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Chapter 15

Laboratory Studies to Investigate Subsurface Mechanics

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Abstract

Fracturing laboratory studies to support understanding of fracturing behavior in the field have been performed for more than six decades. These research studies have focused on various aspects of fracturing, including fracture orientation and borehole orientation with respect to the orientation of principal stresses, rock anisotropy, the effects of various types of discontinuities (also with respect to orientation), leak-off into the formation, fracturing fluid viscosity, and nontraditional methods. The studies have advanced in complexity and scale over the decades, with initial tests performed on very simple isotropic systems at the sub-15 cm scale, to very elaborate anisotropic natural and composed media at the near-meter scale. Studies have included laboratory-manufactured samples with known characteristics and natural samples with natural flaws. Although the potential experimental matrix of tests is very large and thus incompletely covered, the tests performed have provided much insight into subsurface fracturing behavior.

15.1 Introduction

Laboratory studies on the nature of fracturing applicable to hydrocarbon production or

enhanced geothermal systems have been performed over six decades. Most of these studies are applicable to hydraulic fracturing with the focus on improving the understanding of the fracturing process to enhance hydrocarbon recovery. This chapter walks through the literature of laboratory fracture experiments conducted over the last six decades. A good number of studies are reviewed in this chapter, but the intention is not to include every study.

In the laboratory, tests have been performed to investigate numerous subsurface conditions to gain understanding on many of the conditions of interest in the subsurface, including homogeneous media using gelatins, hydrostone, cement, natural samples, polymethyl methacrylate; anisotropic media using gelatins, hydrostones, cements, natural samples; media with specific weaknesses, fractures, and flaws, various stress conditions, and various borehole angles with respect to principal stresses. Sample sizes range from centimeter-scale cores under hydrostatic and triaxial stresses in some earlier tests to nearly meter-scale blocks under true-triaxial stresses in more recent tests. Applied stresses range from those implemented utilizing rubber bands to in-situ reservoir stresses and far beyond. Viscous fluids including slickwater and non-water fluids like supercritical CO₂ (scCO₂) and liquid nitrogen have been investigated to a limited extent. Because the experimental matrix for full understanding and testing each parameter to capture the possible fracturing conditions and fluids is very large, it is of course incomplete.

In a long-view looking back on fracture testing, Warpinski stated “When rocks are fairly simple, the fractures behave the way we expect them to. We did a fairly good job of

predicting how they would propagate. Conversely, when the geology gets very complicated, you have lots of natural fractures and the hydraulic fracturing became very unpredictable and complicated.” (King, 2014)

In evaluating the literature for the laboratory studies on hydraulic fracturing, de Pater, et al. (1994) stated “We conclude from the literature survey that very few valid tests have been conducted. Moreover, many tests have been performed to study complicated situations without properly representing the conditions for simple propagation. It might be possible that such tests yielded some correct conclusions; e.g., regarding fracture containment. The possibility exists that the results of these experiments bear no worthwhile relation to field-size hydraulic fractures.” In this chapter, laboratory tests will be reviewed more broadly and although many of the covered studies do not meet dePater et al. (1994) standards for validity, some truths of fracturing have been revealed and recorded.

In this chapter, the studies summarized are presented chronologically. With the number of independent variables that can be investigated, the studies are difficult to group. A header is provided for each study, however these headers are often oversimplified. The final section of the chapter cross-cuts through the studies, attempting to generalize some of the results. The terms “horizontal” and “vertical” are used from the perspective of vertical wellbores and generally considering the vertical lithostatic stress as the maximum principal stress.

15.2 Laboratory Studies of Fracturing

15.2.1 Homogeneous medium and Anisotropic medium

In a very early laboratory fracturing demonstration, Hubbert and Willis (1957) examined hydraulic fracturing in quite an elegant way. A hardened 12% gelatin solution was used as the medium and it was contained in a 2-gallon polyethylene bottle with the top cut off. Using appropriate glass tubing, the gelatin was hardened with a well in the center. Stresses were applied by either squeezing the container to make its circular cross section elliptical causing one horizontal stress to exceed the other, or by wrapping a stretched rubber tubing around the plastic bottle to stretch it vertically minimizing the vertical stress. Plaster of paris was injected into the well as the fracturing fluid resulting in a solid impression of the resulting fracture.

With the horizontal stresses uneven and smaller than the vertical stress, the expected vertical bi-wing penny-shaped fracture formed and hardened, allowing its removal and quantification. Wrapping the polyethylene bottle with a rubber tube following hardening of the gelatin caused a reduction in the magnitude of the vertical stress relative to the horizontal stresses. When fracturing was performed, a horizontal fracture perpendicular to the vertical borehole formed. To investigate anisotropy, stratified layers of alternating weak and strong gelatin were poured. As expected, this resulted in a horizontal fracture. A vertical fracture an experiment considering anisotropy is shown in Figure 15.1 identifying the importance of boundaries and geological layering.

[Insert Figure 15.1 here]

15.2.2 Heterogeneous Flawed Media

Lamont and Jessen (1963) examined the effect of an existing fracture or joint plane on hydraulic fracture propagation. 106 model systems were investigated using as many as six rock types, having dimensions of 1.5 x 3.5 x 4 to 8 in. The pre-fractures were either mated together, filled with a layer of sand, and in some cases large enough to represent vugs. In 70 tests, the hydraulic fracture extended across the existing fracture. It was noted that hydraulic fractures tended to alter direction near the discontinuity so that the plane of the hydraulic fracture intersected the plane of the existing fracture at right angles. The rates of fracturing were considerably greater than would occur in the field.

15.2.3 Homogeneous medium

Haimson and Fairhurst (1967) presented the criteria for fracture initiation in porous-permeable materials by considering all the possible stress fields around the wellbore. About 200 fracturing tests were performed on hydrostone (gypsum cement) cubical and cylindrical samples with a characteristic dimension of about 5 inches. In these tests, the effect of hydraulic fracturing fluids viscosity (7 oil viscosities), rock strength (varied by using three hydrostone compositions), and stress orientations were investigated. In these tests, all fractures were tensile and there was no shear fractures. Vertical fractures were always oriented in a direction perpendicular to the smaller horizontal compressive load. Fractures always originated at the borehole boundary in the pressurized zone and propagated outwards. “Horizontal” fractures, perpendicular to the borehole, usually

occurred near the bottom end of the pressurized hole.

In a series of tests performed at constant pressurizing rate, the critical breakdown pressures ranged between theoretical breakdown pressures for impermeable and permeable rock. This was explained by the formation of a plastic region near the borehole. Larger boreholes required lower breakdown pressures, and lower pressurization rates required lower breakdown pressures.

15.2.4 Homogeneous Flawed Medium, Joint Effects

Daneshy (1974) studied the effect of the size of open and filled material flaws on hydraulic fracturing. Granite blocks 6 x 6 x 10 in. were used. The blocks contained natural fractures having remaining tensile and shear strengths, and the ability to flow water. Small material flaws (compared with the hydraulic fracture size) do not change the overall orientation of the hydraulic fracture. The hydraulic fracture can encircle such small defects, or if not, the influence of these flaws is local. Large material flaws, however, were observed to drastically change fracture orientation.

15.2.5 Homogeneous and flawed media

Zoback et al. (1977) performed tests on three types of rock to evaluate the effect of fluid penetration into the rock prior to fracturing and the influence of pre-existing cracks on hydraulic fracturing operations. The rock types included Ruhr sandstone (a fine-grained, massive, weakly-bedded carboniferous sandstone from the Ruhr area of Germany),

Weber sandstone (a very well-indurated Permian sandstone) used in triaxial tests, and a low-porosity South African gabbro was used in tests with no external load.

Three types of tests were performed. Tests were performed on 6 cm long, 3 cm diameter triaxially loaded specimens pre-loaded by a constant axial stress of about 40MPa, by pressurizing a 2-3 mm diameter axial borehole. Larger-scale tests were performed on 12cm cubical samples having a 1.05 cm diameter borehole through the center of the specimen perpendicular to the loading axis. These 2.5 MPa uniaxially-loaded blocks were pressurized over 6.5cm length of the borehole. This setup was used for pre-fractured samples as well.

The rate of borehole pressurization strongly influenced breakdown pressures, with the breakdown pressure increasing with increasing pressurization rate, as also seen by (Haimson and Fairhurst, 1969). When the effect of fluid penetration is negligible, the pressure at which hydraulic fractures initiate (and thus tensile strength) is independent of the rate of borehole pressurization. In tests performed on pre-fractured samples where the fracture was oriented such that the applied uniaxial stress would close the fracture, fractures could be formed and propagated perpendicular to the pre-fracture if a viscous fracturing fluid was used.

15.2.6 Homogeneous medium, varying stresses

Lockner and Byerlee (1977) performed hydraulic fracturing experiments on cylindrical 3 inch diameter Weber sandstone samples at very high stress (4 kbar axial, 1 kbar radial)

and showed that the resulting fracture could be followed using acoustic emissions. A further series of tests was performed using 1-inch diameter cylindrical samples at various differential stresses and injection rates. The results of these tests led to the conclusion that either shear or tensile failure could be achieved under the proper combination of injection rate and differential stress.

15.2.7 Homogeneous and heterogeneous media

Blanton (1982) performed hydraulic fracturing experiments on naturally fractured blocks of Devonian shale. Additionally, fracturing tests were performed on blocks of hydrostone, which could be tested in a more uniform manner. In these tests, the angle of approach of the hydraulic fracture to an existing fracture was varied systematically. Experiments in both the Devonian shale and hydrostone indicate that the hydraulic fracture morphology is strongly affected by the natural fractures. The hydraulic fractures tended to cross pre-existing fractures only under high differential stresses between horizontal stress components and high angles of approach. At intermediate values of either of these, natural fractures tended to open or divert fracturing fluid or arrest hydraulic fracture propagation.

15.2.8 Anisotropic Medium, Joint Effects

Teufel and Clark (1984) performed numerous hydraulic fracturing laboratory experiments under uniaxial stress on monolithologic and dilithologic sandstone assemblies. The assemblies were composed of three layers of 20 cm x 20 cm x 8 cm blocks of sandstones having the same (monolithologic) or different properties

(dilithologic). Different polishing steps were taken to evaluate the effect of friction between layers on arresting vertical-traversing fractures. Weak interfacial shear strength between the layers (smooth surfaces) required an increase in the axial stress needed for the fracture to continue. The authors concluded that a weaker interfacial layer under greater horizontal stress than the fracturing layer will tend to arrest fracture growth.

15.2.9 Homogeneous Medium, Effect of Borehole Angle

El Rabaa (1989) present results from 22 fracturing tests in 6" x 12" x 18" hydrostone blocks. The tests were performed to evaluate the effect of the length of a spirally perforated or open borehole region relative to the diameter, and the effect of borehole angular offset from σ_{hmin} . For long perforated or open regions (length > 4 x diameter) multiple fractures can be created, with one fracture eventually becoming predominant. For shorter regions, one fracture is likely to occur. Perforations more closely spaced than 1 diameter are likely to result in a connected fracture. An "H-shape" fracture (Figure 15.2) can occur in open holes having a length exceeding 4 times the diameter oriented parallel to the minimum principal stress.

The authors presented their results schematically as shown in Figures 15.2 and 15.3. In Figure 15.2, for a horizontal hole drilled in the minimum principal stress direction the effect of perforated or open borehole length is shown on the horizontal axis. Short perforated lengths result in single fractures, whereas long perforated lengths result in a number of fractures, with one becoming dominant. The open hole allowed a fracture that paralleled the borehole which connected two perpendicular fractures that formed at the

ends of the open hole. As the deviation angle increases, induced fractures tend to follow the borehole in the near-borehole region, and then transition to fractures propagating in the maximum horizontal stress direction. The rock in the transition zone tends to have significant roughness, which has implications for shear-slip propping. Fractures in boreholes drilled in the direction of the maximum principal stress tend to parallel the borehole as in vertical well fracturing.

[Insert Figure 15.2 here]

[Insert Figure 15.3 here]

15.2.10 Homogeneous Isotropic Medium

de Pater et al. (1994) derived a set of five dimensionless groups to scale planar fracture propagation (“universal scaling laws”) and provided an analysis of numerous reported laboratory tests on hydraulic fracturing. Based on these scaling laws, the authors concluded that for laboratory tests at in-situ stress, low fracture toughness and low permeability media should be used, with very high fracturing fluid viscosity to reduce the influence of toughness and to compensate for the low injection rate in laboratory models. Based on their evaluation of the numerous laboratory fracturing tests and based on their derivations, it was concluded that most tests neglected scaling and stability of fracture propagation, thus the information gained from these tests is not likely to relate to hydraulic fracturing in the field. The authors point out that studying crack propagation in real rock may be useful in terms of material science, but simplification is required to allow for repeatable measurements.

The authors performed tests in 10 cm transparent PMMA blocks, and 30 cm biaxially and triaxially loaded cement blocks, and their results compare adequately to their scaling. In their tests pressure strokes were applied causing growth rings on the fracture surfaces, which allowed measurement of the radius of the fractures. Linear elastic material behavior was thought to adequately describe the fracture propagation in their tests.

15.2.11 Homogeneous Medium, Borehole Angle

Abass et al. (1996) performed hydraulic fracturing tests in 6 x6 x10 in. hydrostone blocks with borehole angle ranging from parallel to the maximum principal strength (0 degrees) to parallel to the minimum principal strength (90 degrees). Their results are similar to those of El Rabaa (1989) however a few additional details are flushed out. For the case of the borehole perpendicular to the maximum principal stress direction, these authors also showed a “T-shaped” fracture (similar to the “H-shaped” fracture observed by El Rabaa (1989)) with an axis-parallel fracture extending about one wellbore diameter from the borehole, and a wellbore-perpendicular fracture consuming most of the energy and fracturing fluid. Fracture initiation pressure was also evaluated with respect to the borehole angle. Boreholes aligned with the maximum principal stress direction had the minimum fracture initiation pressure, with the pressure increasing as the borehole deviated from that orientation. In their measurements, there is almost a factor of 2 in the fracture initiation pressure between the borehole parallel to σ_{hmax} and one parallel to σ_{hmin} . The authors also noted that the pressure signal during the relief in pressure events can be used to estimate the fracture angle with respect to the borehole.

15.2.12 Uniform Medium with Discontinuities

Beugelsdijk et al. (2000) examined the effect of discontinuities in rock by forming 30 cm cement cubes that were then dehydrated to form dehydration cracks. The blocks were subjected to triaxial stress of 8, 10, and 20 MPa, and a viscous fracturing fluid (100 Pa·s) was used. At low flowrates, fluid leaked off into discontinuities hindering fracturing and lowering shear strength in the discontinuities. The authors concluded that initiating hydraulic fractures by increasing the flow rate in steps, a so-called step-rate procedure, will hamper hydraulic fracture initiation and result in an unfavorable conditions or complete leak-off. At high flowrate fracturing, the fracture propagated largely as expected, thus high flowrates tend to minimize the effect of discontinuities.

Discontinuities can affect fractures anywhere along the flow path, ultimately this may affect proppant transport as well.

15.2.13 Large Discontinuous Homogeneous Block, Effect of Joint Properties

Casas et al. (2005, 2006) performed a pair of laboratory hydraulic fracturing tests on a 0.76 m x 0.76 m x 0.91 m (high) block of Colton Sandstone having a permeability of about 0.19 mD. In spite of the sample size, the stresses were set to realistic stresses - $\sigma_v=35.9$ MPa, $\sigma_{hmax} = 29.0$ MPa, and $\sigma_{hmin} = 16.5$ MPa. Two large discontinuities (slots) were cut into the rock across the top and partially through the block. These were parallel to each other and at an angular offset from the principal stresses. One was filled with a stiff grout having rock-like properties, and the other was filled with low modulus epoxy. Tubes attached to pressure transducers were sealed in at a number of locations where the

fracture was anticipated to pass to attempt to identify the time the fracture passed the location. At different times, fracturing was performed in two perpendicular directions, first by setting the stresses as stated, and then by reversing the horizontal stresses without releasing the vertical stress. A high-viscosity silicone fluid (586 Pa·s, akin to peanut butter) was used for fracturing.

Fracturing results were compared to scaling analysis given by de Pater et al. (1994). Higher pressures than predicted were required to fracture the sandstone in both tests. Of particular interest is that one of these experiments provided data that may validate the concept of a rarified region at the fracture tip of a moving fracture. For the pressure transducers that intersected the fracture, pressure decreases were observed that preceded the expected pressure increases when the fracturing fluid passed the monitored location. Both tests produced planar fractures that propagated in the in the directions of the larger two principal stresses. The fracture crossed the stiff rock-like grout discontinuity, which had a higher modulus than the sandstone. The hydraulic fracture was arrested however at the epoxy discontinuity (low modulus) inclusion. The authors note that clays and some sandstones may behave similarly to the epoxy in arresting a fracture. The fracture tip propagation velocity was on the order of those expected in the field.

15.2.14 Large Block Homogeneous, and Anisotropic Media

Athavale and Miskimins (2008) fractured one cement block and a layered sandstone/cement(s)/epoxy/polyurethane block, both having dimensions of 11" x 11" x 15". Applied stresses were 1500, 2500, and 3500 psi. Two vertical fracturing experiments

were performed in each block, controlled by changing the direction of σ_{hmax} as was done by Casas et al. (2006). Scaling relationships by dePater et al. (1994) and (Bunger et al., 2005) were considered in the experiment design, and the fracturing time (~5 – 8 minutes) and fracturing fluid viscosity (100,000cP ~ somewhere between ketchup and lard) were specified from these analysis. In fracturing one direction of the cement block, a penny-shaped bi-wing fracture was created. However in the second fracturing test in the orthogonal direction, a single wing fracture was generated. It was noted that the borehole was not notched, and that notching the borehole may have produced a bi-wing fracture.

The results of fracturing in the layered block are as complex as the block itself. From top to bottom, the block composition includes layers of varying thicknesses of Lyons sandstone, polyurethane adhesive, 15.8 pounds per gallon (ppg) cement, Lyons sandstone, an unbonded surface, 16.2 ppg cement, Lyon sandstone, epoxy, and 15.8 ppg cement. In one test a fracture formed in the expected direction above the unbonded interface between sandstone and cement. The fracturing fluid spread in this unbonded layer, and two fractures formed beneath this layer. One of these fractures continued until it met with the low modulus epoxy layer where it was arrested. In the perpendicular fracturing test, a small single-winged fracture formed in one direction. Interestingly, the fracturing fluid wandered in the unbonded plane during both fracture tests, however did not leak out on the sides that experienced limited fracturing. Stresses on this block were 1700, 2700, and 4200 psi.

15.2.15 Heterogeneous Flawed Media (desiccated cement)

Zhou et al. (2010) investigated the effect of natural flaws created using desiccation fractures on hydraulic fractures. The desiccation fractures were created by placing 30 cm cubic cement blocks in an oven at 400C for 3 hours to cause dehydration followed by air-cooling. Consistent with Blanton (1982), the authors concluded that at intermediate and low differences between the principal horizontal stresses, and at low angles of approach, pre-existing fractures tend either to open and divert fracturing fluid or arrest propagation of the hydraulic fracture.

Zhou et al. (2010) also described fracture morphology for varying stress differentials. Experiments were performed using the cement blocks over a range of K_h values from 1 to

10, where $K_h = \frac{\sigma_{hmax} - \sigma_{hmin}}{\sigma_{hmin}}$. For K_h values greater than 2.5, a vertical main fracture

formed with multiple subfractures. For K_h values between 1.5 and 2.5, the hydraulic fracture tends to be a partly vertical dominating fracture (one wing) with random branches. When K_h is below 1.5, the fracture geometry is radial random fractures.

15.2.16 Heterogeneous Flawed Media, Natural Fort Hays Limestone

Frash et al., (2015) performed a hydraulic fracturing experiment on a block of Fort Hays Limestone, part of the Niobrara Shale Formation. The 30 cm cubic sample contained natural bedding planes - one of which was poorly cemented - and the borehole was oriented perpendicularly to these features. The sample was placed under triaxial stress and the fracturing was monitored with pressure and volume measurements in addition to

acoustic emissions. The horizontal stresses applied were 5 and 10 MPa and the vertical stress was 13 MPa. The fracturing fluid was a black epoxy having a 90-minute working time. After the test, the block was sectioned and the location and characteristics of the fractures were identified by the presence of the black epoxy. The test resulted in a complex fracture network composed of a vertical tensile penny shaped fracture, a shear activation along a pre-existing discontinuity, and dilation of two bedding plane fractures. Fracture stranding and complex fracturing zones were observed in the experiment suggesting an increased volume of stimulated rock as compared to simple singular fractures. The authors suggest that a three-dimensional fracture propagation criterion may be necessary to model multiple fracture interaction and pre-existing discontinuity activation.

15.2.17 Homogeneous Media, Water-Blasting

Huang et al. (2014) investigated “water blasting” and hydraulic fracturing following water blasting. Water blasting consists of setting off a small explosion in a water-saturated well. The effect of the explosion is to cause numerous micro- and small fractures to form around the borehole. Experiments were performed in 30 cm cubic concrete specimen, with $\sigma_v = 12.31$ MPa, $\sigma_{hmin} = 3.08$ MPa, and $\sigma_{hmax} = 7.69$ MPa. Acoustic emissions were used to monitor the tests in addition to pressure monitoring. Acoustic emissions were frequent and of medium intensity when loading the block, very strong upon the water blasting event, and weaker following that. With hydraulic fracturing following the water blasting, the acoustic emissions were frequent and medium intensity, and during unloading, acoustic emissions were frequent and low intensity.

Water blasting induced small and microfractures in a bulb shape around the borehole. Subsequent hydraulic fracturing occurred along several planes and followed several initial smaller fractures, resulting in a complex fracture pattern. However, it is not clear how such a pattern would scale to the field. For comparison, hydraulic fracturing without water blasting occurred as expected with planar fractures propagating in the direction of the maximum principal stress, however a radial fractures occurred at the toe of the borehole, “blowing off” the bottom of the borehole. Hydraulic fracturing pressure and subsequent peak injection pressure for the water-blasted samples greatly exceeded those values for the hydraulic fractured cases. The increase in these values was attributed to water leakoff and loss. The water-blasted hydraulic fractured samples had numerous fractures and low integrity at the end of the tests. The hydraulic fractured blocks on the other hand had few fractures and good integrity at the end of the tests.

15.2.18 Uniform Media, Cryogenic Fracturing

Cha et al. (2014) and Alqatahni et al. (2016) investigated cryogenic fracturing in 8-inch cement cubes. In their initial evaluation, room temperature blocks were semi-submerged in liquid nitrogen (temperature = -196°C) to induce a sharp thermal gradient, thus a sharp stress gradient. Fractures were observed at the point of submersion, and X-ray CT scanning showed that the fractures extended substantially into the block. Because of the direction of the stress gradient, some shear likely occurred. Experimental setups and procedures were developed to conduct cryogenic fracturing tests from boreholes in 20 cm cubical samples with and without confining stress, including cryogen transport, measurements, and fracture characterization. Active acoustic signals and pressure decay

were used to characterize the flow properties of natural and induced fractures before and after the experiments. When cryogenic tests were performed without confining stress, cracks formed in the experimental blocks and altered the rock properties. Repeated stimulation resulted in enhanced fracturing by both creating new cracks as well as widening the existing cracks. Cryogenic fracturing test results from unstressed weak concrete and sandstone showed that fracture generation depends on material properties. Water in the formation may play a role because it initially expands as it freezes competing with contraction from cryogenic cooling. For cryogenic stimulation, rapid cooling is desired to achieve high thermal gradient.

Alqatahni et al. (2016) extended the work by Cha et al (2014) and in samples under triaxial stress showed permeability increases with liquid nitrogen treatments, in addition to lowering breakdown pressure following treatment with liquid nitrogen.

15.2.19 Homogeneous Medium, Different Fracturing Fluid Viscosities

Using 170 mm anisotropic cubes all cut similarly, Chen et al. (2015) investigated hydraulic fracturing in Kurokami-jima granite, a coarse-grained biotite granite from Yamaguchi Prefecture, Japan using scCO₂, water, and hydraulic oil at 10 mL/minute. The tests were performed under 3, 6, and 4 MPa triaxial stress. The fractures were filled with fluorescent epoxy, and thin sections were cut from the blocks. Microscopy was used to examine the fractures. The lowest viscosity scCO₂ created the most tortuous fracture paths at the scale examined, in addition to the most branching pathways. The low viscosity scCO₂ was able to move around grains, whereas the water and oil tended to

fracture through grains. The authors point out that the lack of a planar surface in any fracture means that there will be some shear on some scale in a tensile fracture.

15.2.20 Heterogeneous Large Block Samples, Effect of Slickwater and Gel

Wang et al. (2015) discuss the results of six large-scale (762mm x 762 mm x 914mm(height)) laboratory fracturing tests on two types of shale, and mention the results of three large-scale laboratory fracturing tests on a tight sandstone, a fractured sandstone, and a coal sample. In the shales, two fracturing fluids were tested, slickwater (viscosity = 5 mPa·s) and a crosslinked gel (viscosity = 150 mPa·s). Two different stress regimes (13, 13, 10 MPa and 24, 24, 10 MPa), and three flow rates were used. Under low horizontal plane stress difference (3MPa), the natural fracture system was opened by slickwater more easily and no main fracture formed. With cross-linked gel under the same conditions, a simple fracture formed, and opened part of the natural fractures at the same time. Slickwater at higher horizontal stress difference (14MPa), formed a new fracture perpendicular to the minimum horizontal stress direction. Slickwater fluid leak-off into an open discontinuity hampered the extension of the hydraulic fracture. Under the same stress regime, cross-link gel formed only a single main hydraulic fracture without any discontinuity connections. Figure 15.4 shows a matrix of observations. Low viscosity fracturing fluid (left side of Figure 15.4) tends to activate natural fractures, and under high differential stress tends to form hydraulic fractures. Higher viscosity cross-linked gel (right side of Figure 15.4) tended to generate hydraulic fractures

[Insert Figure 15.4 here]

15.2.21 Direct Observation of Fracturing in Small Samples

Hyman et al. (2016) used X-ray videography to observe hydraulic fracturing in 2.5 cm diameter samples under constant radial confining pressure and axial stress. Five samples including three acrylic samples, one shale, and one cement were fractured by applying fluid pressure to a circular notch in the sample top. A gasket was used to localize the flow. The method allows for injection of proppant, however in the demonstration test, no proppant was taken into the fracture. This method has applicability for the study of proppant transport, hydraulic fracture toughness, and hydraulic fracture permeability as a function of confining stresses.

15.2.22 Heterogeneous Media (Shale and Sandstone), Water, Liquid CO₂, and Supercritical CO₂

Zhang et al. (2017) compared hydraulic fracturing using water, liquid CO₂, and supercritical CO₂. In each test, 3 x 20 cm cubical shale samples were fractured. One sandstone cube was fractured with water and another with scCO₂. In addition, four shale samples were fractured using scCO₂ while varying horizontal stress ratios. The brittle shale cubes were from an outcrop of the Lower Silurian Longmaxi Formation in the Sichuan basin, China, having about 3.8% plagioclase, 11.7% calcite, 40.2% quartz, and 15.1% clay minerals. Hydraulic fracturing was accomplished through a 15 mm diameter hole perpendicular to bedding planes drilled 110 mm in length into the center of each cube. The injection rate of all the fluids was the same (30 mL/min). Along with pressure and acoustic emissions, X-ray CT and digital radiography were used to monitor the

fracturing or examine the resulting fractured system. Because of the variability of the shale, tests were repeated three times to compare the breakdown pressure for water, lCO₂, and scCO₂ fracturing. Interestingly, the breakdown pressure decreased significantly as the viscosity of the fracturing fluid decreased. The breakdown pressure decreased by a factor of 2 from water to lCO₂ and was reduced an additional 15% upon the use of scCO₂. Acoustic emission monitoring showed many more events for the scCO₂ fracturing than the water fracturing prior to the major fracturing event, indicating the formation of a large number of smaller fractures with the less viscous scCO₂.

The fracture patterns from each of the fracturing liquids were different as well. With water (hydraulic fracturing), a planar fracture was formed. With lCO₂, a more complex fracturing pattern was formed. The complexity of the fracturing pattern increased even more for the scCO₂ with irregular and multiple cracks that tended to connect with the natural bedding. scCO₂-induced fractures have larger widths and more crack volume than the hydraulic fractures. With scCO₂ fracturing, the acoustic emission energy ratio data showed sharp peaks in the data several times before the specimen ruptured. With respect to the ratio in horizontal stresses with a low differential stress, fractures initiated in weak locations near the borehole and propagated along paths of weakness. As the stress difference increases, the orientation of the fractures trends towards propagation in the maximum principal stress direction, however the fracture network remains complex and includes bedding planes. This is consistent with Zhou et al. (2010) and shows some of the complexity observed by Athavale and Miskimins (2008).

15.3 Discussion

Over the last six decades, many laboratory studies related to subsurface fracturing have been performed. Because the experimental matrix needed to cover all the expected conditions that could be encountered in subsurface fracturing is so large, the experiments covering that matrix are sparsely distributed. In spite of that, the tests that have been performed have yielded valuable information. One clear observation of laboratory studies is they have evolved over the years, and the topics of study and tests have increased in complexity. Tests have evolved from the small samples from which much has been learned, to the desire for larger scale tests (Haimson, 1981), to the realization of meter-scale tests (Wang et al., 2015). Media as simple as gelatin and hydrostone and as complex as natural shale or anisotropic assemblies of rock have been examined. Fracturing fluids and methods have evolved along with the laboratory tests. In spite of the sparsity in coverage of the experimental matrix, some take home messages are apparent and discussed below along with references illustrating the message.

15.3.1 Stress

The directions and relative magnitudes of stress exert the strongest control on the direction and morphology of induced fractures in geologic media. Fractures will tend to open in the direction of least resistance (minimum principal stress), and propagate perpendicular to that direction (e.g. Hubbert and Willis, 1957, Haimson and Fairhurst, 1967, Zoback et al., 1977 and others). The effects of the relative magnitude of stresses have also been investigated, showing the possibility of shear or tensile fractures

depending on the relative difference between stresses (Lockner and Byerlee, 1977), and the relative difference between stresses may also induce different fracture patterns (Zhou et al., 2010, Zhang et al., 2017). High stress differentials tend to result in a main fracture formed with multiple subfractures. Medium differentials tend to result in the hydraulic fracture tending to be a partly vertical dominating fracture (one wing) with random branches, and low differentials resulted in radial random net-fractures. Larger borehole diameters result in lower critical breakdown pressures (Haimson and Fairhurst, 1969). (de Pater et al., 1994) concluded that linear elastic material behavior was adequate to describe fracturing in their tests.

In large-scale tests considering the scaling laws described by dePater et al. (1994), Athavale et al. (2008) and coworkers fractured a large laboratory cement block in two perpendicular directions. One test generated a penny-shaped bi-wing fracture, however the test in the perpendicular direction a single wing fracture was formed. This showed that even under fairly ideal conditions, the expected case is not always generated. Hyman and coworkers (2016) attempted to observe fracture formation directly using X-ray radiography. In their apparatus, the fracture is formed from a notch carved into the top of the sample providing a stress concentration location.

15.3.2 Anisotropy

Anisotropy has been investigated by many researchers (e.g. Teufel and Clark, 1984, Athavale and Miskimins, 2008, Hubbert and Willis, 1957). The additional complexity of varying properties was shown in very visual tests (Hubbert and Willis, 1957) using a very

simple setup and a layered gelatin medium. Figure 15.1 shows some of these complexities from this very simple system including fracturing fluid penetrating the interfaces between layers and bi-wing fractures in some layers and single wing in others. Fracturing layers of sandstone blocks with different moduli under uniaxial stress showed that frictional force between layers is important as to whether a fracture will continue between the layers (Teufel and Clark, 1984). Below a limiting combination of low normal stress or low frictional characteristics resulted in fracture arrest at the boundary between layers. In the very complex system investigated by Athavale and coworkers (2008), a number of behaviors were observed. Fracturing fluid flowed in a “wandering” pattern in the unbonded interface between sandstone and cement resulting in a very different distribution of fracturing fluid than expected, and more fractures in the block and at different locations than from a simple pressurized borehole. Fractures perpendicular to this layer formed from various locations in the unbonded joint (more in *Discontinuities* section below).

15.3.3 Borehole Angle

Two studies investigating the angle between the borehole and the orientation of the principal horizontal stresses were considered (El Rabaa, 1989, Abass et al., 1996). This is very important, as it is often difficult to know the directions of the principal stresses with certainty. Boreholes that are parallel to the maximum horizontal stress direction give fractures parallel to the borehole and fracture at the lowest breakdown pressures. As the angle of the borehole increases with respect to the maximum principal stress, fractures tend to start parallel to the borehole and turn towards the direction of the maximum

principal stress. A number of fractures may initiate, with one eventually taking the majority of the fluid. In the case of the borehole being perpendicular to the maximum principal stress, a short open or perforated region will provide a fracture perpendicular to the borehole at a significantly higher pressure than for the parallel case. A longer perforated or open hole may result in a short-extent borehole-parallel fracture which will intersect borehole-perpendicular fractures. Away from the near-wellbore region, a borehole-perpendicular fracture will form and take the fracturing fluid.

15.3.4 Discontinuities

Many researchers have addressed discontinuities, as these are ubiquitous in the subsurface. In fractured sandstone with the fracture parallel to the minimum principal stress, Zoback et al. (1977) showed that fractures could be formed in the direction perpendicular to the initial fracture if the fracturing fluid were viscous enough. Daneshy (1974) showed that small discontinuities relative to the induced fracture do not significantly affect the direction of the fracture.

Blanton (1982) systematically investigated the angle of approach of a hydraulic fracture to an existing fracture. Experiments performed in both the Devonian shale and hydrostone indicate that the hydraulic fracture morphology is strongly affected by the natural fractures. The hydraulic fractures tended to cross pre-existing fractures only under high differential between horizontal stress components and high angles of approach. At intermediate values of either of these, natural fractures tended to open or divert fracturing

fluid or arrest hydraulic fracture propagation. Zhou et al. (2010) performed similar tests and their conclusions are in line with Blanton (1982).

Lamont and Jessen (1963) showed that under many conditions, fractures will cross discontinuities, and they typically adjust to cross them perpendicular to the direction of the discontinuity. Teufel and Clark (1984) showed that adequate frictional forces are required to allow the fracture to cross the discontinuity. Casas and coworkers (2006) showed that fractures would continue through a grouted high modulus discontinuity, whereas they would be arrested at a low modulus epoxy discontinuity. The authors pointed to conditions in sandstone and clays where the clay might arrest a fracture. Athavale et al. (2008) showed the impact of an unbonded interface taking up the fracturing fluid and resulting in fractures in unexpected locations in the direction of the maximum principal stresses.

Beugelsdijk et al. (2000) concluded that approaching discontinuities with an increasing step-rate procedure could enhance the impact of the discontinuity, and that high-flowrate fracturing resulted in fractures in the expected directions. They expressed the concern that proppant transport will be affected by discontinuities as well.

15.3.5 Permeability and Fracturing Fluid Viscosity

The uptake of fracturing fluid by the medium is impacted by the medium permeability, injection pressure, and the fracturing fluid viscosity. The invasion of fracturing fluid into the medium reduces the breakdown pressure (Hubbert and Willis, 1957). Both Zoback et

al. (1977) and Haimson and Fairhurst (1969) show data to support this from experiments performed using different viscosity fluids and different pressurization rates. Zhang et al. (2017) investigated the use of water, liquid CO₂, and scCO₂ as fracturing fluids, fracturing multiple cubes of brittle shale. The breakdown pressure decreased by a factor of 2 from water to liquid CO₂ and by another 15% for scCO₂ - in order of their declining viscosities. Fracture morphology became more complex as the viscosity of the fracturing fluid decreased. Comparing fractures generated using hydraulic oil, water and scCO₂ in granite at the microscale, Chen et al. (2015) found that fractures formed using hydraulic oil and water tended to go through grains, whereas fractures formed using the less viscous scCO₂ tended to go around grains. The fractures induced by the scCO₂ were the most tortuous and branched (on the microscale). At the large laboratory scale, Wang et al (2015) compared fracturing using slickwater and gel in shale samples under a variety of conditions. The two fracturing fluids resulted in different fracturing behaviors. Slickwater under low differential horizontal stress opened the natural fracture system and did not form a main fracture. With the cross-linked gel, however a simple fracture was formed in addition to some opening of the natural fracture system. This is conceptually in agreement with Zoback et al. (1977). Higher horizontal stress differential resulted in a simple fracture with slickwater. Slickwater fractures were more easily hampered by discontinuities.

15.3.6 Different technologies

Though not a comprehensive study of fracturing techniques that are not purely hydraulic, two other stimulation methods were mentioned here: water blasting, and cryofracturing.

Both of these concepts can initiate fractures differently than hydraulic fracturing and the initial fracture location may be different as well. Because these studies were limited in extent, many questions remain, including scaling to the field.

In water-blasting a small explosion is carried out in the wellbore to initiate fractures prior to hydraulic fracturing. Contrary to intuition, in the experiments by Huang et al. (2014) the subsequent hydraulic fracturing required much higher breakdown pressure and peak injection pressure than the nonwater-blasted samples. This increase in pressure was attributed to enhanced leakoff.

The use of extreme thermal gradients by applying cryogenic fluids was investigated by Cha et al. (2014). In this method, liquid nitrogen was injected into samples causing the near-wellbore rock to contract. Results indicate that the permeability of the samples increased with the number of treatments, and that in some cases shear may occur.

15.3.7 Sample size

Samples sizes in the tests described in this chapter range from centimeter-scale to meter scale. All sample properties affect the measurements and data interpretation. Small preserved samples may represent the actual properties of the rock to be fractured well, however contain artifacts from unloading, machining, exposure, and reloading. Large samples are often manufactured in the lab or extracted from outcrops where the rock has weathered, and are also unloaded and machined. From the upscaling perspective large block tests exhibit better similarity to field cases. Measurements on small preserved core

samples while applying true triaxial stress and scaled test parameters on the other hand, will be the most suitable to match the relevant physics realistically. Samples composed of artificial materials are useful to test models, however, the real rock formation behavior will deviate from these artificial materials behavior due to the differences material properties. The sample material and size need to be selected to address the purpose of the data collection.

15.4 Conclusions

Laboratory studies into fracturing to support understanding of subsurface stimulation have provided important insights into the behavior of fluids and rocks during fracturing. The range of possible studies is extremely large, and the studies performed to date have covered many of the important questions.

- Stress is the overriding control of fracturing, and because it typically cannot be controlled, it must be understood and worked with. The relative differences in the principal stresses control the resulting fracture orientation and morphology. Low stress differentials result in fractures that may follow existing rock weaknesses, whereas high stress differentials may result in simple fractures opening against the minimum principal stress and propagating perpendicular to that.
- The borehole angle with respect to the stresses strongly affects the behavior of fracturing with boreholes parallel to the maximum principal stress providing fractures parallel to that borehole and at low breakdown pressures, and boreholes perpendicular to the maximum principal stress provide very complex near-borehole fracturing at high breakdown pressure. Ultimately these situations result

in fractures perpendicular to the wellbore at a short distance away from the wellbore.

- High-viscosity fracturing fluids are less influenced by discontinuities than low viscosity fluids, and low viscosity fluids may provide more fracturing pathways with more fracture tortuosity.
- Discontinuities affect fracturing with less viscous fluids, more than viscous fluids. They also will affect proppant transport.
- Anisotropy can significantly alter fracturing, particularly if a layer is very weak, arresting the propagation of the fracture.
- Nontraditional methods are being investigated to improve fracturing technology. These can be more simply investigated in the lab than the field, however simulation is required to help understand behavior scaled to the field.

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Figure 15.1 Solidified plaster of paris fracturing fluid from a vertical fracturing experiment. (from Hubbert, 1956)

Figure 15.2. Top view of fractures induced at various wellbore deviation angles (from ElRabaa, 1989)

Figure 15.3 Principal findings of horizontal well fracturing. From ElRabaa (1989)

Figure 15.4. Matrix of results of fracturing large laboratory shale blocks. Effects of viscosity and differential horizontal stress. Low viscosity fracturing fluid (left) tends to activate natural fractures, and under high differential stress to form hydraulic fractures.

Higher viscosity cross-linked gel (right) tended to generate hydraulic fractures. (Wang et al., 2015)