Mechanics of Hydraulic Fracturing

Experiment, Model, and Monitoring

Edited by Xi Zhang • Bisheng Wu
Diansen Yang • Andrew Bunger

WILEY

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Foreword

For about 15 years until his retirement from the Commonwealth Scientific and Industrial Research Organization (CSIRO) in 2015, Rob Jeffrey led a group of scientists, technical officers, students, and academic visitors, all engaged in hydraulic fracturing research. Under Rob's direction, the CSIRO Hydraulic Fracturing (CSIRO HF) group, located in Melbourne, was a vibrant center, unique in the diversity of its activities that involved field testing, laboratory experiments, theoretical modeling, and numerical simulations. Many authors of this book have been associated with the CSIRO HF group, and their contributions are tributes to Rob's inspired leadership.

A permanent focus of the CSIRO HF group was to support the development of hydraulic fracturing as a means to precondition a rock mass for cave inducement of ore bodies and coal mine goafs. This application of hydraulic fracturing to mining was Rob's brainchild, an invention foreshadowed by the experience and expertise Rob gained in the United States while working, first, for the mining industry and later for the petroleum industry in research and development. His patented technique is now being used routinely in mines in several countries, including Australia, Chile, and Indonesia. Preconditioning by hydraulic fracturing has a profound economic impact on hard rock mines relying on block caving and on longwall coal mines, in some cases ensuring the economic viability of these operations.

One of Rob's outstanding achievements at CSIRO was the establishment of a world-class laboratory dedicated to hydraulic fracturing research with a large polyaxial cell as its centerpiece. A particular point of pride for Rob was the heavy-duty equipment used to conduct field tests. The lab was the birthplace of innovative experiments; some were conducted in glass or polymethyl methacrylate (PMMA) to enable visualization of the fracture evolution and photometric measurements of the aperture field to test computational models, while others explored the interaction of a hydraulic fracture with discontinuities or with a free surface, to cite a few. Although experiments in the field or in the lab are Rob's passion, he was always enthusiastically supportive of theoretical and computational work.

Some members of the former CSIRO HF group have moved to academic positions in China, Europe, and North America, but they remain engaged in hydraulic fracturing research. With this migration, the theoretical expertise and know-how for innovative experimental work gained in the CSIRO lab has been kept alive and further flourished. This is one of Rob's enduring legacies.

On a personal note, I am indebted to Rob for giving me the wonderful opportunity to work in his group. It was initiated at the ARMA Vail Symposium in 1999, when Rob asked me "would you be interested to spend some of your sabbatical in Melbourne ...." This led to a long-term collaboration and a chance to discover Australia on multiple occasions.

Emmanuel Detournay, University of Minnesota,
Minneapolis, USA

Preface

This volume of contributed chapters comes from the network of researchers working on mechanics of hydraulic fracturing in theory, experiments, and applications. Many of these contributors comprised the participants in a series of Hydraulic Fracturing Summits held from 2001 to 2015. These workshops provided a venue for lively debates and effective exchanges of ideas. The success of these Summits is attributed to Rob Jeffrey and Emmanuel Detournay, who initiated this series of annual meetings and fostered the community in their collaborations. They recognized the scientific significance of this fast-growing field prior to the surge of unconventional oil and gas reservoir stimulation, and through this workshop mentored a generation of hydraulic fracturing researchers.

This volume is devoted to celebrating the 70th birthday of Rob Jeffrey, who was the program leader at Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia, when three of the editors worked there. Rob is one of the pioneers for the application of hydraulic fracturing in coal seam gas reservoir stimulation and the foundation of the knowledge on hydraulic fracture growth in naturally fractured rocks. During his forty years working in hydraulic fracturing field, he launched many important research directions, being among the first to work in areas such as fracture network formation, novel fracture monitoring methods, mine-through mapping of full-scale hydraulic fractures, and use of hydraulic fracturing to modify rock mass properties for both block caving and longwall coal mining. All of his work brought together theoretical and experimental methods in order to address new issues with rigor and pragmatism. In recognition of Rob's outstanding contributions both to the field and to their careers, his Hydraulic Fracturing Summit colleagues and others are happy to contribute this book that is in his honor.

This volume contains 17 chapters, covering a wide range of relevant research topics and important application areas. The editors wish to thank every contributor for their diligence and careful choice of topics. The chapters will provide the first comprehensive story on these experimental and field monitoring results, including comparisons of several numerical methods with industrial applications. This book will benefit a wide spectrum of readers, ranging from newcomers seeking an efficient orientation to the field to seasoned experts looking for a unique set of references on some of the most important issues within the hydraulic fracturing community over the past two decades.

The editors are grateful to those anonymous reviewers of the book proposal for their positive comments and constructive suggestions and to the many volunteer reviewers who spent tremendous amount of time and effort in the evaluation of each chapter. We also owe much to Dr. Rituparna Bose, Layla Harden, and Stefanie Volk at Wiley, who are aware of the rapid-growing knowledge and social impact of hydraulic fracturing, and along with other editorial team members supporting this book. Without their vision, enthusiasm, and diligent efforts, this book would not have been possible.

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Hydraulic Fracture Geometry from Mineback Mapping

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KEY POINTS

- Details of full-size hydraulic fracture geometry are only available from mapping of mined fractures.
- Hydraulic fractures mapped in naturally fractured coal, sandstone, and in crystalline rock show many similarities that result from interactions with natural fractures and shear structures.

1.1 Introduction

Hydraulic fractures have been mapped during mining in a range of rock types and in a variety of geologic and in situ stress settings. Mapping has occurred for fractures placed into clay and soil [1], welded tuff [2], coal ([3–5]), andesite [6], and other crystalline and metamorphic rocks in porphyry ore bodies [7–9].

Coal seams are typically fractured for the purpose of stimulating production of seam gas (coalbed methane), either for commercial use of the gas or to improve drainage of gas from the coal before mining. Approximately 50 hydraulic fractures have been mined and mapped in detail in coal seams in the United States and Australia ([3, 4, 10, 11]; Jeffrey et al. 1993). In comparison, fractures mapped in other materials (soil and rock) total less than 20, with 10 of these located in porphyry copper and gold orebodies ([6, 7, 9]; containing intrusive monzonites and metamorphosed volcanic sediments. These fractures were placed as part of investigations into fracture geometry expected to be produced by hydraulic fractures used to precondition the orebody in advance of mining. The fractures placed into welded tuff were part of early research into hydraulic fracture growth [2] and the soil fractures were part of a study of fracturing for waste remediation [1].

By comparing the fracture geometry mapped in these different natural materials, common and disparate features of the fractures are highlighted. To help with the comparison, dimensionless groups that have been shown to be important in hydraulic fracture growth are calculated or estimated for each mapped fracture. There is an extensive body of work using experimental, analytical, and numerical methods to investigate interactions of hydraulic fractures with bedding and natural fractures and faults. This paper limits itself to the mapped geometry exposed by mining of full-size hydraulic fractures and presents a comparison of features found in coal, sandstone, and stronger metamorphic or igneous rocks.

1.2 Summary of Mapped Fracture Geometries

Selected hydraulic fractures that were placed in coal, sandstone, and hard rock are described in this section. For each fracture the treatment parameters, rock properties, and in situ properties are listed.

1.2.1 Fractures in Coal

Two fractures placed into coal seams will be described, one located in Australia as described by Jeffrey et al. (1993) and one located in the United States [10]. The fracture descriptions include details of the treatment and site characterization, including rock mechanical properties and in situ stress data.

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1.2.1.1 DHM-7 Fracture

As part of a program to better understand hydraulic fracture stimulation of coal, well DHM-7 was fractured using linear gel with sand proppant [10]. DHM-7 was drilled and completed open hole through the Blue Creek coal seam in Alabama. The well was located over the Oak Grove Mine in the Warrior Basin. Table 1.1 summarizes the parameters of the site and the treatment parameters. It is difficult to measure σ_H in coal because the cleat and natural fractures make overcoring impractical and the determination of fracture initiation is difficult when using a microfrac stress test. A value for σ_H that is larger than the vertical stress has been selected because the mine back mapping revealed no development of propped fractures at right angles to the direction of the main vertical fracture branch.

Room and pillar mining exposed the fracture in the coal rib around the sides of two pillars and along the coal rib nearest the well (Figure 1.1). A vertical and horizontal propped fracture (T-shaped) was found with the vertical part consisting of a number of parallel strands. The vertical fracture extended for more than 30 m to the north of the well. A horizontal propped fracture, extending over the vertical fracture, was located at the coal-roof rock interface and was mapped in detail (see Figure 1.2). The fracture was not mined to the south, but based on the area and fracture widths mapped, the propped fracture mapped on the north side of well DHM-7 was estimated to contain approximately 75% of the sand proppant injected [12].

The treatment pumped into DHM-7 used a non-crosslinked guar-based gel fluid that was injected at an average rate of 8.3 barrels/min (0.022 m^3/s). A thick resin-coated sand system was pushed into the near-well part of the fracture on the morning following the main treatment. This resin coated sand was used to test its ability to stabilize the wellbore region. It is designed to retain 80% of the sand's permeability after curing. Much of the vertical fracture exposed nearest the wellbore, at location A in Figure 1.1, was filled with this resin-coated sand. Samples of this propped fracture were excavated and taken from the mine for later analysis and display. No resin-coated sand was found at the next exposure at location B. Mapping of the horizontal fracture was done at the detail level represented in Figure 1.2 along all propped exposures.

Table 1.1 DHM-7. Coal, well, and treatment parameters.

Parameter	Value	Units	Description
σ_H	>8.1	MPa	Maximum horizontal stress
σ_h	6.2	MPa	Minimum horizontal stress
σ_v	8.1	MPa	Vertical stress
P_o	<3	MPa	Pore pressure (estimated)
k	1.2	md	Permeability, millidarcy
E	4000	MPa	Young's modulus of coal
ν	0.3		Poisson's ratio of coal
Q	0.022	m^3/s	Injection rate
μ	25×10^{-9}	MPa s	Apparent fluid viscosity, at $170\ s^{-1}$
Depth	331.3	m	Depth to top of Blue Creek seam
r	0.108	m	Wellbore radius

The mapped geometry in DHM-7 and other cases presented below rely on the proppant to mark the fracture path. The hydraulic fracture typically extends beyond the proppant, especially when less viscous fluids are used. Hydraulic fractures cannot in general be found or mapped if they do not contain proppant. The distribution of the proppant, especially in a horizontal fracture, depends on both the fracture width and the fluid velocity field. Proppant transport in horizontal fractures is an area of study that has received little attention, primarily because horizontal fracture growth is thought to be a rare occurrence at depths greater than approximately 300 m. The hydraulic fractures described below that were placed into the orebody at Northparkes at a depth of 580 m were horizontal. T-shaped fractures are common in stimulation of coal and better models that can deal with horizontal fracture growth and the associated proppant transport problem would be welcome.

1.2.1.2 DDH 190 Fracture

An uncased HQ-size cored borehole (DDH 190) was drilled through the German Creek coal at Central Colliery in Queensland and was hydraulically fractured using a borate crosslinked hydroxypropyl guar gel fluid. The site was characterized by undertaking well testing, stress measurement, core testing, and fracture testing before the main fracture treatment. Table 1.2 summarizes the site parameters relevant to the treatment as given by Jeffrey et al. [5].

Mapping of the fracture during and after development of the roadways in this area of the mine revealed a vertical fracture in the coal that extended into the roof rock (Figure 1.3). The fracture trace in the roof rock (Figure 1.3a) was primarily a single fracture, but interactions with natural fractures resulted in the formation of some offsets and short parallel branches. The vertical fracture trace in the coal at the north side of 13 cut-through (Figure 1.3b) was typical of other vertical sections mapped at this site, consisting of a single fracture that interacted with bedded and sheared coal. The 150 mm-thick mid-seam shear zone (mssz) runs through much of the German Creek seam and is composed of sheared coal, with particles

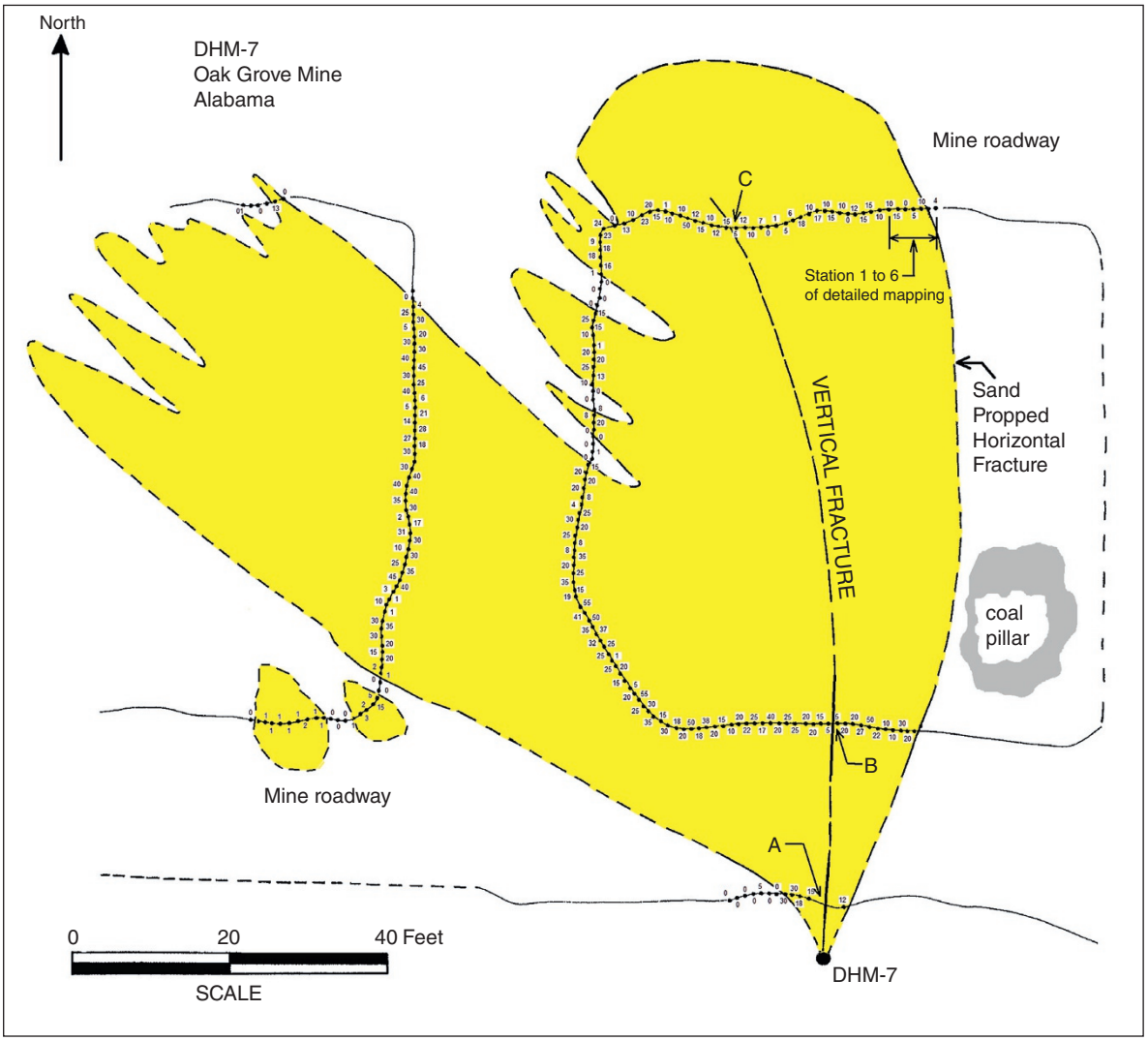

Figure 1.1 A plan view of the propped hydraulic fracture mapped at the DHM-7 site is shown in the top drawing while three mapped vertical fracture sections exposed at the coal rib are shown in the lower drawing. Mapping of the horizontal fracture occurred along the ribs of the roadways where the fracture was exposed near the roof (*Source:* Boyer et al. [12]/Gas Research Institute).

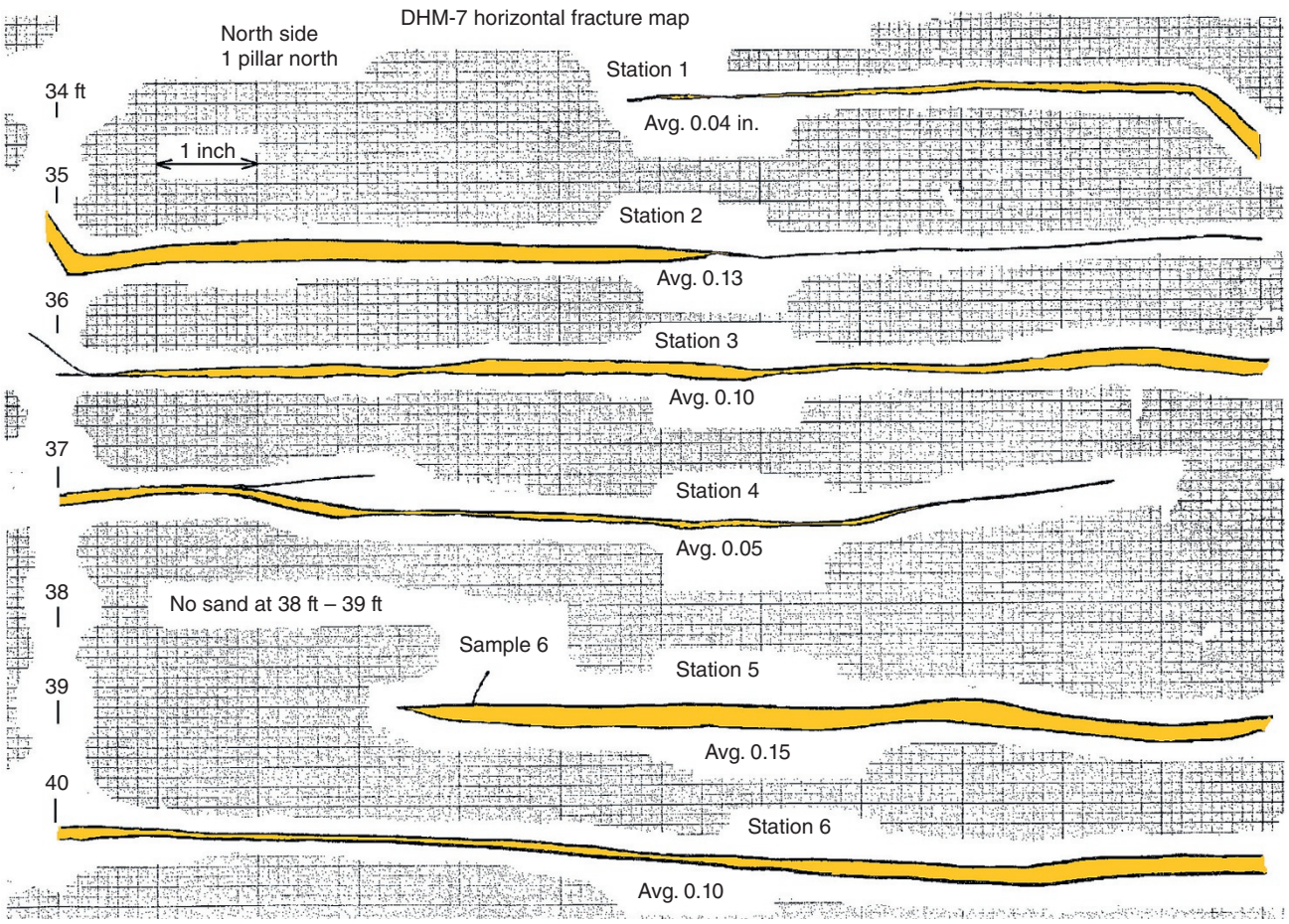

Figure 1.2 Seven linear feet of horizontal fracture mapped along the north side of the coal pillar (*Source:* Boyer et al. [12]/Gas Research Institute). The location of this portion of the horizontal fracture is indicated in Figure 1.1 and labeled as station 1 through 6. The entire horizontal fracture was mapped at this level of detail and the numbers in Figure 1.1 along the pillar boundary indicate the average propped width in hundredths of inches (e.g. 30 represents 0.30 in.).

Table 1.2 DDH 190 site parameters.

Parameter	Value	Units	Description
σ_H	>4	MPa	Max horizontal stress, in roof
σ_h	2.5	MPa	Min horizontal stress in coal
	1.9	MPa	Min horizontal stress in roof
σ_v	4.5	MPa	Vertical stress
P_o	1.08	MPa	Pore pressure
k	4.2	md	Permeability, millidarcy
E	2 000	MPa	Young's modulus, coal
	25 000	MPa	Young's modulus, roof rock
ν	0.35		Poisson's ratio, coal
	0.13		Poisson's ratio, roof rock
Q	0.002 5	m^3/s	Injection rate
μ	610×10^{-9}	MPa s	Apparent fluid viscosity at 170 s^{-1}
Depth	193.5	m	Depth to top of German Creek seam
r	0.048	m	Wellbore radius

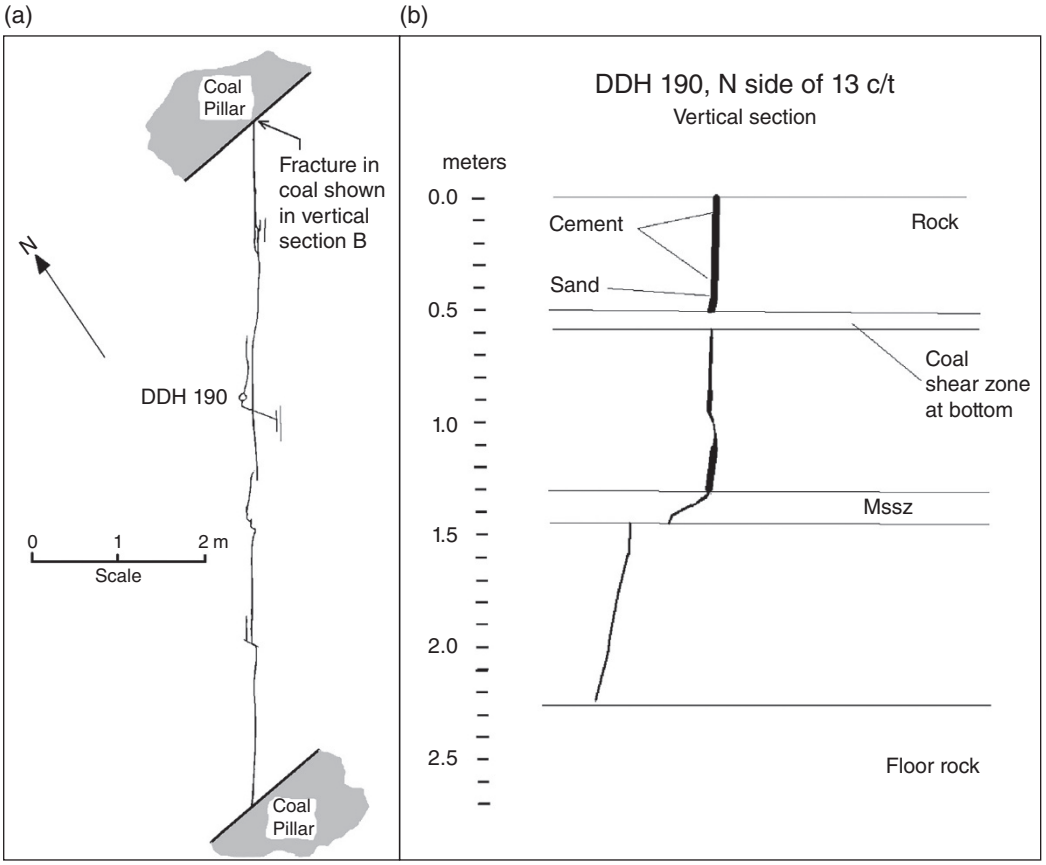

Figure 1.3 Looking down on propped fracture trace (a) in sandstone roof rock at 13 cut-through. Vertical section (b) showing propped fracture exposed on north coal rib of 13 cut-through near borehole DDH 190 (*Source:* Jeffrey et al. [5]/Coalbed Methane Association of Alabama).

ranging from clay size to a few centimeters in size. The mssz is softer and weaker than the coal above and below it. This hydraulic fracture and others mapped in this coal seam often developed an offset across the mssz.

The fracture at DDH 190 extended into the lower stress roof rock with only 12% of the proppant injected estimated to be accounted for by the propped fracture in the coal seam. The mapping clearly shows the trace of the propped hydraulic fracture in the roof and in the coal, but does not reveal if the fracture was growing primarily laterally or vertically at the sections mapped. Modeling of this fracture suggests upward growth of 7 m into the roof rock at the borehole [13].

1.2.2 Fractures in Hard Rock

Hydraulic fracturing is used in mining to induce caving and to precondition rock for caving [7]. More recently, preconditioning has been used in areas of high stress as a means of reducing the potential for the occurrence of large, damaging seismic events [14]. A total of nine fractures have been mined and mapped at four metalliferous mine sites in Australia [7, 9, 15] and Chile [6]. The fractures described by Jeffrey et al. [9] will be compared to the fractures placed into coal seams.

1.2.2.1 Northparkes E48 Mapped Fractures

Six hydraulic fractures were placed ahead of a tunnel at 580 m depth at the E48 Northparkes mine as part of a mine-through experiment [9]. The fractures were propped with colored plastic and sand and were monitored by microseismic and tiltmeter arrays. The mapped hydraulic fractures at Northparkes consist of nearly horizontal segments with offsets at intervals along them produced as the fracture grew into and along dipping veins, natural fractures, and shear zones. Fracture branches and sub-parallel propped sections were also mapped, making up 10–15% of the total fracture extent. The rock mass at the site is naturally fractured, containing approximately five natural fractures per meter. Additional details of the site, fracturing, and mine-back can be found in Jeffrey et al. [9]. Table 1.3 lists site and rock parameters. The stress directions given in Table 1.3 are based on overcoring data measured near the fracture site.

Table 1.3 Site and rock parameters for Northparkes E48.

Parameter	Value	Units	Description
σ_H	40	MPa	Max horizontal stress, 290^0, 8^0 dip
σ_h	22	MPa	Min horizontal stress, 22^0, 11^0 dip
σ_v	15	MPa	Vertical stress, 165^0, 76^0 dip
P_o	<1	MPa	Pore pressure
k	0.005	md	Permeability, millidarcy
E	50 000	MPa	Young's modulus
ν	0.2		Poisson's ratio
Q	0.007 5	m^3/s	Injection rate
μ	610×10^{-9}	MPa s	Apparent crosslinked gel viscosity at $170\ s^{-1}$
	1×10^{-9}	MPa s	Viscosity of water
Depth	580	m	Depth below surface
r	0.048	m	Wellbore radius

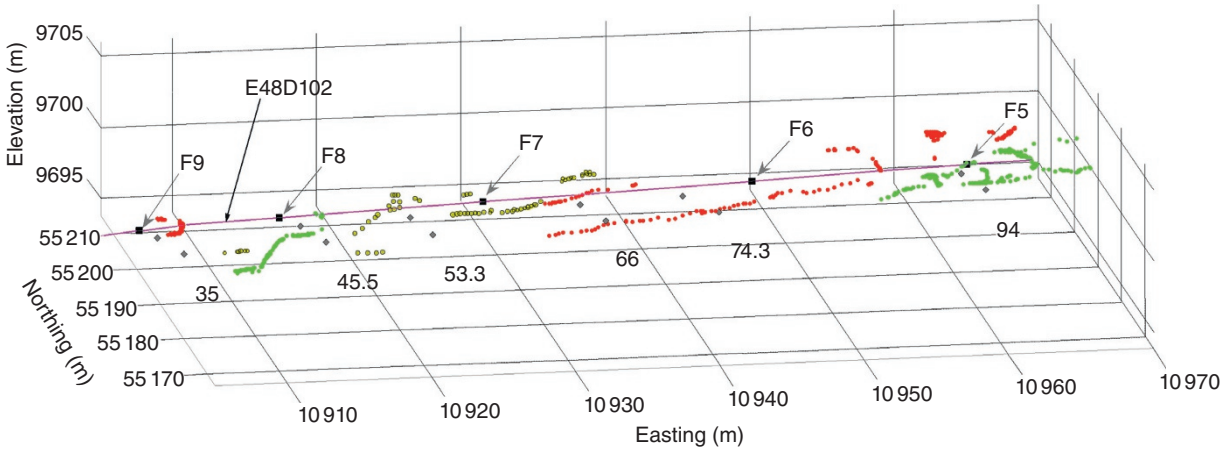

Figure 1.4 Hydraulic fractures mapped along a tunnel at the Northparkes E48 mine (*Source:* Jeffrey et al. [9]/Society of Petroleum Engineers). The initiation point of each fracture is indicated along the borehole which is drawn with a purple line.

The minimum stress was nearly vertical with the maximum stress oriented nearly horizontal and directed approximately east–west.

The hydraulic fractures were mapped along the E48D102 tunnel as it was driven. The fractures were horizontal with steps along their path often forming where they interacted with natural fractures and shear structures. These offsets were large enough to increase the average dip because the fracture trace following a stair-step pattern. Figure 1.4 shows an overview of the five fractures that were propped with colored plastic and mapped along the sides of the tunnel.

Fractures 6 and 7 were placed using crosslinked guar gel while fractures 5, 8, and 9 were placed using water. The colors of the points mapped along each fracture shown in Figure 1.4 correspond to the colors of the plastic proppant used. The grid lines shown are the mine coordinates in meters. The initiation point of each fracture is indicated by a black square symbol and the borehole is shown by the line connecting these symbols. Figure 1.5 contains a more detailed sketch of Fracture 8, which contained the largest offset or step mapped in any of the fractures at this site. The injection interval, which was in the borehole E48D102, is shown. This interval is located approximately 2.5 m out of the plane of the fracture trace shown because the borehole was drilled along the centerline of the tunnel. Fracture growth is likely to have been semi-radial from the injection interval and should not be visualized as occurring purely along the fracture trace. Fracture 7 contained an offset similar in size to the one shown in Figure 1.5 and a series of smaller offsets (but consisting of 200–400 mm steps) were