks and to design safe and sustainable geological storage systems. In addition to preventing subsidence, borehole instabilities and contaminant leakage, the proposed models will be applicable for predicting fault rupture during earthquakes, improving manufacturing methods and designing sustainable materials.

3.1 Continuum Damage and Healing Mechanics

Crack opening. Continuum Damage Mechanics (CDM) provides an efficient framework to predict deformation and stiffness changes (including anisotropy) from purely energetic considerations [65, 68]. However, most damage models proposed for porous rocks were designed for saturated geomaterials and restricted the damage criterion to mechanical tensile loads. Very few studies include an anisotropic dam-

aged permeability model [75]. Almost all models proposed for unsaturated porous media resort to Bishop’s effective stress concept, i.e. the extension of Terzaghi’s effective stress to unsaturated media, e.g., [14], which partially uncouples damage evolution and poromechanical phenomena. Alternatively, Arson and Gatmiri [3] formulated an orthotropic thermo-hydro-mechanical damage model, using independent strain state variables. Rate-independent CDM models are based on a minimum of two postulates [24]: the expression of the free energy, a damage criterion, plus a dissipation potential if dissipative flow rules are non-associated (Table 2).

Crack Closure. The rotation of the principal base of damage induced by crack closure makes classical CDM frameworks inconsistent [20]. Most models proposed for mechanical crack closure are either isotropic, or restricted to mode I fracture propagation, e.g., [87]. An exception is the model proposed by [49] for cohesive materials, which accounts for the recovery of the shear modulus due to friction. Bargellini et al. [8] proposed an original (but complex) discrete formulation, in which crack displacements are projected on a set of basic tensors of various orders. Crack opening is sometimes assumed to generate irreversible deformation due to geometric incompatibilities at the faces of the cracks that close. It is possible to introduce a damage-induced irreversible component to the deformation tensor, without having to resort to any additional plasticity potential. However, this kind of formulation often falls short when the material response is very different in tension and compression, like in rocks [116]. Moreover, damage and total deformation must be considered as thermodynamically independent, which leads to thermodynamic inconsistencies. As a result, the ambivalent definition of damage used to account for both stiffness degradation and irreversible deformation requires formulating CDM models in terms of general stress variables. Even so, using only one dissipation potential in the formulation makes it challenging to express the lumped damage potential and the corresponding

Table 2 Main postulates needed to formulate a rate-independent CDM model

| Postulate | Constitutive relationship |
|---|---|
| Solid skeleton free energy $\Psi_s(\epsilon, \mathbf{D}, \mathbf{X})$ | $\sigma = \frac{\partial \Psi_s(\epsilon, \mathbf{D}, \mathbf{X})}{\partial \epsilon}, \mathbf{Y} = \frac{\partial \Psi_s(\epsilon, \mathbf{D}, \mathbf{X})}{\partial \mathbf{D}}, \mathbf{R} = \frac{\partial \Psi_s(\epsilon, \mathbf{D}, \mathbf{X})}{\partial \mathbf{X}}$ |
| Damage criterion $f_d(\sigma, \mathbf{Y}, \mathbf{X})$ | $(**) \dot{\mathbf{D}} = \dot{\lambda}_d \frac{\partial f_d(\sigma, \mathbf{Y}, \mathbf{X}(\mathbf{D}, \epsilon^{id}))}{\sigma \mathbf{Y}},$ $\dot{\epsilon}^{id} = \dot{\lambda}_d \frac{\partial f_d(\sigma, \mathbf{Y}, \mathbf{X}(\mathbf{D}, \epsilon^{id}))}{\partial \sigma}$ |
| Damage potential $g_d(\sigma, \mathbf{Y}, \mathbf{X})$ | $\dot{\mathbf{D}} = \dot{\lambda}_d \frac{\partial g_d(\sigma, \mathbf{Y}, \mathbf{X}(\mathbf{D}, \epsilon^{id}))}{\sigma \mathbf{Y}}, \dot{\epsilon}^{id} = \dot{\lambda}_d \frac{\partial g_d(\sigma, \mathbf{Y}, \mathbf{X}(\mathbf{D}, \epsilon^{id}))}{\partial \sigma},$ $\dot{\mathbf{R}}^{id} = \dot{\lambda}_d \frac{\partial g_d(\sigma, \mathbf{Y}, \mathbf{X}(\mathbf{D}, \epsilon^{id}))}{\partial \mathbf{X}}$ |

ϵ : deformation tensor

σ : stress tensor

\mathbf{D} : damage tensor

\mathbf{Y} : damage-driving force;

\mathbf{X} : tensor lumping hardening variables

\mathbf{R} : thermodynamic “force”, work-conjugate to the hardening tensor \mathbf{X}

ϵ^{id} : irreversible deformation induced by damage

Often, $(\mathbf{D}, \epsilon^{id})$ are hardening variables

λ_d : damage multiplier

(**) If associate flow rules

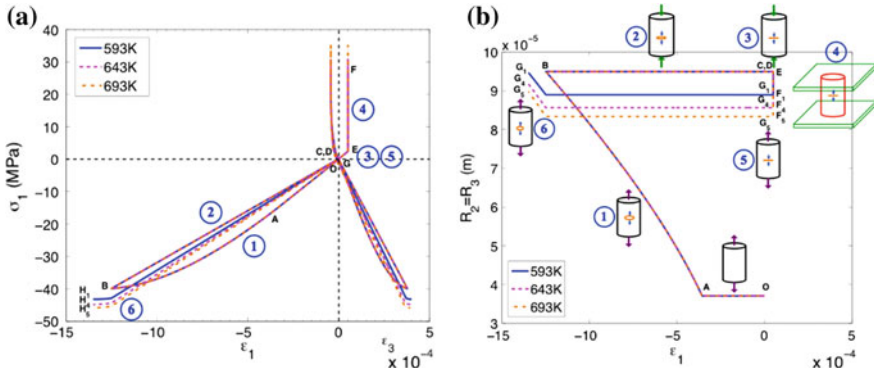


Fig. 3 Simulation of a stress path including a tensile loading (OB), followed by unloading and compression (BE), a heating phase that triggers Diffusive Mass Transfer (DMT) and healing (EF), cooling (FE) and reloading (EH). Stress/strain curves (a) and average crack lateral crack radii (b) for different heating temperatures. Modified after [119]

damage-driving forces, which become anyway non-physical. It is anticipated that a truly hyper-elastic framework could overcome the shortcomings of CDM models currently available to capture irreversible damage-induced deformation [2].

Crack rebonding. At the scale of a Representative Elementary Volume (REV), measurements of porosity and permeability can be used to assess clogging due to precipitation, but only loading and unloading cycles can provide a measure of potential stiffness recovery by crack rebonding [36]. Recent developments in polymer sciences explain interactions involved in complex chemical chains by modeling molecular movements as crawling mechanisms [115]. The concept of healing by Diffusive Mass Transfer (DMT) was initially introduced to model atomic interactions in cracked glass [114], and refers to crack rebonding by the migration of ions in the lattice forming the solid mass. Numerous studies were conducted at the microscopic scale on halite because this natural geomaterial can heal even in the absence of impurities [98, 102]. Phenomenological healing models proposed for salt rock assume that both crack opening and closure are time-dependent, which makes it possible to represent cracking and healing effects by a viscoplastic dilatant deformation [56]. Some authors combined rate-dependent or rate-independent damage and healing variables [79]. Most damage and healing models are formulated with a “net damage” variable defined as the difference between the CDM damage variable and a healing variable [1]. Figure 3, taken from Zhu and Arson [119], shows an example of salt rock model in which the net damage is alternatively defined as a second-order equivalent crack density tensor, which represents the volume of open cracks, determined by statistical analyses of images taken during a creep test.

The model predicts that in tension, the sample behaves elastically (OA) before horizontal cracks start to open (AB). During the unloading phase, the slope of the stress/strain curve is less steep than during the initial elastic loading phase and the value of damage components remain constant (BC). Unilateral effects are then noted

during the compression phase (DE); internal compressive stress develops due to the restrained thermal expansion of the sample during the creep phase at high temperature (EF), and partial mechanical recovery is achieved after the healing phase (FG₁). Additional damage is produced after recovery (G₁H) when the new damage threshold is reached (larger than the initial threshold but smaller than the threshold obtained after the tension phase). The proposed modeling strategy is ad hoc to model stiffness changes induced by crack opening, closure and healing. However, the expression of the net damage depends on open crack volumes estimated from 2D images. Moreover, simplifying crack shape assumptions were made to distinguish closed and rebonded cracks. Fabric enrichment can circumvent these limitations.

3.2 Homogenization Schemes

Micro-mechanics and microplanes. Micromechanics-based damage models [91] assume that the REV is populated with a distribution of cracks characterized by a specific shape (e.g., penny-shaped), with a tractable density. These geometric hypotheses lead to an explicit expression of the strain concentration tensor and of the free energy of the rock-solid skeleton. For pure mode I cracking, the only damage variable needed to express the energy dissipation associated to the degradation of elastic moduli is the second-order crack density tensor [61], which is a particular form of Oda's fabric tensor, commonly used in structural geology [85]. Mixed crack propagation modes (inducing a non-zero tangential displacement at crack faces) require higher-order damage tensors—of at least order four, e.g., [19]. Increasing the order of the damage tensor improves the compliance of the model to symmetry properties required for the elasticity tensor [72]. In microplane models, e.g., [10], a kinematic constraint is applied to projections of strains on the crack planes. The principle of virtual work is applied on a discrete set of crack plane orientations, which are assigned weights to satisfy macroscopic energy balance equations at the scale of the unit sphere. Bazant's [12] discrete scheme with a 2×21 microplane distribution provides satisfactory accuracy at reasonable computation cost. A detailed discussion about the performance of numerical integration schemes is discussed in Levasseur et al. [69]. In the microplane theory, anisotropy stems from complex microplane orientation distributions and from the use of different evolution criteria for different microplanes orientations.

Homogenization and upscaling. Homogenization schemes were proposed to upscale microscopic gliding mechanisms in granular [6] and polycrystalline [80] media. For instance, in salt polycrystals, plastic and viscous deformation result from several fundamental mechanisms, e.g., dislocation glide, dislocation climb, polygonalization, inter-granular slip, dissolution-precipitation. Under stress and temperature typical of storage conditions, dislocation glide is the predominant mechanism that contributes to macroscopic salt rock deformation [98]. Pouya et al. [89] used the Hill's incremental interaction model to upscale viscous gliding mechanisms formulated at the crystal scale and to predict the viscous behavior of polycrystalline salt.

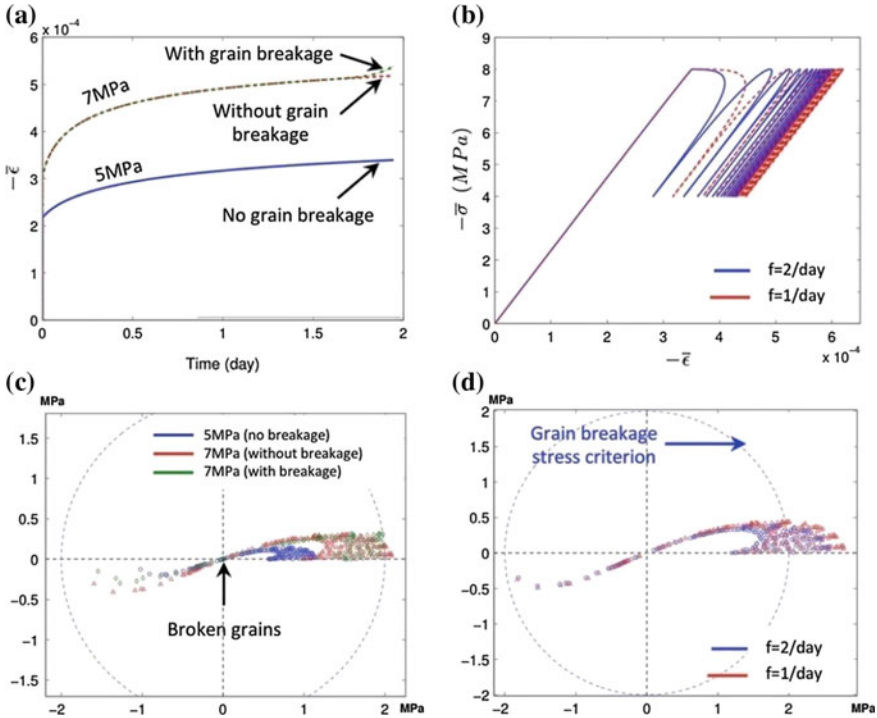


Fig. 4 Macroscopic deformation (a, b) and major principal micro-stresses (c, d) during creep tests (a, c) and a cyclic loading test (b, d). The micro-stress maps show the stress components in the radial (horizontal axis) and axial (vertical axis) directions. Each of the 200 dots represents the stress in one of the 200 crystals included in the REV. All salt crystals have a different crystallographic orientation, and are thus subject to a different gliding mechanism. Visco-plastic strains that result from glide induce local stress concentrations. When the local major principal stress exceeds salt tensile strength (2 MPa), the crystal is assumed to break and its stress vanishes. Crystal breakage correlates with the initiation of tertiary creep (a, c). For cyclic loading, the self-consistent approach predicts higher damage at lower frequency, which is consistent with in situ observations. Modified after [89]

Although some simplifying assumptions were made in the micro- macro-approach, the model provides micro-mechanical interpretations to important aspects of salt rock viscoplastic and fatigue behavior, such as strain hardening, creep recovery, as well as damage and accelerated creep due to grain breakage (Fig. 4a, c). Moreover, incremental viscoplastic strains decreased over the cycles, in agreement with the phenomenon of “shakedown” observed in elasto-plastic media; see Fig. 4b, d.

A review of incremental, secant, tangent, affine and variational formulations may be found in [76, 80]. Homogenization schemes allow computing poro-mechanical properties of rock subject to Thermo-Hydro-Chemo-Mechanical (THCM) processes [111]. However, increasing the number of physical processes (e.g., pore-throat suction, DMT) multiplies the number of scales of observation needed. Moreover, crack

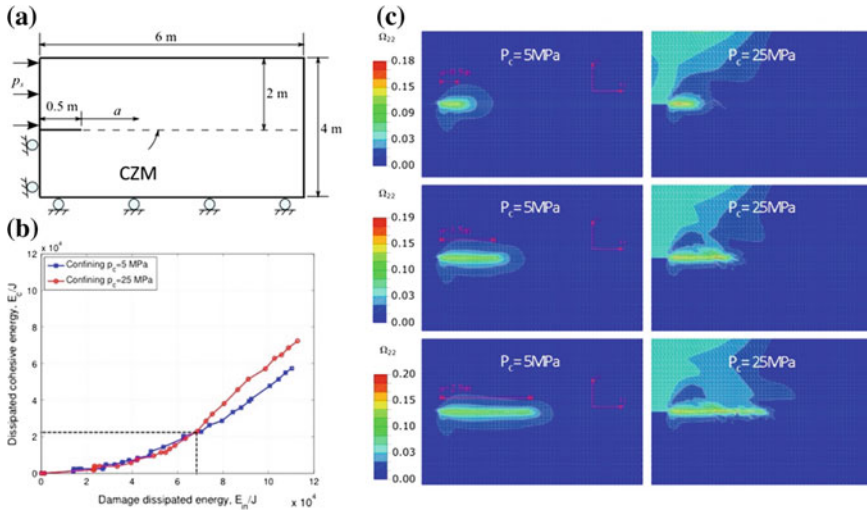


Fig. 5 Propagation of a mode II fracture (CZM) within its damage zone (CDM FEs). **a** Dimensions and boundary conditions. **c** Fracture and damage zone evolution. Ω_{22} is the damage component that refers to horizontal micro-cracks. Under a confining pressure of 5 MPa, the fracture propagates steadily within the damaged zone, while under a confining pressure of 25 MPa, the fracture propagates in ‘stick-slip’ mode. **b** In both cases, more energy is dissipated by micro-crack propagation than by macro-fracture advancement. Modified after [60]

coalescence poses the problem of separation of scale, due to statistical homogeneity requirements. The emergence of macroscopic cracks as a result of the coalescence of micro-cracks can alternatively be predicted by coupling a CDM model to a discrete fracture mechanics model. Figure 5, extracted from Jin et al. [60] shows an example in mode II: when the continuum damage variable exceeds a critical value in a Finite Element (FE), the neighboring Cohesive Zone (CZ) opens, energy in the FE dissipates, and stress relaxes around the CZ. Coupling CDM and Cohesive Zone Models (CZMs) or other discrete fracture models is a very active research area.

3.3 Microstructure Enrichment

Microstructure-based permeability models. Several relationships were established between permeability and microstructure, including: Models based on Kozeny-Carman formulas, initially derived to model fluid flow in a bundle of parallel pipes and modified to account for tortuosity, e.g., [93]; Statistical flow networks models [47] which involve the probability density functions (pdfs) of the dimensions, aspect ratios and orientations of geometric elements of the network (e.g., tubular capillaries, penny-shaped cracks, ellipsoidal pores); Fractal network models [109]; and Mechanical homogenization schemes adapted to fluid flow [31]. Although non-

uniform pore arrangement produces hysteresis in retention curves [92], most models that relate capillary pressure to pore size [110] assume that the pore network is a bundle of pipes of constant cross section, which are entirely filled with either wetting or non-wetting fluid. Several models were proposed to predict emergent porosity modes and consequent permeability changes upon damage propagation [4, 94] and to model fracture propagation in a thermo-poro-elastic rock [28]. However, in continuum mechanics, crack coalescence can only be accounted for if a sufficient number of groups of connected cracks are contained in the REV. In the percolation theory [103], a characteristic flow path length is postulated, and transitions in flow regimes can only be predicted if the probability of fluid saturation is known for each pore or crack.

Non-local damage models. Internal lengths are used to scale the influence of a variable defined at x on a point located at $x + dx$. In differential formulations, local field variables are developed in Taylor series [27]. In integral formulations [10], space averages are weighted by attenuation functions. Enriched continuum models have additional degrees of freedom for microscopic translations and rotations [40, 41]. Microstructure- and gradient-enriched formulations involve non-physical variables (e.g., third-order tensors), which raises a number of issues for numerical implementation [118]. Non-local models are used to regularize localization problems often encountered in damage and plasticity models with softening [11]. Alternatively, diffusion equations can be used for deformation and dissipation evolution laws: the diffusion coefficient is inversely proportional to the square of an internal length parameter (e.g., percolation distance for DMT). However, the use of a diffusive creep law for brittle-elastic solids can lead to thermodynamic inconsistencies [108].

Fabric tensors. A direct relationship can be established between fabric tensors and rock stiffness tensor [26]. According to Oda [85], the fabric tensor F_{ij} is expressed as:

$$F_{ij} = \int_{\Omega} n_i n_j E(\Omega) d\Omega \quad (i, j = 1, 2, 3) \quad (1)$$

where n_1, n_2, n_3 are projections of a unit vector \mathbf{n} on the Cartesian reference coordinates; Ω is the whole solid angle corresponding to a unit sphere, and equals 4π ; $E(\Omega)$ is a pdf. The key is to choose pdfs with relevant microstructure descriptors to capture damage and healing processes. As shown in Fig. 6, taken from Shen et al., [100], macroscopic deformation and stiffness changes in salt rock correlate to changes of the fabric tensors of grain orientation (G), branch orientation (B), local solid volume fraction (L; the solid volume fraction over a polygon with edges matching grains centroids) and grain solidity (S; the ratio of grain area over the area of the grain's circumscribed circle).

The 'total' fabric tensor H is defined as:

$$H^i = \gamma G^i B^i L^i S^i \quad (2)$$

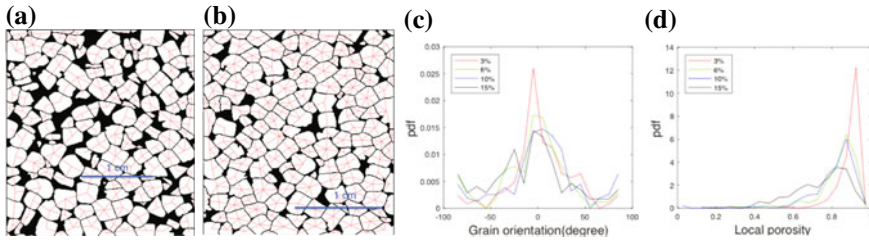


Fig. 6 Dry reagent-grade granular salt samples subjected to a uniaxial compression under 150 °C at 0.034 mm/s. Microstructure images at (a) 15% and (b) 6% porosity (white area: salt grains, black area: voids, red lines: branches linking the centers of two grains in contact). Evolution of the pdfs of (c) grain orientation and (d) local porosity for 15, 10, 6 and 3% total macroscopic porosity. Modified after [100]

where γ is a normalizing coefficient. The second-rank fabric tensor H can be written as $kI + K$. k is a scalar, and K is a traceless second-rank tensor. According to Zysset [121], the expressions of the free energy as functions of k , K and the strain E , are given as:

$$\begin{aligned} \psi(E, k, K) = & a_1 I \otimes I + a_2 I \bar{\otimes} I + a_3 K \otimes K + a_4 \left(K \bar{\otimes} I + I \bar{\otimes} K \right) \\ & + a_5 K^2 \otimes K^2 + a_6 K \bar{\otimes} K + a_7 (I \otimes K + K \otimes I) \\ & + a_8 (K \otimes K^2 + K^2 \otimes K) + a_9 (I \otimes K^2 + K^2 \otimes I) \end{aligned} \quad (3)$$

Rock microstructure and mineral composition can be determined in the laboratory and thermodynamic models can be established to explain healing at the mineral scale, e.g., [57]. That is why fabric-enrichment is particularly appealing to model the macroscopic effects of crack propagation and rebonding in rocks.

4 Damage Detection Inside Rock

The mechanical and hydraulic properties of rocks are often controlled by the discontinuities or joints present in the rock mass. The importance of fracturing is attested by the large body of work geared at understanding the problem. Most of the research, understandably, has been concerned with observable damage; that is, at the macroscopic scale. Observations in the laboratory have relied on visual inspection using optical magnification and high-speed cameras. Digital Image Correlation (DIC) is an advanced experimental technique that has been utilized to observe the fracturing process on the surface of specimens by measuring full-field displacements similar to particle tracking in fluids. DIC has been used effectively for kinematic measurements along discontinuities and fractures [70]. While surface imaging techniques have been

instrumental in the understanding of cracking phenomena at the macroscopic scale, what is needed is a local or microscopic characterization of new cracks forming inside brittle materials.

One of the problems that limits advancements in the field of rock mechanics is our inability to scrutinize the interior of the material for the presence of damage and new cracks, and to infer engineering properties of the cracks. Indeed, the state-of-the-art still resides in the work done by Germanovich and his co-workers who observed the initiation of internal cracks in Polymethyl Methacrylate, which is a transparent material [32, 42].

Acoustic Emission (AE) is based on the idea that fracturing and crack propagation produce elastic waves that are somewhat characteristic of the deformation process [104]. AE has been successfully used to provide insights into deformation and damage occurring in intact rocks [46, 74] and along existing discontinuities [95–97] or associated with hydraulic fracturing [17, 50] and mining [113]; however, it is unclear whether AE events are precursors to damage or the results of damage [83]. In addition, it is uncertain whether AE can provide information about the engineering properties or nature of the cracks, as both tensile and shear cracks produce acoustic events [18, 117]. Also, in experimental studies performed on granite samples undergoing frictional sliding, the rate of emission events was nearly constant and did not increase before slip. In other words, AE events may not be precursors to damage, but rather the results of damage [21]. An alternative, or at least complementary technique to the passive AE method, is active seismic monitoring.

Active seismic monitoring, in particular compressional and shear wave propagation, has been used as a successful tool to locate discontinuities, assess the state of the stress along discontinuities and provide information about their engineering properties such as stiffness [23]. The seismic monitoring method includes an array of piezoelectric transducers that transmit elastic waves in the form of ultrasonic pulses through the rock to an array of receivers. Seismically, the fracture behaves as a low pass filter and attenuates the high frequency components of the signal [90]. The seismic monitoring method provides a continuous and non-destructive way to probe the internal structure of the rock and the discontinuity, and has been proven to be successful in detecting slip along pre-existing discontinuities [51], new cracks [81, 82], and impending shear failure of frictional joints [52].

The potential for active seismic monitoring to illuminate the interior of a rock mass was confirmed through Mode I fracture experiments. Three-point bending tests were performed on Berea sandstone, a flat-bedded, light gray, medium- to fine-grained protoquartzite cemented with silica and clay, with uniform grain distribution ranging from 0.1 to 0.8 mm. A prismatic beam with a center notch length of 10 mm was

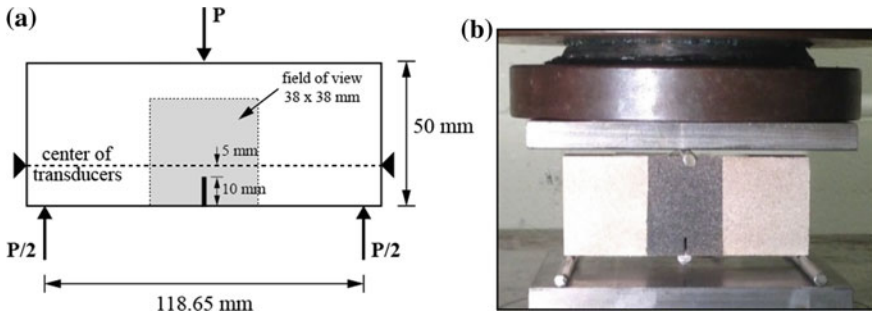


Fig. 7 Three-point bending tests (a) specimen geometry and (b) testing of sandstone specimen

tested with a span of 118.65 mm, 125 mm long, 50.0 mm tall, and 21.0 mm thick; see Fig. 7a. One surface was selected to place the speckle pattern for image analysis, as shown in Fig. 7b.

An Instron loading machine was used to apply the load to the specimen using a constant displacement rate of 0.03 mm/min. Crack initiation and propagation were identified with the DIC system, which showed that, at the tip of the crack, the horizontal displacement increased linearly at the early stages of loading, consistent with elastic deformation. As additional load was applied, a loss of linearity occurred that indicated damage to the specimen. As the axial load was increased to 86% of the failure load, the process zone grew and large jumps in displacement were observed farther from the tip of the crack. Because crack initiation is unstable in three-point bending tests, the DIC observations can be viewed as indication of the development of the process zone.

Two transducer pairs, one source (on the right side) and one receiver (on the left side), were used to monitor the sample during loading; see Fig. 7a. Two tests were used to determine the best type (P or S) of transducer to detect damage. The transducers were attached to the surface of the specimens using epoxy. After the transducers were placed, the load was increased at a constant displacement rate until the specimen reached failure. Full waveform measurements were taken during loading every 0.2 s. Figure 8 shows some of the waveforms recorded from the tests. The arrival time of the signals (both P-wave and S-wave transducers, irrespective of the polarization of the S-wave transducers) increased and the amplitude decreased with loading.

Graphs of normalized arrival time and amplitude (normalized by their values at the start of the test) as a function of load are shown in Fig. 9a, b, respectively. The arrival time increased monotonically until failure, and thus it did not provide an indication of damage to the specimen. However, the amplitude showed a distinct decrease at the time of formation of the process zone or damage. The amplitude increased with loading up to 1100 N where it reached a maximum, and then decreased until failure. The maximum in amplitude correlated well with the observation of the process zone based on DIC, which is indicated in the plots with a vertical dashed line. The three-

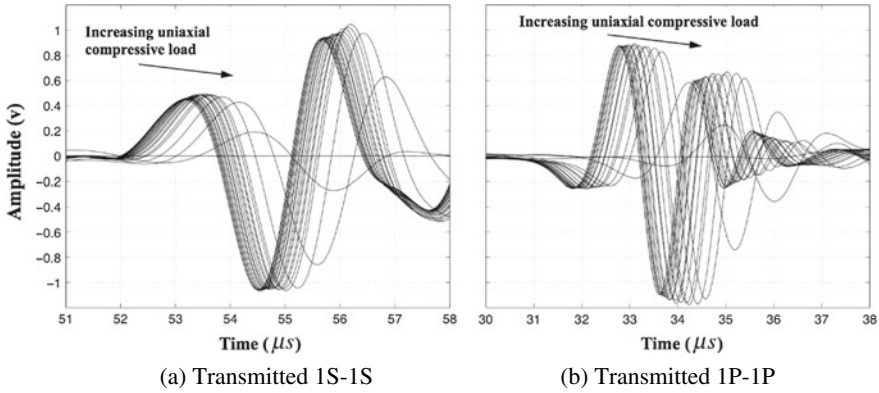


Fig. 8 Waveforms from three-point bending tests (a) amplitude of shear waves and (b) amplitude of compressional waves

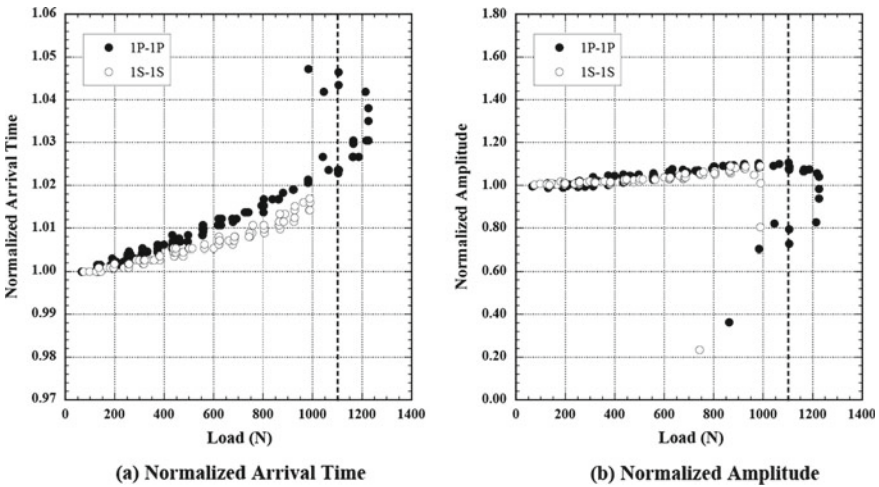


Fig. 9 Changes in arrival time and amplitude with load for P- and S-wave transducers, for three-point bending tests

point bending tests showed that the transducers, when located close to the tip of the notch, reached a maximum in amplitude during loading that was indicative of the formation of the fracture process zone, and thus could be taken as precursors to failure. In fact, the maximum in amplitude was consistently observed at 80% of the failure load.

The ability of detecting the onset of damage in the three-point bending tests by placing the transducers such that the path of the seismic wave intersected the area of impending damage, was tested in uniaxial compression tests on limestone. Figure 10 is a photograph of the experiment setup. Specimens of Indiana limestone with dimen-

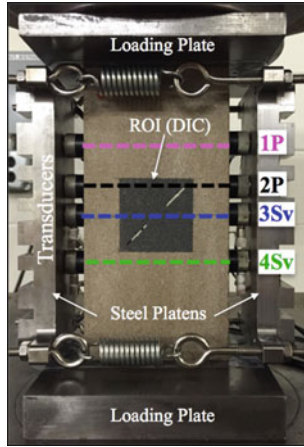


Fig. 10 Experiment setup on Indiana limestone

sions 203.2 mm height, 101.6 mm wide and 38.1 mm thick were loaded in uniaxial compression, at a constant displacement rate of 0.04 mm/min. The specimens had two parallel flaws cut through the thickness of the specimens, each 19.05 mm long. Different flaw arrangements were chosen such that coalescence occurred through a shear crack.

The displacements in the ROI (Fig. 10) were monitored using 2D-DIC imaging. In addition, full waveform compressional, P, and shear, S, waves were recorded, through transducers placed inside steel plates on the sides of the specimen, which were held in place by springs.

Figure 11 plots select results for a specimen with two coplanar flaws inclined at 45° with the horizontal, with a ligament length (distance between the internal tips of the flaws) of 19.05 mm. Figure 11a plots the amplitude of the transmitted waves of transducers 1P, 2P and 3S (polarized in the vertical direction) with load. The amplitude is normalized by the amplitude of each transducer at the start of the test. Transducer pair 1P-1P is located far from the flaws, to monitor the response of the intact rock during the test; transducer pair 2P-2P aligns with the upper tip of the top flaw to monitor crack initiation at this location, and pair 3S-3S goes through the ligament area to monitor crack initiation at the inner tips and crack coalescence. Figure 11b shows the cracks produced at the tips of the flaws and Fig. 11c the cracks at coalescence.

Crack initiation was monitored by both the DIC and the transmitted amplitude through the specimen. The plots of normalized amplitude in Fig. 11a indicate that the tensile crack at the exterior tip of the top flaw was detected by transducers 2P, prior to detection with DIC (see arrows in Fig. 11; T represents a tensile crack, S a shear crack, and “wave” or “DIC” the method of detection). Note that no damage is detected by pair 1P until coalescence, which is followed by unstable cracking, with the tensile crack from the external tip of the upper flaw crossing at this moment the path of the

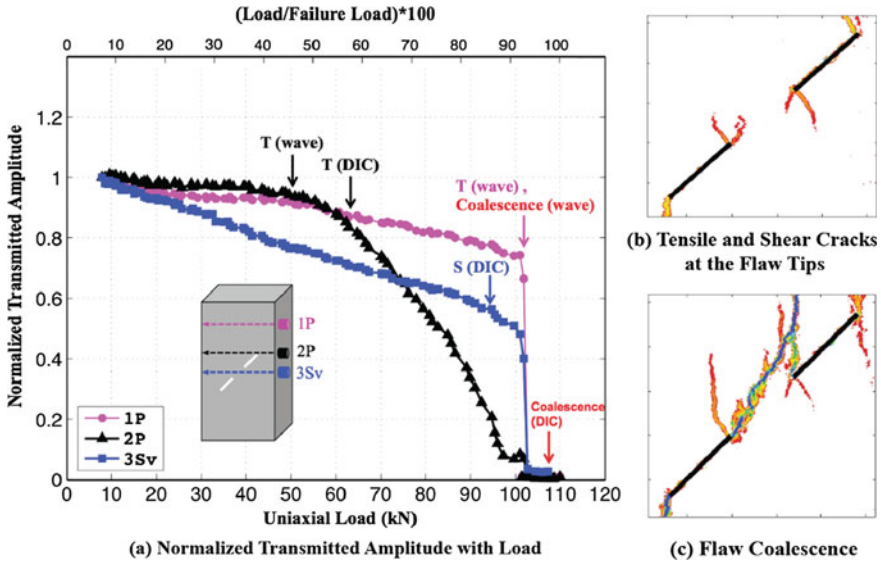


Fig. 11 Crack detection using active seismic monitoring

transducer pair. Coalescence is easily distinguished in the plot of transmitted waves from pair 3S by the abrupt loss of transmission due to the formation of the large, open, shear crack.

Additional tests with different flaw arrangements showed similar results, in that cracking can be detected using active seismic monitoring when the path of the crack intersects the path of the seismic wave [82].

5 Coupled Processes for Energy Extraction

Global challenges towards increase in sustainable and renewable energy extraction and decrease in carbon dioxide production define new directions in fundamental geotechnics research. Mechanical, hydromechanical, thermal and chemical processes in rock mass are coupled across spatial and temporal scales. Hydraulic fracturing, wellbore drilling, short and long-term fluid circulations, poro-elasticity and injections of carbon-dioxide gas in rock mass and saline aquifers are fundamentally not well understood due to coupled processes. Emergent technologies with relevance for energy sustainability and increase in renewable energy production which involve coupled processes in rocks are Enhanced Geothermal Systems (EGS) and Carbon-dioxide Capture and Sequestration (CCS). Development of renewable and sustainable geothermal energy source utilization, particularly through location independent EGS,

as well as CCS has a huge potential for addressing climate change challenges and decreasing global warming due to increase in CO₂ in the atmosphere.

Geothermal reservoirs serve for renewable and sustainable energy production, where the hot rock mass turn cold water into steam. Water re-circulation through the fractures of hot rock formation enables running electrical production power plant turbines or is combined with housing heating back on the ground surface. In enhanced geothermal reservoirs (EGS), the basement or sediment reservoir rock permeability enhancement will enable sustainable and long-term stable heat extraction. However, enhancing permeability involves deep well drilling and hydraulic fracturing of highly stressed and hot rock mass, which are still performed with a limited success. An overview of geological, geomechanical and physical characteristics of current pilot EGS sites shows foundation for coupled processes understanding. Most of the experimental EGS sites reside in basement rocks below the sedimentary section, defined as areas of metamorphic or igneous rocks [105].

In the western USA, Tester et al. [105] identified several potential EGS areas with high temperatures (>200 °C) at relatively shallow depths (3–5 km). The Great Basin in USA has extensional stress regime, and highly variable rocks with depths of 4–10 km, where rock is mostly sedimentary with some granite or other basement rock types. At Snake River Plain, details of the geology and stress regime at depths 3–10 km are unknown, but probably volcanic and sediments overlay low permeability granitic basement at 3–5 km deep. In Oregon, the Cascade Range dominates volcanic and intrusive rocks. In Southern Rocky Mountains geothermal areas, which include the northern Rio Grande Rift and the Valles Caldera, big crustal radioactivity and high mantle heat flow were detected. Salton Sea is a young sedimentary basin with very high heat flow, characterized by young metamorphosed sedimentary rock types. Clear Lake Volcanic Field contains low-permeability Franciscan sediments and granite at deeper depths. There are possibilities at the Chena Hot Springs near Fairbanks in Alaska for further development of the existing conventional geothermal power plant. Hawaii is characterized with high temperatures in the basaltic rift, where they use conventional hydrothermal resources, while there is little subsurface information available outside the existing east rift of Kilauea volcano power plant.

Similar favorable conditions for potential development of EGS can be found in other continents, for example Cooper Basin and Paralana in Australia. In Europe, Soultz-sous-Forêts in the Upper Rhine Valley area is represented with extensional stress regime [9, 13, 29] at the granitic highly fractured and faulted basement under 1.4 km thick sediment. Several pilot sites exist in Germany, for example granite Falkenberg test site is in northern Bavaria which proved that hydro-fractures can be propagated over significant distances in fractured crystalline rock, Bad Urach and Horstberg in northern Germany near Hannover. The Horstberg geothermal site contains low-permeability sediments which are experimented for geothermal energy extraction. In Basel, Switzerland, a pilot geothermal reservoir is placed in hot granitic basement at depth of 5 km, where the reservoir temperature is 200 °C. The Fjällbacka site in west coast of Sweden is developed as a research facility for studying hydro-mechanical aspects of hot dry rock reservoir development and for addressing geological and hydrogeological questions of Bohus granite.

Other pilot geothermal sites in Europe are Le Mayet de Montagne site in France where granite extends to the surface, Rosemanowes in Cornwall, UK is characterized with continuous granite batholith of early Permian age of more than 200 km in length, where the base of the granite extends below 9 km depth. The Hijiori site in Japan is placed on the edge of the caldera of the Pleistocene Gassan volcano with a very complex stress regime, and the reservoir contains several faults and many existing fractures. Ogachi site in Japan has very hot (> 230 °C) Grano-diorite rock. Despite numerous efforts put into EGS research through pilot sites, only few locations reached a commercial scale level for electricity production, for example Soultz-sous-Forets in France [105].

Numerical, theoretical and experimental work has been conducted along with the field work for obtaining a better understanding of various issues of geothermal reservoirs. EGS target hot granite rock mass, sedimentary reservoirs or interface between sediment cover and basement. As a result, the pilot sites yielded different problematic features ranging from in situ stress field to the pre-existing faults and fracture networks [39]. Poorly understood geology is one of the biggest obstacles in development of efficient EGS [58]. The competing tensile or shear failure mechanisms often occur simultaneously in geologically complex reservoir conditions. Non-linearity of key thermal and mechanical rock properties is related to stress state change, pore pressure changes and temperature change, which are accompanied by rock across-scale matrix alterations from micro to macro fracturing and fault shearing mechanisms.

5.1 Coupled Processes in Rock Mass

Coupled hydro-thermo-bio-chemo-mechanical (HTBCM) mechanisms in fractured rock mass are related to a short- and long-term reservoir behavior and energy extraction with respect to fracturing, permeability enhancement, biological microorganism growth and mineral precipitation-dissolution processes at fracture walls in geothermal reservoirs. Hydraulic processes include liquid and gas flow, air dissolution and diffusion in water, phase changes, vapor diffusion and gas generation and transport. Thermal processes are related to conductive and advective heat flow and transport in porous rock mass, but can also be part of thermomechanical gas behavior. Biological processes are considered through bringing up a variety of ancient or unknown simple organisms from the rock mass. Chemical processes include dissolution and precipitation of minerals into rock pore fluids or fluids which migrate through fractures, and changes in pore fluid chemistry. Finally, mechanical processes are changes in stress, strain, and rock strength, constitutive relationships and laws. Mechanical processes also include poroelastic behavior of rock mass which can be described using Biot's theory.

Although there has been a significant effort to evaluate HTCM processes [15, 38, 43, 44, 54, 64, 77, 106, 107], the long-term HTCM effects have not yet been completely understood in the context of deep fractured geo-reservoirs. First, it was shown that evolution of fluid chemistry is linked to the rock permeability changes under dif-

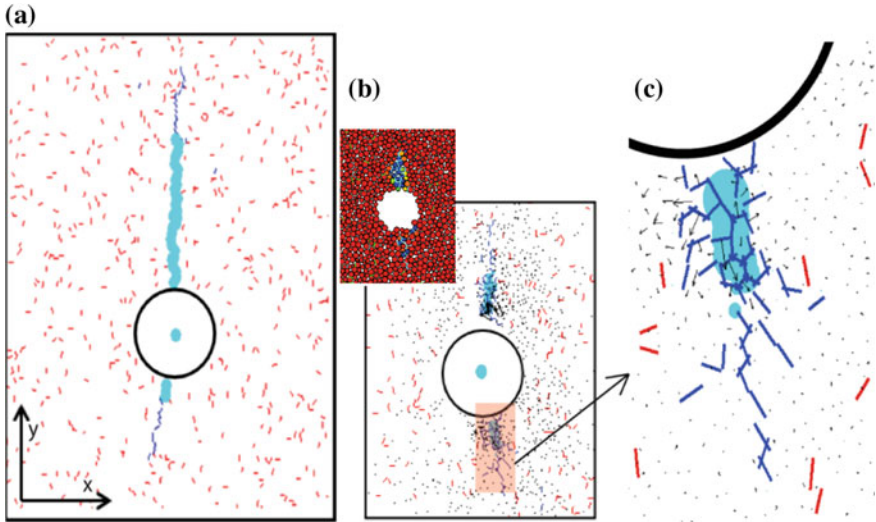


Fig. 12 Effect of hydro-thermo-mechanical coupling on micro-mechanics of hydraulic fracture propagation from a EGS reservoir wellbore in granite [107]

ferent stress states [86]. Second, thermo-mechanical stress changes cause irreversible strain and micro-cracking in granite as a consequence of complex mechanisms [53, 66, 67]. Thermal crack patterns in brittle materials are driven by inhomogeneous shrinkage stress fields, which can be described by fracture mechanics bifurcation analysis [5]. The crack propagation under thermal loading was studied to understand the instability from a straight to a wavy crack propagation [25]. Figure 12 shows results of a Discrete Element Method simulation with the development of a hydraulic fracture and micro-cracks under geothermal reservoir conditions. By comparing a model with and without thermally induced stresses, it can be seen that HTM processes result in a shorter hydraulic fracture, with significant thermal damage and microcracks [107]. As a result, it is still not clear to what extent linear elastic fracture mechanics can be applied to quasi-brittle rocks in geologic reservoirs; also, rock features (micro-structure, grains and existing fractures) effects on fracture propagation have not yet been completely quantified.

5.2 Multi-physics and Across-Scales Problems in Deep Geo-Reservoirs

Besides various process couplings, problems with understanding the rock mass behavior in geothermal reservoirs are due to multi-physics processes which may occur across various temporal and spatial scales. The hydraulic, mechanical, thermal and chemical mass transport and response will propagate throughout the systems at

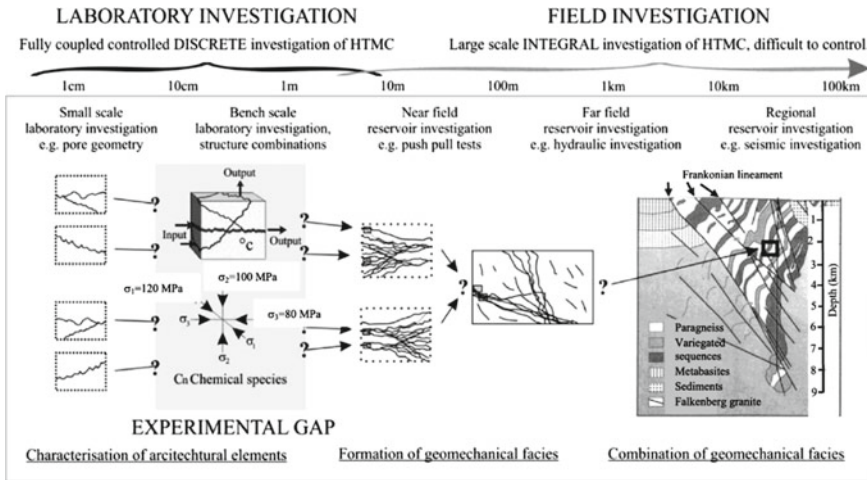


Fig. 13 Across-scale processes in geo-reservoirs, investigation approaches and the experimental gap [78]

rates which are several orders of magnitude different from each other [63]. Fluid flow, energy and mass transport in fractured-porous subsurface formations are characterized by complex interactions between fluid and solid phases, mainly controlled by thermal, hydraulic, mechanical and chemical (THMC) processes. The investigations of complex flow process relationships require both the identification of the relevant fundamental processes and the quantification of process parameters in the laboratory and in the field, as well as development and application of prognostic numerical tools. Linear and non-linear relationships and feedback mechanisms between the processes, the relative importance of processes and process parameters, as well as the influence of the large spectrum of spatial and temporal scales on the long-term performance of a reservoir are a challenge in the investigation and systems quantification. Figure 13 shows complexity of problems related to spatial scale investigation ranging from 1 cm to 100 km scales. Integral large-scale investigation of HTMC is difficult to control [78].

Despite the research efforts conducted in geothermal reservoirs, fundamental multi-physics in fractured subsurface rock simulated in reservoir situ-conditions have not yet been completely understood. Laboratory investigation is usually conducted in high stress and high temperature triaxial tests, but on relatively small rock samples. Larger sample sizes collected from the reservoir wellbores need to be considered, considering existing and new fractures and geological variations within samples. Specifically, further research is needed on: (1) stress-strain behavior in the light of cross-scales rock anisotropy parameters under high stress and increased temperature contrast between rock matrix and fluid in fractures and pores; (2) impact of the in situ stress magnitude, contrast and principal stresses rotation on rock fracture system and fluid flow in fractures; (3) fluid flow field through realistically rough, stressed and

deformable fracture systems; and (4) hydro-thermo-mechanical effects on fracture propagation and induced seismicity in various geological conditions.

Structural heterogeneities of basement rocks are widely present in geo-reservoirs across several spatial magnitude scales. For example, at the Desert Peak geothermal field in Nevada, USA, the basement stratigraphy was found to be complicated by thrust faults and other Mesozoic-aged faults [73]. Decreasing the size of the observed geological rock in geothermal reservoirs from the reservoir scale towards the laboratory scale, numerous petrologic effects on mechanical parameters have been previously identified which cannot be studied on a small lab sample. Some examples include matrix composition, matrix fabric, pre-existing foliation planes, crystal and clast content, ductile grains and clays, vein mineralogy and fracture intensity and primary and secondary porosity [73].

Failure criteria of heterogeneous rocks are complicated due to rock composition. While testing on homogeneous rocks usually results in either elastic-plastic or elastic-brittle stress-strain behavior, highly heterogeneous rocks with a mixture of weak and strong components yield a strain hardening behavior [16]. Fracture propagation upper bound depends on the sample size because of the adjacent crack closure, which occurs before the fracture propagates [30]. Structural heterogeneities are present not only due to rock mineralogy but also at a flow system of fractures in rock mass. Figure 14 shows a current approach for experimenting on fracture-porous rock systems. Even at the laboratory scale, several different scenarios can be identified. Quasi 2-D single fracture flow experiments vary from artificial to natural fracture roughness identification and representation, while in linear core flood experiments flow occurs either through a full flow fracture, a system of porous matrix and isolated fracture or a fracture system. Figure 14f shows a photograph of a fractured rock sample with highlighted flow fractures. Due to a complexity of isolated and interconnected fractures, the flow in the rock mass is still a challenge to understand and relate across scales processes.

Strain hardening and anisotropic rock parameters understanding requires cyclic triaxial testing of rocks. During the cyclic testing, hysteresis loops are observed in stress-strain curves, which correspond to loading-unloading cycles and are associated with fractures and micro-crack development [35]. Particularly, microscopic processes demonstrate initiation, propagation and coalescence of micro cracks or damage, which eventually forms macroscopic features of a brittle failure. The character of the obtained non-linear stress-strain curves depends on the magnitude of the confining pressure in triaxial tests [35]. After initiation by the initial flaw, the fracture can arrest instead of propagating further into the heterogeneous rock, which questions the applicability of the linear elastic fracture mechanics principles for reservoir rocks. Particularly, it was observed how cracks may extend readily through a crystal grain but cannot continue across the grain boundary without a significant increase in driving stress or a reduction in confinement beyond the grain scale [22]. Rotation of principal stresses in rock influences crack propagation, interaction and ultimately coalescence and failure in numerical models [30]. Four patterns of stress changes were identified in rock in the vicinity of fractures; the stress orientation rotates abruptly in the vicinity of fractures; the orientation rotates gradually, breakouts are suppressed at fractures

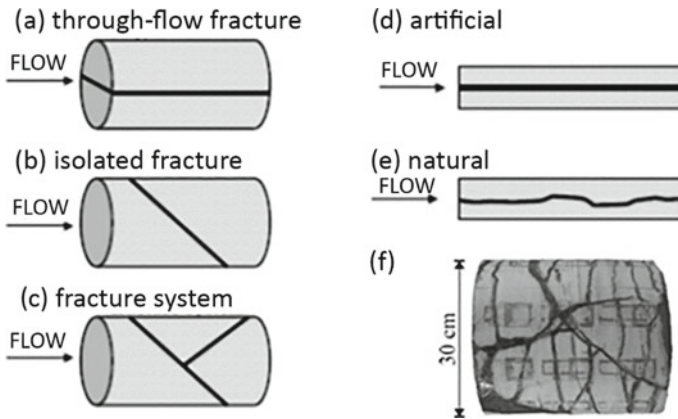


Fig. 14 Types of fracture-porous rock systems used in the experiments. Linear core flood experiments (a, b, c) and quasi-2D single fracture flow experiments (d, e) [101], with a photography of a fractured rock sample (f)

or lithological boundaries; the orientation does not change across fractures [71]. Regions around the wellbore in georeservoirs fail in a manner which is strongly controlled by the magnitude and orientation of the in situ stress field, and they can be also used to identify the in situ stress field [120].

Key Questions: How are chemical, mechanical, thermal and bio processes coupled? Which coupling mechanism is relevant at which temporal or spatial scales? Can some processes be treated as un-coupled in analysis? What is the impact of biological species bringing up to the surface from deep geo-reservoirs? How is mineral dissolution and precipitation affecting long-term performance of geothermal reservoir or carbon dioxide underground storage? How can long-term processes be studied in the laboratory, is there a way to catalyze chemical reactions without negatively affecting the process coupling mechanisms?

6 Sustainable Recovery of Subsurface Energy Resources

Worldwide and US baseload capacity is of the order of 10-15TW and currently relies on large scale industrial processes (~90% thermal combustion of fossil fuels and fission) rather than on distributed generation by truly renewable means (< 10% wind, solar, hydropower). Despite a desired transition to true renewables, the imbalance between energy production by traditional fossil means versus that by renewables is formidable and transitional fuels and bridging energy sources are needed. Feasible transition to a low carbon economy includes the switching from high-carbon coal and oil to lower-carbon natural gas present in gas shales and in potentially augmenting fossil combustion with CO₂ sequestration and in ultimately replacing these methods

with deep geothermal energy and nuclear fission. These transformations require the ability to characterize and control the evolution of the subsurface, in particular the evolution of transport properties that allows the recovery of such fuels and energy and the entombment of undesirable products. This must be completed with minimal environmental impact, including fugitive fluids and induced or triggered seismicity. The following explores the linkage between seismicity and permeability—first where seismicity exists as a hazard and then where it may be applied as a useful tool in characterizing the subsurface.

6.1 Induced Seismicity as a Hazard

Human-induced versus naturally-triggered seismicity differ principally in the magnitude and related duration of the events—human-induced events have historically been smaller but are nonetheless problematic and are not necessarily limited to small events where faults of sufficient size are present [37]. Modern observations in earthquake seismology have identified a rich spectrum of events spanning six decades of duration (e.g. [88] for large “earthquakes” that may evolve either seismically (duration $\sim 10^1$ s) or aseismically (duration $\sim 10^7$ s) for similar seismic moments (seismic moments of $\sim 10^{20}$ Nm) (Fig. 15). The energy release in these two prototypical classes of events is identical but the related hazard and prospective damage is much less for the longer duration events because the energy release is dissipated over a period one million times longer.

Slow slip events are also observed in laboratory scale experiments [62] where the length of the fault is necessarily limited to the dimension of the sample (but the stress drop commensurate with that of a plate boundary scale) and in underground research laboratories at the scale of meters [48]. Correspondingly, this richness in the deformation-duration spectrum is inferred at all length scales including those likely for slip in reservoirs. Thus, we seek to understand how this behavior is manifest at the scale of intermediate length fractures and faults in the range of meters to kilometers, rather than tens to hundreds of kilometers, as in the case of earthquake seismology—and infer that laboratory experimentation coupled with mechanistic upscaling provides a viable method to explore this behavior.

Seismic events in reservoirs result where slip occurs typically on pre-existing fractures that are reactivated by a changing stress regime. Depending on the environmental factors, changes in effective stress are induced by fluid pressures, thermal stresses or chemical (dissolution or desorption, [37, 59, 112]) stresses in the reservoir. These effects have been observed in geothermal reservoirs, most notably for the evolution of seismicity at the ill-fated EGS project in Basel, Switzerland [45, 99] and for those at other EGS projects around the world [99]. More prevalent, however is the recent spate of seismicity associated with the reinjection of produced waters from depleting conventional hydrocarbon reservoirs in the mid-western United States, from the reinjection of hydraulic fracturing fluids [33] and triggered from hydraulic fracturing itself [7]. These events can be large ($4 < M < 6$) and are both induced

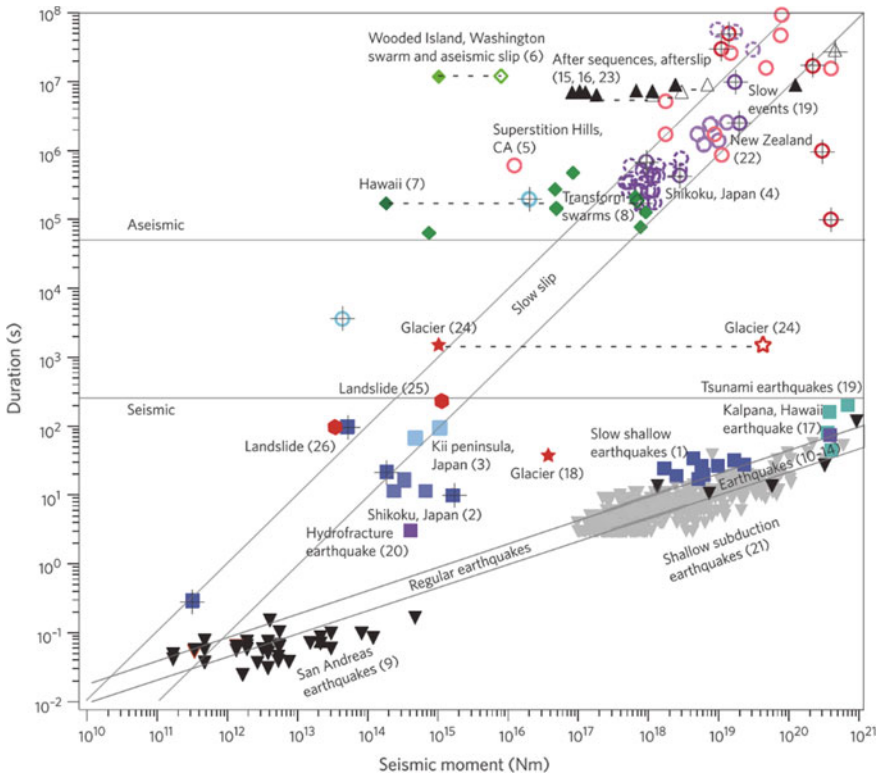


Fig. 15 Classification of slip events with respect to duration and released seismic moment [88]

and triggered. The events result from reducing the clamping stresses on critically oriented faults that may be blind and may be located within the reservoir itself or in underlying basement rocks (Fig. 16).

Key Questions: What is the size of the maximum credible seismic event? What are the controls on this transition in behavior from aseismic to seismic? How do mineralogy, global system stiffness, roles of fluid pressurization and dilatancy affect this transition? How are these individual mechanisms characterized? What are the prospects for control if these features are understood?

6.2 Induced Seismicity as a Tool

Evaluating both initial and evolving hydraulic properties of fractured reservoirs is vital for the development of both deep geothermal and shale gas reservoirs and in defining the integrity of caprocks. In this, the presence of passive seismicity as

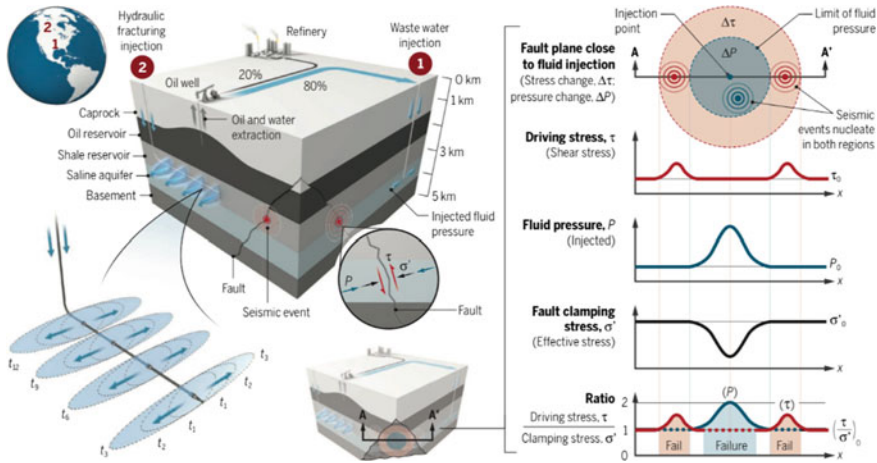


Fig. 16 A vertical well taps a conventional oil reservoir whereas a horizontal well accesses a shale reservoir for gas. Wastewater reinjection into a saline aquifer (shown in 1) and the injection of fracturing fluid (principally water) into the shale reservoir (shown in 2) have the same impact in elevating fluid pressures and driving the stress state on a deeply penetrating fault to failure. In cross section A-A', injection of fluid near the fault causes slip by contrasting mechanisms in both the near-field and the far-field. The net effect of these two mechanisms is to elevate driving stress above the clamping stresses in these two concentric regions, and to potentially induce seismic slip [33]

micro-earthquakes (MEQs) may be used to image the subsurface for the evolution of permeability that is crucial to the recovery of the resource.

During stimulation, the virgin hydraulic diffusivity can be estimated from the spatio-temporal growth rate of abundant in situ microearthquakes (MEQs) (Fig. 17). This method can estimate the permeability at reservoir scale. However, it has limitations in constraining the subsequent evolution of fracture permeability at relatively smaller length scales that are important in defining reservoir response during stimulation and then production.

To constrain regional initial and evolving permeability at relatively smaller length scales, it is possible to provide a linkage between moment magnitudes of observed MEQs and the measured evolution of fracture-network permeability [34]. Thus, the location and moment magnitude of MEQs (Fig. 18) may be used to estimate fracture apertures of individual events that are a function of in situ stresses, fluid pressure, shear displacement and fracture size. Assuming the veracity of the cubic law, results show that the equivalent virgin permeability at reservoir scale may be enhanced by about one order of magnitude while some local fracture permeability can be enhanced by ~2 to ~3 orders of magnitude. This method is of importance as it allows abundant observations of MEQs to constrain the structure and distribution of in situ permeability evolution. Since in situ geomechanical conditions (e.g., fracture stiffness, dilation and friction) also play a crucial role in affecting the accuracy of the permeability estimation, in situ fracture characterization is an important component in constraining these observations.

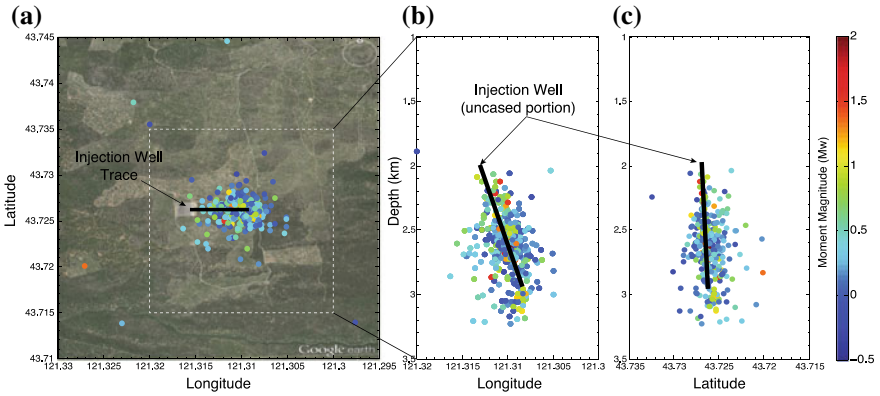


Fig. 17 a Map view of distribution of 350 seismic events in Newberry EGS reservoir during 2014 stimulation; b Vertical view of MEQ distribution with Longitude; c Vertical view of MEQ distribution with Latitude [34]

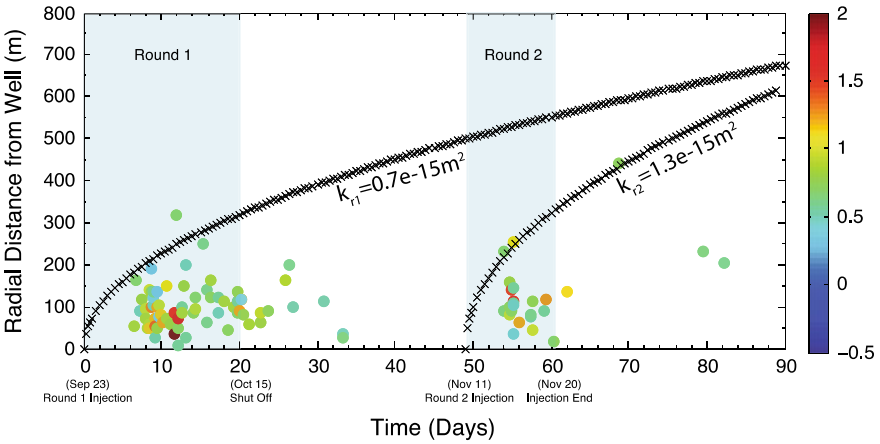


Fig. 18 Spatio-temporal distribution of fluid-injection-induced seismicity during the 2014 Newberry EGS stimulation. Diffusion-length versus time curve labeled for equivalent permeabilities at reservoir scale [34]

Key Questions: What are key mechanisms of permeability evolution in fractured reservoirs? What is the interplay between mechanisms that result in either the creation or destruction of porosity? What are their respective characteristic timescales? How are changes in porosity scaled to the evolution of permeability? How does the seismic energy budget relate to permeability evolution? What are key mechanisms heralding the transition between seismic and aseismic permeability evolution? What is the feasible minimum resolution of detection?

7 Discussion

The material included in this chapter aligns, to a larger extent, with the interest and expertise of the authors. The underlying motivation, and first objective, for putting together all these different views and opinions was to highlight fundamental and key questions that need to be tackled, if the Grand Challenges are to be addressed in ways that will enhance the ability of rock mechanics and rock engineering to aid in solving the problems that our society faces in the 21st century. The second objective was to identify research priorities to address the Grand Challenges. The following topics have been identified, based on the material included in the chapter and on discussions among all the participants of the NSF-sponsored workshop “Geotechnical Fundamentals in the Face of New World Challenges”.

Transparent Earth: One of the problems that limits advancements in the field of rock mechanics is the inability to scrutinize the interior of the Earth to assess the current state at every single point and its evolution with time, as well as constitutive behavior. New techniques and approaches are required to characterize the underground at multiple scales.

Complex Coupled Processes across Time and Spatial Scales: Rocks are highly heterogeneous, with complex behavior that is not only stress and time dependent, but also, and this is most important, scale dependent. The interplay that exists between the rock matrix, discontinuities, fluid, temperature and biological processes across scales is not well understood, and such knowledge is critical for many applications such as energy extraction and storage. The theory of damage and healing poromechanics is in its infancy; coupled effects of crack opening, closure and rebonding on stiffness and permeability have not been investigated. Rock permeability models do not account for anisotropic healing processes. Predicting the critical sequences of events that lead to pore connectivity is a challenge. New tools that are robust and accurate are needed.

Fault Reactivation and Induced Seismicity: There is clear evidence that the interaction between anthropogenic activities that change the state of stress in the underground are responsible for both inducing and triggering earthquakes that have the potential to cause severe damage to existing infrastructure. The knowledge required to identify hidden faults as well as assess their potential for slip and to quantify the impact of such slip is insufficient.

Risk removal from underground construction: Significant resources are obtained from the underground, which are then used for critical human activities such as transportation, energy and waste storage, shelter, etc. The risks associated with such activities continue to be much larger than with the aboveground, and impact both human as well as environmental and infrastructure safety. A better holistic approach is needed to reduce the risk to acceptable levels, at least similar to those of the aboveground.

Water, Environmental Impact: Potable water supplies in the subsurface are a critical resource. Any detrimental impact on underground water resources and quality has the potential to have large spatial and temporal consequences that may reach the bio-

sphere. This is a complex coupled problem that requires a comprehensive approach through different scales. New tools to predict flow through the rock mass and coupled bio-chemical-thermal processes between fluid flow and mechanical behavior of the rock are needed.

Selective extraction for more efficient mining: Ore extraction from mining is still based on practices that are rooted on empiricism. The result is a process that is largely inefficient, can rarely be extrapolated to different environments and is associated with high risk, large environmental impact and is not sustainable. Better approaches to benefit resource extraction through mining are required to continue to meet the increasing human needs.

Advances in disciplines such as sensing and remote sensing, numerical methods, theoretical and computational poromechanics, synthetic materials and 3D printing, big data and artificial intelligence, among others, provide opportunities to probe the behavior of the subsurface and obtain new insights, as well as open new avenues for research and education. This cross-disciplinary partnership is required to address the challenges of this century. New approaches and new solutions will be demanded by the public, which will require close collaboration among disciplines. One such challenge will stem out of society's continuous demand for improved levels of comfort and access to sustainable, safe and renewable resources. The science required to face these problems is inherently interdisciplinary, but not yet available. Finding solutions for these questions is a great challenge but also a great opportunity. If the rock mechanics/geomechanics profession wants to participate, it has to do so by outgrowing its traditional niches and embracing other fields.

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