

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

186,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Fractures and Fracturing: Hydraulic Fracturing in Jointed Rock

Charles Fairhurst

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/56366>

Abstract

Rock in situ is arguably the most complex material encountered in any engineering discipline. Deformed and fractured over many millions of years and different tectonic stress regimes, it contains fractures on a wide variety of length scales from microscopic to tectonic plate boundaries.

Hydraulic fractures, sometimes on the scale of hundreds of meters, may encounter such discontinuities on several scales. Developed initially as a technology to enhance recovery from petroleum reservoirs, hydraulic fracturing is now applied in a variety of subsurface engineering applications. Often carried out at depths of kilometers, the fracturing process cannot be observed directly.

Early analyses of the hydraulic fracturing process assumed that a single fracture developed symmetrically from the packed off-pressurized interval of a borehole in a stressed elastic continuum. It is now recognized that this is often not the case. Pre-existing fractures can and do have a significant influence on fracture development, and on the associated distributions of increased fluid pressure and stresses in the rock.

Given the usual lack of information and/or uncertainties concerning important variables such as the disposition and mechanical properties of pre-existing fracture systems and properties, rock mass permeabilities, in-situ stress state at the depths of interest, fundamental questions as to how a propagating fracture is affected by encounters with pre-existing faults, etc., it is clear that design of hydraulic fracturing treatments is not an exact science.

Fractures in fabricated materials tend to occur on a length of scale that is small; of the order of the 'grain size' of the material. Increase in the size of the structure does not introduce new fracture sets.

Numerical modeling of fracture systems has made significant advances and is being applied to attempt to assess the extent of these uncertainties and how they may affect the outcome of practical fracturing programs. Geophysical observations including both micro-seismic activity and P- and S-wave velocity changes during and after stimulation are valuable tools to assist in verifying model predictions and development of a better overall understanding of the process of hydraulic fracturing on the field scale. Fundamental studies supported by laboratory investigations can also contribute significantly to improved understanding.

Given the widening application of hydraulic fracturing to situations where there is little prior experience (e.g., Enhanced Geothermal Systems (EGS), gas extraction from 'tight shales' by fracturing in essentially horizontal wellbores, etc.) development of a greater understanding of the mechanics of hydraulic fracturing in naturally fractured rock masses should be an industry-wide imperative. HF 2013 International Conference for Effective and Sustainable Hydraulic Fracturing is very timely!

This lecture will describe examples of some current attempts to address these uncertainties and gaps in understanding. And, it is hoped, it will stimulate discussion of how to achieve more effective practical design of hydraulic fracturing treatments.

1. Introduction

The term 'rock' covers a wide variety of materials and widely different rheological properties often proximate to each other in the subsurface. Tectonic and gravitational forces, sustained over millions of years, have deformed and fractured the rock on many scales. These forces are transmitted in part through the solid skeleton of the rock, and in part through the fluids under pressure in the pore spaces. Long-term circulation through rock at high temperatures at depth involves dissolution and precipitation along the fluid pathways, producing changes in the chemical composition of the fluids and modifying the overall fluid circulation.

Rock in situ is 'pre-loaded' and in a state of changing equilibrium. Any engineering activity changes this equilibrium (see Appendix 1). Often the changes can be accommodated in stable fashion, but serious instabilities can develop.

The rock mass is opaque. Although geophysics is making impressive advances in defining large structures such as faults and bedding planes, most of the features that influence the rock response to engineering activities remain hidden. Mining and civil engineering activities allow three-dimensional access to the underground and direct observation of smaller features such as fracture networks, but most of the newer engineering applications involve essentially one-dimensional access by borehole. Rock engineering problems fall into the 'data -limited' category, as defined by Starfield and Cundall (1988), and strategies to address them must follow a different strategy than engineering problems where detailed and precise design information is available.

Faced with such complexity and lack of structural details, traditional subsurface engineering design has been guided by empirical procedures developed and refined through long experience.

Projects are now venturing well beyond current experience, and for many, 'novel' applications now considered (e.g., Enhanced Geothermal Systems, Carbon Sequestration, see Appendix 1). There is little experience, few guiding rules and very little data to guide the engineering approach.

Such obstacles notwithstanding, subsurface processes, both long-term geological and short term responses, to engineering activities do obey the laws of Newtonian Mechanics.

Classical continuum mechanics has long been used to guide some aspects of design, but considerable care is required in practical application, due to the need to simplify the representation of the real conditions in order to obtain analytical solutions.

The remarkable developments in high-speed computation and associated modeling techniques over the past one to two decades provide an important new tool, which complemented by the appropriate field instrumentation, can augment the classical continuum analyses and help overcome the lack of prior experience. Some empiricism and general practical guidelines may still be useful for the design engineer, but these can and should be mechanics-informed.

This lecture attempts to illustrate the 'mechanics-informed' approach with respect to the practical application of hydraulic fracturing and related engineering procedures to rock engineering.

2. Hydraulic fracturing

Hydraulic fracturing first was used successfully in the late 1940's to increase production from petroleum reservoirs (Howard and Fast, 1970). The technology has evolved since and is now a major, essential technique in oil and gas production. This and other impressive oil industry developments, such as directional drilling, have attracted interest in application of these technologies to a variety of other subsurface engineering operations. Enhanced Geothermal Energy (EGS) is a notable example. Geothermal Energy is a huge resource. Commenting on the EGS resource in the USA, Tester et al. (2005), state:

"...we have estimated the total EGS resource base to be more than 13 million exajoules (EJ)¹. Using reasonable assumptions regarding how heat would be mined from stimulated EGS reservoirs, we also estimated the extractable portion to exceed 200,000 EJ or about 2,000 times the annual consumption of primary energy in the United States in 2005. With technology improvements, the economically extractable amount of useful energy could increase by a factor of 10 or more, thus making EGS sustainable for centuries."²

1 1 exajoule = 10¹⁸ joules = 10¹⁸ watt.seconds.

2 Future of Geothermal Energy (2005) Synopsis and Executive Summary.1-4 (2).

“At this point, the main constraint is creating sufficient connectivity within the injection and production well system in the stimulated region of the EGS reservoir to allow for high per-well production rates without reducing reservoir life by rapid cooling.”³

Field experiments to extract geothermal energy from rock at depth by hydraulic fracturing were started in 1970 by scientists of the Los Alamos National Laboratory, USA. Two boreholes were drilled into crystalline rock (one 2.8 km deep, rock temperature 195°C; the other 3.5 km rock, 235°C) at Fenton Hill, New Mexico. Hydraulic fracturing was used to develop fractures from the boreholes in order to create a fractured region through which water could be circulated to extract heat from the rock. The experiment was terminated in 1992. Commenting on what was learned from the Fenton Hill study, Duchane and Brown (2002) note:

“The idea that hydraulic pressure causes competent rock to rupture and create a disc-shaped fracture was refuted by the seismic evidence. Instead, it came to be understood that hydraulic stimulation leads to the opening of existing natural joints that have been sealed by secondary mineralization. Over the years additional evidence has been generated to show that the joints oriented roughly orthogonal to the direction of the least principal stress open first, but that as the hydraulic pressure is increased, additional joints open.”

This is an early indication that pre-existing fractures mass significantly affect how hydraulic fractures propagate in a rock mass.

3. Influence of fractures and discontinuities on the strength of brittle materials

Hydraulic fracturing can be considered as a technique to overcome the strength of a rock mass in situ, initiation and propagation of a crack through a system of pre-existing fractures, essentially planar discontinuities (e.g., bedding planes), and intact rock.

In examining the fracture propagation process, the pioneering work of Griffith (1921, 1924) is a logical point of departure. Griffith had identified planar discontinuities, or flaws, in fabricated materials as the reason why the observed technical strength of brittle materials was about three orders of magnitude lower than the theoretical inter-atomic cohesive (tensile) strength.⁴ Using an analytical solution by Inglis (1913) for the elastic stresses generated around an elliptical crack in a plate, Griffith observed that the maximum tensile stress at the tip of the crack $\sigma_t = \sigma_0 (1 + 2a/b)$, where a and b are the major and minor semi-axes of the ellipse, and as the ellipse degenerated to a sharp crack or flaw (i.e., as the ratio a/b became very high)⁵, the stress σ_t could rise to a value high enough to reach the inter-atomic cohesive strength sufficient to cause the original crack to start to extend.

³ Future of Geothermal Energy (2005) Synopsis and Executive Summary p.1-5 (5).

⁴ A fractured rock mass is typically about two orders of magnitude lower in strength than the strength of a laboratory specimen taken from the rock mass [Cundall (2008); Cundall et al, (2008)].

But would the crack continue to extend and lead to macroscopic failure? To address this question, Griffith invoked the *Theorem of Minimum Potential Energy*, which may be stated as “The stable equilibrium state of a system is that for which the potential energy of the system is a minimum.” For the particular application of this theorem to brittle rupture, Griffith added the statement, “The equilibrium position, if equilibrium is possible, must be one in which rupture of the solid has occurred, if the system can pass from the unbroken to the broken condition by a process involving a continuous decrease of potential energy.”⁶

Griffith’s classical work has provided the foundation for the field of “Fracture Mechanics” [Knott (1973); Anderson (2005)] responsible for major continuing advances in the development of high-performance fabricated materials.

Since we will make reference later to this specific definition by Griffith, it is useful to re-state it here.

4. Theorem of minimum potential energy

“The stable equilibrium state of a system is that for which the potential energy of the system is a minimum. The equilibrium position, if equilibrium is possible, must be one in which rupture of the solid has occurred, if the system can pass from the unbroken to the broken condition by a process involving a continuous decrease of potential energy.”

Although much of classical Fracture Mechanics has emphasized applications to problems of Linearly Elastic Fracture Mechanics (LEFM) it is important to recognize that the theorem of minimum potential applies equally to inelastic problems.

5. Mechanics of hydraulic fracturing

As used classically in petroleum engineering, hydraulic fracturing involves sealing off an interval of a borehole at depth in an oil or gas bearing horizon, subjecting the interval to increasing fluid pressure until a fracture is generated, injecting some form of granular proppant into the fracture as it extends a considerable distance from the borehole into the

5 Hydraulic fractures generated in classical petroleum applications typically extend (2b) of the order of 25m ~ 50m from a wellbore. The fracture aperture (2a) at the wellbore then will be typically of the order of 0.01 m. Thus, the tensile stress concentration at the tip is very high of the order of 103.

6 In his second paper, Griffith (1924), demonstrated that tensile stresses also developed around similar cracks loaded in compression, provided the cracks were inclined to the direction of the major principal (compressive) stress. (He also assumed that the cracks did not close under the compression.) For the optimum crack inclination, an applied compressive stress of eight times the magnitude of the tensile strength was required to develop a tensile stress on the crack boundary (close to, but not at the apex of the crack) equal to the limiting value in the tensile test. He concluded that the uniaxial compressive strength of a brittle material should be eight times greater than the tensile strength. Interestingly, he did not invoke his second (minimum potential energy) criterion. It was later determined that although a tensile crack could initiate in a compressive stress regime as predicted by Griffith (1924), the crack was stable (i.e., did not satisfy the minimum potential energy criterion). The compressive/tensile strength ratio is greater than 8 (see Hoek and Bieniawski, 1966).

petroleum bearing formation, and then releasing the pressure. This causes the sides of the fracture to compress onto the proppant, creating a high-permeability pathway to allow oil and/or natural gas to flow back to the well and to the surface.

Figure 1 shows a simple two-dimensional cross-section through an idealized hydraulic fracture. The borehole injection point is at the center of the fracture, which is assumed to be a narrow ellipse that has extended in a plane normal to the direction of the maximum⁷ (least compressive) in-situ stress.

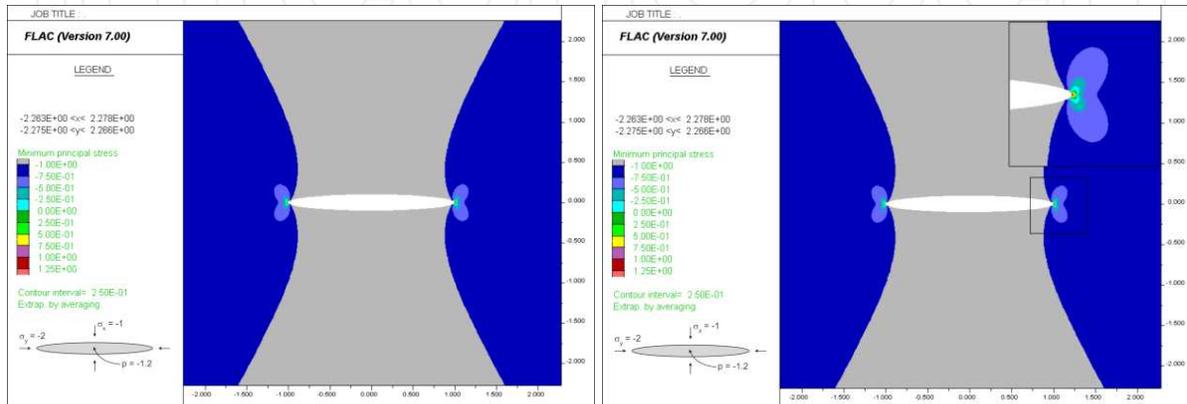


Figure 1. Left) Major and (right) minor principal stresses in the vicinity of an internally pressurized elliptical crack in an impermeable rock.

In the case shown, the crack major/minor axis ratio a/b is 10:1. The internal fluid pressure $p = 1.2$, while the least compressive principal stress $\sigma_x = 1.0$. This results in a tensile stress concentration at the crack tip. The magnitude of the elastic stress concentration at the crack tip increases directly with $2a/b$, (Inglis, 1913). Hence for the case of $a \gg b$, i.e., a ‘sharp’ crack⁸, the concentration is very high, and the crack will extend essentially as soon as the fluid pressure exceeds the magnitude of the least compressive principal stress (σ_x in Figure 3) it begins to extend, and there will be a pressure gradient from the injection point towards the crack tip as the fluid flows towards the tips. This gradient will depend on the fluid viscosity. Also, since the rock will exhibit some level of permeability, fluid will also flow (or ‘leak-off’) into the formation as it flows under pressure along the fracture; the rock has a finite strength, or ‘toughness’ so that energy will be required to extend the crack.

An analytical solution for the stresses in the elastic medium and the crack-opening displacement along the crack was first published by Inglis (1913) and served as the basis for early applications to hydraulic fracturing and fracture treatment design. The Perkins, Kern (1961) and Nordgren (1972) (PKN) and Geertsma and de Klerk (1969) (GDK) models are still used, although numerical models and combinations are now popular. Details of the PKN and GDK models can be found on the SPE website: http://petrowiki.spe.org/Fracture_propaga

⁷ Tension is assumed to be positive in Figure 3.

⁸ A typical hydraulic fracture may have a length ($2a$) of the order of 50m and a maximum aperture ($2b$) of 5mm, so that the stress concentration will be of the order of 2000:1.

tion_models. Several differences between the stationary crack assumed by Inglis (1913) and a hydraulic fracture introduce significant difficulties in developing an accurate model of the fracturing process. Thus, the fracture is generated by application of an increasing fluid pressure until the fracture is initiated and extends away from the injection point. Flow of fluid in the fracture is governed by classical fluid flow equations of Poiseuille and Reynolds (lubrication); the pressure drop along the fracture depends on the viscosity of the fluid, and the permeability of the rock (leading to fluid 'leak-off'); the fracture aperture depends on the stiffness of the rock mass and the fluid pressure distribution along the crack; and fracture extension depends on the mechanical energy supplied to the region around the crack tip. The tip may propagate ahead of the fluid, leading to a 'lag,' a dry region between the crack tip and fluid front.

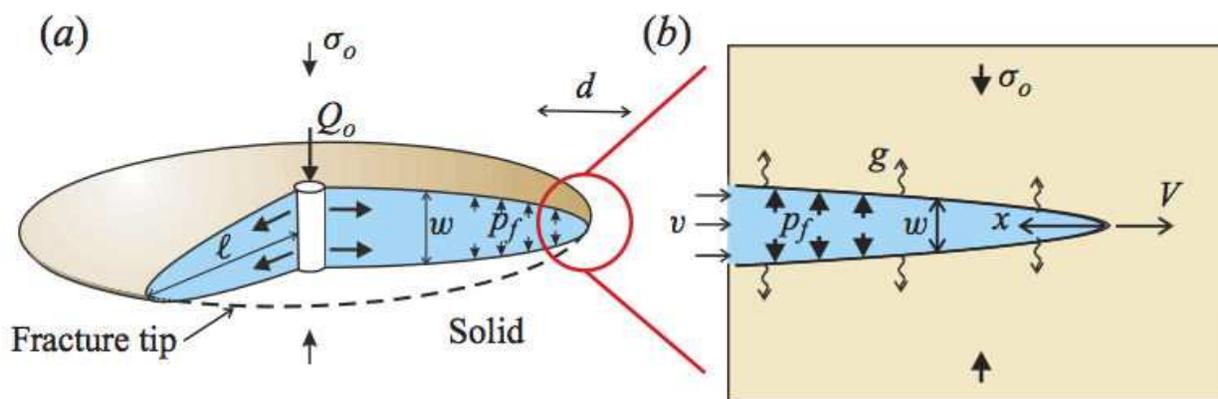


Figure 2. Radial Model of Axi-symmetric Flow and Deformation associated with Hydraulic Fracturing.

Figure 2 illustrates these features for the classical Radial Model in which it is assumed that the fracture propagates symmetrically away from the borehole in a plane normal to the minimum (least compressive) principal in-situ stress, σ_0 .

Development of efficient and robust Hydraulic Fracturing (HF) simulators is central to successful practical HF treatment of petroleum reservoirs. As noted earlier, competing physical processes are operative during the fracturing operation. This has led to a sustained effort over many years to understand and map the multi-scale nature of the tip asymptotics that arise as a result of these competing physical processes in fluid-driven fracture. These asymptotic solutions are critical to the construction of efficient and robust HF simulators. For example, in an impermeable medium, the viscous energy dissipation associated with driving fluid through the fracture competes with the energy required to break the solid material. Breaking of the bonds corresponds to the familiar asymptotic form of linear elastic fracture mechanics (LEFM), i.e., the opening in the tip region is of the form, e.g., (Rice, 1968), with denoting the distance from the tip. However, under conditions where viscous dissipation dominates, the coupling between the fluid flow and solid deformation leads to (Spence and Sharp, 1985; Lister, 1990; Desroches et al., 1994), on a scale that is considerably larger than the size of the LEFM-dominated region, but still small relative to the overall fracture size. In other words, in the viscosity-dominated regime, the zone governed by the LEFM asymptote is negligibly small

compared to the crack length. Thus, in the viscosity-dominated regime, the HF simulator should embed a $2/3$ power law asymptote rather than the classic $1/2$ asymptote of LFM. Garagash et al.(2011) discuss the generalized asymptotics near the tip an advancing hydraulic fracture, an extension of two particular asymptotics obtained at Schlumberger Cambridge Research Laboratory in the early 1990's (Desroches et al., 1994; Lenoach, 1995).

Three classes of numerical algorithms for HF simulators have now been built: (i) a moving grid for KGD, radial, PKN and P3D fracture simulators; (ii) a fixed grid for plane strain and axisymmetric HF with allowance for a lag between the fluid front and the crack tip, and fracture curving (a versatile code has been developed at CSIRO⁹ Melbourne to simulate the interaction of a hydraulic fracture with other discontinuities); and (iii) fixed grid for simulating a arbitrary shape planar fracture in a homogenous elastic rock. These codes rely on the displacement discontinuity method (Crouch and Starfield, 1983) for solving the elastic component of the problem, i.e., the relationship between the fracture aperture and the fluid pressure.

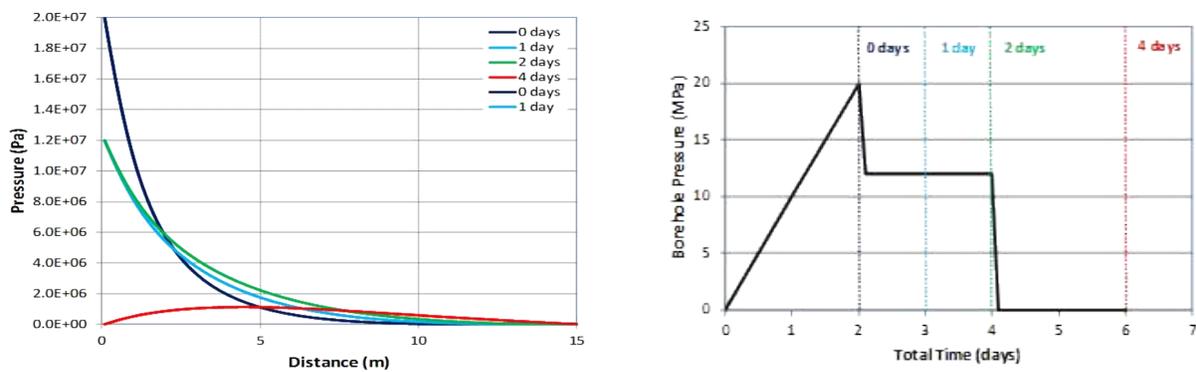


Figure 3. Fluid Pressure Distribution along the Central Axis (Ox) of Figure 1 for a permeable rock due to pressurization and de-pressurization of the borehole.

Figure 3 is presented to illustrate that the fluid pressure in a permeable rock can continue to flow away from the point of injection even after the borehole pressure is reduced to zero. The example shows the distribution of fluid pressure in the rock mass (permeability 5 mD) after (i) 2 days of pressurization up to the peak pressure of 20 MPa in the fracture; (ii) stop pumping and reduce fluid pressure quickly to 12MPa at the point of injection; (iii) hold the pressure constant for 2 days; and (iv) drop the pressure to zero.

It is seen that the pressure in the rock (red curve) has a maximum at some distance from the borehole such that fluid continues to flow into the rock for some time after the pressure in the borehole is reduced to zero. Different combinations of rock permeability, pumping rates and durations can lead to higher peak pressure values in the rock, and longer periods during which fluid can continue to flow away from the well. Such flow may contribute to slip on pre-existing fractures after the pressure in the borehole is reduced to zero.

6. Hydroshear

Hydraulic fracturing is considered to be initiated from a packed-off interval borehole when the net state of stress around the well bore reaches the tensile strength of the rock. It is important to recognize that fluid pressurization of a well in permeable rock will result in flow of the fluid into the rock as soon as the fluid pressure stimulation process is started. This changes the effective stress state in the rock mass and can lead to slip on pre-existing fractures at fluid pressures below the pressure required to create and extend a hydraulic fracture. This process of inducing slip on pre-existing fractures is termed 'Hydro-shear'. Flow of pressurized fluid into the rock reduces the effective normal stress ($\sigma_n - p$) everywhere in the rock [σ_n = normal stress at any point; p = fluid pressure.] If c and μ respectively represent the cohesion and coefficient of friction acting across the surfaces of a fracture in the rock, then the effective resistance of the fracture to (shear) sliding, τ_r , will be:

$$\tau_r = c + \mu (\sigma_n - p) \quad (1)$$

Thus, if the pressure p is raised progressively then τ_r will be reduced correspondingly until it reaches the limit at which sliding will occur. The situation is illustrated graphically in Figure 3. The rock is subjected to a three-dimensional state of stress represented by the principal stresses σ_1 , σ_2 , σ_3 and the fluid pressure p . The series of points 'X' indicate the effective state of stress on an array of pre-existing fractures in the rock. As illustrated in Figure 5, the effect of increasing the fluid pressure in the medium is to move the stress state on these cracks close to the limiting shear resistance, i.e., to the limiting value represented by the Mohr-Coulomb limit. As the stress state reaches this limit, the cracks will slip. In order to initiate a hydraulic fracture, the fluid pressure would need to be increased further, until the limiting Mohr circle reaches the tensile strength limit of the failure envelope. Since crack surfaces are often not smooth, shear slip will tend to result in crack dilation, and an associated increase in fluid conductivity. It is suggested that hydro-shearing could be more effective than hydraulic fracturing as a stimulation technique in certain applications, e.g., in stimulation of high-temperature geothermal reservoirs. Cladouhos et al. (2011) discuss the application of hydro-shearing as a geothermal stimulation technique. The possibility that silica proppant may dissolve in the aggressive high-temperature fluid environment of some geothermal reservoirs whereas slip on rough fractures develops aperture increase without the need for proppant is also presented as an argument in favor of hydroshearing.

7. Deformation and failure of rock in situ

As with fabricated materials, the deformation and failure of brittle rock is also dependent strongly on fractures and discontinuities. In a rock mass, however, the fractures occur over a very wide range of scales from sub-microscopic to the size of tectonic plates. A large specimen of rock will probably include some large fractures, and as the scale of the rock mass increases, fractures from different tectonic epochs.

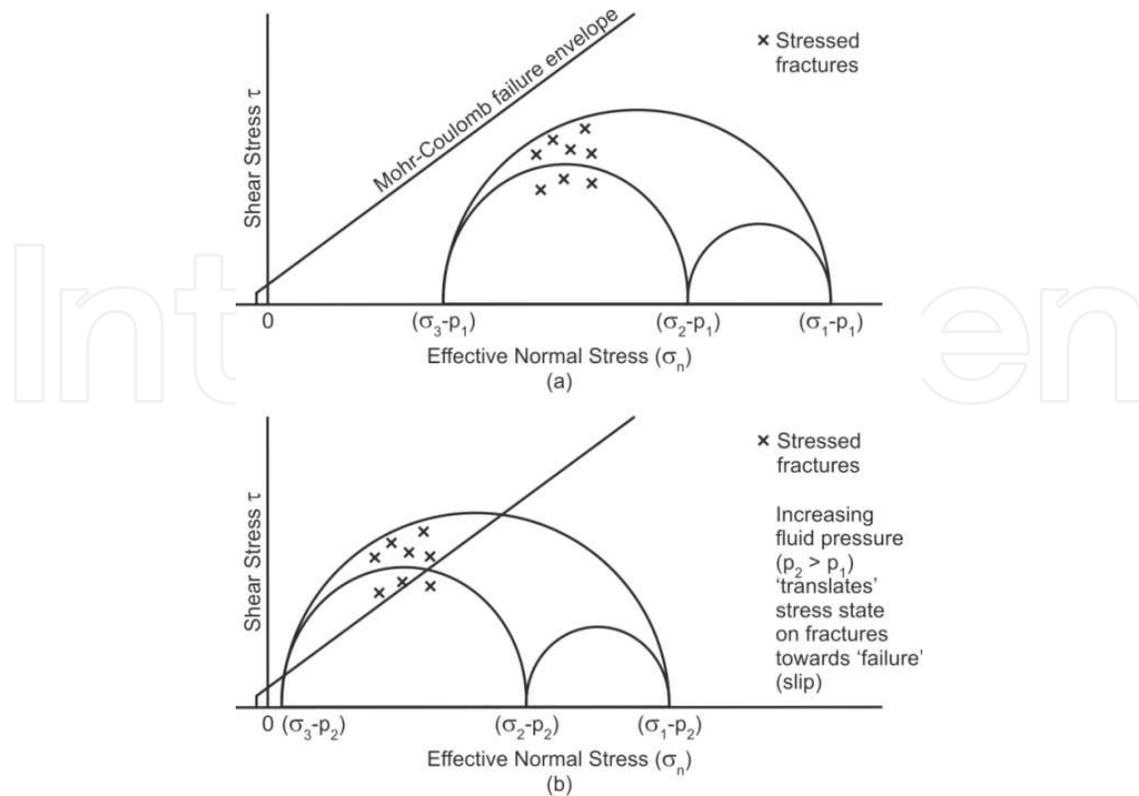


Figure 4. Hydro-shearing — a procedure to generate slip on pre-existing fractures by increasing the fluid pressure to a level below that required to generate a hydraulic fracture.

Study of fracture systems underground in mines and in civil engineering projects allow systems of fractures to be identified and classified statistically into discrete fracture networks (DFN's). The network will include intersecting sets of planar fractures, but individual fractures will tend to be of different lengths, and though organized in two or three spatial orientations, of variable, finite length and not collinear.

Figure 7 presents a two-dimensional illustration of the application of DFN's to the numerical modeling of a fractured rock mass. The in-situ rock mass is considered as a large specimen of intact rock that has been transected by the DFN determined from field observations and fracture mapping underground or at surface outcrops. The properties of the intact rock are built into a Bonded Particle Model of the rock (using the Particle Flow Code (*PFC*) code) based on results of laboratory tests of the intact rock deformability and strength. The intact rock representation is shown on the left of Figure 6. The DFN (shown on the upper right in Figure 6) then is superimposed onto the intact rock.

Cohesion and friction values are assigned to the joint planes.¹⁰ The 'unconfined' strength of a typical large SRM is of the order of a few percent of an intact rock specimen of the same rock (Cundall, 2008). Much of the in-situ strength is derived, of course, from the in-situ stresses imposed on the SRM in situ. One of the consequences of the finite length and lack of collinearity

¹⁰ Typically, computer tests indicate the unconfined strength of a Synthetic Rock Mass of the order of 50-m to 100-m side length, to be a few percent of the unconfined strength of the laboratory specimen.

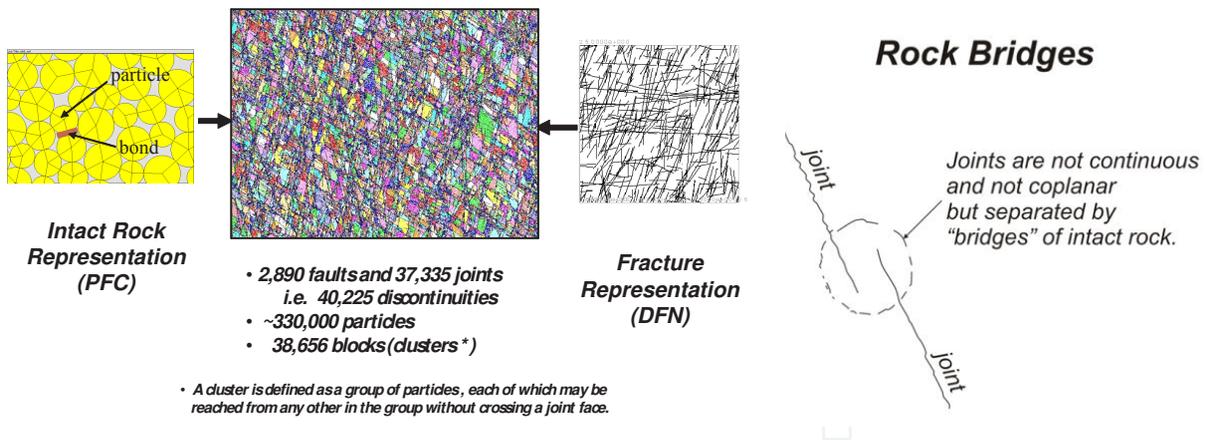


Figure 5. The Synthetic Rock Mass (SRM) representation of a fractured rock mass (in two dimensions). Damjanac et al. (2013) present a discussion of the 'construction' of an SRM in three dimensions. Pierce (2011) presents a comprehensive discussion of practical guidelines and factors involved in the construction of DFN's.

of joint sets in DFN's is the formation of bridges of intact rock Figure 4 within the SRM. These bridges provide regions of intact rock, and of stress concentration, in the SRM and account for a significant part of the overall strength of the rock mass. Earlier models of a rock mass, considered to consist of several sets of through-going fractures, exhibited much lower rock mass strength (Hoek and Brown, 1980).

Figure 5 presents selected extracts from a two-dimensional PFC simulation of the development of a hydraulic fracture in a jointed Synthetic Rock Mass. The SRM model was developed following the procedure outlined in Figure 5. The joint distribution was based on a DFN obtained at the Northparkes Mine in Australia.¹¹ Figure 5(a) shows the location of a vertical borehole that was pressurized by fluid until a hydraulic fracture was initiated. The rock mass is assumed to be impermeable. (The path of the fracture has been traced in blue for clarity.) Displacements in the rock mass produced by the hydraulic fracture are shown as vectors on each side of the fracture. It is seen that the fracture started more or less symmetrically on each side of the borehole, but propagation of the right wing was arrested when the hydraulic fracture encountered an adversely oriented pre-existing joint (Figure 5(b)). With increasing pressure, in the borehole, the hydraulic fracture continued to extend asymmetrically towards the left (Figures 5(c) and 5(d) Figure 5(d) is simply an enlarged view of Figure 5(c)). It is seen that the propagating fracture extended partially by opening existing fractures and partially by developing new fractures through intact rock. Although local deviations occur, the overall path of fracture growth is approximately perpendicular to the direction of the minimum compression stress. The existing fractures introduce an asymmetry to the rock mass. In terms of the idealized symmetric crack of Figure 2, the system in Figure 3 can be considered as two cracks, one extending to the right and one to the left of the borehole with a higher 'fracture toughness' on the right compared to the left, etc.

¹¹ A number of important subsurface engineering problems involve borehole access only. This often means difficulty in establishing reliable, realistic DFN's. In such cases there is no recourse, at least at the start of the project, other than to try to infer fracture networks from borehole observations, perhaps supplemented by local observations of structural geological features. The DFN for Northparkes was available and convenient to use in the example shown in Figure 5.

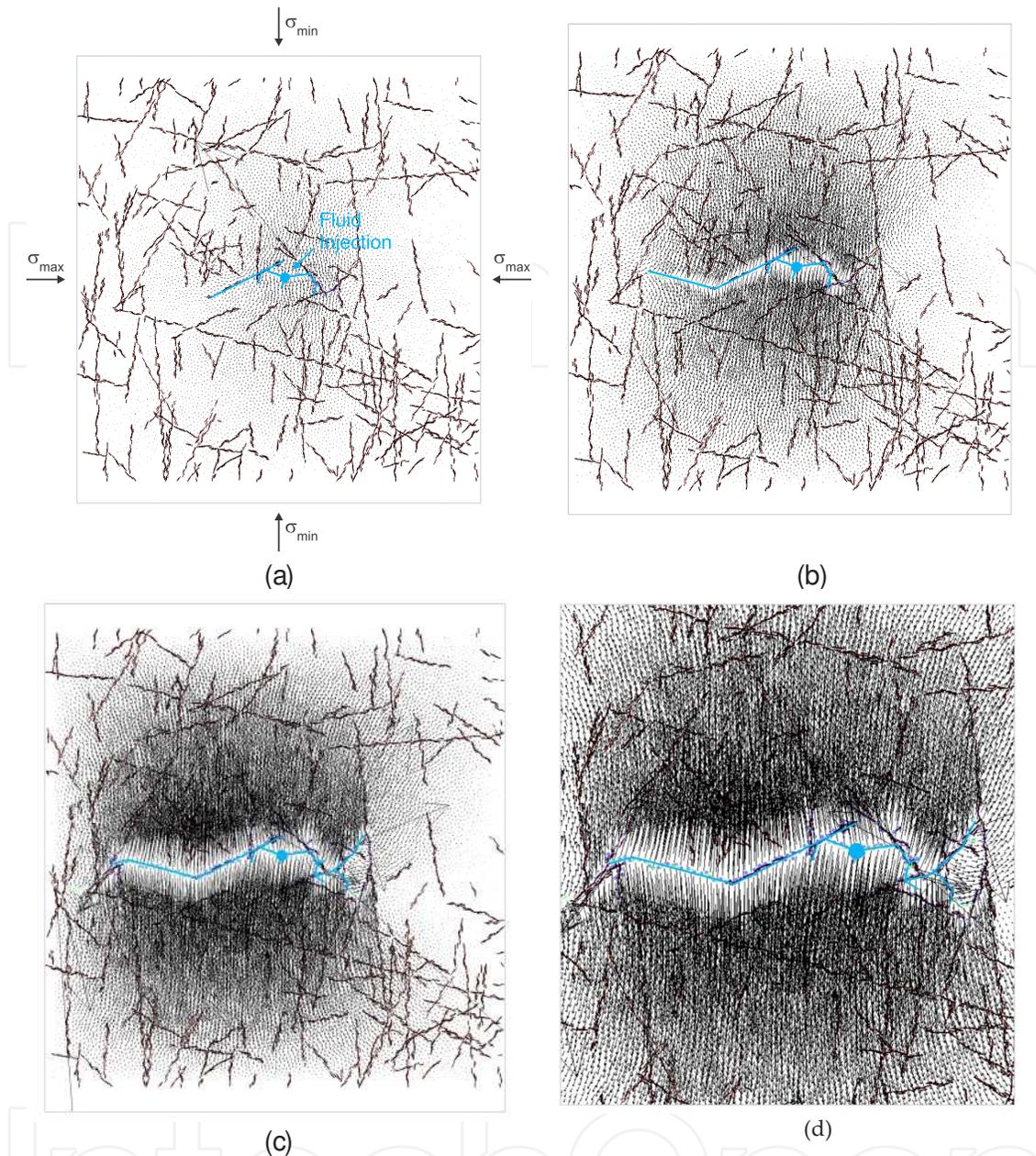


Figure 6. Extracts from simulation of the propagation of a hydraulic fracture in a two-dimensional impermeable SRM (Synthetic Rock Mass). (The horizontal stress σ_{\max} is 29 MPa and the vertical stress σ_{\min} is 12 MPa – Figure 5(a)). Note that the intact rock between the fractures has a finite strength and can break by rupture of the cemented bonded particles shown in Figure 5. The pressure required to propagate the fracture after breakdown was approximately 10 MPa above the minimum (i.e., least compressive) principal.

Jeffrey et al. (2009) conducted an underground test in the Northparkes Mine, Australia to observe the propagation of a hydraulic fracture in naturally fractured rock. Figure 7 shows part of the path of the fracture, as seen in a tunnel excavated into the fractured rock. The fracture path shows similar characteristics to those shown in the *PFC* simulation in Figure 6.



Figure 7. Hydraulic fracture (green plastic) crossing a shear zone on the face of a tunnel excavated through the fracture. "The arrows indicate the trace of the fracture with green plastic contained in it. There is no clear fracture between points 1 and 2 but the fracture may have crossed this zone either deeper into the rock or in the rock that has been excavated. Approximately 2 m of fracture extent is visible" (Jeffrey et al., 2009).

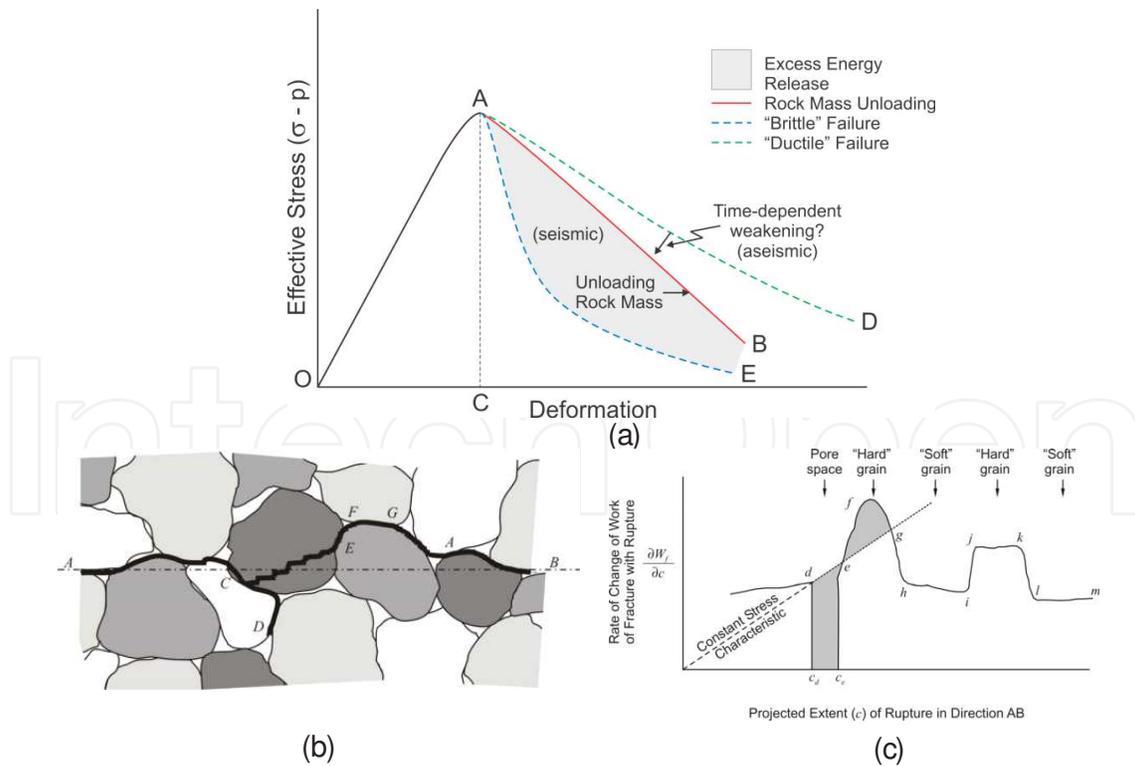


Figure 8. Energy changes during propagation of a fracture through heterogeneous rock.

The energy required to initiate crack propagation is represented by the area OAC in Figure 7(a). Whether or not the crack will extend depends on the energy that becomes available from the intact rock around the crack. If the energy released from the rock mass, represented by the area under the red curve AB, is greater than the energy required to extend the crack, represented by the area under curve AE, then the crack will extend; the excess energy represented by the shaded area serves to accelerate the crack and release seismic energy. If the energy required to extend the crack is represented by the area under the green curve AD, it is greater than the energy that would be released from the rock mass, and hence the crack would not extend. It is possible that the crack could exhibit some form of time-dependent weakening (e.g., due to fluid flow to the crack, viscous behavior, etc.) such that the energy required to extend the crack would be reduced. This could lead to crack extension, i.e., as the slope AD increased to overlap AB, but with no excess energy to produce seismicity. Figures 7(b) and 7(c)¹² illustrate another feature of crack extension on the granular scale. The energy required to extend a crack through or around a grain will be variable; the fracture may encounter pore spaces where no crack energy is required. Application of a constant load to such a heterogeneous system will result in local acceleration and deceleration of the crack-producing bursts of microseismicity. Similar effects can arise in rock fracture propagation at all scales.

It is worth noting that all of these processes of fracture propagation, albeit complex, develop in accordance with the principle of seeking the minimum potential energy of the system.

Much of the preceding discussion has focused on two-dimensional analysis or models. In reality, we are dealing with three-dimensional space (as noted in Figure 6), plus the influence of time (e.g., with respect to fluid flow, or time-dependent rock properties). Figure 8 provides an example from an actual record of hydraulic fracture propagation.

Figure 8 shows the sequence of microseismic events observed during hydraulic fracture stimulation ('treatment' in Figure 8(a)) of a borehole. Early time events are shown as green dots; later events are in red. The microseismic pattern indicates that fracturing started on both sides of the borehole at the injection horizon, but then moved up some 100 m to a higher horizon. As pumping continued, fracturing continued (red locations) on both horizons. It was concluded that the initial fracture in the lower horizon had intercepted a high-angle fault, allowing injection fluid to move to the higher level where it opened up and extended another fracture. Continued pumping led to fracture extension on both horizons. Numerical analysis Figure 8(b) indicated that initial fracture propagation at the lower level resulted in induced tension on the fault above the horizon, but compression on the fault below the lower injection horizon. This explains why injection fluid did not penetrate along the fault below the horizon, and provides a good illustration of the benefit of combining numerical analysis with field observation in understanding fracturing processes.

8. Microseismicity as an indicator of slip on fractures

Microseismicity stimulated during hydraulic fracturing and associated stimulation techniques (e.g., hydroshear) is often used to indicate slip and deformation on fractures in the rock. In

¹² Adapted from Fairhurst (1971).

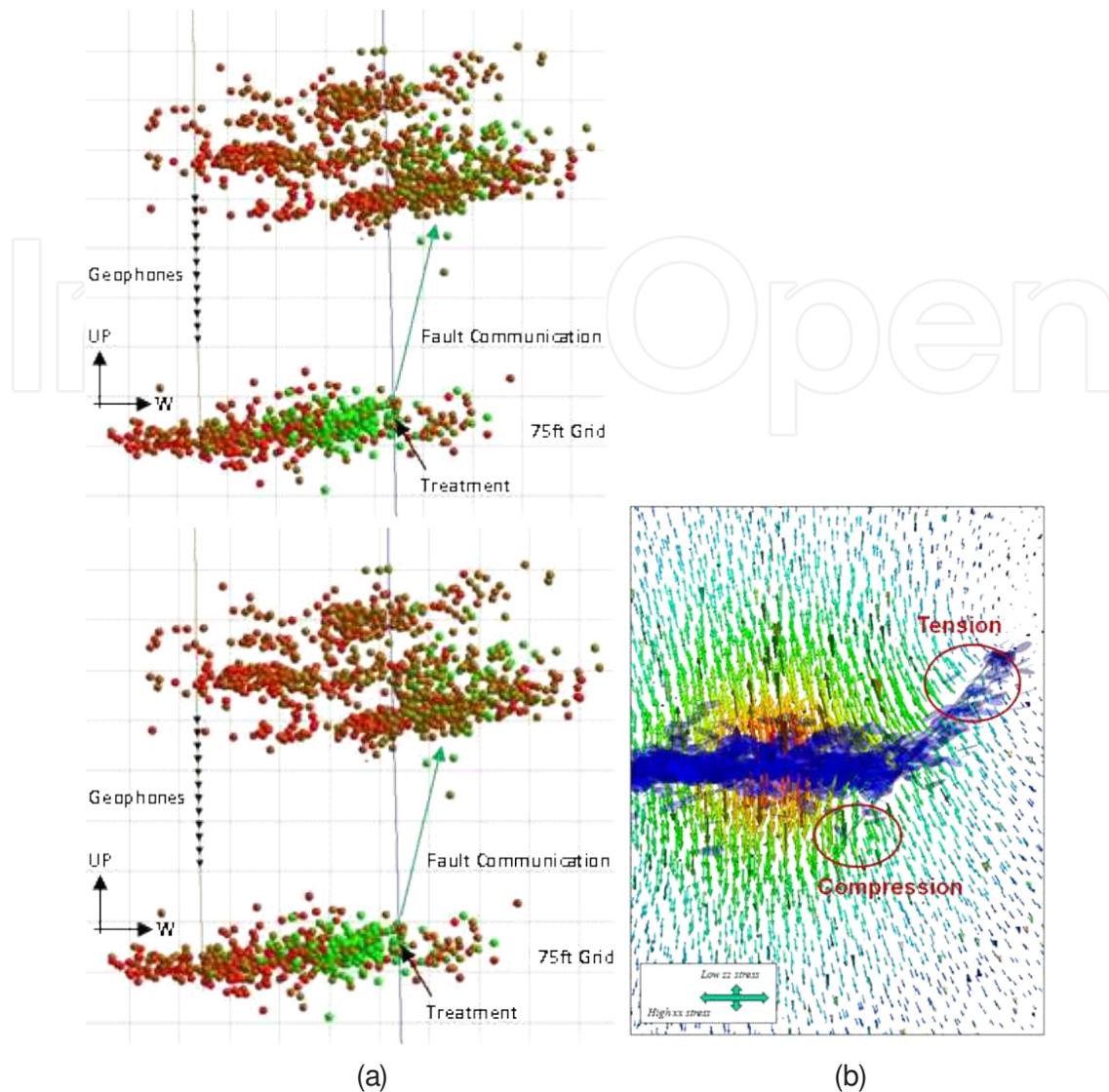


Figure 9. a) Microseismicity observed during hydraulic fracturing in a deep borehole; (b) numerical 'explanation' of the behavior observed in (a).

some cases, it is tacitly assumed that absence of microseismicity indicates absence of slip or deformation. In fact, there is growing evidence that microseismicity does not present a complete picture of deformations induced by stimulation or other effects leading to stress change. Figure 9, reproduced from Cornet (2012) (with permission from the author), shows P-wave velocity changes observed by 4D (time-dependent) tomography during the stimulation of the borehole GPK2 in the year 2000. A detailed discussion of the procedure used to observe and determine the P-wave changes is presented by Calo et al. (2012).

It is seen that the region of detected microseismicity (the cloud of black dots is small compared to the region where the P-wave velocity is reduced by as much as 20% in some regions). Some of the changes in velocity were temporary, suggesting that they may be related to temporal

changes in fluid pressure; other changes appeared to be more permanent deformation that occurred aseismically.

These observations indicate that microseismicity, although a valuable indicator of the response of a rock mass to stimulation by fluid injection, does not identify the complete region influenced by a stimulation.

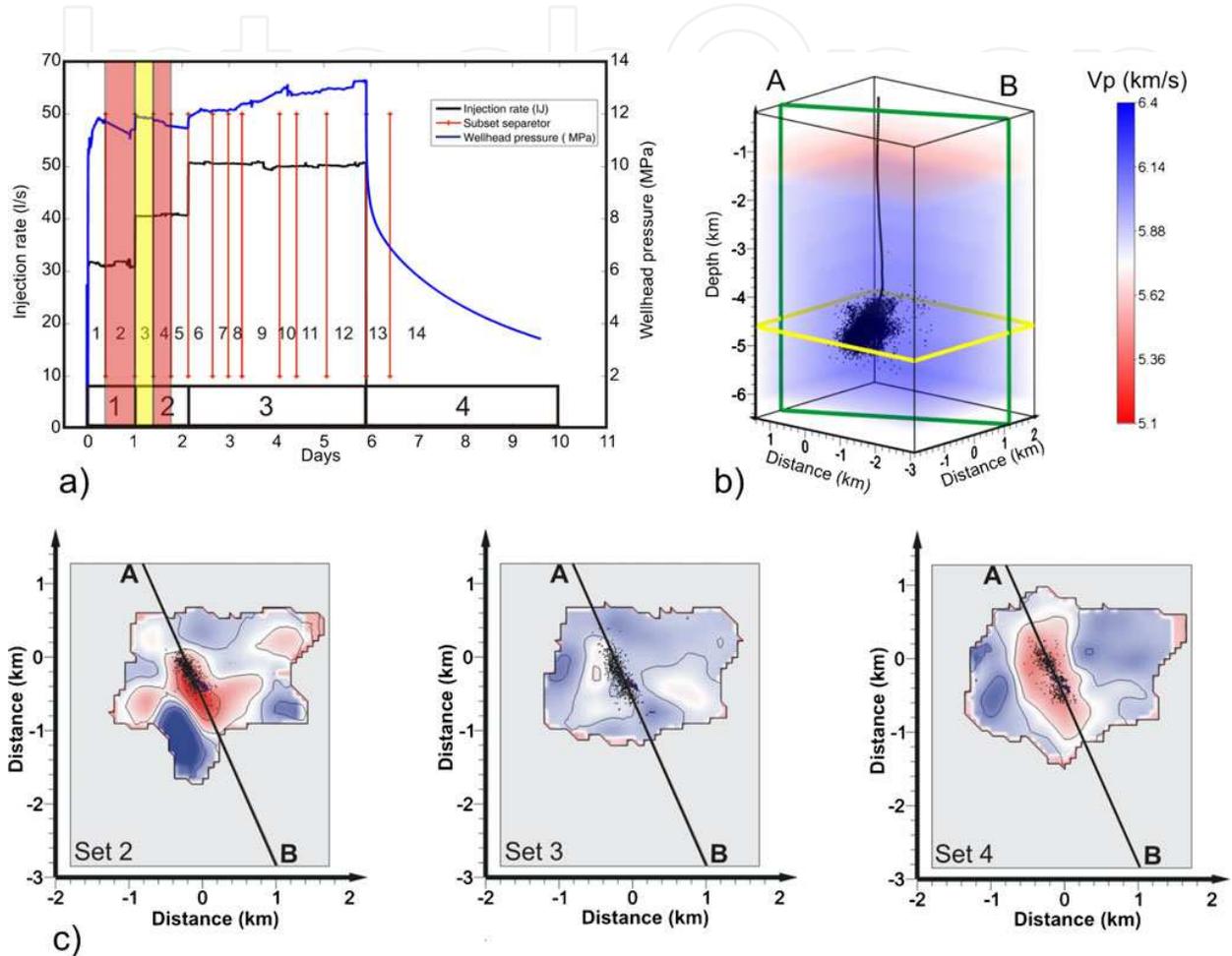


Figure 10. Aseismic slip induced by forced fluid flow as detected by P-wave tomography. (Soulz- sous- Fôrets, France. (a) The injection program (black curve is flow rate, blue curve is well head pressure, horizontal axis is time in days); (b) 3D view of the seismic cloud with respect to the GPK2 borehole. Vertical axis is depth and horizontal axes are distances respectively toward the north and toward the east; and (c) horizontal projections corresponding to the yellow horizontal plane. The vertical green plane is shown as line AB in the plots of part c. P-wave velocity tomography for sets 2, 3 and 4 are indicated respectively by orange, yellow and green colors in the injection program. The vertical axis corresponds to North.

9. In-situ stress

As already noted, hydraulic fractures tend to develop in a more or less planar fashion, extending normal to the minimum regional principal stress. Determining the direction, and perhaps the magnitude, of the regional minimum stress is an important element of hydraulic

fracturing strategy, especially with the development of directional drilling, which allows borehole to be drilled in the direction considered most favorable for fracturing with respect to stress direction. (see e.g., Figure 15 and related discussion).

Determination of the in-situ stress state also can be a significant challenge.

Stress in rock is distributed throughout the mass, and is influenced by the complicated structure of the mass¹³. Most techniques of stress determination rely on what are essentially ‘point’ determinations. One difficulty of determining the regional stress is illustrated by the simple, albeit somewhat artificial, example of Figure 11. This shows a two-dimensional numerical model of the stress distribution in an elastic plate containing several finite frictional fractures.

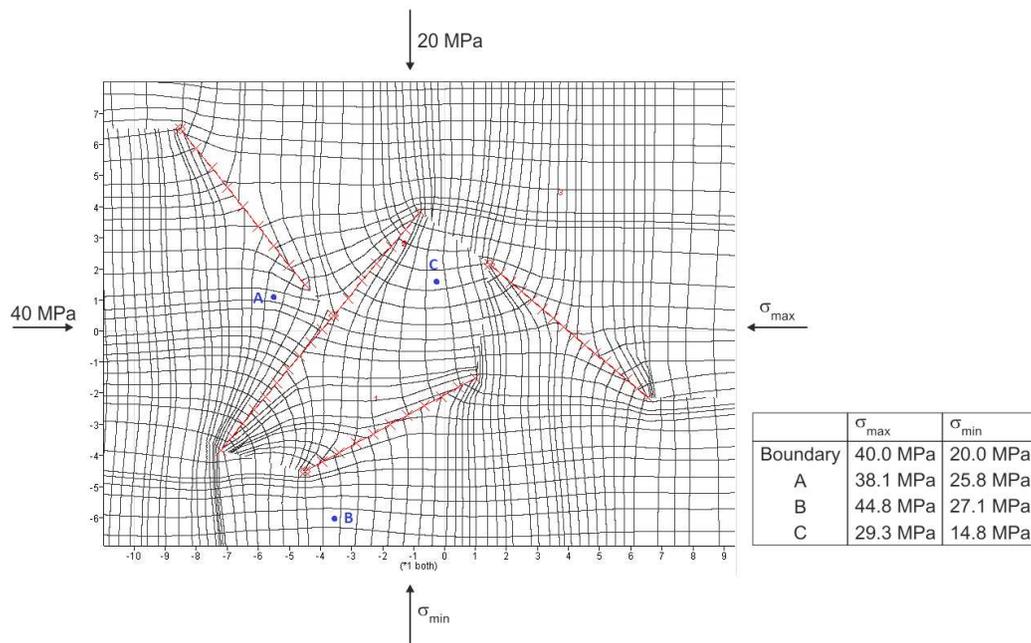
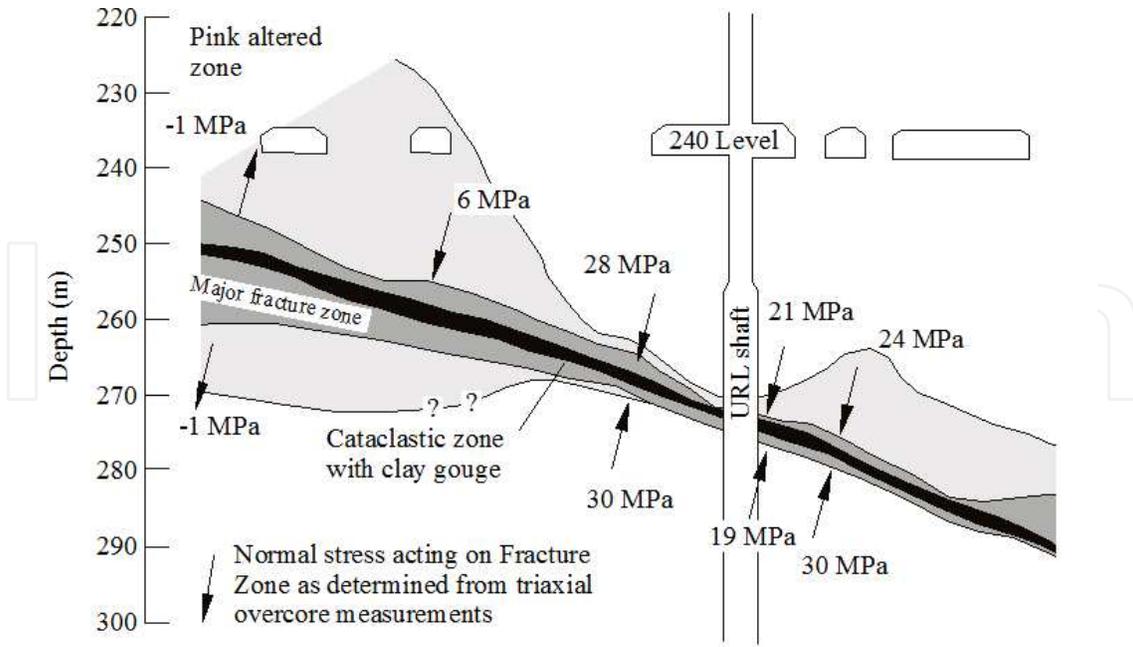


Figure 11. Influence of frictional cracks on the distribution and orientation of principal stresses, illustrative example.

The exercise serves to illustrate the difficulty of making stress determinations from local point measurements, be they in a borehole or on the surface. Stresses can change in orientation and magnitude locally due to geological inhomogeneities, fractures, faults, etc., many of which may be hidden or cannot be observed from the measurement location. Although determinations made at points A and B are reasonably close to the boundary values, point C is considerably different, and the directions of principal stress, as indicated by the principal stress trajectories, can be very different from the (regional) orientations, i.e., at the model boundary.

Figure 12 provides an actual example of the variability of stress over relatively short distances. (The vertical and horizontal scales are equal in Figure 12). In this case, the main interest was to assess how normal stresses were affected by the thickness of gouge in the plane of the thrust fault.

¹³ See also footnote 17 –Appendix 1.



Observed Variability of Normal Stress Across a Thrust Fault Underground Research Laboratory Pinawa, Canada.

Figure 12. Normal stress variation across a thrust fault, Underground Research Laboratory, Canada.

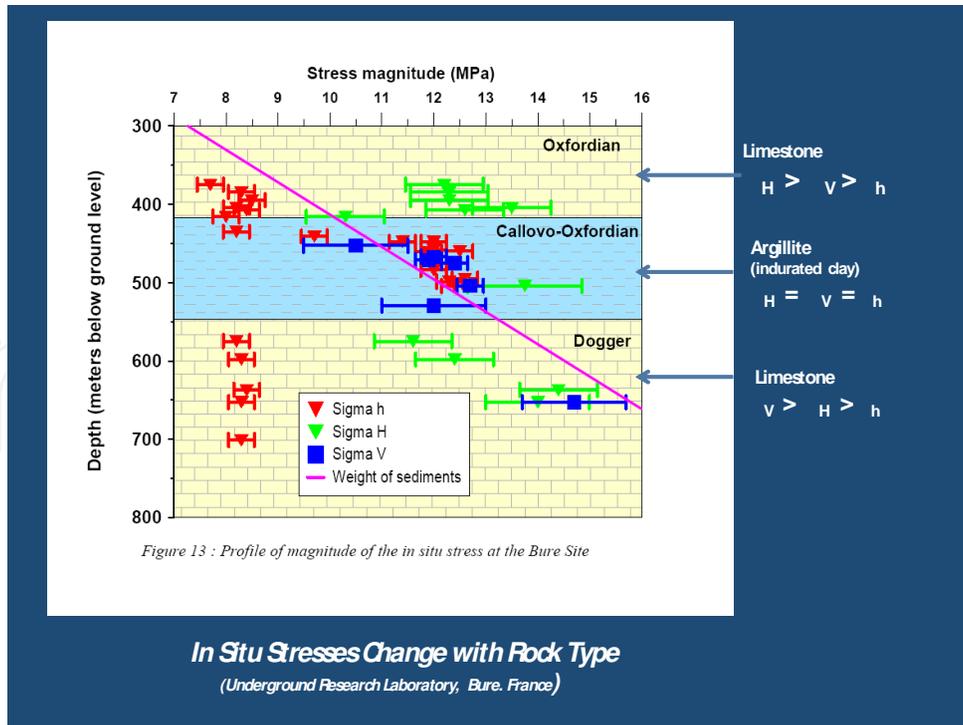


Figure 13. Observed stress distributions in argillite and limestones at the Underground Research Laboratory, Bure, France.

Figure 13 illustrates another important geological influence on stress distribution, changing lithology. This example is from the French Underground Research Laboratory (URL) ¹⁴at Bure in NE France. Laboratory tests on specimens of the Callovo-Oxfordien Argillite indicate a long-term viscosity of this rock suggesting that any imposed deviatoric stresses would tend towards an isotropic stress state over the order of 10 million years.

Test specimens from the limestones above and below the argillite do not appear to exhibit such viscosity. The stress distributions determined from field measurements support such differences in rheological characteristics of the rock formations.

Commenting on the in-situ stresses observations at Bure (i.e., as shown in Figure 13) Cornet (2012) notes as follows:

“Further, the complete absence of microseismicity in the Paris Basin (Grünthal and Wahlström, 2003, Fig. 4) and the absence of large scale horizontal motion as detected by GPS monitoring (Nocquet and Calais, 2004) indicate that no significant horizontal large-scale active deformation process exists today in this area.

“The important conclusion here is that the natural stress field measured on a 100 km² area at depth ranging between 300 m and 700 m does not vary linearly with depth and is not controlled by friction on preexisting well-oriented faults. Rather, the stress magnitudes seem to be controlled by the creeping characteristics of the various layers rather than by their elastic characteristics, with a loading mechanism that remains to be identified but which is neither related directly to gravity nor apparently to present tectonics.

“It is concluded here that the smoothing out of stress variations with depth into linear trends may be convenient for gross extrapolation to greater depth. But it should not be taken as a demonstration that vertical stress profiles in sedimentary rocks are governed by friction along optimally oriented faults, given the absence of both microseismicity and actively creeping fault. It should not be used for integrating together stress tensor components obtained within layers with different rheological characteristics.”

Other examples could be cited, but the message is clear. Determination of in-situ stress in rock is an extremely challenging task, with results subject to considerable variability and uncertainty.

Stress orientations can be estimated from consideration of regional tectonics, faulting and interpretation of evidence from local structural geology supported in some cases by evidence based on borehole logs (e.g., tensile fractures induced along the well bore). Stress magnitudes are, in general, more difficult to determine and usually less significant, except as indicators of how stresses may be distributed across a site where the geology and engineering design are complex. In such cases, interpretation of stress distribution is best done in conjunction with a

¹⁴ The URL at Bure was developed in order to determine the suitability of the Callovo-Oxfordien Argillite formation for permanent storage of high-level nuclear waste.

numerical model of the site, preferably one that includes the influence of important uncertainties and discussion with structural geologists familiar with the area under study.

10. 'Critical stress state' in the Earth's crust

It is sometimes asserted that the Earth's crust is everywhere close to a 'critical state of stress,' i.e., that a small change in the deviatoric stress in the rock is likely to produce slip on one or more faults with associated seismic activity. The current global interest in development of major resources of natural gas, the central role of hydraulic fracturing in this development, and the public apprehension that hydraulic fracturing will 'trigger earthquakes' has led to strong opposition to fracturing, and even legislation to ban the use of hydraulic fracturing in some countries and some States in the USA.

As illustrated by Figure 14, the seismic hazard, (i.e., probability of a damaging earthquake) varies very considerably from place to place. Thus, an earthquake of a given magnitude is 1000 times more likely to occur in Southern California than it is in the Eastern United States. The hazard is even lower in regions such as Texas, North Dakota and in the stable Canadian Shield region of the North American tectonic plate. While many earthquakes are initiated at depths considerably greater than depths where hydraulic fracturing is applied, it seems plausible to suggest that there may be less potential for fracturing to induce seismic activity in regions that have low seismic hazard. Also, as indicated by the comments of Cornet in the previous section of this paper, there is evidence that the critical stress hypothesis warrants detailed scrutiny, at least. This could have major implications for development of the world's major natural gas and EGS (enhanced geothermal systems) resources. Two recent studies, National Research Council (2012) and Royal Society – Royal Academy of Engineering (2012), have each concluded that the risk that hydraulic fracturing as used in development of energy resources would trigger significant seismic activity is small, but it would be valuable to examine the critical stress hypothesis more rigorously than has been done to date.

11. Hydraulic fracturing in tight shales

The development of inclined and horizontal drilling (see Appendix 1 - Figure A1-2) has helped stimulate intense activity to develop natural gas production from so-called tight shale, i.e., rock in which natural gas is held tightly within the very fine pore structure of the rock. Figure 15 illustrates the procedure used to stimulate these shales. The well is drilled horizontally in the gas-bearing formation, more or less in the direction of the minimum principal stress. Hydraulic fractures are generated (and propped) at intervals along the well to generate a network of connected flow paths that will allow the gas to flow to the well. Depth (i.e., extent) and spacing of the fractures should be optimized to produce the formations effectively. Bunger et al. (2012) discuss the factors in the design of an effective fracture strategy.

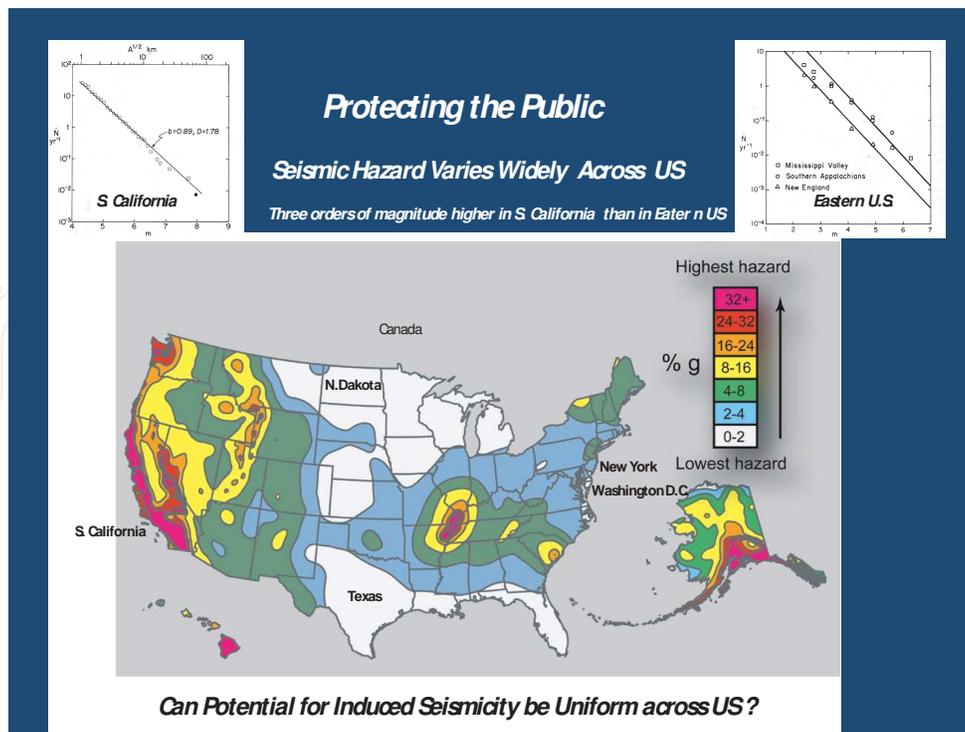


Figure 14. Seismic hazard map of the United States — US Geological Survey.

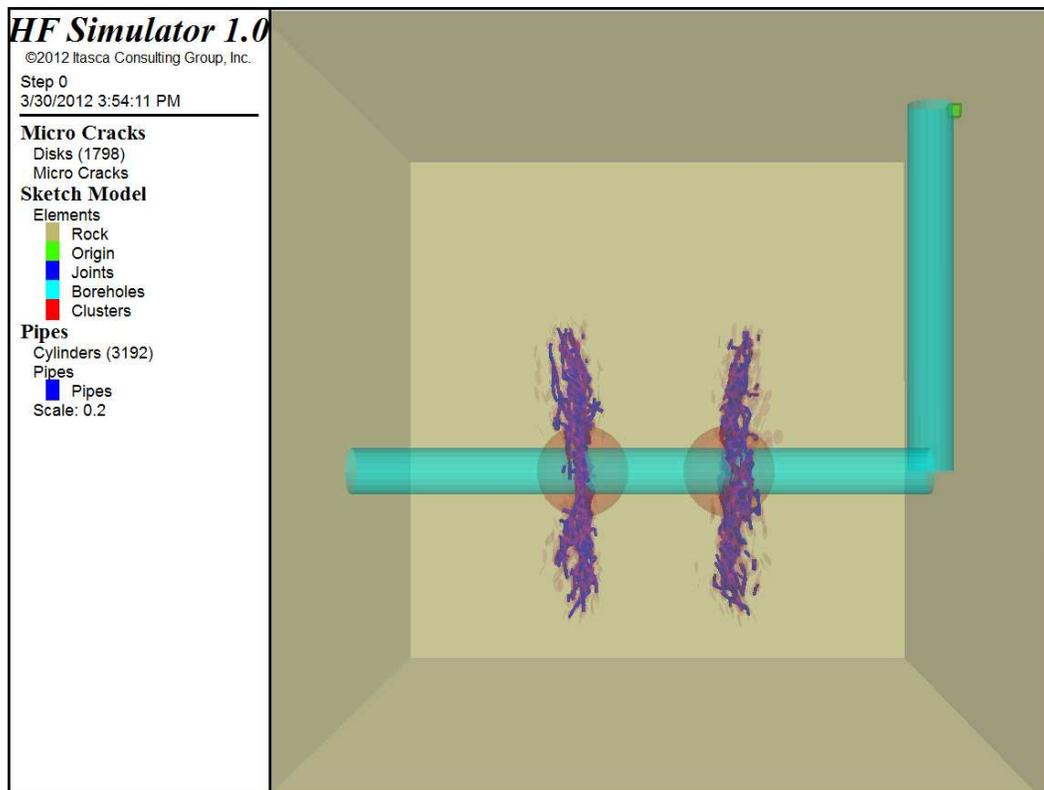


Figure 15. Staged hydraulic fracturing in a horizontal well. There may be many such wells along the horizontal well.



Why Doesn't Microseismicity Correlate With Production?

The Total Rock Volume Affected by Microseismicity Accounts for Less Than 1% of Gas Production in First 6 Months



9

Figure 16. The volume of rock defined by microseismicity is a very small fraction of the volume producing gas.

Figure 16 shows a slide from a recent presentation by Prof. Mark Zoback, who kindly agreed to allow the author to include it here. Although on a somewhat smaller scale, the fact that considerable deformation and fracturing must be taking place that is not associated with detected microseismicity is similar to the phenomena discussed in connection with Figure 10. Prof. Zoback refers to such aseismic deformation as slow slip, and is conducting research to understand the underlying mechanisms, including the possible influence of the clay content of the shale. As can be seen in Figure 17 (courtesy of Prof. Zoback), the clay content can be large.

Figure 18 illustrates the very fine, micron scale, pore structure of a typical tight shale. Although the mechanism(s) by which flow pathways are established in such a fine structure is not clear, the level of microseismic energy release associated with brittle breakage of one or a few bonds will be very small and of high frequency (such that the radiated energy would be rapidly attenuated), and hence, not detectable by any geophone. Thus, absence of microseismicity may not indicate an absence of breakage of brittle bonds. Some mechanism must be operative that generates flow pathways. Intuitively, it might be expected that the clay content of the shale might lead to ductile and viscous deformation that could tend to close the pathways.



Average Shale Properties

	BARNETT	MARCELLUS	EAGLE FORD	FLOYD
Depth (ft)	3 - 9,000	2 - 9,500	4 - 13,500	6 - 13,000
TOC (%)	1 - 10	1 - 15	2 - 7	1 - 7
RO (%)	0.7 - 2.3	0.5 - 4+	0.5 - 1.7	0.7 - 2+
Porosity (%)	2 - 14	2 - 15	6 - 14	1 - 12
Qtz + Calcite (%)	40 - 50	40 - 60	50 - 80	20 - 30
Clay (%)	20 - 40	30 - 50	15 - 35	45 - 65
Areal Extent (mi ²)	22,000	60,000	15,000	6,000
Resource Size (Tcf)	25 - 250	50 - 500	10 - 100	<<1

How many Floyd Shales are There?

33

Figure 17. Clay content of some typical 'tight' gas shales.

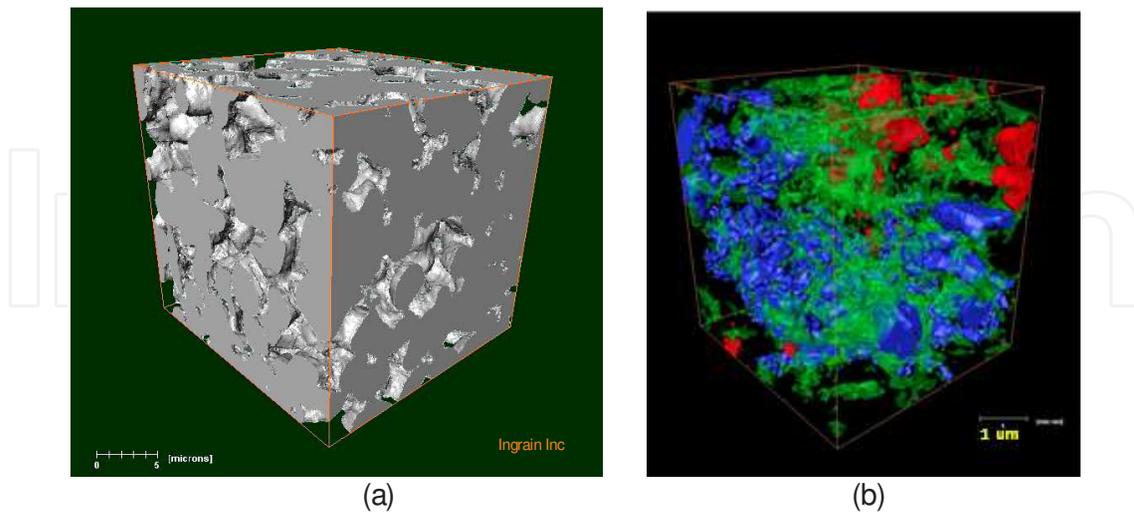


Figure 18. a) Outer surface of a FIB-SEM (Focused Ion Beam- Scanning Electron Microscope) volume of Eagle Ford Shale; (b) Transparency view of the distribution of connected pores (blue), isolated pores (red) and organic matter (green). (Courtesy of Prof. Amos Nur and J. Wallis (see Wallis et al., (2012) for details of technology.)

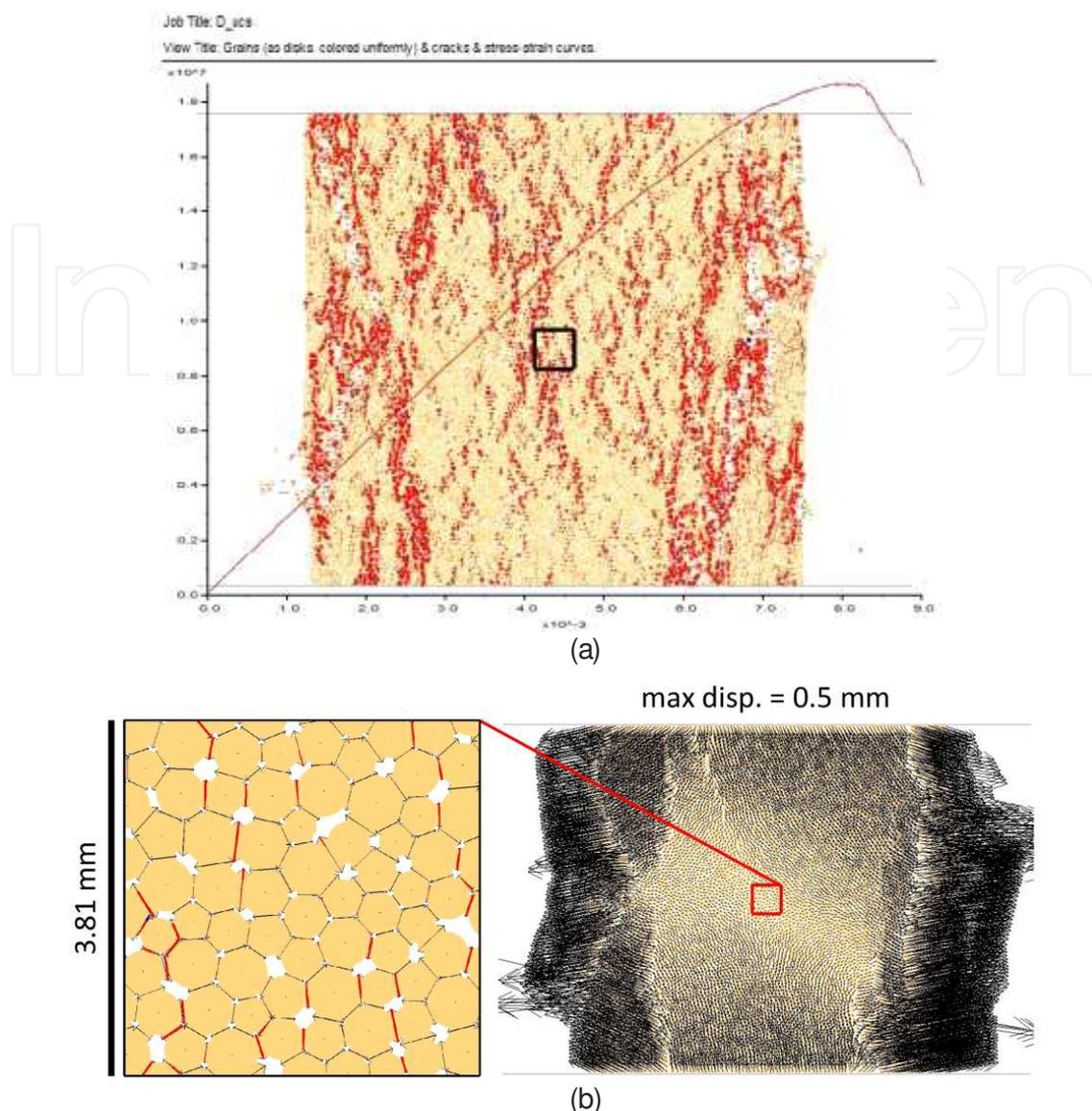


Figure 19. Micro-rupture of bonds within a *PFC* model of a rock loaded to failure, and beyond, in uniaxial compression. The darker red regions in (a) indicate coalescence of smaller groups of bonds that have ruptured. Eventually these larger regions develop to provide a mechanism that leads to collapse of the specimen. It is seen that bond breakage occurs throughout the specimen as the load is increased. The larger dark red regions will release larger amplitude, lower frequency waves that can be detected, whereas the smaller ‘pathways’ cannot be detected seismically. The load-deformation curve is shown as an ‘overlay’ on the specimen.

12. Fracture network engineering

This paper has emphasized the central role of fractures in rock, primarily natural fractures developed on a wide spectrum of scales over many tectonic epochs and many millions of years. These fractures and fracture systems are of special significance with respect to hydraulic fracturing and related techniques of fluid injection into rock since the fluid will tend to seek

out those fractures that can be more readily opened against the local in-situ stress field as the fluid is injected. Given the complexity and lack of information on the fracture system, stress environment, etc., how can the engineering of hydraulic fracturing and related fluid injection programs advance most effectively?

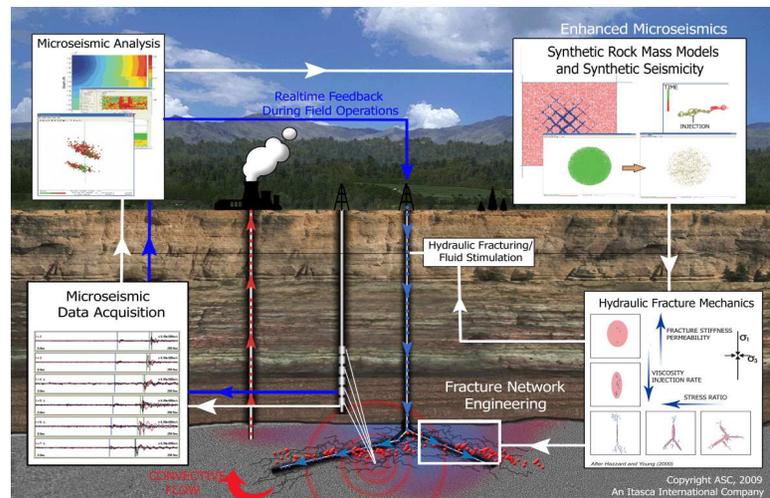
Confronted with the same complexity of rock in situ, civil engineers and mining engineers have tended to adopt the 'Observational Approach' (Peck, 1969). In essence, this approach involves developing an initial engineering design for the problem, based on a first assessment/estimate of the rock (or soil) properties. Observe the actual performance and modify the initial design as needed to arrive at the desired performance. An example of the Observational Approach (as used in the New Austrian Tunnelling Method) is discussed in Fairhurst and Carranza-Torres (2002), see pp. 24-30.

Application of the Observational Approach to Hydraulic Fracturing and related fluid injection techniques faces some disadvantages and some advantages. We do not have 3D access to the engineering site. We do have powerful numerical modeling tools to help make a more informed initial estimate of how the system will perform; and we have sensing systems, both downhole and remote. Figure 20 illustrates a procedure that tries to apply the Observational Approach to hydraulic fracturing and related systems. The illustration describes an application to the extraction of Geothermal Energy.

Stones have begun to speak, because an ear is there to hear them.

Goos, Conversations with the Earth (1954), 4

Microseismicity –predicted and observed.



Fracture Network Engineering. Synthetic Rock Mass and Synthetic Seismicity Models are compared with observed microseismic signals for **real time control of fracture network development.** (Enhanced Geothermal Systems.)

Figure 20. Fracture network engineering system.

In this application, an initial design approach is developed based on a numerical modeling study incorporating any available data, insight, etc., on the site. This model provides an initial

prediction of the performance. Instrumentation, both downhole and on-surface observes the initial response of the system and compares it with the prediction. This triggers a feedback signal to modify the design input to move the performance closer to the one desired. This iteration continues, changing progressively towards the performance desired.

Although the writer knows of no such Fracture Network Engineering system currently in operation, many of the components are available and it is time to start.

13. Conclusions

Expectations for higher living standards of a rising world population, and the associated demand for Earth's resources of energy, minerals and water, lead inevitably to greater focus on resources of the subsurface.

This focus includes the need to develop improved technology to develop these resources, and a better understanding of the nature of the subsurface environment as an engineering material.

Earthquakes and dynamic releases of energy are a daily reminder that on the global scale, Earth is critically stressed, and constantly trying to adjust seeking to achieve a condition of minimum potential energy for the entire system.

On going for many, many millions of years, such adjustments have resulted in the heterogeneous assembly of blocks of rock bounded by essentially planar surfaces; fault, fractures and similar 'discontinuities' varying in scale from tectonic plates and continents down to micron and even nanometers.

Some of these volumes are critically stressed; others are far from a critical condition. National maps of seismic hazards provide evidence of this heterogeneity on a larger scale.

Although Earth Resource Engineering activities may be kilometers in extent, they are small-scale within the larger Earth context. Subsurface engineering in a critically stressed region can be a much different challenge than in a stable region. It is important to assess the initial conditions carefully for each case, and especially where fluid injection is a main component of a project.

The sub-surface is opaque in several ways. Details of the key features that can control the response to an engineering activity in the sub-surface are often unknown. Problems are data-limited. This is particularly the case when the engineering is based on deep borehole systems, as in hydraulic fracturing and related fluid injection technologies.

Although operating in ways that may appear complex, the response of the subsurface to stimulation does obey the laws of Newtonian mechanics, and it is clear that pre-existing natural discontinuities have a major influence on how the subsurface responds to engineered changes.

The advent of powerful computers and developments in numerical modeling provide a potentially major tool to help develop better-informed strategies of subsurface engineering. Used interactively in close conjunction with instrumentation, both downhole and surface

based, it should be possible to progressively develop a mechanics-informed understanding and path forward for more effective subsurface engineering.

Much as the field of Fracture Mechanics has led, and continues to lead, to major technological improvements for fabricated materials, so can development of the field of Rock Fracture Mechanics be of transformative value to subsurface engineering, and to society in general.

Hydraulic fracturing and related injection-stimulation systems will certainly be a central element in the future of Earth Resource Engineering. The organizers of HF 2013 are to be commended for focusing attention on this critically important topic.

Appendix 1

Earth resources engineering

In 2006, the US Academy of Engineering introduced the term ‘Earth Resources Engineering’ to replace ‘Petroleum, Mining and Geological Engineering’ in recognition of the broader range of engineering activities and concerns associated with use of the subsurface. The new title, it is hoped, will also stimulate important synergies between the various disciplines involved. Mining and civil engineers, for example, have direct three-dimensional access to the subsurface not available to colleagues in other subsurface activities. This access provides a major opportunity to conduct research and gain understanding of the mechanics of subsurface processes under actual in-situ conditions, as exemplified by Jeffrey et al. (2009), see Figure A1-1.

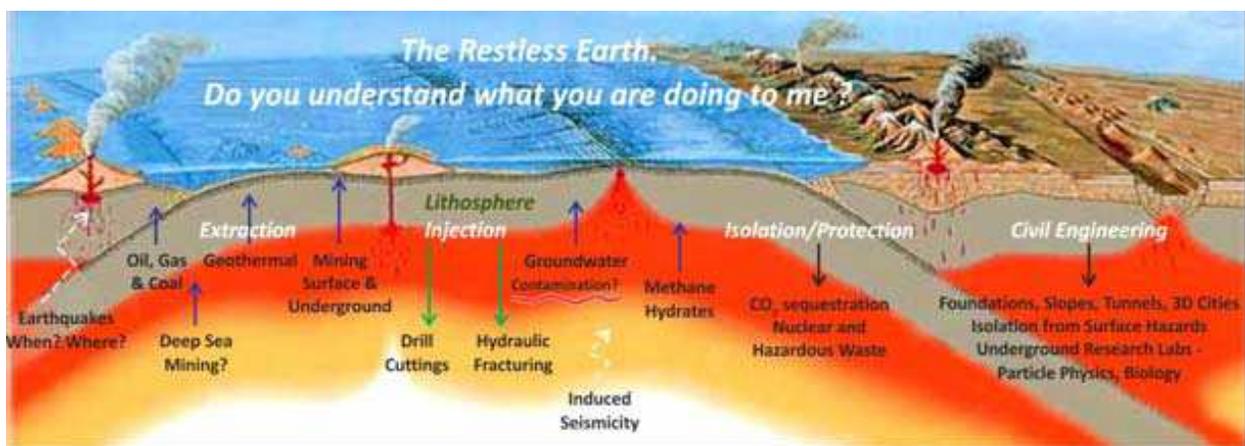


Figure A1-1. The restless Earth. Earth Resource Engineering activities are all confined to a very shallow part of the 40 km -700 km thick Earth’s solid crust (lithosphere). Deepest borehole ~ 12 km; mine ~ 4km. Rock stress increases vertically $\sigma_v \sim 27\text{MPa/km}$; laterally $\sigma_h \sim (0.5- 3.0)\sigma_v$. Pore water pressure $p = 10\text{ MPa /km}$ depth. temperature increase $\sim 25^\circ\text{C /km}$ depth.

Study of slip on active faults is a good example.

“The physics of earthquake processes has remained enigmatic due partly to a lack of direct and near-field observations that are essential for the validation of models and concepts.

DAFSAM¹⁵ proposes to reduce significantly this limitation by conducting research in deep mines that are unique laboratories for full-scale analysis of seismogenic processes. The mines provide a 'missing link' that bridges between the failure of simple and small samples in laboratory experiments, and earthquakes along complex and large faults in the crust. There is no practical way to conduct such analyses in other environment. To unravel the complexity of earthquake processes, this project is designed as integrated multidisciplinary studies of specialists from seismology, structural geology, mining and rock engineering, geophysics, rock mechanics, geochemistry and geobiology. The scientific objectives of the project are the characterization of near-field behavior of active faults before, during and after earthquakes".¹⁶See also http://www.iris.edu/hq/instrumentation_meeting/files/pdfs/IRIS_Johnston.pdf

Petroleum engineers can now reach depths in excess of 6 km and have developed advanced drilling control technologies that allow precise access to locations extending horizontally to more than 10-15 km from a single vertical hole (see Figure 2).

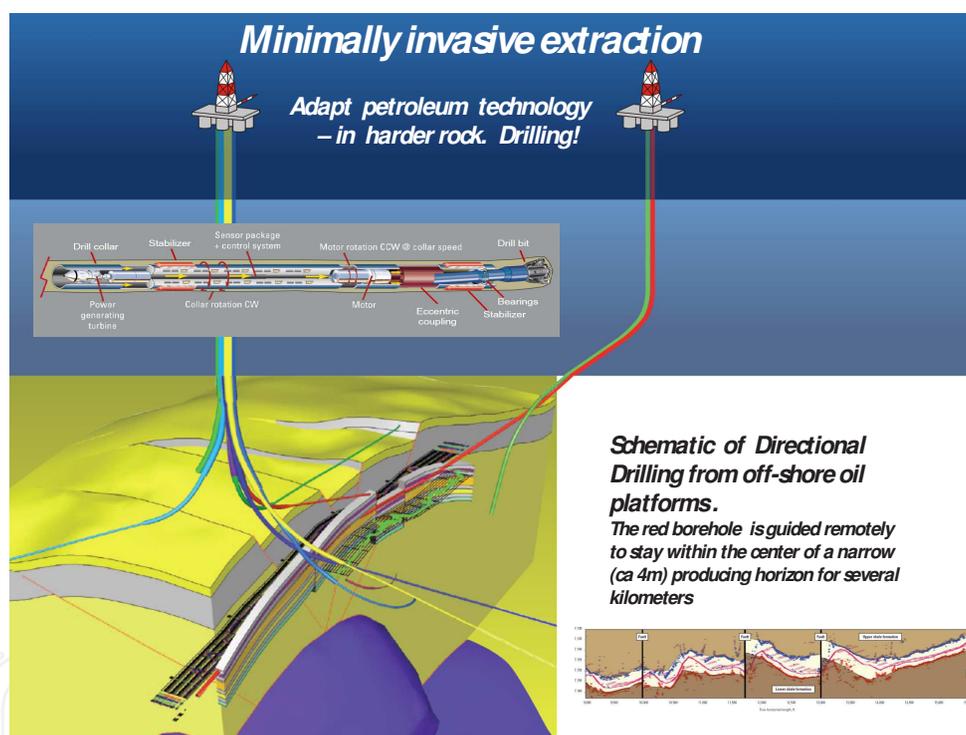


Figure A1-2. Schematic illustration of directional drilling for petroleum production.

These and related developments are stimulating interest in application of borehole technologies to other areas of subsurface engineering, including the development of less-invasive mining technologies, i.e., borehole extraction of minerals. Some applications, e.g., where crystalline rocks are involved, are contingent on the development of significantly lower-cost drilling technologies. The critical dependence of society on reliable and economic subsurface

15 DAFSAM -Drilling Active Faults in South African Mines.

16 http://www.icdp-online.org/front_content.php?idcat=460

engineering is illustrated by the fact that currently more than 60% of the world’s energy is delivered via a borehole. The Deepwater Horizon accident in the Gulf of Mexico in April 2010 provides a sober example of the consequences of error. In summary, hydraulic fracturing and related stimulation technologies are likely to see application to an increasing range of subsurface engineering challenges. HF2013, the first International Conference for Effective and Sustainable Hydraulic Fracturing, is very timely.

Appendix 2

Effect of coring in pre-stressed rock

The consequences of disturbing a pre-stressed rock medium are illustrated by examining the rock coring operation. Figure A2-1 shows the stress concentrations in a rock core in a brittle

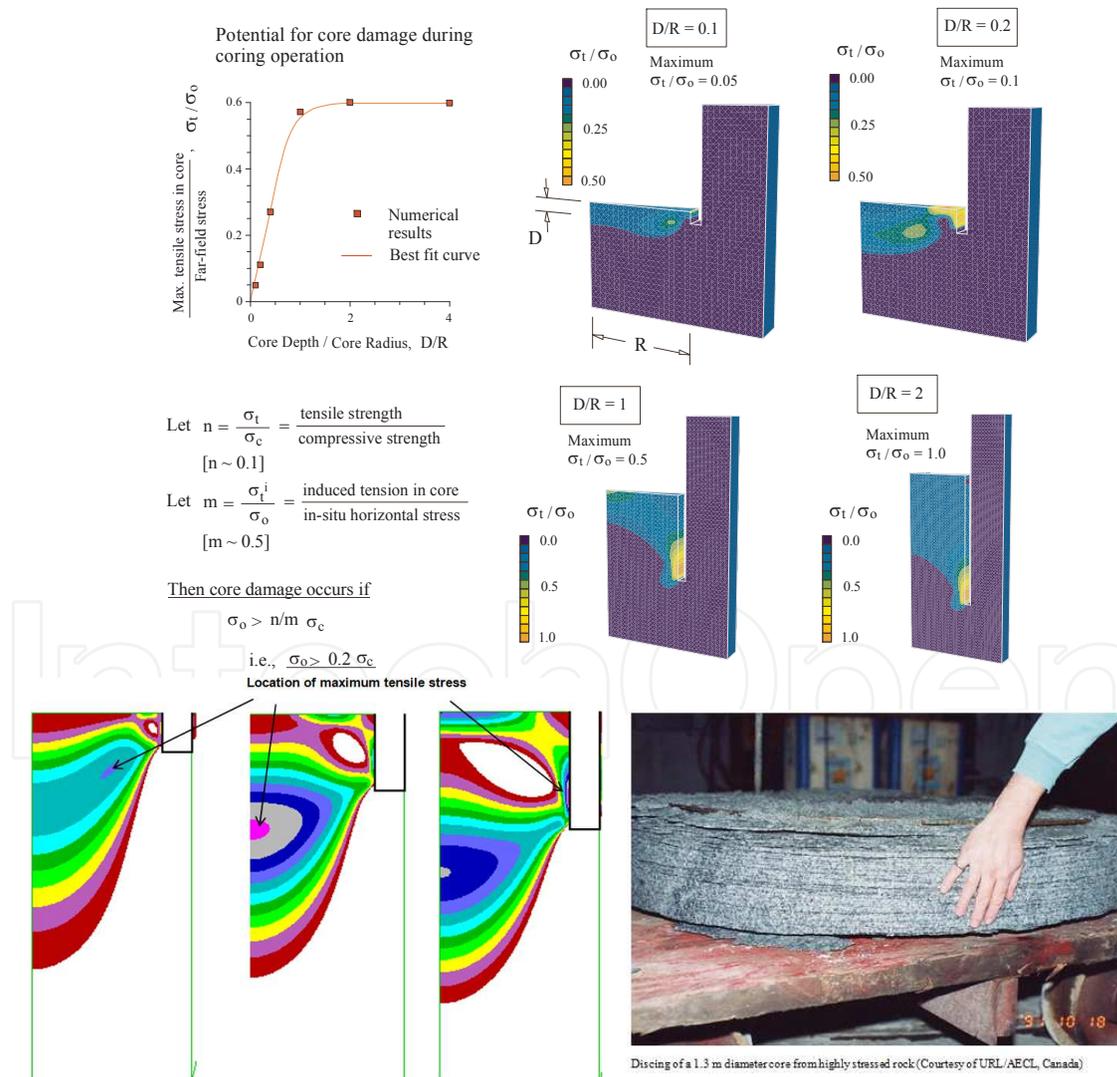


Figure A-2.1. Tensile stress concentrations induced in a brittle rock during coring.

rock. If the in-situ stress normal to the axis of drilling is sufficiently high tensile cracks can develop in the core. Where lateral stresses are very high, then tensile ‘spalling’ may result, as shown in the photograph of the bottom right of Figure A2-1. Where the rock is more ‘ductile’ the core may undergo permanent deformation without fracturing. In both cases, the mechanical properties of these cores may differ significantly from those of the rock in situ from which the core was obtained.

Acknowledgements

Much of the material and concepts discussed in this paper is the result of work and discussions over many years with colleagues at Itasca Consulting Group, Inc. in Minneapolis and faculty in GeoEngineering at the University of Minnesota, especially in this instance, Professor Emmanuel Detournay. Particular help was received from Itasca colleagues Varun, Branko Damjanac, David Potyondy and Mark Lorig, The influence of numerous stimulating discussions with Professor François Cornet of the Institut de Physique du Globe, Strasbourg, France are clearly evident in the paper. Professors Amos Nur and Mark Zoback, of Stanford University, USA and of Ingrain, Inc., Houston, USA assisted with valuable material, as acknowledged in the text. Dr. Rob Jeffrey and Andrew Bungler of CSIRO, Melbourne, the leaders in arranging HF2013, have provided valuable comments, assistance and understanding throughout. To all, I am very grateful. Such invaluable assistance notwithstanding, I accept full responsibility for the interpretations and views expressed in the paper.

Author details

Charles Fairhurst^{1,2*}

1 Senior Consultant, Itasca Consulting Group, Inc, Minneapolis Minnesota, USA

2 Professor Emeritus, University of Minnesota, Minneapolis, Minnesota, USA

References

- [1] Anderson, T. L. (2005). Fracture Mechanics: Fundamentals and Applications. 3rd edition, CRC Press (0-84931-656-1)
- [2] Artyushkov, E. V. (1973). Stresses in the Lithosphere Caused by Crustal Thickness
- [3] Inhomogeneities, J. Geophys. Res. November 10, (1973). , 78(32)
- [4] Bungler, A. P, Zhang, X, & Jeffrey, R. G. (2012). Parameters Affecting the Interaction Among Closely Spaced Hydraulic Fractures” SPE Journal March 2012, , 292-306.

- [5] Calo, M, Dorbath, C, Cornet, F. H, & Cuenot, N. (2011). Large scale aseismic motion identified through 4D P-wave tomography; *Geophys. J. Int.* , 186, 1295-1314.
- [6] Cundall, P. A. (2008). An Approach to Rock Mass Modelling," in *From Rock Mass to Rock Model-CD Workshop Presentations (15 September, 2008)- SHIRMS 2008 (Proc. 1st Southern Hemisphere International Rock Symposium, Perth, Western Australia, September 2008)* Y. Potvin et al., Eds. Nedlands, Western Australia: Australian Centre for Geomechanics.
- [7] Cladouhos, T. T, Clyne, M, Nichols, M, Petty, S, Osborn, W. L, & Nofziger, L. (2011). *Newberry Volcano EGS Demonstration Stimulation Modeling" GRC Transactions* , 35, 317-322.
- [8] Cornet, F. H. (2012). The relationship between seismic and aseismic motions induced by forced fluid injections." *Hydrogeology Journal* (2012) 20: 1463-1466
- [9] Cornet, F. H, & Röckel, T. (2012). Vertical stress profiles and the significance of "stress decoupling". *Tectonophysics* , 581(2012), 193-205.
- [10] Cundall, P. A, & Pierce, M. E. and D. Mas Ivars. ((2008). Quantifying the Size Effect of Rock Mass Strength" in *SHIRMS 2008 (op.cit.)* , 2, 3-15.
- [11] Damjanac, B, & Fairhurst, C. (2010). Evidence for a Long-Term Strength Threshold in Crystalline Rock,|| *Rock Mech. Rock Eng.*, 43, 513-531 (2010).
- [12] Damjanac, B, Detournay, C, & Cundall, P. A. and Varun, ((2013). Three-Dimensional Numerical Model of Hydraulic Fracturing in Fractured Rock Masses" *Proc. HF The International Conference for Effective and Sustainable Hydraulic Fracturing, Brisbane, May 20-22, 2013, 2013.*
- [13] Damjanac, B, & Fairhurst, C. Evidence for a Long-Term Strength Threshold in Crystalline Rock,|| *Rock Mech. Rock Eng.*, 43, 513-531 ((2010). Duchane, D and D. Brown, (2002) "Hot Dry Rock (HDR) Geothermal Energy Research and Development at Fenton Hill, New Mexico" *GHC (Geo-Heat Center) Bulletin*, December. 2002 , 13-19.
- [14] Fairhurst, C, & Carranza-torres, C. (2002). Closing the Circle- Some Comments on Design Procedures for Tunnel Supports in Rock," in *Proceedings of the University of Minnesota 50th Annual Geotechnical Conference (February 2002)*, J. F. Labuz and J. G. Bentler, Eds. Minneapolis: University of Minnesota, 2002. [available at www.itascacg.com go to 'About' and Fairhurst Files], 21-84.
- [15] Fairhurst, C. (1971). Fundamental Considerations Relating to the Strength of Rock. *Colloquium on Rock Fracture*, Ruhr University, Bochum, Germany, April 1971. (see <http://www.itascacg.com/about/ff.php>) Revised and published in *Report of the Workshop on Extreme Ground Motions at Yucca Mountain, August 23-25, 2004*, U.S. Geological Survey, USGS Open-File Report T. C. Hanks et al., Eds. Reston, Virginia: USGS, 2006., 2006-1277.

- [16] Geertsma, J, & De Klerk, F. (1969). A Rapid Method of Predicting Width and Extent of Hydraulic Induced Fractures. *J Pet Technol SPE-2458-PA*. <http://dx.doi.org/10.2118/2458-PA>, 21(12), 1571-1581.
- [17] Geyer, J. F, & Nemat-nasser, S. (1982). Experimental Investigation of Thermally induced Interacting Cracks in Brittle Solids *Int. J. Solids and Structures* , 18(4), 349-356.
- [18] Griffith, A. A. (1921). The Phenomena of Rupture and Flow in Solids *Phil. Trans. R. Soc. Lond. A* 1921,, 221, 163-198 doi:rsta.1921.0006
- [19] Griffith, A. A. (1924). Theory of Rupture. *Proc. First Int. Cong. Applied Mech* (eds Bionzo and Burgers). Delft: Technische Boekhandel and Drukkerij. 1924, 55-63.
- [20] Grünthal, G, & Wahlström, R. (2003). An Mw-Based Earthquake Catalogue for Central, Northern and Northwestern Europe using a Hierarchy of Magnitude Conversions. *J. Seismol.* 7, 507-531 (Available at http://seismohazard.gfzpotdam.de/projects/en/eq_cat/menue_e?q_cat_e.html)
- [21] Hoek, E, & Bieniawski, Z. T. (1966). Fracture Propagation Mechanism in Hard Rock," in *Proceedings of the First Congress of the International Society of Rock Mechanics*. Lisbon, September-October, J. G. Zeitlen, Ed. Lisbon: LNEC., 1, 243-249.
- [22] Hoek, E, & Brown, E. T. (1980). *Underground Excavations in Rock.*" Inst'n of Mining and Metallurgy (London) Revised 1982, , 164.
- [23] Howard, G. C, & Fast, C. R. (1970). *Hydraulic Fracturing*" SPE Monograph 2. Henry L.Doherty Series 203 pp. SPE 30402
- [24] Inglis, C. E. (1913). Stresses in a Plate Due to the Presence of Cracks and Sharp Corners," *Trans. Inst. Naval Arch.*, London, 55(1), , 219-141.
- [25] Jeffrey, R. G, et al. (2009). Measuring Hydraulic Fracture Growth in Naturally Fractured Rock. SPE 124919; SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, October 2009, 4-7.
- [26] Knott, J. F. (1973). *Fundamentals of fracture mechanics*, Wiley (0-47049-565-0)
- [27] National Research Council(2012). *Induced Seismicity Potential in Energy Technologies.*" Washington, DC: The National Academies Press, 2012. (300p.) View online at http://www.nap.edu/catalog.php?record_id=13355
- [28] Nocquet, J. M, & Calais, E. (2004). Geodetic Measurements of Crustal Deformation in the Western Mediterranean and Europe " *Pure Appl. Geophy.*, 161; , 661-668.
- [29] Nordgren, R. P. (1972). Propagation of a Vertical Hydraulic Fracture. *SPE J. SPE-3009-PA*. <http://dx.doi.org/10.2118/3009-PA>., 12(4), 306-314.
- [30] Peck, R. B. (1969). Advantages and limitations of the observational method in applied soil mechanics. *Geotechnique*, , 19(2), 171-187.

- [31] Perkins, T. K, & Kern, L. R. (1961). Widths of Hydraulic Fractures. *J Pet Technol SPE-89-PA*. <http://dx.doi.org/10.2118/89-PA.>, 13(9), 937-949.
- [32] Pettitt, W. S, Hazzard, J. F, Damjanac, B, Han, Y, Pierce, M, Katsaga, T, & Cundall, P. A. "Microseismic Imaging and Hydrofracture Numerical Simulations," in *Proceedings, 21st Canadian Rock Mechanics Symposium (Alberta, Canada, May 5-9, (2012).*
- [33] Pierce, M. (2011). "Discrete Fracture Network Simulation" DFN training session LOP (Large Open Pit). [ppt slides available on request. Itasca Consulting Group: www.itascacg.com]
- [34] Riahi, A, & Damjanac, B. (2013). "Numerical Study of Interaction between Hydraulic Fractures and Discrete Fracture Networks" *Proc. HF The International Conference for Effective and Sustainable Hydraulic Fracturing, Brisbane, May 20-22, 2013, 2013.*
- [35] Royal Society and Royal Academy of Engineering ((2012). Junep. "Shale Gas Extraction in the UK: a review of hydraulic fracturing" Issued: June 2012, DES2597] View report online at: royalsociety.org/policy/projects/shale-gas-extraction and raeng.org.uk/shale
- [36] Scotti, O, & Cornet, F. H. (1994). In-Situ Evidence for Fluid-Induced Aseismic Slip Events along Fault Zones. *Int. J. Rock Mech Min.Sci. &Geomech. Abstr. Control in Mines (1965)*. South African Institute of Mining and Metallurgy, Johannesburg, 606p, 31(4), 347-258.
- [37] Starfield, A. M, & Cundall, P. A. (1988). Towards a Methodology for Rock Mechanics Modelling" *Int. J. Rock Mech. Min. Sci.& Geomech. Abstr.* 25 (3) , 99-106.
- [38] Tester, J. F, et al. (2006). "The Future of Geothermal Energy"-Impact of Enhanced Geothermal
- [39] *Systems (EGS) on the United States in the 21st Century* MIT Press.
- [40] Wallis, J. D, Devito, J, & Diaz, E. (2012). "Digital Rock Physics- A New Approach to Shale Reservoir Evaluation" *Oilfield Technology, March 2012* [<http://www.ingrain-rocks.com/articles/a-new-approach-to-shale-reservoir-evaluation/>]
- [41] Zhang, X, & Jeffrey, R. G. (2008). "Re-initiation or termination of fluid-driven fractures at frictional bedding interfaces" *JGR, BO 8416*, doi:10.1029/2007JB005327,, 113

