CHARACTERIZATION OF BRITTLENESS AND FRACKABILITY FOR UNCONVENTIONAL SHALE

BY

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Dedication

To my father who passed away 18 years ago,

My mother,

My wife

and my beloved son.

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To Allah (SWT) for his guidance and sustenance; my Mother for teaching me to be independent and staying with me for 6 months in Saudi Arabia to nurse my son; my siblings, parents-in-law, brother-in-law for their support and encouragement; my wife for sharing my excitement, disappointments and frustrations and my beloved son for his contagious laugh and smile.

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TABLE OF CONTENTS

ACKNOWLEDGMENTS v

TABLE OF CONTENTS vii

LIST OF TABLES x

LIST OF FIGURES xi

LIST OF SYMBOLS xii

LIST OF ABBREVIATIONS xiii

ABSTRACT IN ENGLISH xv

ABSTRACT IN ARABIC xvi

CHAPTER 1 INTRODUCTION 1

1.1 Thesis Outline 2

1.2 Thesis Motivation 3

1.3 What is shale? 4

1.3.1 Lamination and Fissility of Shale 5
1.3.2 Anisotropy and Shale 6
1.3.3 Permeability and Porosity of Shale 8
1.3.4 Significance of Shale in the Petroleum Industry 9
1.3.5 What is Unconventional about Shale? 10
1.3.6 Shale Plays of the World 11
1.3.7 Shale Play Attributes 13

CHAPTER 2 LITERATURE REVIEW 14

2.1 Mechanical Properties of Shale 14

2.2 Early Ideas on Brittleness 15

2.3 Brittleness of Rock 20

2.4 Brittleness of shale 21

2.5 Frackability of Shale 28

CHAPTER 3 LABORATORY EXPERIMENTS 30

3.1 Rock Description and Preparation 30

3.2 Micro CT Imaging 31

3.3 Density and Porosity Measurements 31

3.4 Velocity Measurements 34

3.5 Mineralogical Composition and XRD Analysis 36

CHAPTER 4 QUANTIFYING BRITTLENESS 38

4.1 The Stress-Strain Curve and Brittleness 38

4.2 Selecting Best Brittleness Attributes from the ratio of Elastic Constants 40

CHAPTER 5 FRACKABILITY 51

5.1 A Brief Overview 51

5.2 Frackability and Shale Reservoir 53

5.3 The First Principle of Frackability (FPF) 53

5.4 The Second Principle of Frackability (SPF) 57

5.5 ANALYTICAL EXPRESSION FOR THE FRACKABILITY OF ROCK 59

5.5.1 Formulation of the Problem 61

5.5.2 The Physical Principle and Conservation Law 61

5.6 Future Works 65

Chapter 6 Conclusion 67

Appendix A 69

Micro CT Imaging 69

Waveforms of Velocity 71

XRD ANALYSIS 72

References 76

Vitae 100

LIST OF TABLES

Table 1.1: Shale Play Revolution Timeline 13
Table 2.1: Equations for Brittleness Estimation 26
Table 3.1: Dry bulk density, grain density and Porosity measurements 32
Table 3.2: Velocity measurement of vertical shale plug at constant orientation 35
Table 3.3: Velocity measurement of horizontal shale plugs at different orientations 35
Table 3.4: Mineralogical Composition of Eight Shale Samples 37
Table 4.1: Data from Goodway et al 1997 43
Table 4.2: Combination of Elastic Constants 43
Table 4.3: Brittleness of Vertical Shale Plug at constant orientation 46
Table 4.4: Brittleness of horizontal shale plugs at different orientations 46

LIST OF FIGURES

Figure 1.1: Schematic of the Geological Hierarchy of Sedimentary Rocks 2
Figure 1.2 :(a) Shale (b) Mudrock. Courtesy of Jones C.E (Geologic Image Archive) 5
Figure 2.1: Ternary plot for brittleness prediction from Perez and Marfurt (2013) 22
Figure 4.1a: Stress strain curve of ideal rock *from subsurfwiki* 40
Figure 4.1b: Stress strain curve of shale from UCS testing 40
Figure 4.2: Brittleness versus Confining Pressure for Vertical Shale Plug 47
Figure 4.2a: Brittleness versus Confining Pressure Horizontal Shale Plug at 0 Degree .. 47
Figure 4.2b: Brittleness versus Confining Pressure Horizontal Shale Plug at 45 Degree 48
Figure 4.2c:Brittleness versus Confining Pressure Horizontal Shale Plug at 90 Degree . 48
Figure 4.2d: Brittleness versus Confining Pressure 2H at 0, 45 and 90 Degree Orientation 49
Figure 4.2e: Brittleness versus Confining Pressure 3H at 0, 45 and 90 Degree Orientation 49
Figure 4.2f: Brittleness versus Confining Pressure 4H at 0, 45 and 90 Degree Orientation 50
Figure 5: Schematic of Rock to be fracked 61

LIST OF SYMBOLS

Symbols	Meaning
α	surface energy, Biot poroelastic parameter
β	effective stress parameter
δ	Thomsen Parameter, length of the borehole
$\delta_{ij}\delta_{kl}$	Kronecker delta
ε	Thomsen Parameter
ε_h	Minimum strain
ε_H	Maximum Strain
ε_{kl}	Strain tensor
ε_{p_f}	Plastic strain at failure
ε_{p_c}	specific strain after failure
ε_r	reversible strain
ε_t	total strain
η	Parameter that depends on Poisson ratio and Biot poroelastic paramter
ρ	density
σ	effective stress gradient
σ_c	uniaxial compressive strength; compressive strength, critical stress
σ_{ij}	Stress tensor
σ_t	tensile strength
$\sigma_{\times}$	Maximum horizontal stress
σ_y	Intermediate horizontal stress
σ_z	Vertical stress
σ_{NC}	Uniaxial compressive strength at normal consolidation
τ_P	peak strength
τ_R	residual strength
θ	angle of internal friction ; polar angle
γ	Thomsen parameter
λ	Lame Parameter; microcrack length scale
μ	Lame parameter, rigidity, shear modulus
v	Poisson ratio; instantaneous Poisson ratio
ν_h	Horizontal Poisson ratio
v_{min}	Minimum Poisson ratio
v_{max}	Maximum Poisson ratio
ν_v	Vertical Poisson ratio
σ_V	effective vertical stress; the present day effective pressure
σ_{P_M}	maximum effective pressure in the past
γ_s	specific surface energy

LIST OF ABBREVIATIONS

Abbreviation	Meaning
a	crack half-length
A	borehole pressurization rate
AD	average diameter
AL	Average Length
AVO	the amplitude versus offset
B	Empirical Constants
B	Brittleness
B_H	horizontal Brittleness
B_T	Tilted Brittleness
B_V	Vertical Brittleness
BI	Brittleness Index
B_N	Normalized Brittleness
B_{min}	Minimum brittleness
B_{max}	Maximum brittleness
C	Diffusivity coefficient, half crack length
C	Calcite
C_{ij}	Elastic constants of rank two,
C_{ijkl}	Elastic constants Tensor of rank four or Stiffness tensor
CFI	Complex Frackability Index
CP	Confining Pressure
Carb	Carbonates
CLY	Clay
D	Dolomite
E	Young's modulus; instantaneous Young's modulus
E_h	Horizontal Young's modulus
E_{min}	minimum Young's modulus
E_{max}	maximum Young's modulus
E_V	Vertical Young's modulus
E_N	Normalized Young's modulus
NER	New England Research
F	Frackability
FI	Frackability Index
FPF	First principle of frackability
G	Strain energy rate, energy release rate G, crack driving force or energy per unit surface area
G_{min}	Minimum Strain energy rate
G_{max}	Maximum Strain energy rate

G_N	Normalized Strain energy rate
h(λ)	dimensionless pressurization rate
H	macro-indentation hardness
H_μ	micro-indentation hardness
K	Empirical constant, Permeability, Bulk modulus, Fracture toughness, stress intensity factor
K_{IC}	rock toughness
K_I	stress intensity factor under mode 1
K_{min}	Minimum Fracture toughness
K_{max}	Maximum Fracture toughness
K_N	Normalized Fracture toughness
1H	Shale Plug No 1 Horizontal
1V	Shale Plug No 1 Vertical
2H	Shale Plug No 2 Horizontal
2V	Shale Plug No 2 Vertical
3H	Shale Plug No 3 Horizontal
3V	Shale Plug No 3 Vertical
4H	Shale Plug No 4 Horizontal
4V	Shale Plug No 4 Horizontal
LEFM	Linear elastic fracture mechanics
LMR	Product the two Lame's parameter with density
M	post peak modulus
q	percentage of fines
Q	Quartz, flow rate
QFM	Quartz, Feldspar and Mica
P_b	breakdown pressure
P_p	Pore Pressure
S_{ijkl}	Compliance tensor
T	time of injection
TOC	Total organic content
V_P	P wave velocity
V_{S1}	Fast S wave velocity
V_{S2}	Slow shear wave velocity
V_s	Average of S wave velocity
VTI	Vertical Transverse Isotropy
W	weight fraction
$w_p(K, \alpha)$	plastic deformation at the crack tip
W_T	Total weight fraction
W_r	reversible energy
W_t	total energy
X,Y,Z	First horizontal, second horizontal and vertical axis respectively

ABSTRACT IN ENGLISH

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Thesis Title : CHARACTERIZATION OF BRITTLENESS AND FRACKABILITY OF UNCONVENTIONAL SHALE

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Brittleness and frackability are two important “attributes” that have been used interchangeably in literature to characterize the feasibility of the hydraulic fracturing of unconventional shale formations.

The objective of this thesis research has been to understand if the two attributes are indeed the same, which of them is more useful and how best to quantify each of them.

These research problems were addressed based on previous studies, by carrying out micro-CT imaging, ultrasonic velocity, and mineralogical measurements on eight subsurface shale plugs. Published data was used for the sensitivity analysis of the elastic constants for brittleness and verified with an experiment based on the velocity data. The conservation law of physics and Darcy law was used for theoretical analysis on frackability.

The findings show that brittleness and frackability are both dimensionless quantities, but that they are not equivalent. Analytical expressions for both attributes show that frackability could depend on brittleness.

The results of this thesis can be used to accurately characterize the brittleness and frackability of unconventional shale, make fracking technically and economically meaningful, and eventually contribute to hydrocarbon production optimization.

ABSTRACT IN ARABIC

ملخص الرسالة

الإسم	:	لطيف أولابي لوول
عنوان الرسالة	:	توصيف الهشاشة والقابلية للتشقق لصخور الطفل الغير تقليدية.
التخصص	:	الجيوفيزياء
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تعتبر الهشاشة والقابلية للتشقق من " السمات " الهامه التي تم استخدامها تبادليا في المراجع العلمية لتوصيف جدوى التكسير الهيدروليكي لصخور الطفل الغير تقليدية.

إن الهدف من هذه الرسالة هو أن نفهم إذا ما كانت هاتين السماتين في الواقع متشابهتين، وأيهما أكثر فائدة وكيف نقيسهما.

أقوم بمعالجة هذه المسائل البحثيه إعتمادا على دراسات سابقة، من خلال إجراء بعض القياسات الصخرية والمعدنية على عينات الطفل التحت سطحية ومن خلال بعض التحاليل النظرية الجديدة.

وبناءا على إستنتاجاتي، تعد كلا من الهشاشة والقابلية للتشقق كميات خاليه الوحدات ولكنها غير متكافئة. قمت بإشتقاق تعابير تحليلية للسماتين ولقد وجدت أن القابلية للتشقق قد تعتمد على الهشاشة.

يمكن إستخدام نتائج هذه الرسالة لتوصيف دقيق للهشاشة والقابلية للتشقق لصخور الطفل الغير تقليدية، وجعل التكسير ذا مغزى تقنيا واقتصاديا، وفي نهاية المطاف تحسين إنتاج النفط والغاز.

CHAPTER 1

INTRODUCTION

> "We must continue research into new forms of energy and into more efficient use of existing energy sources"
> Mac Thornberry

The availability and sustainability of energy (oil, gas, coal, solar, wind etc.) for mankind is one of the major reasons for scientific research across different disciplines. Arguably, among these energy options, oil and gas produced from sedimentary rocks are the most viable options. The sedimentary rock is the lithification (consolidation) of sediments under different climatic and geological conditions. Among the geological hierarchy of the sedimentary rock (Figure 1), sandstone and carbonates (limestone and dolomites) have been for long the well-established sources of oil and gas. However, the depletion of these geologically simple formations has led to the development and production of oil and gas from unconventional plays (coal bed methane, tight sand, tar sand, shale, carbonates source rock e.g. marl). The above mentioned "geological simplicity" refers to the porous and permeable nature of these formations that classify them as the conventional reservoirs. Unconventional plays are generally autogenic (self-sourcing) and geologically complex. These characteristics and uncertainties call for more scientific and technical advances.

As a result, oil and gas development and production from unconventional plays are more difficult and expensive than from conventional ones. These challenges, that require more scientific research effort, explain the unprecedented interest in, and growth of the number of, shale plays among the unconventional ones.

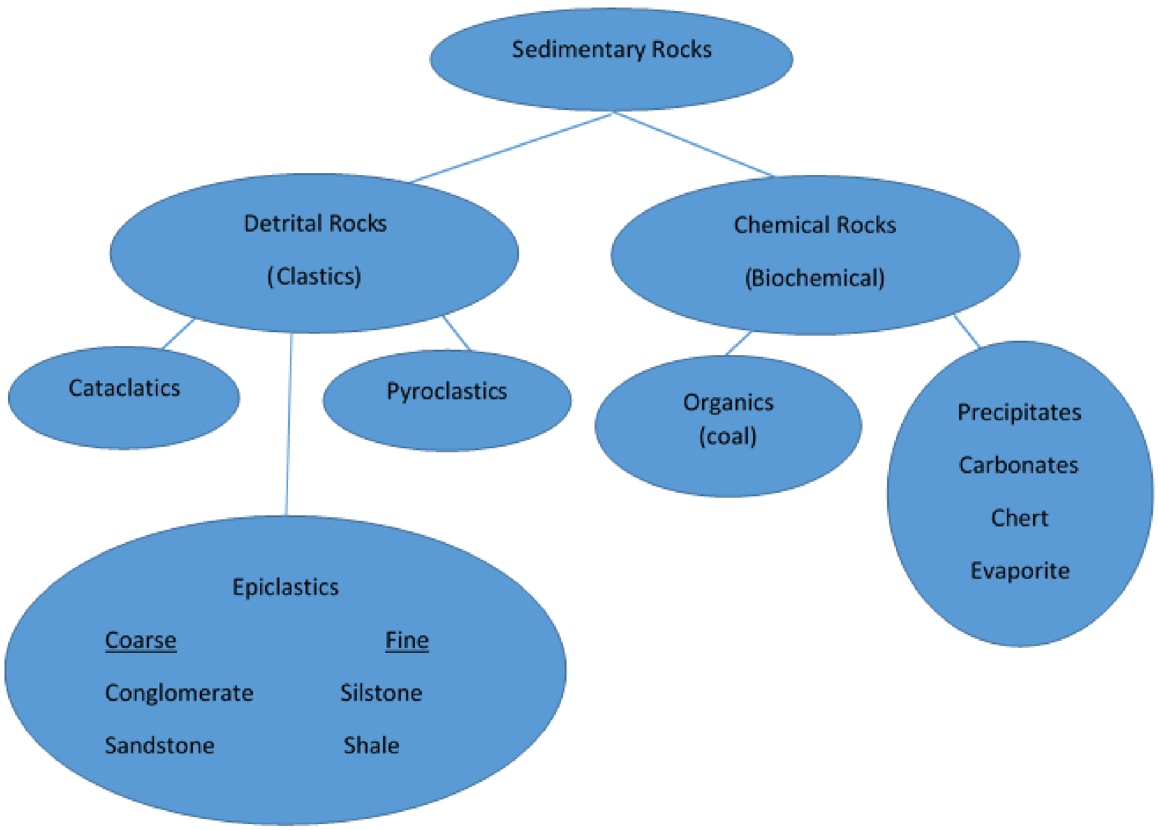


Figure 1.1: Schematic of the Geological Hierarchy of Sedimentary Rocks

1.1 Thesis Outline

Chapter one gives a brief overview of sedimentary rock as a viable energy source; the motivation of this research; the conflicting names for shale and its characteristics; the significance of shale in the petroleum industry and the energy revolution of shale plays around the world. Chapter two is a collection of paper on brittleness of rock in general and on shale in particular. It mentions also, the confusion of brittleness and frackability. Chapter three is devoted to experimental studies on some subsurface shale samples. These studies serve as an insight to the subsequent chapter. Chapter four clarifies how to quantify brittleness from elastic constants. Chapter five explains the technical, economic, social and political implications of the word fracking, the two fundamental principles of hydraulic fracturing and a new expression for frackability is derived.

1.2 Thesis Motivation

Shale plays have been established in North America, particularly in the United States to be economically viable sources of energy. They have now emerged as the exploration targets of the Petroleum Industry for oil and gas development around the world including Saudi Arabia. However, they are still challenged with the huge cost of investment, need for a substantial quantity of water, adverse environmental impacts, recovery factor and problems with well spacing for optimum drilling and completion design. These challenges have further stimulated research into the science and petroleum engineering of shale. Hence, my scientific curiosity motivating this study is partly due to the economic importance of hydrocarbon production from shales, and partly to the realization that there is still the need to better understand the petrophysics and geomechanics of shales.

Accurate estimation of brittleness and frackability from well log data and from measurable geomechanical properties would prevent hit or miss fractures. Hence, fracking would be technically more efficient and cost effective. To achieve this purpose the following research questions will be addressed: (1) Is brittleness the same as frackability? (2) If different, which concept is more useful? (3) Is the isotropy of the elastic constants and that of the vertical stress assumption valid for the estimation of brittleness and frackability of shale? (4) Some equations have already been published and used to estimate brittleness of shale. Are they sufficient? Or is there a need to derive further ones? (5) Some seismic attributes have already been used to estimate shale brittleness and frackability. Analysing these attempts critically: Are they satisfactory or new ones are needed? (6) Which other seismic (or wireline log) attributes would be the best to estimate brittleness and frackability? (7) Can we/ should we incorporate the Thomsen's anisotropy parameters to estimate brittleness and frackability?

1.3 What is shale?

It is unfortunate that a multitude of names have been used to call and describe shale. For example, mudstone, mudrock, claystone or clay, argillaceous material, soil, weak rock, soft rock and shale. Consequently, there is no single definition that would be able to capture these different terminologies used to describe shale. These terminological inconsistencies are based on different disciplines interested in the scientific and engineering study of shale. Therefore, different specialized definitions are available for shale but will not be discussed here. However, shale is the most famous term among these different terminologies used to describe fine grained sediment predominant in clay (Lal, 1999, Gale et al, 2007). For example, the Barnett Formation usually referred to as Barnett Shale is really mudstone in the geological lexicon and taxonomy (Gale et al, 2007). It suffices to say that the geological definition of shale as the lithification of fine grained sediment (clays or muds) deposited under marine (lacustrine) and/or terrestrial environment is the generally acceptable one.

The characteristics properties (physical and chemical) of shale including lamination, fissility, anisotropy, porosity, permeability, fluid interaction, wettability and many others are based on their different constitutive compositions under influence of geological (diagenesis) and man-made factors (hydraulic fracturing). Some of these characteristics will be discussed.

1.3.1 Lamination and Fissility of Shale

Lamination simply means to consist of fine layers. The lamination in shale is one of the distinguishing factors of shale from claystone and mudstone. Shale is finely layered. Lamination thickness for rock is generally between 0.05 to 1.0 mm and 0.1 to 0.4 mm for shale. The different laminae can be detected by visual inspection or with modern experimental techniques based on color, composition and grain size.

Fissility means that shale can be broken or split into sheets along its laminations. The fissility in shale is decreased by increasing content of siliceous or calcareous material. As a result shale and mudstones break into thin and blocky pieces, respectively. Based on the fissility, shale should have less clay content compared to mudrock or mudstone.

Figure 1.2 : Courtesy of Jones C.E (Geologic Image Archive)

1.3.2 Anisotropy and Shale

A material is said to be anisotropic if its properties (e.g. elastic response to a given stress) depend on orientation. For anisotropic materials, the moduli of elasticity vary, depending on the direction in which they are evaluated. There are basically two types of anisotropy: intrinsic and induced that can be referred to as small and large scale anisotropy respectively. The intrinsic anisotropy is due to preferential orientation of the sediment grains (due to lamination and fissility) and pores that can be created by sediment composition, grain size and shape, deposition and compaction.

The induced anisotropy is caused by geological deformations like tectonic forces, strain associated with applied stress and fractures created by hydraulic fracturing. At large scale, the presence of geological structures (foliation, lineation etc.) results in a certain degree of anisotropy. Conversely, at small scale this anisotropy exists due to the presence of the anisotropic minerals forming the rocks.

The generalized Hooke's law for any anisotropic material is (using Einstein's summation convention)

$$\sigma_{ij} = S_{ijkl}\varepsilon_{kl} \tag{1.1}$$

Alternatively Equation 1.1 could be written in the inverse form as:

$$\varepsilon_{ij} = C_{ijkl}\sigma_{kl} \tag{1.2}$$

where σ_{ij} is the stress tensor, ε_{kl} is the strain tensor, S_{ijkl} is the 9x9 elastic stiffness tensor and C_{ijkl} is the 9x9 elastic compliance tensor respectively. In the general case, the

9x9 elastic tensor would require 81 independent components in an anisotropic medium, the symmetry of stresses and strains reduces this number to 36 and a further reduction to 21 gives the maximum number of independent elastic constants that a medium can possess assuming the presence of unique strain energy potential.

Shale exhibits anisotropic characteristics in terms of strength and deformational properties (differences between elastic moduli measured parallel and perpendicular to bedding). The anisotropy can be simple (i.e. polar anisotropy for un-fractured shale). Earth materials are generally transversely isotropic, that is symmetric about an axis normal to a plane of isotropy ("bedding plane"). The number of independent elastic constants in this case is reduced to 5 (2 Young's moduli, 2 Poisson's ratios and one shear modulus).

For fractured shale, the anisotropy is more complicated (i.e. azimuthally anisotropic – orthorhombic or monoclinic). Three distinct directions of anisotropy are needed to define orthorhombic anisotropy, and in this case we have 9 independent elastic constants (3 Young's moduli, 3 Poisson's ratios and 3 shear moduli).

For simplicity, I will assume that all horizontal directions are equivalent and different from the vertical direction – the case of Vertical Transverse Isotropy (VTI). The VTI is also called transverse isotropy with vertical axis of symmetry. This is a plausible idealization for the not hydraulically fractured shale that is, the shale not containing induced fractures. The transverse isotropy with a vertical symmetry axis (VTI) is also referred to as polar anisotropy (Thomsen, 2012). Some of the literature on shale refers to its intrinsic anisotropy (Rai and Hanson 1988; Vernik and Nur 1992; Vernik et al., 1994; and Sayers 2005).

1.3.3 Permeability and Porosity of Shale

Permeability is a measure of a rock's ability to allow fluid to flow through the interconnected pores (the path of least resistance). The permeability of a conventional porous reservoir is the rock's natural capability to allow the flow of oil and gas driven by pressure differences in the formation. Conversely, the permeability of intact shale is an intrinsic local permeability that should be enhanced by creating additional interconnected fractures by a process called hydraulic fracturing to allow the flow of oil and gas. This intrinsic permeability of intact shale is generally in the range of micro to nano Darcy ($1\times10^{-18}\,m^2$ to $1\times10^{-21}\,m^2$, with 1 Darcy $= 0.97\,x\,10^{-12}\,m^2$) in a perpendicular direction to the bedding. The Darcy, denoted D, is widely used in geophysics and petroleum engineering, while m^2 is used in physics. Remarkably, this property of shale (low permeability) serves two purposes: (1) for oil and gas entrapment in the conventional reservoir and (2) in creating an extensive areal deposit of hydrocarbon due to the absence of primary migration (movement of oil and gas from the shale source rock to the reservoir). However, this very small original permeability of unconventional shale makes hopeless any economic recovery of oil and gas without hydraulic fracturing. The mode of formation of the shale from extremely fine-grained sediments (mostly clay platelets) that are tightly packed together explains their very low permeability.

The *total porosity* of a sedimentary rock is the ratio of the non-solid volume (pore volume) to total volume while the *effective porosity* is the fractional volume of connected pores only. Same way as permeability, the porosity of shale is very low. Oil and gas can be held in natural fractures, adsorbed on pore surfaces or within the organic component of shale. Permeability in shale is highly dependent on the structure of the pores (the degree of connectivity of the nano-pores). There is a wide dynamic range difference between these two parameters (permeability and porosity), which excludes any meaningful mathematical relation between porosity and permeability for shale. Two shale samples with the same porosity may have orders of magnitude differences in permeability.

1.3.4 Significance of Shale in the Petroleum Industry

The source rock that stores the organic matter for the generation of hydrocarbon is the most significant among the elements of the petroleum system. Any sedimentary rock can store organic matter for the hydrocarbon generation but weathering could later remove it. The characteristic low porosity and permeability of shale prevent the loss of organic matter by weathering and thus make shale the most common source rock.

Shale that can store organic matter is found in different combinations (Eremenko and Ulyanov, 1960),

1. Shale with limestone interbeds and lenses and vice versa;
2. Shale and sandstones (sands) with limestone (dolomite) interbeds and vice versa
3. Shale and marl with sandstone and sand interbeds;
4. Shale with sandstone and sand interbeds and lenses.

In a conventional reservoir, the cap rock is another element of the petroleum system. The non-permeable nature of shale which prevents the escape of hydrocarbon makes it an excellent seal.

The combination of horizontal drilling and multistage hydraulic fracturing has made extraction of oil and gas from shale feasible. Also, shale makes up about three fourths of drilled formations with wellbore instability problems (Steiger and Leung, 1992; Lal 1999) causing delays in the drilling program. All these factors have accelerated the recent interest in the study of shale geomechanics.

1.3.5 What is Unconventional about Shale?

Unconventional shale, unlike the conventional reservoir, is a self-contained, integrated system in which the source, trap and cap rocks respectively are synonymous and the migration paths outwards are insignificant. The elements of the whole petroleum system are in one rock type 'shale'. The unconventional shale is the source rock. Therefore, unconventional shale as a source rock is simply organic shale. The quantity and quality of organic matter (kerogen) in the shale is the decisive ingredient to establish it as play or seal. Consequently, the presence of kerogen in substantial amount qualifies shale as unconventional play. Usually, the darker and denser the shale is, the larger is its organic richness. The grade of colour from red, brown, grey to black in this order tells the organic richness of shale by visual inspection, with black shale being the richest in organic content.

Also, unconventional shale that is now the main exploratory target has been known for many years in Petroleum Industry. It has been known as a vast deposit of hydrocarbon but unknown as how to be developed and produced because of its complex and peculiar geology. Its geology implies that: (1) it is an oil and gas play - an extensive deposit of hydrocarbon because of its low permeability that had prevented secondary migration of hydrocarbon to the conventional porous reservoirs; (2) it must be stimulated by hydraulic fracturing and/or produced by horizontal drilling; (3) its characterization needs approaches different from the conventional reservoirs, for example seismic monitoring (micro seismic); (4) integrating geoscience and engineering is essential (5) basic research is needed to meet up with the research pace on the conventional reservoirs.

In general, ease and cost associated with the development of oil and gas are the major differences between unconventional and conventional plays. However, advancement in technology, body of geologic knowledge and politics could make what was unconventional yesterday become conventional today. For example, before 1978, unconventional natural gas deep in the Anadarko Basin (centered in western Oklahoma and Texas Panhandle) was not feasible for exploitation for economic and technical reasons. However, regulatory changes and passage of the *Natural Gas Policy Act* of 1978 boosted the development of unconventional natural gas.

1.3.6 Shale Plays of the World

Low permeability and porosity in shale indicate that there is insignificant secondary migration to trapped hydrocarbon in the reservoir, only the primary migration (movement of hydrocarbon within the source rock) has taken place. The dominance of the primary migration makes unconventional shale play an extensive areal deposit of oil and gas that are regionally distributed across the world.

The United States pioneered the development of oil and gas from unconventional shale (see the timeline of shale revolution in Table 1.1). Unconventional shale being an economically viable source of energy was amply demonstrated in the United States and has now emerged as the exploration target around the world including Saudi Arabia.

Prominent shale gas plays in the United States are the Marcellus (Appalachia), Haynesville (Louisiana/Texas), Barnett (Texas), Fayetteville (Arkansas), Woodford (Oklahoma), Eagle Ford (Texas) and Antrim (Michigan). As of 2008, the Barnett Shale was already the source of about 6% of all natural gas produced in the Lower 48 states.

Major plays in Canada are Horn River/Muskwa (northeast British Columbia), Colorado Group (west- central Saskatchewan/south-central Alberta) and Montney (Alberta).

Other famous examples are the Cooper Shale of Australia, La Luna Shale of Venezuela, Vaca Muerta Shale of Argentina, the Kimmeridgian Shale of the North Sea, Sichuan Shale of China, the Silurian Shale of Algeria and Libya, the Middle Miocene shale play of the Niger Delta basin in Nigeria, and the Qusaiba Shale of Saudi Arabia. These shales that are now exploitable for oil and gas development are all different from one another; the variability in their characteristics demands that we characterize them independently. They were the source rock to most of the conventional reservoirs we know.

Table 1.1: Shale Play Revolution Timeline

2000		Gas production from shale was more successful than other energy sources
1995	1998	Mitchell Energy commercially extracted gas from shale
1990	1991	The Gas Research Institute (GRI) funded the horizontal well in Barnett Shale for Mitchell Energy
1985	1986	The joint venture between DOE and a private firm drilled the first multi-fractured horizontal well in Wayne County, West Virginia
1980		The U.S Congress established the production tax credit for unconventional gas
1970	1977	Massive hydraulic fracturing in shale (MHF) was established by the U.S Department of Energy
	1976	MERC engineers filled a patent for directional drilling in shale
	1970s	The Eastern Gas Shale Project was established by the Morgantown Energy Research Center (MERC) due to the production decline of domestic gas
1950	1947	Hydraulic Fracturing was first applied to develop natural gas from limestone
1820	1821	The development of natural gas from Fredonia Shale in New York

1.3.7 Shale Play Attributes

Shale plays with hydrocarbon production potential have specific characteristics that distinguish them from shale beds with little or no potential. Such desirable attributes are: high gas content, gross thickness, relatively large gas filled porosity, low water saturations, sufficient volume and maturity of the total organic carbon (TOC), permeability above 100 nD, being over pressured and being at relatively shallow depth. Assuming the geology is favorable for unconventional shale development, the next question is how to fracture the shale to create a permeable fracture network, considering the presence of fracture barriers (that would impede or stop fracture propagation), natural fractures and stress anisotropy. This technical task requires an understanding of the brittleness and frackability of the shale. Nash, 2014 gives a checklist of desirable attributes of shale.

CHAPTER 2

LITERATURE REVIEW

"If I have seen further it is by standing on the shoulders of giants"
Isaac Newton

This chapter entails a review on: (1) mechanical properties of shale, (2) early ideas on brittleness (3), brittleness of rock, (4) the brittleness of shale, and (5) frackability of shale. This review will be serving as a framework to answer some of the research questions listed in the previous chapter and guide the approach in the other chapters of the thesis.

2.1 Mechanical Properties of Shale

There is a rich body of reviews on the physical properties of shale ranging from experimental work (Kaarsberg 1958; Lo et al. 1986; Asef 1995; Asef, 2001; Asef et al. 2000; Reddish et al. 2000; Asef and Reddish 2002; Horsrud, 2001; Chang et al., 2006) to theories (Hornby et al., 1994) modeling the elastic properties of shales using an anisotropic effective-medium theory.

The experimental studies have led to several empirical relations between porosity and other physical properties of sedimentary rocks. Among the semi-empirical relations are those between porosity and acoustic velocity (Wyllie et al. 1956; 1958); elastic moduli and porosity for silisiclastic rocks (Dunn et al., 1973; Hoshino, 1974; Hoshino et al., 1972; Vernik and Nur, 1992 and Hornby 1998); elastic moduli for carbonates (Kowalski, 1966; Kelsall et al., 1986; Jones and Preston, 1987; Allison, 1987; Kamel et al. 1991;

Asef and Farrokhrouz, 2010a); for porosity as the best single-variable predictor of strength in sedimentary rocks (Vernik et al., 1993); compressional and shear wave velocities as function of confining pressure (Jones and Wang 1981) and shale anisotropy (Banik 1983). In general, if porosity is considered, then assuming poro-elastic behavior of shale would be more useful than the model because it does not need the assumption of perfect elastic (Farrokhrouz and Asef 2012a, b).

2.2 Early Ideas on Brittleness

The deformation, fracture and/ or failure of materials (these words have been used interchangeably in the literature) are found to be governed by eight mechanisms Orowan (1949): (1) brittle fracture (cleavage fracture), (2) rupture (by localization of plastic deformation), (3) fibrous fracture, (4) shear fracture, (5) fatigue fracture, (6) intergranular viscous fracture (creep fracture), (7) intergranular brittle fracture, (8) special types of fracture. The prominent among the eight is brittle fracture. Rupture and shear fracture are both classified as ductile fractures. As a result, the deformation, fracture and/ or failure of materials are governed by their tendency of being brittle or ductile. It is worth mentioning that brittle deformation, brittle fracture or brittle failure have the same meaning.

Brittleness usually means being prone to catastrophic damage. It has been a long-standing problem that cuts across material sciences, metallurgy, rock mechanics, geotechnical and mining engineering, petroleum engineering (e.g. drilling and wellbore stability etc.). The earliest and most prominent reference to brittleness is that of Griffith (1921, 1924). Prior to the work of Griffith, two hypotheses were found useful for a solid elastic material to fracture or rupture. Both of these hypotheses state that the maximum tensile stress and maximum extension must be greater than certain critical values. Also, the theoretical strength of a material used to be taken as one-tenth of the Young's modulus. It was later observed that the true strength (critical strength) of a material is much less than the predicted value (about a thousand times lower). In 1921, Griffith found these hypotheses not appropriate and also investigated the discrepancy between the observed and predicted strengths of metals and glass. He postulated that the large reduction in strength is due to the presence of cracks that act as stress concentrator (stress magnifier) causing the material to fracture before reaching the theoretical strength limit. Using the energy approach, he reformulated the minimum energy theorem for brittle materials to describe the behavior of elliptical cracks using the solution of Inglis (1913). He developed a theoretical criterion which states that the formation of new surfaces in the form of cracks requires a potential energy (surface energy) to overcome the cohesive energy of the molecules. In other words, when the gain in the surface energy is in equilibrium with the strain energy loss, then the crack is sufficient to fracture the material. Due to the difficulties of an energy- based experiment, the Griffith energy theory was recast in the form of stress as given in the equations 2.1 to 2.7.

$$W_t = W_e + W_s \tag{2.1}$$

$$W_e = \frac{\pi c^2 (\sigma_t)^2}{E} \tag{2.2}$$

For a thick plate, this Equation (2.2) becomes

$$W_e = \frac{(1-v)\pi c^2 (\sigma_t)^2}{E} \tag{2.3}$$

$$W_s = 4\,\alpha\,c \tag{2.4}$$

where W_t is the total potential energy, W_e is the stored strain elastic energy, W_s is the surface energy due to crack, σ_t is the tensile strength, E is Young's modulus, α is the surface energy and c being the half crack length.

Equations 2.2 and 2.4 led to the first Griffith failure Criterion (Equation 2.5) for crack initiation to occur under plane tensile stress loading.

$$\frac{d}{dc}(W_e - W_s) = \frac{2\,\pi c}{E}(\sigma_t)^2 - 4\alpha \geq 0 \; or \; \sigma_t \geq \sqrt{\frac{2\,\alpha\,E}{\pi\,c}} \tag{2.5}$$

As strain is sometimes more preferable to stress in geophysics, an equivalent form of the Equation 2.5 for plane strain condition is given in the form of the Equation 2.6

$$\sigma_t \geq \sqrt{\frac{2\,\alpha\,E}{\pi\,c(1 - \,v^2)}} \tag{2.6}$$

There are several empirical relations between compressive and tensile stresses, with compressive stress always being greater than the tensile stress. Griffith (1921) expressed compressive stress as eight times larger than the tensile stress and transformed the Equation 2.5 under compression into

$$\sigma_c \geq 8 \times \sqrt{\frac{2\,\alpha\,E}{\pi\,c}} \tag{2.7}$$

where σ_c is the compressive strength.

Sack (1946), Elliott (1947) and Irwin (1957) extended the work of Griffith. Sack (1946) treats the ellipsoidal crack in Griffith's work as a flat oblate ellipsoid, commonly known as “penny shaped” crack. His result only differs from that of Equation (2.5) with $\frac{2}{\pi}$ being replaced with $\frac{\pi}{2}$. Similar to the work of Sack (1946), Elliott (1947) took into consideration the interatomic forces across crack planes and quantified the error due to the assumption of the ellipsoidal crack. Orowan (1934a) takes the molecular cohesion into account to derive an equation similar to the Equation 2.5 but the numerical factor of $\frac{2}{\pi}$ becoming $\frac{1}{2}$.

The results of Sack (1946) and Elliott (1947) give similar fracture condition to the Equation 2.5 except for the differences in the numerical coefficients which are within an acceptable order of magnitude.

The works of Griffith were mainly for brittle materials like glass, ceramic and metals and served as a foundation to understanding the brittleness of materials, Irwin, (1950) extended Griffith's work to ductile materials by introducing an additional energy term for plastic deformation to create the new surface. The contributions of Griffith and Irwin gave birth to the linear elastic fracture mechanics (LEFM) with the introduction of the stress intensity factor. Unlike the stress concentration (stress multiplier) in the case of Griffith, stress intensity factor as introduced by Irwin is the distribution of stresses around a crack that explains the three mechanisms for fracture occurrence as Mode 1 (tensile opening), Mode 2 (shear opening) and Mode 3 (tearing) respectively. A recent study of Ferrill et al. (2012a) suggests that transition between the different modes referred to as hybrid failure should be taken into consideration.

The Griffith’s theory failed to account for the kinetic energy which in turn makes it difficult to use to determine the propagation of the crack. Adopting the results of Mott

(1948), Berry (1960a) proposed the Griffith crack locus on the stress-strain curve as the point at which the crack will begin to propagate. The possibility to estimate the velocity of the crack has been provided by Mott (1948) who suggested correlating the acoustic emissions to the failure of the material (and to its brittleness or ductility), see Scholz (1968); Sondergeld et al., (1984); Byerlee and Lockner (1977); Lockner and Byerlee (1977); Lockner,(1993); Eberhardt et al., (1998); Rao (196, 2004); Rao et al., (2006); Stanchits et al.,(2012) etc. Also, the LEFM gives the relation between the energy release rate G (crack driving force or energy per unit surface area) and the stress intensity factor K in the Equation (2.8).

$$G = \frac{(1 - v^2)}{E} (K_I)^2 \tag{2.8}$$

where E is the Young's modulus, v is the Poisson's ratio, K is stress intensity factor with K_I being the stress intensity factor under mode 1 (opening mode due to tensile stress).

Approximating the surface energy term due to cracks α in Griffith criterion as $\alpha \approx \frac{1}{2} G$

$$\alpha \approx \frac{(1 - v^2)}{2E} (K_I)^2 \tag{2.9}$$

The criterion for crack growth is given in the Equation (2.10)

$$\frac{(1 - v^2)}{E} K^2 \geq 2\,\alpha + w_p(K, \alpha) \tag{2.10}$$

where $w_p(K, \alpha)$ is the work needed for the plastic deformation at the crack tip.

2.3 Brittleness of Rock

Brittle fracturing theory has found useful application in rock mechanics to predict brittle fracture in rocks under load. Murrell (1958) proposed to apply the work of Griffith (1921, 1924) to predict brittle fracture. Rocks subjected to compressive stress field, require the modification of Griffith's theory by McClintock and Walsh (1962) to account for friction. From Griffith's theory (Equation 2.5) it is evident that the strength of a material in terms of the applied stress varies inversely with the square root of the crack length implying that the smaller the crack length, the stronger the material. In the case where the grain boundary acts as a crack that serves as a stress concentrator, the Equation 2.5 has been proven by many authors to be valid for ice Knudsen (1959), quartzite, basalt, and limestone Brace, (1961, 1964), limestone Olsson (1974). Several other theories and empirical relations have been proposed to predict failure of rock: maximum normal stress theory; Tresca yield criterion; distortion energy theory (Von Mises theory); Coulomb-Navier criterion; Mohr - Coulomb and Hoek – Brown criteria. Other parameters that are related to brittleness are fatigue strength, endurance limit, stress concentration factor, stress intensity factor, fracture toughness etc.

While brittleness is considered one of the most important mechanical properties of rocks, there is no standardized definition for brittleness; different concepts are used based on the interest of the researcher. According to Hetenyi (1966) "brittleness is the lack of ductility". According to Ramsey (1967), brittleness is "the collapse of the internal cohesion of rocks". In the opinion of Obert and Duvall (1967), brittleness is the "termination of a material (e.g. cast iron and some rock) by fracture when the yield stress is exceeded". Obert and Duvall (1967). Hucka and Das (1974) define brittleness based on low values of elongation; fracture failure; formation of fines; higher ratio of compressive to tensile strength; higher resilience; higher angle of internal friction; formation of cracks in indentation. Denkhaus (2003) claims that brittleness is "not a rock property but a way to distinguish two processes: ductile fracture with plastic deformation or brittle fracture without plastic deformation". They all agreed on the absence of plastic flow.

The investigation of Baron (1962); Protodyakonov (1963); Coates (1966); Bishop (1967); Hucka and Das (1974); Altindag (2003); Hajiabdolmajid and Kaiser (2003) have led to some semi-empirical equations to estimate brittleness (see Table 2.1). The contributions of Singh (1986); Goktan (1991); Kahraman (1999); Kahraman et al. (2003a, b); Gunaydin et al.(2004); Kahraman and Altindag (2004); Yarali and Soyer (2011) and Yilmaz et al. (2008); Yarali and Kahraman (2011) were also valuable the study of brittleness.

2.4 Brittleness of shale

The recent development of oil and gas from unconventional shale needs to identify, “sweet spots’’ (optimal zones for initiation of hydraulic fractures with high brittleness or frackability indices) in order to optimize hydraulic fracturing. This has boosted a large interest and many contributions from geoscientists and engineers to understand the brittleness and frackability of shale plays. As Ortega and Aguilera (2012) stated, the more brittle a zone in a tight formation, the more likely for this zone to be naturally fractured.

In terms of the composition of shale plays, the brittleness or brittleness index (BI) is defined as the ratio of brittle to total constituents respectively. This approach broached from geochemical analysis had been useful to understand and compute the brittleness of unconventional shale Jarvie et al., (2007). Grieser and Bray (2007) linked brittleness to geomechanical properties popularized by Rickman et al., (2008). Ding et al (2012) claimed that brittleness of shale plays is proportional to the fraction of quartz (high silica content). Ductility on the other hand is attributed to the high fraction of organic matter in clay, the component that is also responsible for creep behavior in shale Abouelresh and Slatt, (2012); Sone and Zoback, (2011); Li and Ghassemi, (2012). The ternary plot (Figure 2.1) of quartz, carbonate and clay plus organic matter based on the mineralogical composition of shale is one popular way to quantify or predict brittleness or ductility.

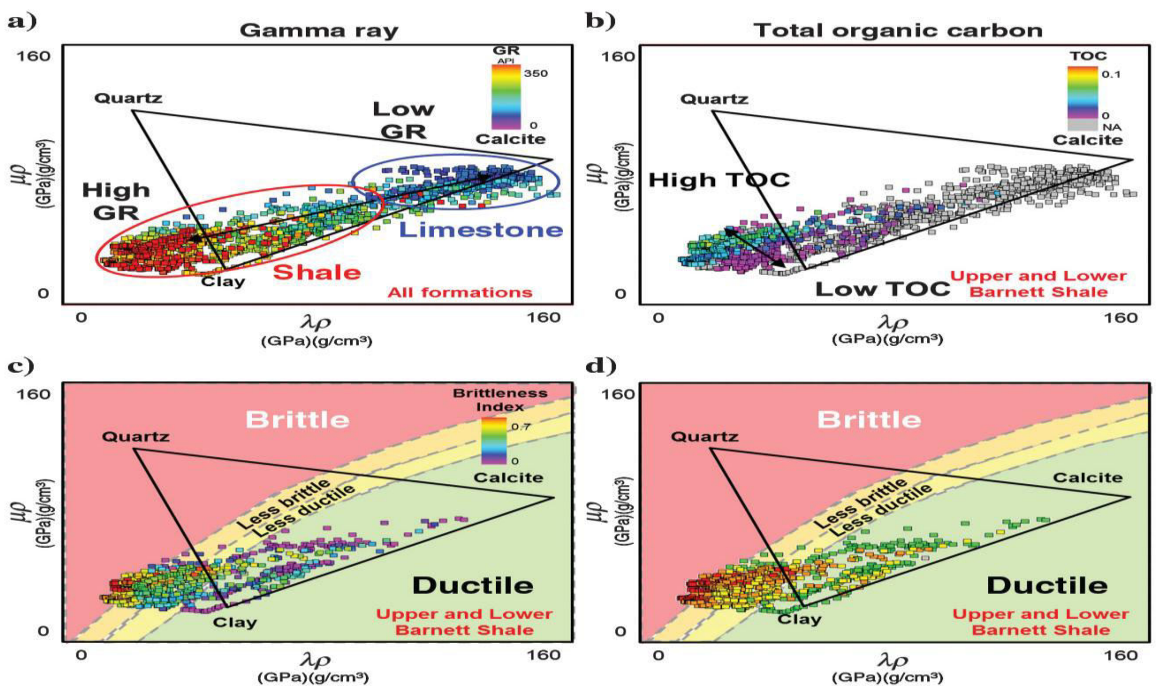


Figure 2.1: Ternary plot for brittleness prediction from Perez and Marfurt (2013)

Apart from the mineralogy of shale, a different way to approach its brittleness is from its elastic parameters, notably Young's modulus, Poisson's ratio, bulk modulus (k), shear modulus (μ) and Lamé's parameter (λ) which are readily available from laboratory (from uniaxial test) as well as from well log data (sonic logs) and seismic data via seismic inversion. Those properties from the laboratory are referred to as static which are normally different from the dynamic (in-situ) properties which are determined from well logs and seismic data. In general, static (laboratory) elastic parameters are lower than the corresponding dynamic parameters. The reason for this deviation may be due to the fluid saturation difference during the measurement of rocks between static and dynamic conditions. Young's modulus is a measure of the stiffness of the rock, Poisson's ratio indicates the tendency of the rock to fail, bulk modulus is a measure of the compressibility of the rock, and shear modulus is a measure of its rigidity. According to Grigg, (2004); Rickman et al. (2008); Brit and Schoeffler, (2009); Parney, and Lange (2010); Slatt (2011);Varga et al., (2012); Gray et al., (2012); Holden et al., (2013) Varga et al., (2013); Sahoo et al., (2013); Wanhui et al., (2014); these elastic parameters have been found useful to predict the brittle and ductile behavior of shale.

The difficulty of estimating the elastic parameters like Young's modulus from seismic attributes has promoted the combination of these elastic parameters with density to delineate brittle intervals in shale for oil and gas development. This idea was pioneered by Goodway et al. (1997) who used the amplitude versus offset (AVO) inversion technique to derive $\lambda\rho$ & $\mu\rho$ (LamdaRho, MuRho short as LMR) to estimate how rocks fracture. However, Leon Thomsen discredits the unknown Lamé's parameter λ in his 2002 *Distinguished Instructor Short Course*. He emphasized further in Thomsen (2012) that the use of isotropic parameters λ, E, ν to understand anisotropic shale remains questionable. Goodway et.al, (2010) disagree with Thomson's assertion, and claim that λ or $\lambda\rho$ are the best discriminators of gas shale from ductile shales, unfrackable calcareous shales and carbonates. Dabagh et al. (2011) found $\kappa\rho$ and $\lambda\rho$, (where κ is compressibility) as useful attributes to discriminate fluid in clastic rocks. Sharma and Chopra, (2013) combine $E\rho$ and $\kappa\rho$ as a lithology and brittleness indicator in shale reservoirs.

Gray et al. (2010) describe a method for the estimation of rock strength and the principal stresses between wells from 3D seismic data. Sharma and Chopra (2013) used the product of Young's modulus and Poisson's ratio with density ($E\rho$ and $\mu\rho$) respectively to predict lithology and estimate the brittleness of shale. Gray et al. (2012) constructed a template of MuRho versus LamdaRho cross-plot to delineate brittle and ductile zones for the estimated ultimate recovery (EUR). Maity (2013) proposed the analysis of various seismic attributes and inversion of 3D seismic volume, integrated (if available) with micro earthquake data, to predict production and optimum drilling and hydraulic fracturing program design. Olusola (2013) analyzed drill cuttings to estimate brittleness for hydraulic fracture design optimization.

While the three prominent ideas to approach brittleness of shale are through mineralogical composition, Young's modulus versus Poisson's ratio (YMVPR) and LMR cross plots, the practical difficulties of the mineralogy approach and its cost make elastic parameters more pertinent to geophysicists. Discrepancies between the three approaches have been pointed out. Authors like Gatens et al., (1990); Ahmed et al., (1991); Miller et al., (1994); Rickman et al., (2007) claimed that high Young's modulus and low Poisson's ratio indicate high quartz (silica), feldspar, and carbonate content and hence greater brittleness. Guo et al., (2012); Perez and Marfurt (2013); on the other hand, find better agreement of the mineralogy based estimate of brittleness with the LMR compared to

YMVPR. Gale et al., (2014) also discredit the YMVPR approach. Herwwanger et al, (2015) advocate brittleness estimated from the ratio of compressive and tensile strength; high Young's modulus and Poisson ratio are respectively equivalent to the brittleness from mineralogy using published data on the elastic constant of minerals.

Other authors like Ingram and Urai (1999); Nygård et.al., (2006); Ishii et al. (2011); Guo et al.,(2012); Han et al., (2013), Jin et al. (2014) consider a different perspective to evaluate brittleness of shale. Slatt and Abousleiman (2011) finds the Gamma Ray (GR) log as a pre-assessment tool to discriminate brittle and ductile couplets of shale. Insights from the laboratory studies of Holt et al., (2011) led them to the conclusion that brittleness is likely to be anisotropic and fluid sensitive. From the acoustic emission monitoring experiment of Sondergeld et al., (2013) and Song et. al., (2014) brittle rocks would have higher acoustic emission rate than ductile ones. Cho and Perez, (2014) claim that, as previous studies fail to account for failure criteria, porosity and mineralogy would give better estimate of shale brittleness. The Equation in B_1 in the next Table and its modified forms can also be found in Gary et.al (2012), Guo et al (2015) and Zhishui and Zandong (2015). The equations for brittleness by some of these authors are listed in Table 2.1.

Table 2.1: Equations for Brittleness Estimation

Brittleness Equation B	Parameters	Reference
$B_1 = \frac{W_r}{W_t}$	W_r :reversible energy, W_t : total energy	Baron (1962)
$B_2 = q\sigma_c$	σ_c:uniaxial compressive strength q:percentage of fines	Protodyakonov (1963)
$B_3 = \frac{\varepsilon_r}{\varepsilon_t}$	ε_r : reversible strain ε_t: total strain	Coates (1966)
$B_4 = \frac{\tau_P - \tau_R}{\tau_P}$	τ_P: peak strength τ_R:residual strength	Bishop (1967)
$B_5 = \sin\theta$	θ : angle of internal friction	Hucka and Das (1974)
$B_6 = \frac{\sigma_c - \sigma_t}{\sigma_c + \sigma_t}$	σ_c: Uniaxial compressive strength σ_t:tensile strength	Hucka and Das (1974)
$B_7 = \frac{H_\mu - H}{K}$	H_μ:micro-indentation hardness, H:macro-indentation hardness, K: constant	Hucka and Das(1974)
$B_8 = \frac{\sigma_c}{\sigma_{NC}}$	σ_c: Uniaxial compressive strength, σ_{NC}: Uniaxial compressive strength at normal consolidation	Ingram and Urai (1999)
$B_9 = \frac{\sigma_c}{\sigma_t}$	σ_c: Uniaxial compressive strength σ_t:tensile strength	Altindag (2002)
$B_{10} = \frac{\sigma_c \times \sigma_t}{2}$	σ_c: Uniaxial compressive strength σ_t:tensile strength	Altindag (2002)
$B_{11} = \frac{\varepsilon_{p_f} - \varepsilon_{p_c}}{\varepsilon_{p_c}}$	ε_{p_f}: Plastic strain at failure ε_{p_c}: specific strain after failure	Hajiabdolmajid and Kaiser (2003)
$B_{12} = \left(\frac{\sigma_{P_M}}{\sigma_V}\right)^b$	σ_{P_M}: maximum effective pressure in the past σ_V: the present day effective, b: empirical constant	pressure Nygård et.al.(2006)
$B_{13} = \frac{Q}{Q+C+CLY}$	Q: quartz, C:calcite, CLY:clay	Jarvie (2008)
$B_{14} = \left(\frac{E-1}{7} + \frac{-1(v-0.4)}{0.25}\right) \times 0.5$	E:Young's modulus, v: Poisson ratio	Rickman et al. (2008)
$B_{15} = \frac{Q+D+C}{Q+C+CLY+TOC}$	Q: quartz, C:calcite,D: dolomite CLY:clay, TOC: Total organic content	Wang and Gale (2009)
B_{16}= Plot of $\lambda\rho$ versus $\mu\rho$	λ and μ: Lame's parameters	Goodway et. al 2010
$B_{17} = \frac{\sigma_c}{\sigma_V}$	σ_c: Uniaxial compressive strength σ_V: effective vertical stress	Ishii et al.(2011)
$B_{18} = \frac{E}{v}$	E: Young's modulus v : Poisson's ratios	Guo et al (2012)
$B_{19} = \frac{\lambda + 2\mu}{\lambda}$	λ and μ are the Lame's parameters	Guo et al. (2012)

Table 2.1: Equations for Brittleness Estimation (Continued)

Brittleness Equation B	Parameters	Reference
$B_{20}= 0.5\ \times \left(\frac{E-E_{min}}{E_{max}-E_{min}} + \frac{v-v_{min}}{v_{max}-v_{min}}\right)$	E, E_{min} and E_{max} : instantaneous, minimum and maximum Young's modulus respectively while v, v_{min} and v_{max} : instantaneous, minimum and maximum Poisson's ratios	Gary et.al (2012)
$B_{21} = E\rho$	E: Young's modulus ρ : density	Sharma and Chopra (2012)
$B_{22} = \frac{M-E}{M}$	E: Young's modulus M: post peak modulus	Tarasov and Yves (2013)
$B_{23} = \frac{E}{M}$	E: Young's modulus M: post peak modulus	Tarasov and Yves (2013)
$B_{24} = \frac{M}{E+M}$	E: Young's modulus M: post peak modulus	Tarasov and Yves (2013)
$B_{25} = \frac{M}{E}$	E: Young's modulus M: post peak modulus	Tarasov and Yves (2013)
$B_{26} = \frac{W_{QFM}}{W_T} + \frac{W_{Carb}}{W_T} \cong \frac{W_{QFM} + W_C + W_D}{W_T}$	w_{QFM} : W weight fraction, QFM: quartz, feldspar and mica), Carb: carbonates, D: of dolomite, C : calcite T: total mineral	Jin et al. (2014)
$B_{27} = \frac{E}{\lambda}$	E: Young's modulus, λ :Lame's parameters	Chen et al. (2014)
$B_{28} = \frac{3K-5\lambda}{\lambda} = \frac{1}{v} - 4$	E: K: bulk modulus v is Poisson ratio	Xin-Rui et. al, (2015)
$B_{29}= \frac{\left(\frac{B}{KIC}\right) I - \left(\frac{B}{KIC}\right) m}{\left(\frac{B}{KIC}\right) M - \left(\frac{B}{KIC}\right) m}$ $B= \alpha\,\frac{E-E_m}{E_M-E_m} + \beta\,\frac{v-v_m}{v_M-v_m}$	B: Dimensionless coefficient, KIC: Fracture toughness, α and β: influence coefficients I, m and M: instantaneous, minimum and maximum respectively	Guo et al. (2015)
$B_{30}= \frac{0.1\,E}{0.25(v-0.4)}$	E: Young's modulus v : Poisson's ratios	Zhishui and Zandong (2015)

2.5 Frackability of Shale

The concepts of frackability F or frackability index (FI) and brittleness of shale plays have led to some controversy among researchers in academia and industry. However, the two concepts have similar definition as the attribute that shows how easy is the creation of hydraulic fractures that would enhance permeability. The basis of these controversies is related to the preferred concept or attribute as regards the hydraulic fracturing of shale. Many authors claimed that brittleness is the same as frackability (Rickman et al. 2008; Brit and Schoeffler, 2009; Parney, and Lange. 2010; Verma S. et al., 2012; Varga et al., 2012; Gray et al., 2012; Holden et al., 2013 Varga et al., 2013; Sahoo et al., 2013; Tran et al., 2014; Wanhui et al., 2014), However, according to Vernik et.al. (2012); Mullen, (2012); Hall, (2012); Jin et al. (2014), frackability is a more useful concept and better technical terminology in the understanding of hydraulic fracturing.

Mullen and Enderlin (2012) introduced the Complex Frackability Index (CFI) that encompasses rock fabric, stratigraphy, distribution of minerals and planes of weakness as well as the brittleness index defined from Brinell hardness as the main input parameter. Jin et al. (2014) find frackability to be more approachable in terms of the fracture gradient, fracture barrier and the strength of formation (fracture toughness). He proposed three equations for frackability as the average of the normalized (1) brittleness and dissipation of strain energy; (2) brittleness and fracture toughness and (3) brittleness and Young's modulus. Hu et al., (2015) presumed frackability to be the same as the fracture gradient and claimed it is in a nonlinear inverse relation with TOC. Some expressions for the frackability of shale in the literature are:

- Jin et al. (2014) $F = \frac{B_N+G_N}{2} = \frac{B_N+K_N}{2} = \frac{B_N+E_N}{2}$ $B_N = \frac{BI-BI_{min}}{BI_{max}-BI_{min}}$ $G_N = \frac{BI-BI_{min}}{BI_{max}-BI_{min}}$ $K_N = \frac{K-K_{min}}{K_{max}-K_{min}}$ $E_N = \frac{E-E_{min}}{E_{max}-E_{min}}$ (2.30)

  where B, G, K, E are brittleness, strain energy rate, fracture toughness, and Young's modulus of the interval of interest. The subscript N, max, min stand for normalized, maximum and minimum.

- Hu etal.,(2015)
  $F = fracture\ gradient = \frac{v}{1-v}\sigma + P_p$ (2.31)
  where v is the Poisson's ratio, σ is the effective stress gradient and P_p is the pore pressure gradient.

CHAPTER 3

LABORATORY EXPERIMENTS

> "The truth is, the Science of Nature has been already too long made only a work of the brain and the fancy. It is now high time that it should return to the plainness and soundness of observations on material and obvious things"
>
> Robert Hooke

This chapter presents the laboratory measurements; whose objective was to characterize the mineralogical and petrophysical properties of eight subsurface unconventional shale samples from the Rub' Al-Khali Basin, Saudi Arabia and to shed light on the subsequent chapters (Chapter 4 and 5). The petrophysical characterization includes Micro-CT imaging, bulk density, grain density-, porosity, and velocity measurements. The mineralogy of the samples' was determined with XRD.

3.1 Rock Description and Preparation

The rock samples used for this study were from the Qusaiba Shale, taken from a 30 ft. interval of the continuous Qalibah Formation (Lower Silurian age) from the Rub' Al-Khali Basin. More detailed description of the geological characteristics can be found in Mustafa et. al; (2014). Four cylindrical pairs of well-preserved subsurface shale plugs (horizontal and its vertical equivalent) making a total of eight plugs of about 25.4 mm (1-inch) diameter was obtained from the repository of the Ministry of Petroleum and Mineral Resources, Saudi Arabia. The plugs were cored from the subsurface, but stored at room condition and this, coupled with the plugging process, could probably have influenced their measured physical properties compared to their *in situ* values. The shale plugs are denoted as 1H and 1V; 2H and 2V; 3H and 3V; 4H and 4V. The plugs are black in color and relatively heavy as compared to other unconventional shale samples. The end faces of the plugs were grinded to a parallelism accuracy of 0.001 and their length after grinding varied from 38 - 55 mm (1.5 - 2.2 inch).

3.2 Micro CT Imaging

The micro-CT imaging facilities of the Centre for Petroleum and Minerals (CPM), KFUPM, was used to visualize the interior structure of four pairs of subsurface shale plugs (horizontal and its vertical equivalent) making a total of eight plugs 1H and 1V; 2H and 2V; 3H and 3V; 4H and 4V. However, the unavailability of the processing software limited the identification and quantification of the pore space, grains and organic minerals from these images presented in Appendix A.

3.3 Density and Porosity Measurements

The densities of the plugs were determined from their weight and dimensional measurements. The geometric dimensions of the samples were averaged over four measurements determined with a digital caliper to estimate their bulk volume. A digital mass balance was used to measure the weight (mass) of the plugs. Hence, the dry density of the samples was determined from the ratio of the mass to the volume. The density of the plugs varied from 2.57 – 2.73 g/cc -3 and the grain density measured with the Pycnometer of Baker Hughes DGTC (Dhahran Global Technology Center). The porosity of the sample was estimated from the dry bulk density and the grain density (see Table 3.1) using the Equation 3.1

$$Porosity = 1 - \frac{bulk\ density}{grain\ density} \tag{3.1}$$

Table 3.1: Dry bulk density, grain density and Porosity measurements

Plug	L (mm)	D (mm)	AL (mm)	AD (mm)	V (cc)	W (g)	Bulk Density (g/cc)	Grain Density (g/cc)	Porosity (%)
1H	41.75	25.21	41.42	25.2	20.65	54.71	2.65	2.81	5.71
	41.46	25.13							
	41.66	25.24							
	40.8	25.23							
1V	38.44	25.25	38.73	25.26	19.40	51.39	2.65	2.75	3.67
	38.9	25.27							
	38.71	25.26							
	38.87	25.25							
2H	52.67	25.23	52.72	25.03	25.93	70.89	2.73	2.78	1.65
	52.78	25.24							
	52.76	24.87							
	52.67	24.78							
2V	52.34	25.23	52.33	25.18	26.05	68.84	2.64	2.77	4.58
	52.33	25.2							
	52.32	25.12							
	52.32	25.15							

Table 3.1: Dry bulk density, grain density and Porosity measurements (Continued)

3H	52.15	25.31	52.15	25.32	26.25	70.14	2.67	2.79	4.21
	52.13	25.35							
	52.18	25.33							
	52.13	25.3							
3V	43.31	25.33	43.31	25.33	21.81	56.1	2.57	2.84	9.44
	42.84	25.36							
	42.24	25.75							
	42.63	25.25							
4H	55.04	25.21	55.05	25.24	27.53	74.93	2.72	2.78	2.09
	55.05	25.25							
	55.05	25.22							
	55.04	25.26							
4V	48.81	25.23	48.59	25.27	24.36	63.95	2.63	2.8	6.23
	48.44	25.25							
	48.49	25.24							
	48.65	25.35							

L: length, D: diameter, AL: average length, AD: average diameter, V: volume, W: weight

3.4 Velocity Measurements

In this study velocity measurements were carried out under hydrostatic condition of varying confining pressures at 5 MPa up to 35 MPa steps, differential load and temperature to simulate in situ condition on four plugs (excluding four other plugs) using the triaxial New England Research (NER) Autolab500 at Baker Hughes DGTC. The limitation of the Autolab500 on the geometric factor of 2 for the length to diameter ratio of the plugs required the exclusion of the four other plugs from velocity measurements.

The orientation of the bedding plane for the vertical plug (2V) was constant for isotropic case. But to account for anisotropy as adopted by Jin et al. (2015), the orientation of the bedding plane respectively at $0^o, 45^o$ and 90^o were repeated in turn for each horizontal plug. The shale plugs were then secured in a cylindrical rubber jacket riveted with a steel wire to prevent the confining fluid from getting into the sample and keep the pore pressure constant. Precautions were taken to properly align the axial and radial transducers to the correct orientation of the bedding planes for all velocity measurements. The parallel end faces of the plugs ensured good coupling of the plugs with the transducers to reduce noise. The waveforms of the compressional and shear wave velocities of each measurement were observed from the oscilloscope. An analysis of raw traces by manual picking of the first arrival was done to calculate the velocities see (Table 3.2 and 3.3).The details of the velocity waveform are given in the Appendix B.

Table 3.2: Velocity measurement of vertical plug at constant orientation

Plugs	Density (g/cc)	CP	Velocity				
			V_P	V_{SI}	V_{S2}	$\left[\frac{V_{SI} - V_{S2}}{V_{S2}}\right] X100\%$	$V_{S\ Average}$
2V	2.64	5	4354	2905	2867	1.33	2886
		10	4629	2958	2951	0.24	2954.5
		15	4767	3083	2984	3.32	3033.5
		20	4986	3186	3029	5.18	3107.5
		25	5004	3274	3064	6.85	3169
		30	5165	3326	3087	7.74	3206.5
		35	5232	3410	3111	9.61	3260.5

Table 3.3: Velocity measurement of horizontal plugs at different orientations

Plugs	CP	0 Degree			45 degree			90 degree		
		$V_{P,0^0}$	$V_{S1,0^0}$	$V_{S2,0^0}$	$V_{P,45^O}$	$V_{S1,45^O}$	$V_{S2,45^O}$	$V_{P,90^O}$	$V_{S1,90^O}$	$V_{S2,90^O}$
2H	5	5112	3235	1887	3985	2628	2366	3320	2181	2057
	10	5212	3275	1966	4033	2736	2392	3495	2187	2100
	15	5424	3343	2031	4330	2784	2466	3705	2261	2163
	20	5439	3329	2067	4426	2844	2512	3971	2341	2205
	25	5499	3343	2089	4578	2854	2552	4135	2376	2248
	30	5537	3343	2109	4610	2895	2585	4148	2426	2267
	35	5575	3343	2131	4610	2885	2619	4236	2456	2300
3H	5	4999	3069	2480	3608	2210	2303	5255	3280	3241
	10	5191	3103	2533	3674	2307	2303	5374	3306	3266
	15	5328	3102	2558	3759	2379	2465	5426	3342	3285

Table 3.3: Velocity measurement of horizontal plugs at different orientations (Continued)

	20	5436	3122	2585	3904	2401	2606	5480	3332	3285
	25	5563	3135	2557	4041	2459	2695	5535	3339	3305
	30	5992	3151	2554	4103	2452	2778	5609	3352	3305
	35	5586	3135	2570	4218	2477	2857	5572	3346	3305
4H	5	5303	3140	2593	4358	2754	2281	3668	2275	2104
	10	5410	3228	2645	4555	2822	2389	3761	2314	2141
	15	5521	3267	2653	4672	2893	2455	3992	2362	2195
	20	5521	3321	2662	4783	2909	2485	4066	2393	2213
	25	5598	3313	2653	4811	2967	2516	4191	2435	2238
	30	5598	3321	2671	4929	2994	2548	4258	2468	2263
	35	5637	3321	2671	4929	3034	2556	4312	2507	2289

CP is the confining pressure in MPA. $V_{P,0^0}, V_{S1,0^0}, V_{S2,0^0}$ are the P wave velocity, the fast and slow shear wave velocity for horizontal plug at 0^0 degree orientation. $V_{P,45^0}$, $V_{S1,45^0}, V_{S2,45^0}$are the quasi P-wave, quasi fast and slow shear wave velocity at 45^0 degree orientation, $V_{P,90^0}$, $V_{S1,90^0}$, $V_{S2,90^0}$ are P wave , the fast and slow shear wave velocity at 90^0 orientation. The velocity is measured in m/s

3.5 Mineralogical Composition and XRD Analysis

From the XRD analysis, the average mineralogical composition of the eight samples in weight percent is given in Table 3.4. The results from the XRD studies show that quartz, albite, muscovite and kaolinite are predominantly present in the shale sample with sample 1V very rich in Quartz and 3V very rich in clay (Kaolinite). It is evident from these results that carbonate minerals are not present or in insignificant amount. The details of the XRD analysis are given in the Appendix C.

Table 3.4: Mineralogical Composition of Eight Shale Samples

Plugs	Quartz (%)	Albite (%)	Muscovite (%)	Kaolinite (%)
1H	63.2	36.8		
1V	66.5	33.5		
2H	20.5	22.5	57	
2V	62	38		
3H	15.8	16.3	68	
3V	13.3	13.6	51	22.3
4H	35.8	26.8	37.4	
4V	18.1	12.9	50	18.9

CHAPTER 4

QUANTIFYING BRITTLENESS

“The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them”
Sir William Bragg

The concept of brittleness is a long-standing problem in material science, engineering and crustal studies and is even becoming more important and controversial for shale exploration. The main problem is that the term brittleness is not well defined and could still not be satisfactorily explained from physical principles. This in turn leads to different ambiguous interpretations.

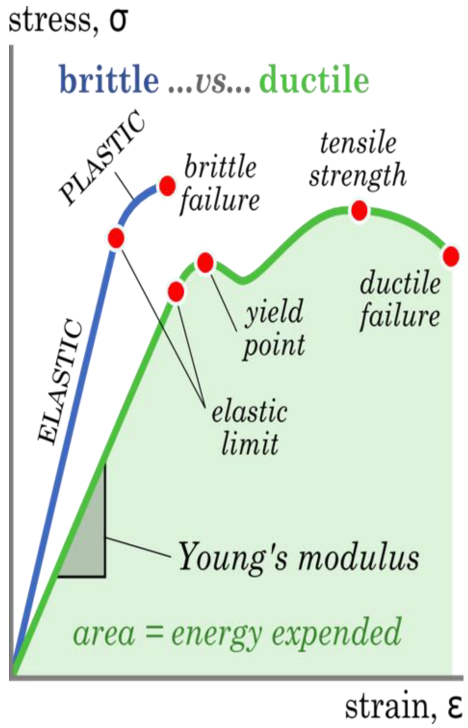
My first attempt to derive an analytical expression for brittleness and ductility as relative scalar parameters using the method of dimensional analysis of Buckingham (1914) was not successful due to the implicit form of these variables (confining pressure, density, depth, velocity, strain rate and viscosity). I went further to consider the constitutive law of Hooke’s and defined the brittleness of the rock as dimensionless parameter with a simple formula derivable from the ratio of elastic constants vis-a-vis acoustic velocities.

4.1 The Stress-Strain Curve and Brittleness

The rheological behaviors of rocks are governed by appropriate constitutive equations. The rheology of rocks at low strain, low pressure and low temperature is typically governed by the linear elastic stress-strain law of Hooke. Hooke’s law for an isotropic rock is given by the Equation 4.1a. From the graphical analysis of the stress-strain curve any material specifically rock would be brittle or undergo brittle deformation at low strain compared to being ductile at relatively large strain. It is therefore easy to qualitatively tell if a material is brittle or ductile from an ideal stress-strain curve (Figure 4.1a) as different materials have unique stress-strain curves. However, the stress-strain curve of rocks with an example shown in Figure 4.1b is not always as simple as in Figure 4.1a. This makes the graphical analysis of the curve to qualitatively or quantitatively characterize as being brittle or ductile more challenging as the area under the curve becomes almost impossible to determine. Apparently, the stress-strain curve analysis is not in all cases suitable to measure the brittleness of rocks and would probably be difficult to implement with petrophysical and well log data. If the elastic constants ultimately depend on the stress-strain ratio, then it is a better choice to consider the brittleness of rock as the ratio of elastic constants. Still, the question remains of what combination of elastic constants to use in defining brittleness.

$$\sigma_{ij} = c_{ijkl}\,\varepsilon_{kl} = \left(\lambda\delta_{ij}\delta_{kl} + \mu\delta_{ik}\delta_{jl} + \mu\delta_{il}\,\delta_{jk}\right)\varepsilon_{kl} \qquad (4.1a)$$

where σ_{ij} and ε_{kl} are the stress and strain tensors of rank two, c_{ijkl} is the elastic constant tensor of rank four and $\delta_{ij}\,\delta_{kl}$ is product of two Kronecker delta functions.



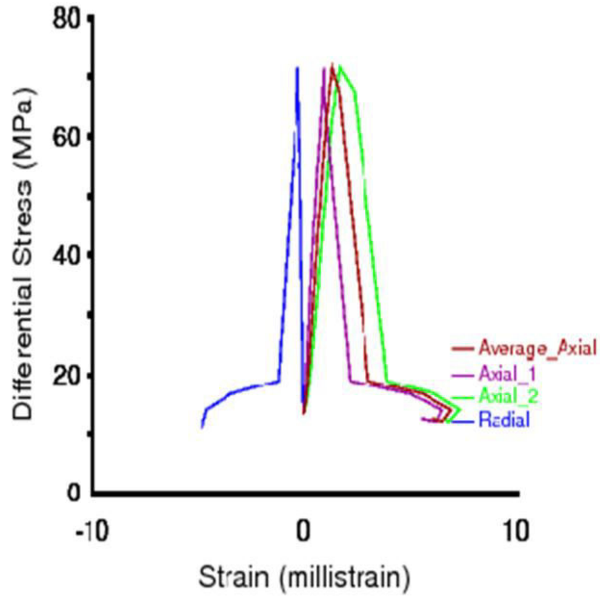


Figure 4.1a: Stress strain curve of ideal rock from subsurfwiki

Figure 4.1b: Stress strain curve of shale from unconfined compressive strength testing

4.2 Selecting Best Brittleness Attributes from the ratio of Elastic Constants

Consider a rock, for example, shale, as a hybrid of brittle and ductile rheological spectra. The condition under which this shale behaves as brittle or ductile depends on its mineralogical composition, which in turn also determines its elastic constants and P- and S-velocity. From the different ways (mineralogy, strength and elastic properties) to estimate the brittleness of rock in the literature, none has gained unanimous acceptance. The two common ways to quantify brittleness of rock particularly for shale in the industry and academia are from elastic constants and mineralogical composition of the rock.

The elastic constants of isotropic rocks are Lame's parameters λ, μ; Young's modulus E, bulk modulus K, and Poisson ratio v. Only two of these constants are needed to characterize an isotropic rock. The Equation 4.2 is used to convert the elastic constants from one form to the other.

$$E = 3K(1 - 2v) = 2\mu(1 + v) = \frac{\mu(3\lambda + 2\mu)}{\lambda + \mu}; \ \lambda = \frac{Ev}{(1 + v)(1 - 2v)}; K = \lambda + \frac{2\mu}{\lambda} \quad (4.2)$$

Empirically or graphically, two of these elastic constants have been combined as a useful attributes to quantify the brittleness of rock. On the other hand, the mineralogical approach of brittleness estimation considers the proportion of the minerals in the rock relative to quartz (assuming that quartz is brittle) Jarvie (2007).

In some cases, these two approaches give inconsistent brittleness estimation; see Perez and Marfurt (2013). However, Herwanger et al. (2015) claimed based on elastic constants of minerals from published data that the ratio of compressive and tensile strength; high Young's modulus and Poisson ratio brittleness methodologies are respectively equivalent to the mineralogical based approach assuming that the quartz-rich rock is brittle and clay-rich rock is ductile.

The possible equations to estimate brittleness from elastic constants were compiled in Chapter 2. In order to select the best possible equation, the relationships between these equations have been analyzed. The elastic constants λ, μ, E, K, and v are combined in equations 3.2 and 3.3. These equations show that the possible equation of brittleness from elastic constants can be expressed as a linear function of $\frac{\mu}{\lambda}$. The sensitivity of the elastic constants from the percentage average using the published petrophysical data on a lithological sequence of gas sand and shale from Goodway (1997) were then quantified. Assuming that the quartz-rich gas sand is brittle and the clay-rich shale is ductile, the most sensitive brittleness attributes are $\frac{3k-5\lambda}{\lambda}, \frac{\lambda}{\mu}, \frac{\mu}{\lambda}$ with average change of 246%, 110% and 106% respectively, see Table 4.1b.

$$E = \frac{6vK\mu}{\lambda} \tag{4.4}$$

$$\frac{3k-5\lambda}{\lambda} = 2\left(\frac{\mu}{\lambda} - 1\right) \tag{4.5}$$

A further step had been to constrain these "three best brittleness attributes", with Poisson ratio. Low and high Poisson ratio respectively imply that the rock is brittle and ductile, Greaves et al; (2011). The limiting cases of Poisson ratio of 0 and 0.5 are physically meaningful for elastic constants between 0 and ∞.

The limiting values of the Poisson ratio 0 and 0.5 for B equals $\frac{3k-5\lambda}{\lambda}, \frac{\lambda}{\mu}$ *and* $\frac{\mu}{\lambda}$ is given as (∞, -2), (0, ∞) and (∞, 0), respectively. The Poisson ratio of 0 corresponding to infinity means a very high brittleness while the Poisson ratio of 0.5 is taken as very high ductility. This observation only holds for the ratio $\frac{\mu}{\lambda}$. Also, on the basis of the real positive value for elastic constants, $(3k - 5\lambda)$ is always negative when $\lambda > 0.6\mu$ and the brittleness is negative for the Poisson ratio greater than 0.25. With these criteria, the ratio $\frac{\mu}{\lambda}$ is considered as the best brittleness attribute because it is sensitive, dimensionless, theoretically meaningful and has supporting seismic evidence.

Table 4.1: Data from Goodway et al 1997

	Vp	Vs	ρ	$\left(\frac{Vp}{Vs}\right)$	$\left(\frac{Vp}{Vs}\right)^2$	ν	λ+2μ	μ	λ	λ /μ
Shale	2898	1290	2.425	2.25	5.1	0.38	20.37	4.035	12.3	3.1
Gas Sand	2857	1666	2.275	1.71	2.9	0.24	18.53	6.314	5.9	0.9
Average change	1.40%	25%	6.40%	27%	55%	45%	9.20%	44%	70%	110%

The velocity Vp and Vs is in m/s, density ρ is in g/cc and elastic constants in Mpa

Table 4.2: Combination of Elastic Constants

	E	k	λ+2μ /λ	(3K-5λ) /λ	K /λ	E/ν	E/λ	E/μ	Eρ	μ/k	μ/ λ	E/k
Shale	11.11	14.99	1.66	-1.34	1.22	29.23	0.90	2.75	26.94	0.27	0.33	0.74
Gas Sand	15.68	10.11	3.14	0.14	1.71	65.32	2.66	2.48	35.67	0.62	1.07	1.55
Average change	34%	39%	62%	246%	33.8%	76%	98%	10%	27%	79%	106%	70%

$$B = \frac{3k - 5\lambda}{\lambda} = 2(\frac{\mu}{\lambda} - 1) = \frac{1}{v} - 4 = \begin{cases} \infty, & v = 0 \\ -2, & v = 0.5 \end{cases} \qquad (4.6a)$$

$$B = \frac{\lambda}{\mu} = \frac{2v}{1 - 2v} = \begin{cases} 0, & v = 0 \\ \infty, & v = 0.5 \end{cases} \qquad (4.6b)$$

$$B = \frac{\mu}{\lambda} = \frac{3k - 3\lambda}{2\lambda} = \frac{1}{2v} - 1 = \begin{cases} \infty, & v = 0 \\ 0, & v = 0.5 \end{cases} \qquad (4.6c)$$

For a meaningful brittleness equation in the range of 1 and 0, a simple mathematical transform is used to transform the range (∞, 0) to (1, 0) to rewrite the Equation 4.6c as the Equation 4.6d.

$$B = 1 - e^{-\frac{\mu}{\lambda}} = 1 - e^{-\left[\frac{1}{\left(\frac{V_p}{V_s}\right)^2 - 2}\right]} = \begin{cases} 1, & v = 0\ (brittle) \\ 0, & v = 0.5\ (ductile) \end{cases} \qquad (4.6d)$$

The expression $\left[\frac{1}{\left(\frac{V_{P,0^0}}{V_{S1,90^0}}\right)^2 - 2}\right]$ in the Equation 4.6d is used as a proxy instead of $\frac{\mu}{\lambda}$.

For the case of anisotropy, assuming transverse isotropy, there is no single λ or μ, only C_{ijkl} or C_{ij} .The constitutive equation of Hooke's relating stress (σ_{ij}) and strain (ε_{ij}) for full anisotropy is given in Equations 4.1 and by 4.7 for transverse isotropy. Here C_{ij} is the 6 by 6 matrix defined by Equations 4.7- 4.7b

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{44} \\ \sigma_{55} \\ \sigma_{66} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ 2\varepsilon_{23} \\ 2\varepsilon_{31} \\ 2\varepsilon_{12} \end{bmatrix} \qquad (4.7)$$

$$C_{11} = \rho\left(V_{P,0^0}\right)^2 \quad C_{33} = \rho\left(V_{P,90^0}\right)^2 \quad C_{44} = \rho\left(V_{S1,90^0}\right)^2 \quad C_{66} = \rho\left(V_{S1,0^0}\right)^2 \qquad (4.7a)$$

$$C_{13} = \sqrt{4\rho^2\left(V_{P,45^o}\right)^4 - 2\rho\left(V_{P,45^o}\right)^2(C_{11} + C_{33} + 2C_{44}) + (C_{11} + C_{44})(C_{33} + C_{44})} - C_{44} \qquad (4.7b)$$

The elastic constants C_{ij} can be combined as ε , γ and δ with Equation 4.7c to characterize the degree of transverse isotropy, following Thompsen (1986).

$$\varepsilon = \frac{C_{11} - C_{33}}{2} C_{33};\ \gamma = \frac{C_{66} - C_{44}}{2C_{44};};\delta = \frac{(C_{13} + C_{44})^2 - (C_{33} - C_{44})^2}{2C_{33}(C_{33} - C_{44})} \qquad (4.7c)$$

If the effect of anisotropy is taken into consideration, then the brittleness of the rock becomes a tensorial quantity as it would vary with direction. Let us define the anisotropic brittleness as horizontal B_H , vertical B_V and tilted B_T corresponding to observation angles of 0^o, 90^o and 45^o. Still keeping Equation 4.6d and using Equations 4.7a and 4.7c, the tensorial brittleness of the rock is given by Equations 4.8a-4.8c

$$B_H = 1 - e^{-\left[\frac{1}{\left(\frac{V_{P,0^0}}{V_{S1,90^0}}\right)^2 - 2}\right]} = 1 - e^{-\left[\frac{1}{\frac{C_{11}}{C_{66}} - 2}\right]} = 1 - e^{-\left[\frac{1}{\left(\frac{(2\varepsilon+1)C_{33}}{(2\gamma+1)C_{44}} - 2\right)}\right]} \quad (4.8a)$$

$$B_V = 1 - e^{-\left[\frac{1}{\left(\frac{V_{P,90^0}}{V_{S1,90^0}}\right)^2 - 2}\right]} = 1 - e^{-\left[\frac{1}{\left(\frac{C_{33}}{C_{44}} - 2\right)}\right]} \quad (4.8b)$$

$$B_T = 1 - e^{-\left[\frac{1}{\left(\frac{V_{P,45^O}}{V_{S1,45^0}}\right)^2 - 2}\right]} \quad (4.8c)$$

Examples

Equation 4.6d was used to quantify the brittleness of plug 2V for isotropic case, with the results given in Table 4.2a. For the case of anisotropy equations 4.8a- 4.8c were used to estimate the brittleness of plugs 2H, 3H and 4H in Table 4.2b. Because of the large variation between VS1 and VS2 in all cases, the average of the S wave velocity V_S is used for the calculation.

Table 4.3: Brittleness of Vertical Shale Plug at constant orientation

	CP	Velocity				Brittleness
		V_P	V_{SI}	V_{S2}	V_S	
2V	5	4354	2905	2867	2886	0.97
	10	4629	2958	2951	2954.5	0.89
	15	4767	3083	2984	3033.5	0.88
	20	4986	3186	3029	3107.5	0.82
	25	5004	3274	3064	3169	0.87
	30	5165	3326	3087	3206.5	0.81
	35	5232	3410	3111	3260.5	0.82

Table 4.4: Brittleness of horizontal shale plugs at different orientations

Plugs	CP	0 Degree		45 degree		90 degree		Brittleness with orientations		
		$V_{P,0^0}$	$V_{S,0^0}$	$V_{P,45^O}$	$V_{S,45^O}$	$V_{P,90^O}$	$V_{S,90^O}$	0 Degree	45 degree	90 degree
2H	5	5112	3235	3985	2628	3320	2181	0.40	0.84	0.89
	10	5212	3275	4033	2736	3495	2187	0.40	0.88	0.78
	15	5424	3343	4330	2784	3705	2261	0.38	0.75	0.71
	20	5439	3329	4426	2844	3971	2341	0.38	0.75	0.61
	25	5499	3343	4578	2854	4135	2376	0.38	0.68	0.57
	30	5537	3343	4610	2895	4148	2426	0.38	0.70	0.59
	35	5575	3343	4610	2885	4236	2456	0.37	0.71	0.57
3H	5	4999	3069	3608	2210	5255	3280	0.55	0.83	0.81
	10	5191	3103	3674	2307	5374	3306	0.51	0.84	0.77
	15	5328	3102	3759	2379	5426	3342	0.48	0.91	0.77
	20	5436	3122	3904	2401	5480	3332	0.46	0.90	0.74
	25	5563	3135	4041	2459	5535	3339	0.42	0.89	0.72
	30	5992	3151	4103	2452	5609	3352	0.34	0.89	0.70
	35	5586	3135	4218	2477	5572	3346	0.42	0.86	0.71
4H	5	5303	3140	4358	2754	3668	2275	0.50	0.63	0.71
	10	5410	3228	4555	2822	3761	2314	0.51	0.61	0.69
	15	5521	3267	4672	2893	3992	2362	0.49	0.61	0.61
	20	5521	3321	4783	2909	4066	2393	0.51	0.58	0.59
	25	5598	3313	4811	2967	4191	2435	0.48	0.60	0.56
	30	5598	3321	4929	2994	4258	2468	0.49	0.58	0.55
	35	5637	3321	4929	3034	4312	2507	0.48	0.59	0.56

The plot of brittleness versus confining pressure for the different shale plugs is given in Figure 4.2 for the vertical plug and Figures 4.2a -4.2f for the horizontal plugs. The plots show that brittleness in most cases monotone decreases with confining pressure.

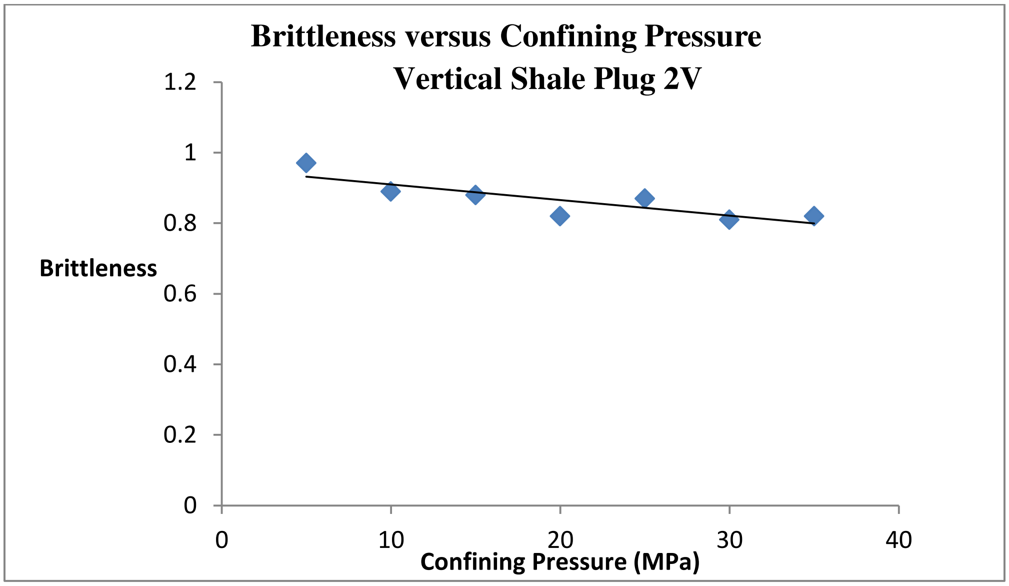


Figure 4.2: Brittleness versus Confining Pressure for Vertical Shale Plug 2V

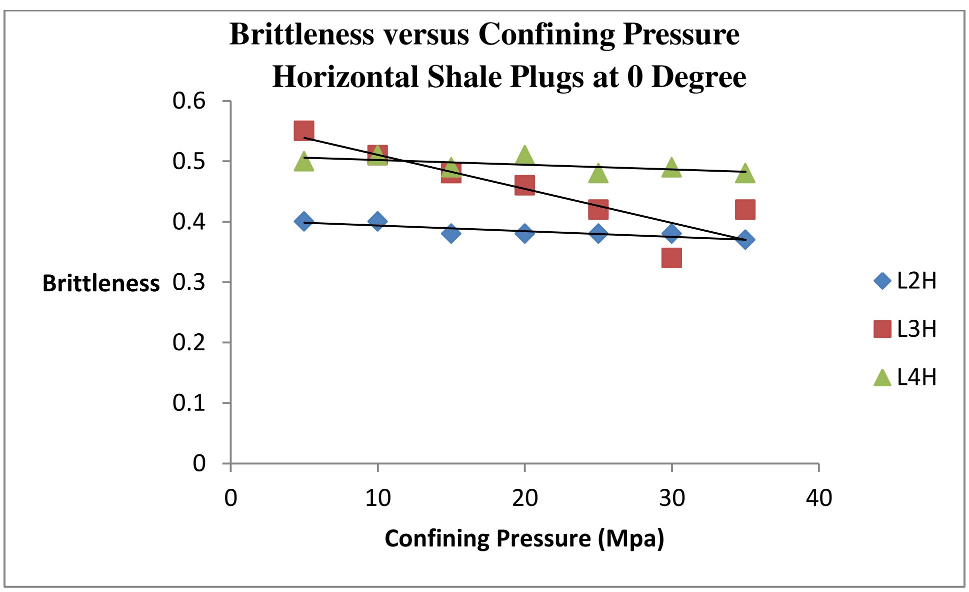


Figure 4.2a: Brittleness versus Confining Pressure for Horizontal Shale Plugs at 0 Degree orientation

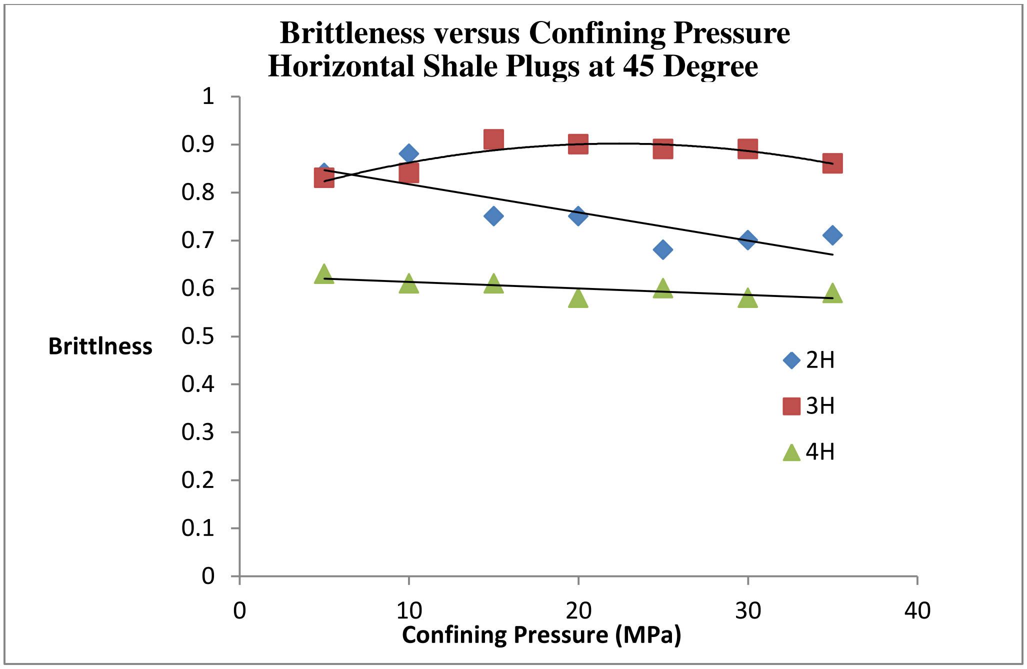


Figure 4.2b: Brittleness versus Confining Pressure for Horizontal Shale Plugs at 45 Degree orientation

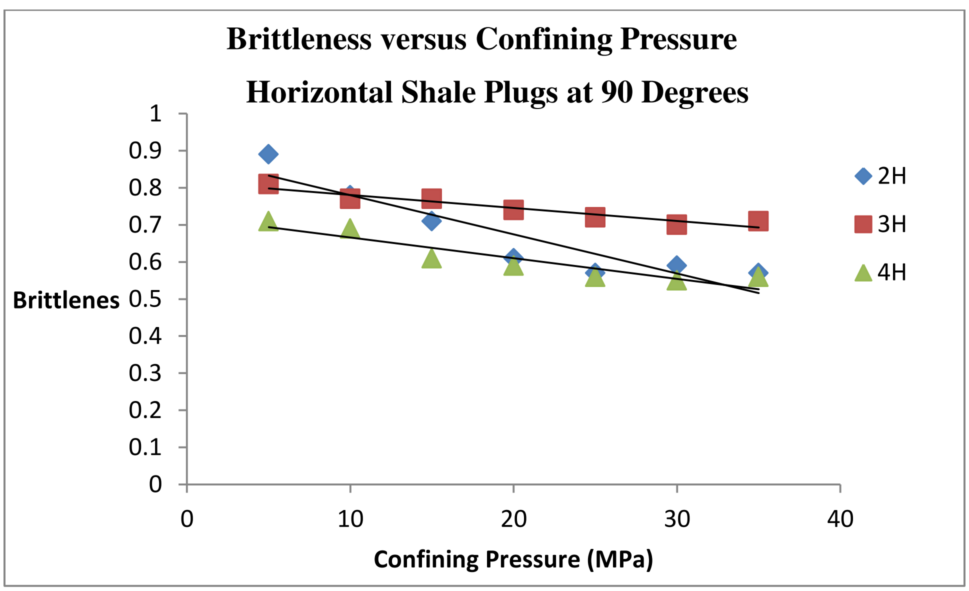


Figure 4.2c: Brittleness versus Confining Pressure for Horizontal Shale Plugs at 90 Degree orientation

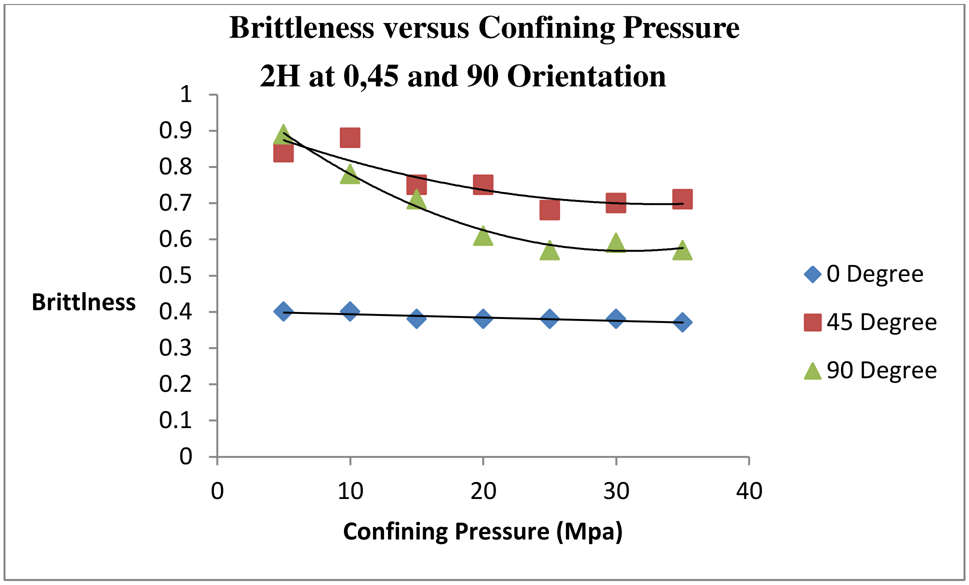


Figure 4.2d: Brittleness versus Confining Pressure for 2H at 0, 45 and 90 Degree Orientations

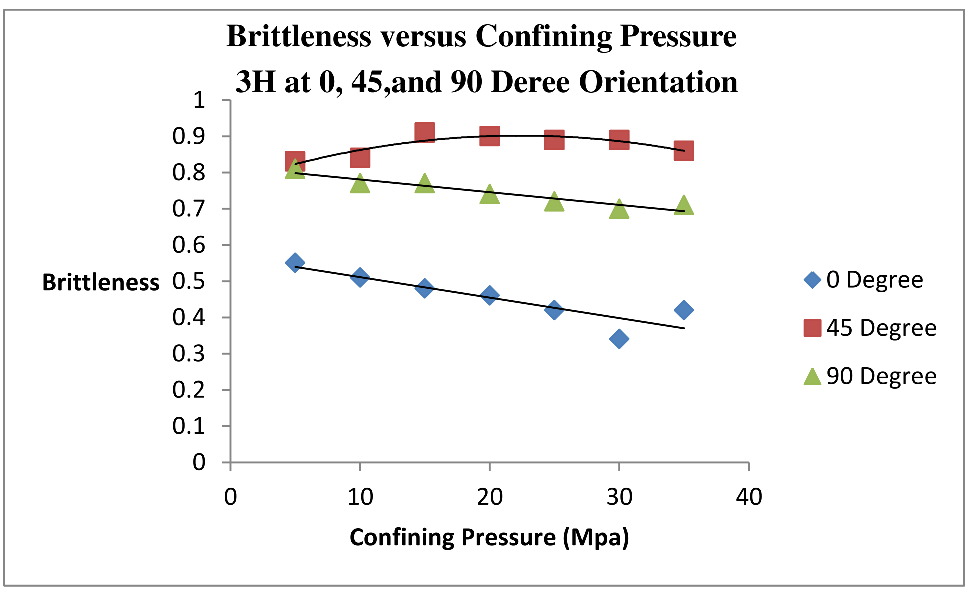


Figure 4.2e: Brittleness versus Confining Pressure for 3H at 0, 45 and 90 Degree Orientations

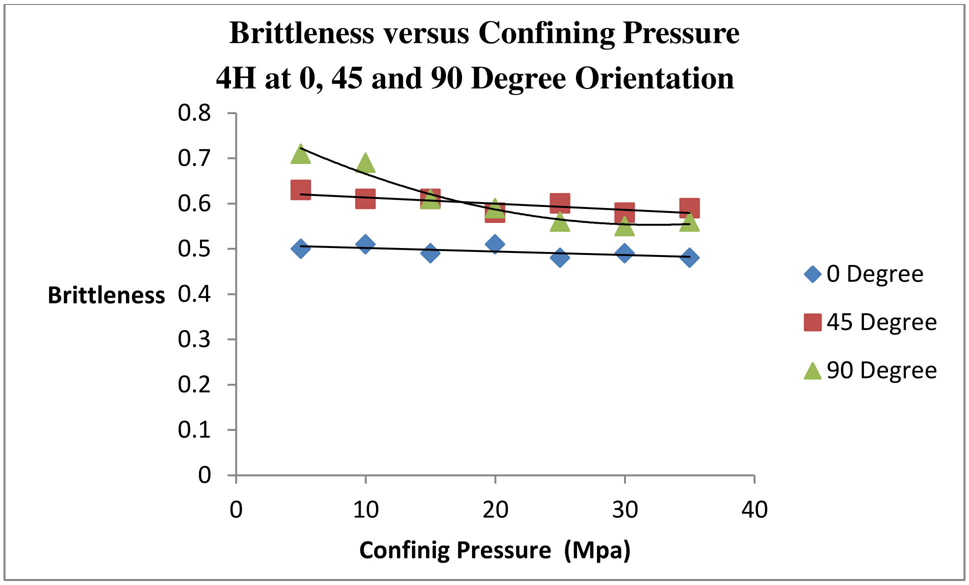


Figure 4.2f: Brittleness versus Confining Pressure for 4H at 0, 45 and 90 Degree Orientations

CHAPTER 5

FRACKABILITY

"Science advances, not by the accumulation of new facts, but by the continuous development of new concepts"
James Bryant Conant

"When everything else fails, frac it"
Ahmed S. Abou-Sayed

The mechanism of frackability entails the initiation, propagation and monitoring of hydraulic fractures. The limitations of the standard laboratory testing for plug-sized shale samples make the frackability experiment to characterize fracture initiation, propagation (fracture geometry, aperture, width and length) and monitoring with acoustic emission unattainable within the scope of this thesis. Instead, the discussion in this chapter will include an overview of the concept of frackability, the underlying mechanism of frackability – the first and second principles for hydraulic fracture initiation, and the derivation of a new expression for frackability. Only the initiation of fractures is considered in this chapter.

5.1 A Brief Overview

Discontinuities or fractures in the Earth crust (rocks) are of different scales with the regional scale being associated with tectonic faults and hydraulic fractures assisted by fluid pressure. Our interest in how these discontinuities are formed, influenced by fluid flow and alter the mechanical properties of rock has been motivated by oil and gas production, energy extraction from geothermal system and disposal of waste. The idea of creating discontinuity in a rock (a kind of stimulation) is as old as the petroleum industry from the early oil finders to later generations of petroleum engineers and geoscientists. It was one of the effective technologies in 1859 after the success of Colonel Edwin L. Drake (sometimes revered as the father of petroleum) who drilled the first commercial oil well in Titusville, Pennsylvania. Subsequently, investors began searching and trading techniques to create discontinuity in the rocks at the bottom of the well. Without realizing it, they were doing fracking, but it was never explicitly mentioned. In 1866, Edward. Roberts accomplished the first frack jobs using explosives. He made his wealth from a patent called *Improvement in Method of Increasing Capacity of Oil-Wells* in which he claimed " I fracture the rock containing the oil to some distance around the wells, thus creating artificial seams, and enabling me to connect the well thereby with seams containing the oil that would not have been otherwise reached." Subsequent approaches to break through rocks due to the fluid/rock interactions had evolved; from explosive, hydrochloric acid to hydraulic fracturing Russell (2014).

Hydraulic fracturing that was developed around 1940 has made a breakthrough in 1947 and in the Oil and Gas Journal in 1948. The process of hydraulic fracturing was referred to as hydrafrac in 1949 (Clark, 1949). In 1953, the same journal published a paper *'Fracking'—A New Exploratory Tool* by Evensen et al., (2014). In the "Preface: Hydraulic fracturing, a technology for all time" to the book *Reservoir Stimulation*, Abou-Sayed quoted the common jest in the fracking community "When everything else fails, frac it" that has become a slogan in petroleum industry Economides, (2000). Due to the negative connotation that the colloquial word “fracking" carries among the opponents of this technique, the technical term "frackability" is becoming more common in journal articles.

5.2 Frackability and Shale Reservoir

The resurgence of interest in shale exploration has made the science, ethics and politics of fracking controversial among stakeholders (petroleum industry, academia, government and environmental advocacy groups). The energy, economic, social and environmental implications of this technology are the main reasons for contending views and opinions. The opponents disregard the economic benefits of enhanced oil and gas recovery due to fracking, but worry about the detrimental effects of water use and disposal, groundwater contamination due to leakage, induced seismicity, and other effects. Whereas, supporters of fracking believe it to be an economic boom and claim that the substantial amount of natural gas from shale could mitigate against climate change (Evensen et al., 2014).

5.3 The First Principle of Frackability (FPF)

The classical theory of Hubbert and Willis (1957) concerning fracture orientation and the in situ stresses is the earliest prominent reference to the frackability of rocks and serves as the first principle of hydraulic fracturing. It states that the fracture would propagate in the direction perpendicular to the plane or axis of the least principal stress. In other words, the fracture would propagate in the direction of the maximum principal stress. For a cube-shaped block of rock, the three principal stresses in the direction of the orthogonal axes of the cube are represented as the least, intermediate and maximum stress respectively. Usually, for a shallow reservoir, the z axis as the vertical direction represents the vertical stress σ_z with the two orthogonal y and x axes representing the intermediate horizontal and maximum horizontal stresses σ_y and σ_x respectively. In this case, if the vertical stress, σ_z is the least principal stress ($\sigma_x > \sigma_y > \sigma_z$) then a horizontal fracture will form in the (direction of the maximum horizontal stress σ_x). If the fluid or hydraulic pressure due to injection is greater than the vertical stress, pore pressure and the tensile strength of the reservoir combined then fracture will occur as shown in Equation 5.1 (Zoback et al., 1977):

$$P_b = \left(\sigma_z + \sigma_t - P_p\right) \tag{5.1}$$

where P_b is the pressure due to injected fluid or the breakdown pressure, σ_z is the least stress (vertical stress), σ_t is the tensile strength of the rock and $P_p$is the pore pressure.

Conversely, when the well is at least 2 km deep, the vertical stress σ_z that is due to the weight of the overburden and is a function of increasing depth is no longer the least principal stress but the maximum stress. In this case, the vertical stress is at least greater than two times principal horizontal stresses. It is practically difficult to ascertain the least principal stress between the two horizontal stresses, assuming the least principal stress is σ_x ($\sigma_z > \sigma_y > \sigma_x$). However, the relationship between the circumferential or hoop or tangential stress σ_θ in the surface of the borehole, fluid pressure (break down pressure) and the horizontal stresses σ_x and σ_y is given in Equation 5.2 of Price (2001) and Gudmundsson (2011).

$$\sigma_\theta = (\sigma_x + \sigma_Y - P) - 2(\sigma_x - \sigma_Y)\cos 2\theta \tag{5.2}$$

where θ is the polar angle.

The polar angles $\theta = 0^0$ and 180^0 correspond to the maximum tangential stress ($\sigma_{\theta MAX}$) responsible for maximum horizontal stress given in Equation 5.3.

$$\sigma_{\theta MAX} = (\sigma_x + \sigma_Y - P_p) - 2(\sigma_x - \sigma_Y)\cos 2\theta \tag{5.3}$$

Similarly, the polar angles $\theta = 90^0$ and 270^0 give the minimum tangential stress ($\sigma_{\theta MIN}$) responsible for the minimum horizontal stress given in Equation 5.4.

$$\sigma_{\theta MIN} = (\sigma_x + \sigma_Y - P_p) - 2(\sigma_x - \sigma_Y)\cos 2\theta \tag{5.4}$$

Thus, the vertical fracture will be formed (in the direction of the vertical stress σ_z) when the fluid or hydraulic pressure due to injection is greater than the two horizontal stresses, pore pressure and the tensile strength of the reservoir combined that is

$$P_b = \left(3\sigma_x - \sigma_Y + \sigma_t - P_p\right) \tag{5.5}$$

where σ_x (minimum horizontal stress) is the least horizontal stress, σ_Y (maximum horizontal stress) is the intermediate stress, σ_t is the tensile strength and P_p is the pore pressure

If isotropic stress state is assumed, that is $\sigma_x = \sigma_Y$ then Equation 5.5 reduces to

$$P_b = \left(2\sigma_x + \sigma_t - P_p\right) \tag{5.5a}$$

The σ_x (minimum horizontal stress) is defined for isotropic and anisotropic states in the following equations (Waters et al., 2011).

$$\sigma_x = \frac{\nu}{1-\nu}\left(\sigma_z - \alpha P_p\right) + \alpha P_p + \frac{E}{1-\nu^2}\varepsilon_H + \frac{E\nu}{1-\nu^2}\varepsilon_h \tag{5.6a}$$

$$\sigma_x = \frac{E_h}{E_V}\frac{\nu_V}{1-\nu_h}\left(\sigma_z - \alpha(1-\eta)P_p\right) + \alpha P_p + \frac{E_h}{1-\nu_h^2}\varepsilon_H + \frac{E_h\nu_h}{1-\nu_h^2}\varepsilon_h \qquad (5.6b)$$

where ν_V, ν_h, E_V, E_h, α, η, ε_H, ε_h are in turn the vertical Poisson's ratio, horizontal Poisson's ratio, vertical Young's modulus, horizontal Young's modulus, Biot's constant, poroelastic parameter, maximum horizontal strain and minimum horizontal strain.

Neglecting pore pressure for simplicity, the first term of Equation 5.6a, given in 5.6c is usually considered for isotropic case.

$$\sigma_x = \sigma_Y = \frac{\nu}{1-\nu}\sigma_z \qquad (5.6c)$$

Subsequent modifications of the Hubbert and Willis theory by Haimson, and Fairhurst(1967); Ito-and Hayashi, (1991); Detournay and Cheng (1992); and Song et al., (2001); with their respective criteria of validity are listed in equations 5.7 to 5.9.

$$P_b = \frac{\left(3\sigma_x - \sigma_y + \sigma_t - 2\eta P_p\right)}{2(1-\eta)} \qquad \text{Haimson,. and Fairhurst,} \quad (1967)\ (5.7)$$

where η is another poroelastic parameter in the interval of $0 \le \eta \le 0.5$ defined by Equation 5.7a.

$$\eta = \frac{\alpha(1-2\nu)}{2(1-\nu)} \qquad (5.7a)$$

α is the Biot poroelastic parameter (Biot and Willis 1957) and ν Poisson’s ratio.

$$P_b = \frac{\left(3\sigma_x - \sigma_y + \sigma_t - P_p\right)}{1+(1-2\eta)h(\gamma)} + P_p \qquad \text{Detournay and Cheng (1992)} \qquad (5.8)$$

where $h(\gamma)$ is the dimensionless pressurization rate in the interval of $0 \leq h(\gamma) \leq \infty$ defined by

$$h(\gamma) = \frac{A\lambda^2}{4cS} \tag{5.8a}$$

where A, λ and c are respectively borehole pressurization rate, microcrack length scale and diffusivity coefficient.

$$S = 3\sigma_x - \sigma_y + \sigma_t - 2P_p \tag{5.8b}$$

$$P_b = \frac{3\sigma_x - \sigma_y + \sigma_t - (1+\beta)P_p}{1 + (\beta - 2\eta)h(\gamma)} + P_p \quad \text{Song et al., (2001)} \tag{5.9}$$

where β is the effective stress parameter in the interval of $0 \leq \beta \leq 1$ that depends on the type of rock.

5.4 The Second Principle of Frackability (SPF)

While the FPF is primarily based on the elasticity or poroelastic theory, the SPF considered the concept of linear elastic fracture mechanics (LEFM) applied by Geerstma and de Klerk, (1969); Perkins and Kern, (1971); Whitney and Nuismer, (1974); Abou-Sayed et al., (1978); Rummel and Hansen (1989); Ito and Hayashi, (1991); Detournay and Carbonell, (1994) to analyze hydraulic fracturing in rocks. The LEFM states that the stress field near a crack tip is dependent on the location and the stress intensity factor K_I that is, in turn, dependent on the loading conditions and the geometry of the rock. In principle, the calculated stress intensity factor K_I from the stress field at a crack tip is compared with fracture toughness K_{IC} obtained from experiment. Hydraulic fracture will be initiated when the K_I reaches the K_{IC}.Unlike the tensile mode and the tensile strength consideration of the FPF, the SPF approach utilized the fracture toughness (K_{IC}) or rock toughness and other fracturing modes (tensile, shearing and sliding, hybrid or mixed). The stress intensity factor K_I is the critical stress σ_c required for crack propagation in rock:

$$K_I = \sigma_c = \sqrt{\left(\frac{2E\gamma_s}{\pi a}\right)} \tag{5.10}$$

where E is Young's modulus of elasticity, γ_s is the specific surface energy and a is one-half length of an internal crack. Toughness (rock or fracture toughness) is ability of the rock to withstand fracture in the presence of a crack (stress-concentrator). The relationship between rock toughness K_{IC} , critical stress for crack propagation σ_c and crack half-length a is given as

$$K_{IC} = Y\sigma_c\sqrt{\pi a} \tag{5.11}$$

K_{IC} has the unusual unit of $MPa\sqrt{m}$. Y is dimensionless parameter that depends on the loading, geometry and size of crack in the rock.

The rock toughness (K_{IC}) is simply related to the tensile strength σ_t by Detournay and Cheng (1992) as:

$$K_{IC} = 1.12\sigma_t\sqrt{\pi a} \tag{5.12}$$

where a is the crack's half-length

The breakdown pressure P_b under the formalism of the SPF is given by the Equation 5.13 (Zeng and Roegiers, 2002).

$$P_b = \left(\frac{\pi\delta(K_{IC})^4}{Qt}\frac{1-\nu^2}{E}\right)^{1/3} \tag{5.13}$$

where P_b is the breakdown pressure, δ the length of the borehole, Q the flow rate, t the time of injection, ν is Poisson's ratio, E is Young's modulus and K_{IC} is the rock toughness.

5.5 ANALYTICAL EXPRESSION FOR THE FRACKABILITY OF ROCK

What is frackability? Admittedly, there is yet no technical definition for frackability. Frackability is simply a fancy terminology for the possibility or feasibility of hydraulic fracturing. Frackability or hydraulic fracturing initiation is the process by which fractures (discontinuities) are created in low permeability reservoirs (1 milliDarcy for oil and 0.01 milliDarcy for gas) such as shale with the injection of fluid that creates substantial pressure in the rock to overcome the toughness or tensile strength. A generalized definition of frackability would entail all phases of hydraulic fracture from initiation, propagation (dilation) and environmental monitoring of the after effects. In a specialized form, frackability will be considered as a coefficient or index for fracture initiation in rock defined as the ratio of volume of fluid injected until the rock is cracked, divided by the total volume of the cracked part of the rock. While a more generalized form would enable incorporation and comparing of ideas of the contending groups of researchers on the subject of frackability; only this specialized form of frackability has been considered in this Thesis.

Significant progress has been made on the hydraulic fracturing of rocks ranging from experiment of Zoback et al. (1977); Lockner and Byerlee, (1977); Solberg et al. (1980); Weijers et al. (1992); Detournay and Cheng (1992); Murdoch (1993); Patzek and Silin (1998); Song and Haimson, (2001); Song et al., (2001); Zeng and Roegiers (2002); Sondergeld et al., (2013), to theory developed by Khristianovic and Zheltov (1955); Hubbert and Willis (1957); Perkins and Kern (1961); Haimson and Fairhurst, (1967); Geertsma and Klerk (1969); Whitney and Nuismer, (1974); Abou-Sayed, et al., (1978); Geertsma and Haafkens (1979); Ito and Hayashi (1991); Carter et al., (1998a); Gundersen et al. (2011); Carrier and Granet (2012); Ghani et. al., (2013) among others.

Until recently, the concept of frackability has been used to describe the hydraulic fracturing of rock. Connotatively, it is used to mean the attribute that measures the ease of the creation of hydraulic fractures in rocks. However, the mathematical definition of frackability is still found elusive among petroleum engineers and geoscientists and it is confused with brittleness.

Hydraulic fractures, unlike natural fractures (that are mainly controlled by geological processes), result from a fluid assisted process and are usually referred to as induced fractures. Consequently, the injection of fluid is a critical factor on the frackability of rock. The volume of the injected fluid (water) remains an important economic question during hydraulic fracturing of rocks. On the one hand, the efficiency of the process depends on the fluids; on the other hand, the availability of one of mankind's most vital resources remains a concern. The leakage of the injected fluid and other related environmental challenges during the fracking of rock are also of significant concern. As the injected fluid plays a dominant role in the initiation of hydraulic fracture, let us consider frackability of the rock as the relative amount of water needed for the initiation of hydraulic fractures, mathematically defined as the ratio of the volume of the injected fluid that is necessary and sufficient to frack the rock through the volume of the rock. The conservation law of physics to estimate the volume of the injected fluid that will fracked a given volume of the rock.

5.5.1 Formulation of the Problem

Given a rectangular block of rock say shale of length L, width W and height H to be fracked as in Figure 5, let it be subjected to a pressure P, velocity field V due to flow rate of Q and injection time t. By introducing the conservation law on the volume of fluid with some simplifying assumptions, an expression for frackability will be derived.

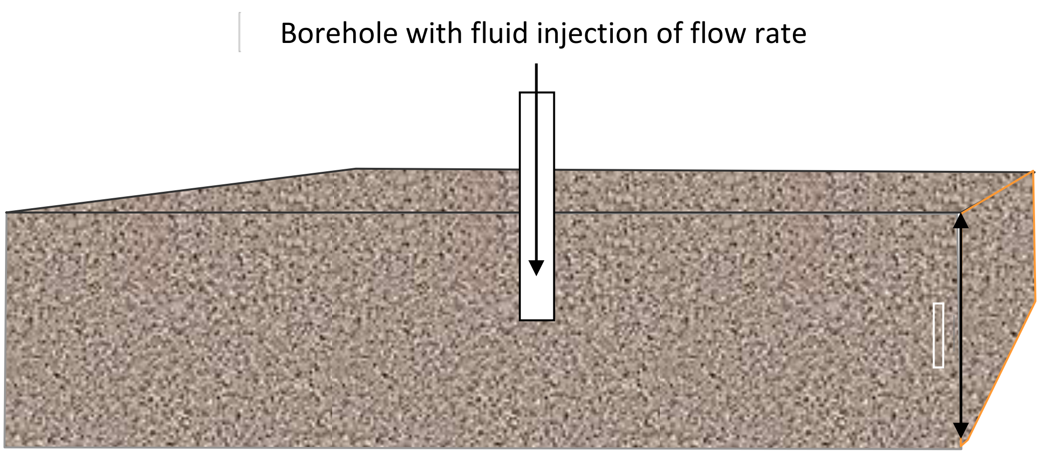


Figure 5: Schematic of Rock to be fracked

5.5.2 The Physical Principle and Conservation Law

Conservation laws have been found useful to formulate systems of differential equations that model different geological and engineering problems, for example, in fluid mechanics and elastic deformations. This principle has also been used to model the initiation of hydraulic fractures (frackability) in the experiment of Murdoch (1993):

$$\mathrm{Qt} = \mathrm{V_{frack}} + \mathrm{V_{stored}} + \mathrm{V_{leak}} \tag{5.14}$$

where t is time, Q is the flow rate of fluid injection, $\mathrm{V_{frack}}$ is the optimum volume to frack, $\mathrm{V_{stored}}$ is the volume accumulated due to porosity and $\mathrm{V_{leak}}$ is the volume that leaks off.

Equation 5.14 can also be written in the form analog to Newton's law of cooling (see Equation 5.15) to develop the pressure diffusion equation that forms the mathematical basis to understand the physics of hydraulic fracturing.

Rate of change of flow = injection –accumulation (5.15)

Equation 5.14 states that the total volume is sum of the volume accumulated due to the fractional porosity, the volume to frack the formation, plus the volume that leaks. For this problem the following are taken into consideration:

(1) The fluid is incompressible and its flow rate varies linearly or bilinearly described by laminar flow

(2) The volume of fluid stored is negligible especially for shale and other low porosity formations

(3) The elastic deformation due to the fluid pressure is negligible and as a result the volume leak off is ignored. The volume of fluid that leaks (usually referred to as leak-off) is detrimental to hydraulic fracturing.

(4) Rocks specifically shale are never homogeneous and isotropic but for simplicity, homogeneity and isotropy is assumed for the permeability K.

(5) The velocity profile of the propagating fluid is symmetrical to the two sides of formation

The flow rate Q through the formation can be calculated from the integral of the velocity profile over the cross-sectional area as given by Equation 5.16 of Patzek and Silin (1998).

$$Q(t) = V_0(t)A(0) + \int_0^t (V_\tau(t)\frac{dA(\tau)}{d\tau}d\tau) + w\frac{dA(t)}{dt} \qquad (5.16)$$

where t is time, Q(t) is the injection rate, A(t) is the fracture area, A(0) is the initial fracture area, $V_0(t)$ is the initial velocity and $V_\tau(t)$ is the velocity at t , w is the fracture width.

For a simple case, the first term of the solution in Equation 5.16, which is equivalent to the Darcy's law, makes a good approximation when increase or decrease in the area of the rock due to the propagating fluid is negligible.

$$Q = \quad \text{velocity} \times \text{Area} \qquad (5.17)$$

Using the Darcy's law that provides a relation between the pressure gradient and Q:

$$Q = \quad \frac{k_f K}{\mu}.\frac{\Delta P}{L}.\text{Area} \qquad (5.18)$$

where K is permeability of the rock, k_f is the relative permeability of the fluid with respect to water, ΔP is the dynamic pressure or the pressure drop, L is the half-length the rock and μ is viscosity of the fluid.

The V_{frack} can be determined from Equation 5.19 when the pressure gradient ΔP is equal to the break down pressure P_b defined by Detournay and Cheng (1992) and Zeng and Roegiers (2002) as the critical or peak value of pressure at which "breakdown" takes place during fluid pressurization of a rock.

$$V_{frack} = \frac{k_f K}{\mu} \times \frac{P_b}{L} \times H \times W \times t \tag{5.19}$$

Frackability is therefore defined as

$$F = \frac{V_{frack}}{\text{volume of rock}} = \frac{k_f K}{\mu} \times \frac{P_b}{L^2} \times t \tag{5.20}$$

It is easy to check that the expression for frackability in Equation 5.20 is dimensionless as it should be, and frackability is growing with time until the whole volume of rock is cracked. Under the formalism of the FPF, inserting equations 5.1 and 5.5 for shallow and deep formation respectively in Equation 5.20 give the corresponding frackability in equations 5.21a and 5.21b.

$$F = \frac{k_f K}{\mu} \times \frac{+\sigma_T - P_p}{L^2} \times t \tag{5.21a}$$

$$F = \frac{k_f K}{\mu} \times \frac{3\sigma_\times - \sigma_y + \sigma_T - P_p}{L^2} \times t \tag{5.21b}$$

Similarly, in the framework of SPF, introducing Equation 5.13 in Equation 5.20 provides the expression for frackability in Equation 5.21c

$$F = \left[\left(\frac{k_f K}{\mu}\right)^3 \frac{\pi\delta(K_{IC})^4 t^3}{L^8 W} \frac{(1-\nu^2)}{E}\right]^{1/4} \tag{5.21c}$$

It is easy to check that F is dimensionless.

In this study, we define $P_b = B.\sigma_z$ as the break pressure and F is given in Equation 5.21d

$$F = \frac{k_f K}{\mu} \times \frac{B.\sigma_z}{L^2} \times t \tag{5.21d}$$

where B is the brittleness of the rock and σ_z is the maximum stress.

It is obvious that F behaves as a 0.75^{th} power of time t, in Equation 5.21c but as a 1^{st} power of time in equations 5.21 b and d. Therefore, equations 5.21 b, c and d should be subjected to further experimental or computational studies to determine which power dependence is theoretically correct.

5.6 Future Works

In future research work, it is recommended to introduce fractures by actually injecting high-pressure fluid to the samples. The experimental apparatus may be similar to that used by Murdoch (1992, 1993) who created hydraulic fractures in laboratory conditions by injecting dyed glycerine at a constant rate into rectangular blocks of silty clay confined within a triaxial pressure cell. There is another experimental approach, adopted by Zoback et al. 1977, where the acoustic emissions created during hydrofracturing were observed and analyzed, but this does not seem to be applicable to small-sized samples as plugs.

Chapter 6

Conclusion

"If geophysics requires mathematics for its treatment, it is the Earth that is responsible not the geophysicist"
Sir Harold Jeffreys

This research investigates the use of brittleness and frackability as "attributes" that measure the ease of creating hydraulic fractures in rocks. The study considers that the mathematical definitions of both attributes remain elusive and controversial among petroleum engineers and geoscientists. For example, 30 equations have been reported in the literature for brittleness while three different ways have been found to quantify frackability when it is not the same as brittleness.

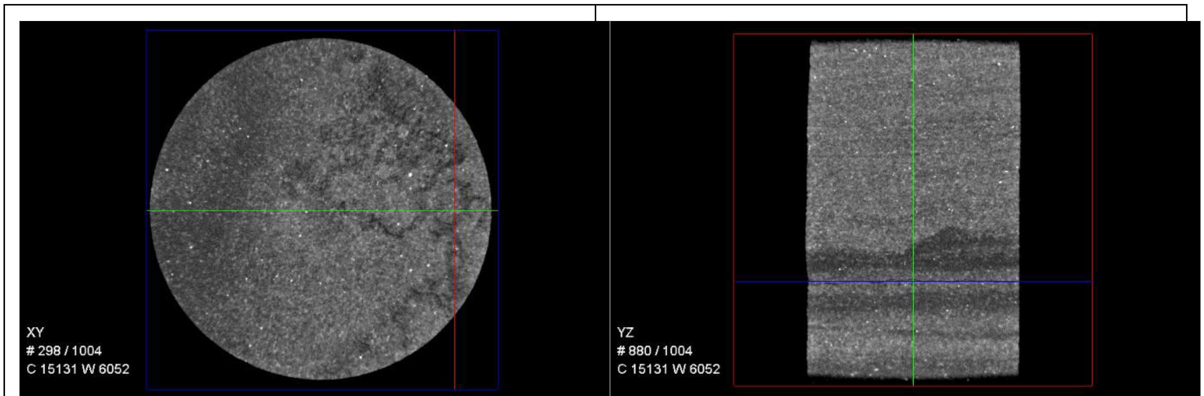
This study shows that brittleness and frackability are both dimensionless but are not equivalent. Based on the reported studies, experimental work and theoretical analysis; independent equations have been derived for both brittleness and frackability. The study results show that isotropic elastic constants can be used to quantify brittleness; Thomsen parameters can be incorporated for the anisotropic case; and brittleness is a function of Poisson's ratio and generally decreases with confining pressure.

Another important finding of this study is that different analytical expressions are possible for frackability, depending on the breakdown pressure. Three equations were derived for frackability in this study as defined from the first principle of frackability (FPF), the second principle of frackability (SPF) and the frackability based on brittleness. As frackability based on SPF behaves as a 0.75^{th} power of time t, while frackability based on the FPF and brittleness behave as a 1^{st} power of time, the three expressions could be subjected to further experimental or computational studies to determine which of them is theoretically correct.

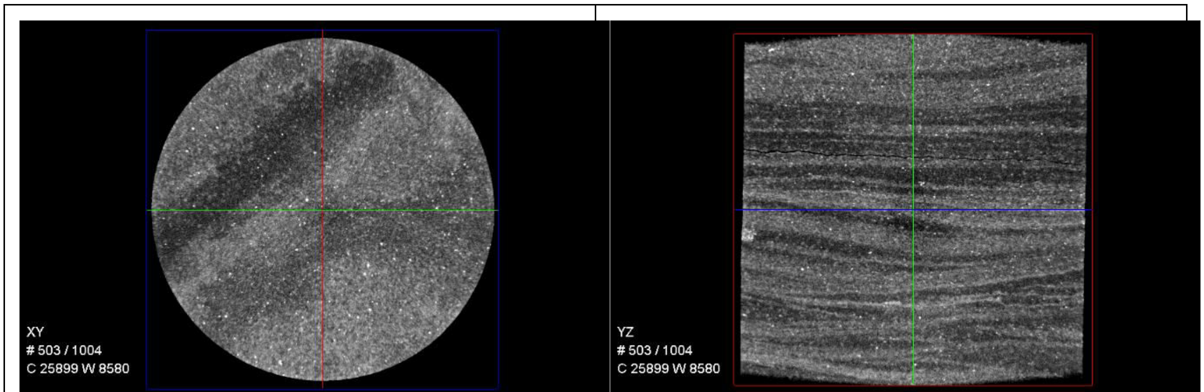
The results of this thesis can be used to accurately characterize the brittleness and frackability of unconventional shale to prevent hit or miss fractures, make fracking technically and economically meaningful and eventually contribute to hydrocarbon production optimization.

Appendix A

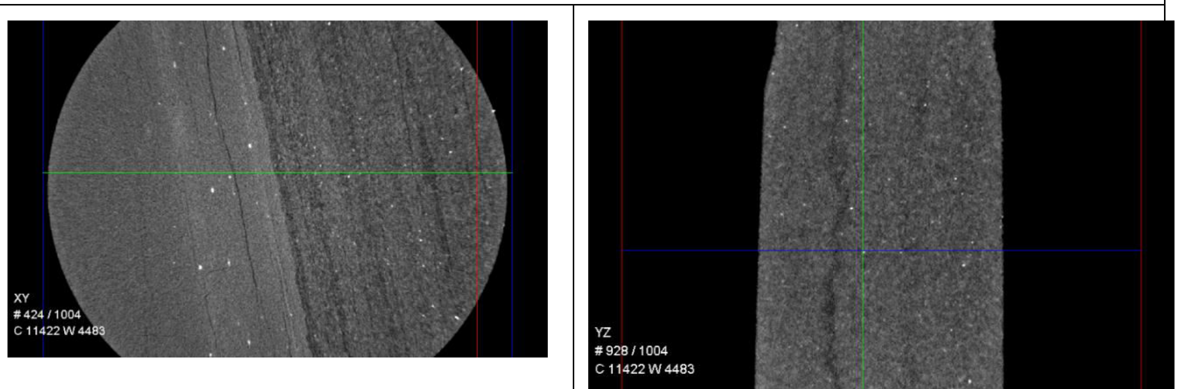
Micro CT Imaging



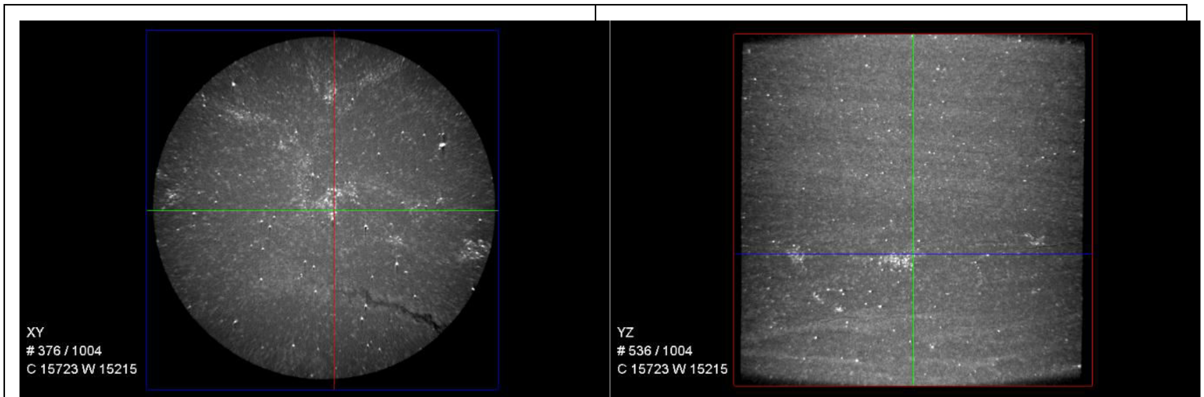
1H



1V



2H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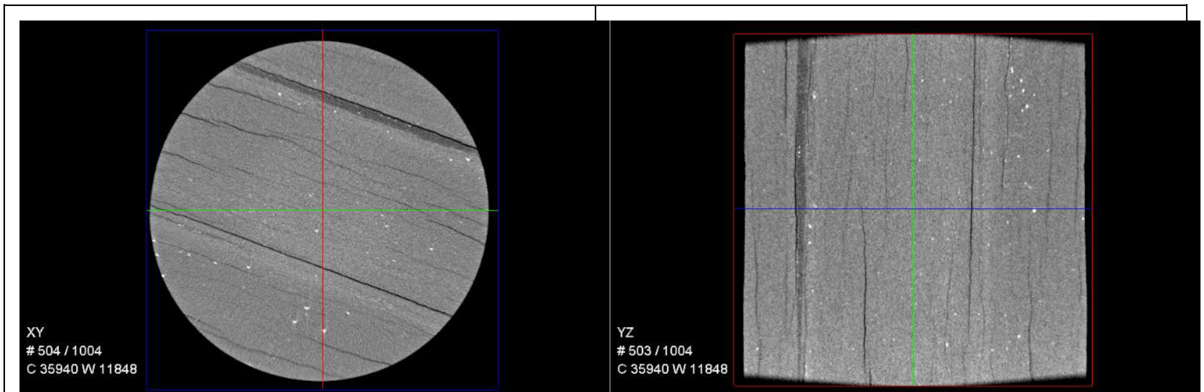
YZ
536 / 1004
C 15723 W 15215

2V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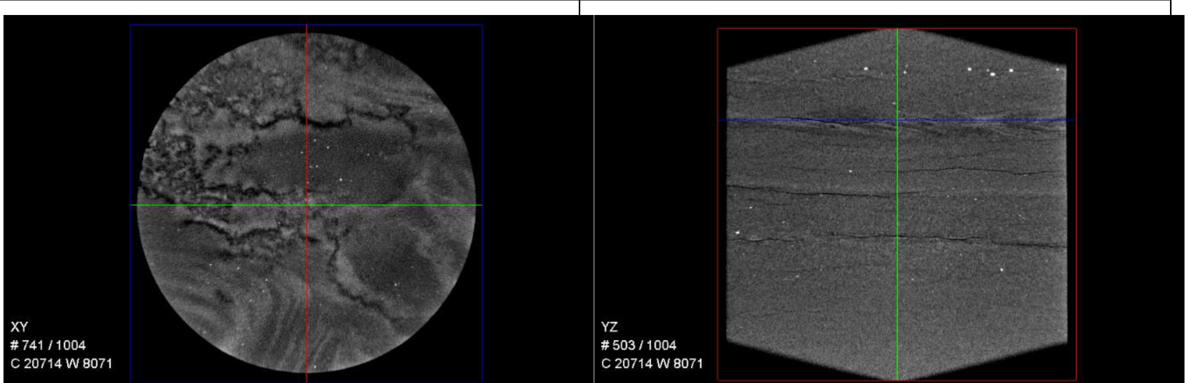
C 35940 W 11848

3H


XY
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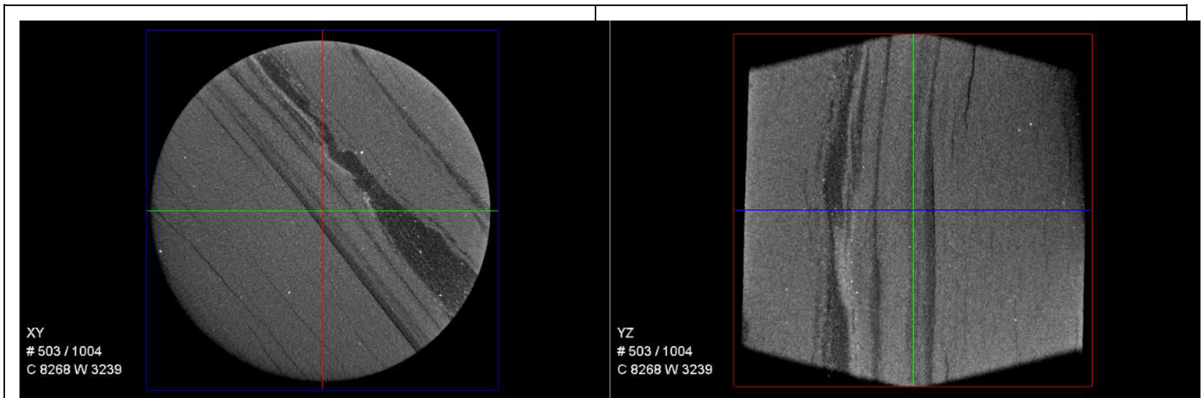
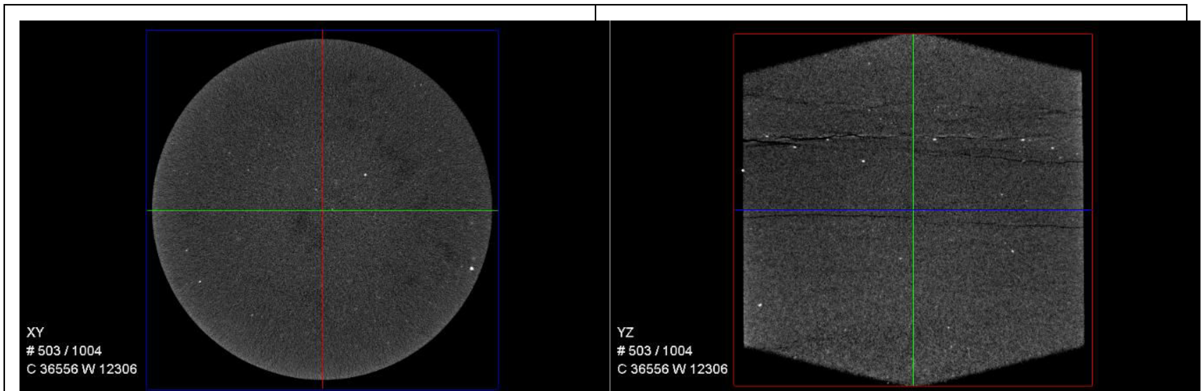
YZ
503 / 1004
C 20714 W 8071

3V


XY
503 / 1004
C 8268 W 3239
YZ
503 / 1004
C 8268 W 3239

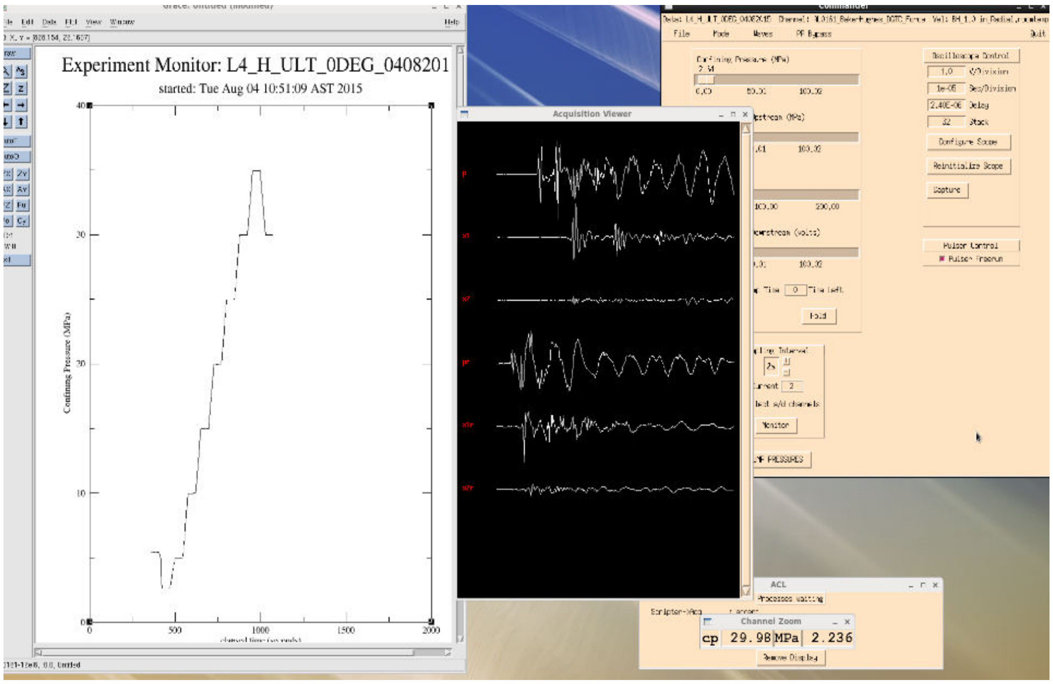
4H

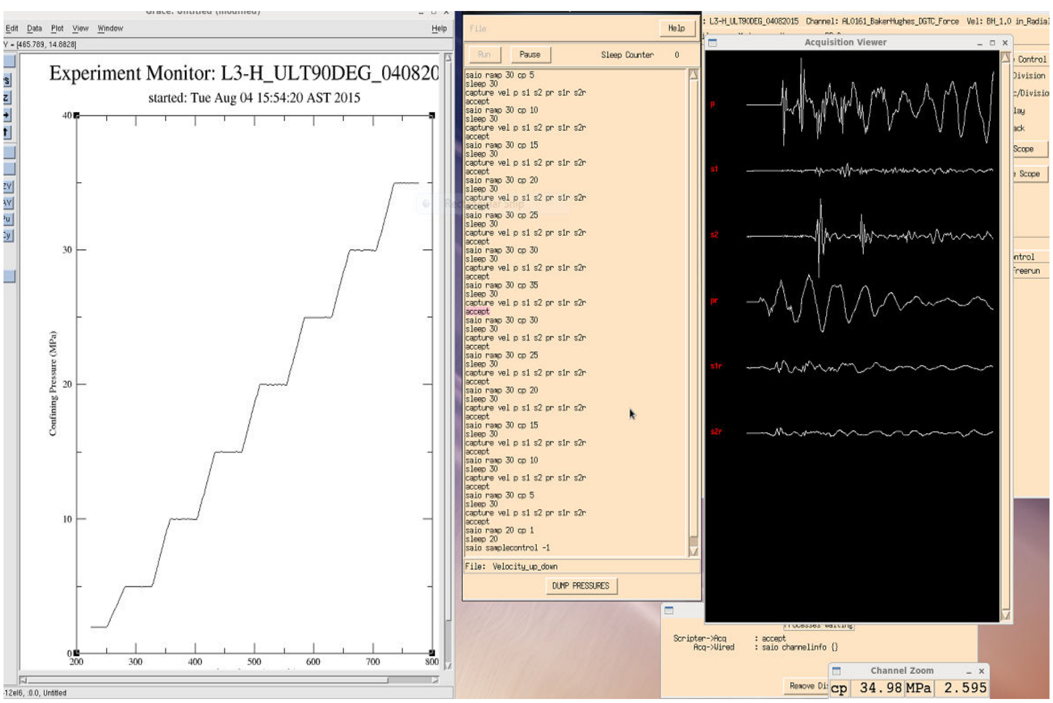

XY
503 / 1004
C 36556 W 12306
YZ
503 / 1004
C 36556 W 12306

4V

Appendix B

Waveforms of Velocity

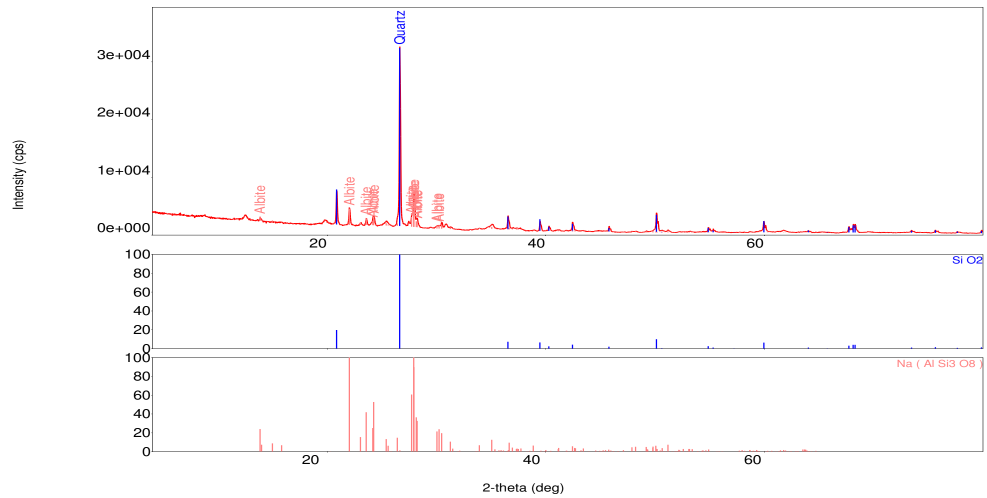




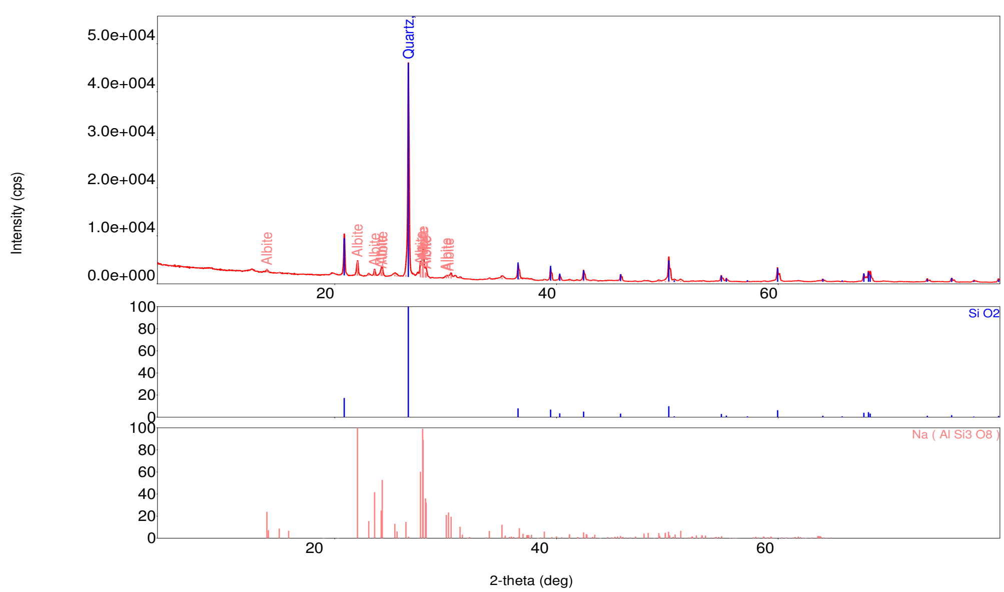
Appendix C

XRD ANALYSIS

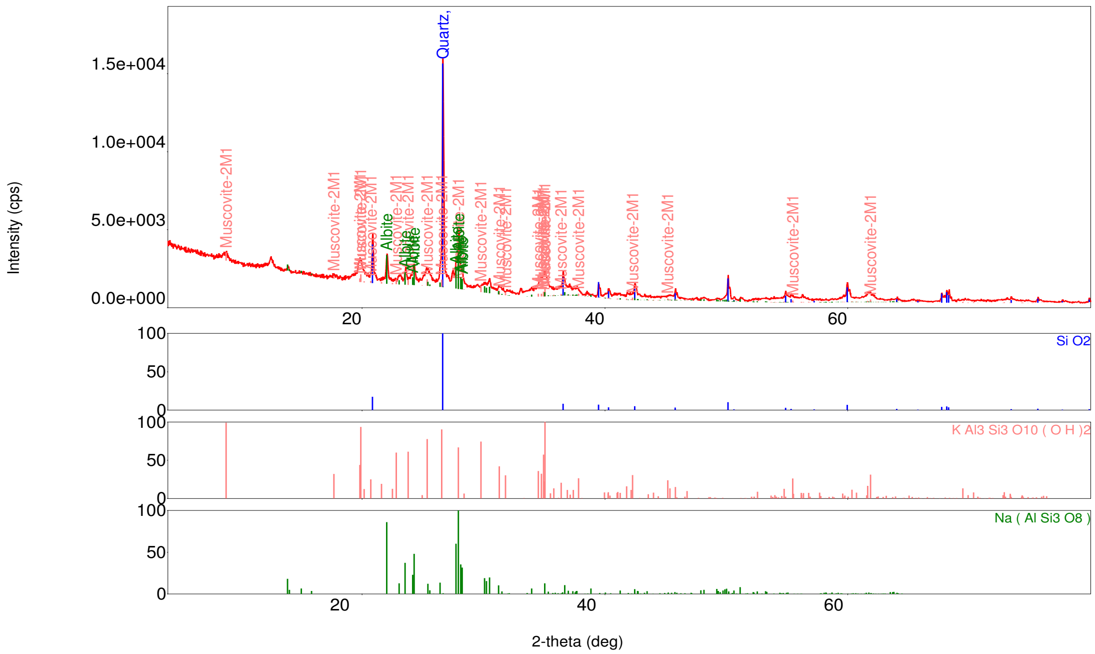
Measurement Profile 1H



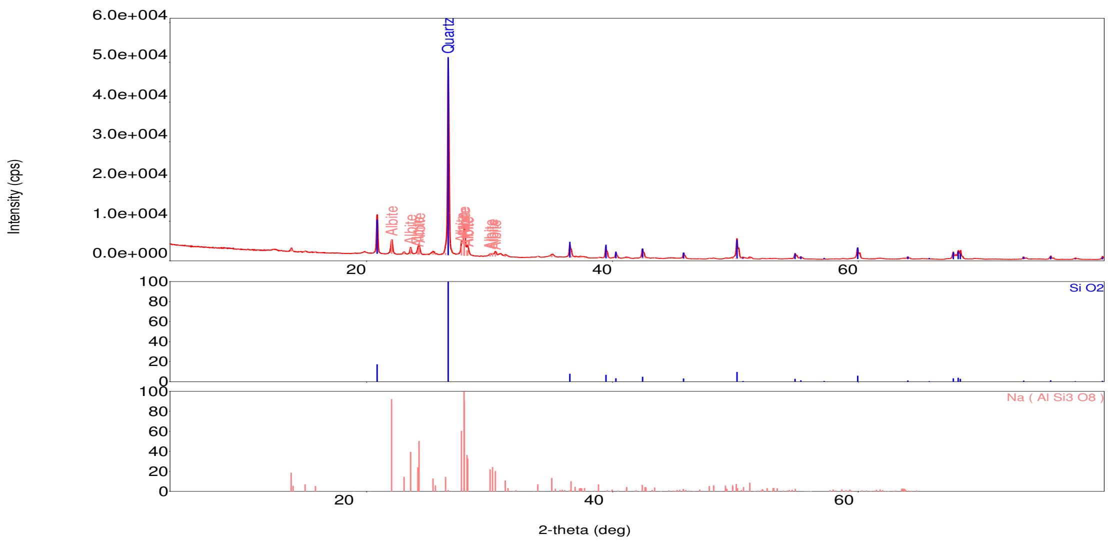
Measurement Profile 1V



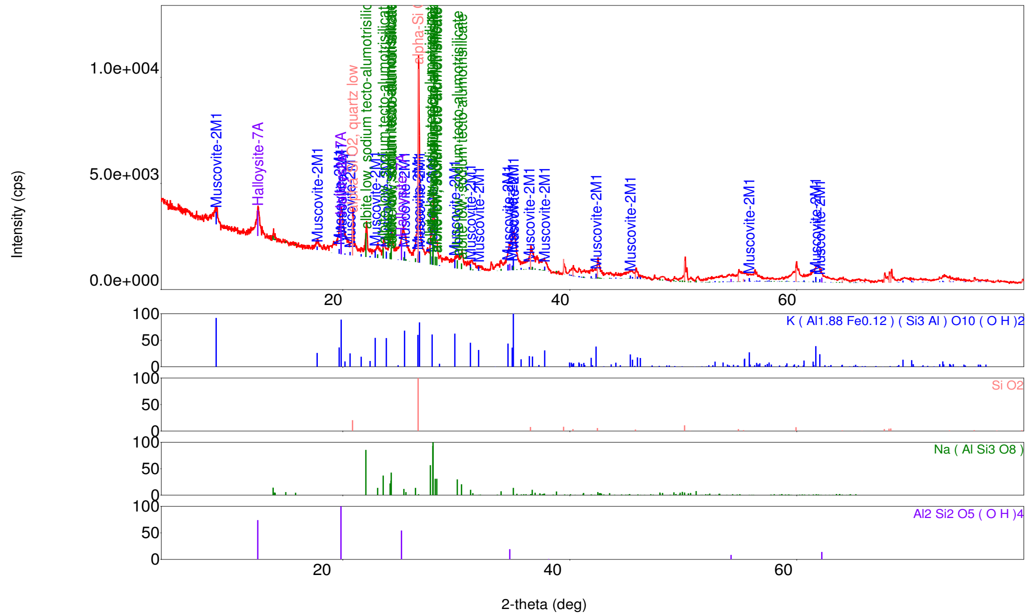
Measurement Profile 2H



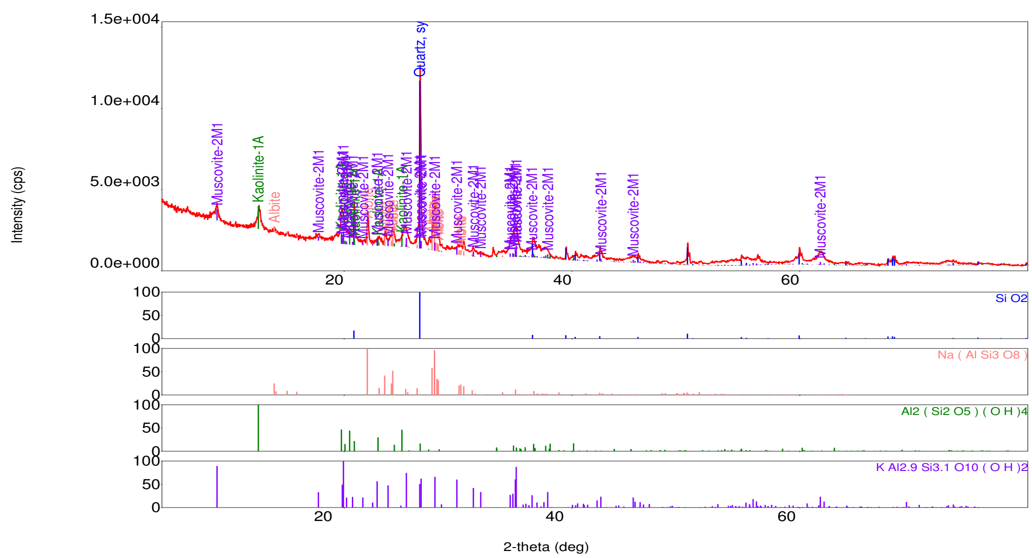
Measurement Profile 2V



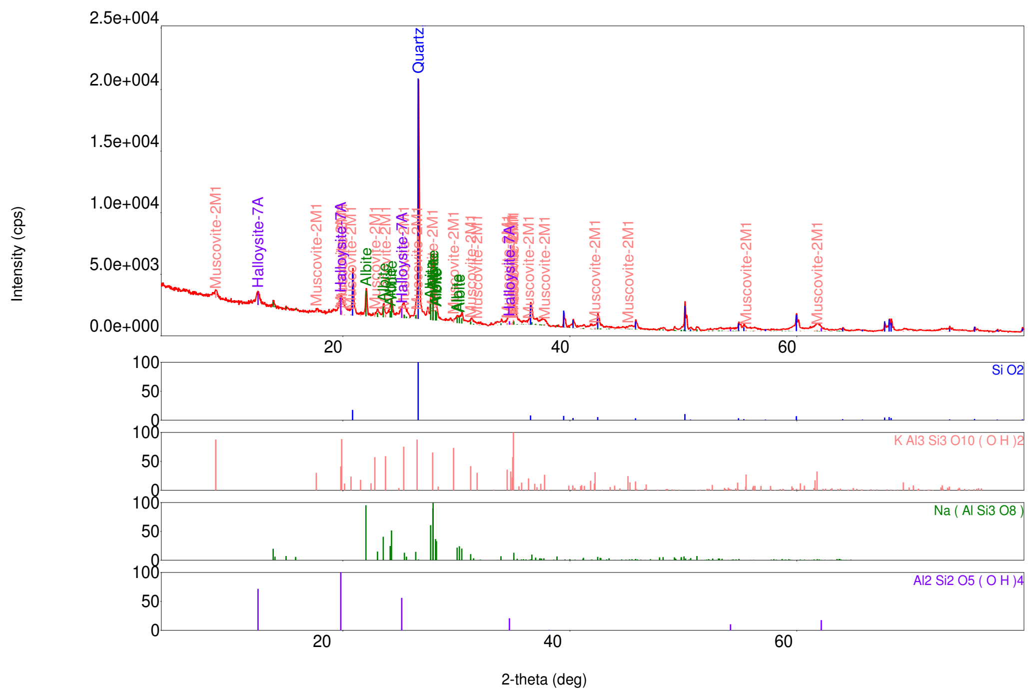
Measurement Profile 3H



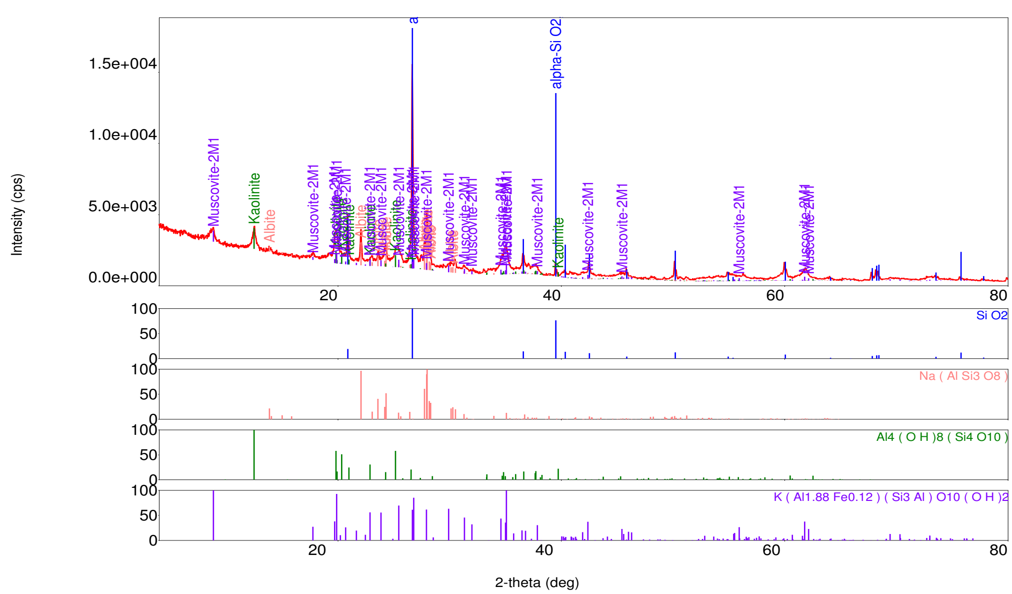
Measurement Profile 3V



Measurement Profile 4H



Measurement Profile 4V



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