Geomechanical Characterization of Hydraulic Fracturing through Pre-existing Faults and Fractures and Induced Micro-Seismicity in Tight Gas Shales

ABSTRACT

Development of Tight gas shale reservoirs requires a hydraulic fracturing to be safe and commercially productive. Geomechanics of this process is very critical in such shales.

Components of mechanical stratigraphy and material behavior are complex in tight gas shales. Because of their ultra-low permeability, such shales exhibit as a heterogeneous. This heterogeneity is a main function of anisotropy i.e. mechanical and stress properties vary continuously. Also, Geomechanical properties such as young's modulus and Poisson's ratio are important parameters for defining ductility and brittleness of these shales at which some shales could either fail in brittle or ductile manner, based on the clay contents. Dispersion behavior of such shales was also studied to define velocities, V_{Shear} and $V_{Compessional}$.

Technology of hydraulic fracturing was conducted to indicate most used horizontal stimulation techniques, fracturing fluids and post-frac evaluation techniques in tight gas shale reservoirs. Research studies show that the multi-stage horizontal fracturing is mostly used technique in such shale reservoirs. Also, treatment concepts, such slick water fracturing and hybrid fracturing are mostly used to frack brittle and ductile tight gas shales, respectively. Field experience also shows that direct-far field and near wellbore fracturing monitoring techniques are essentially used in monitoring fractures in such gas shales.

Two stimulation mechanisms were explored and found to be modeling fracturing in

tight gas shales: Tensile and shear fracturing mechanisms, known as *Hybrid Tensile-Shear Stimulations* (*HTSSMs*). In tight gas shale reservoirs, hydraulic fracturing requires injection of large volume of treatment fluids in order to generate a complex network of both newly tensile formed fractures and shear stimulated pre-existing fractures and faults. The fracturing initiation and breakdown defines in terms of both tensile and shear Modes. In addition, the generation of such network could lead to induce shear slip in large fault zones and thus cause micro-seismic events around stimulated fractures in gas shale reservoirs, as a result of pore pressure increases to a level lower than that required to create the tensile opening fracture.

The role of pre-existing natural fractures and faults is a very critical in shale gas production, particularly for US Barnett shales, if spacing between fractures is healed by deposited minerals such as calcite. Also, the presence of these fractures near fault zone may lead to migration of stimulation fluids into the underlying formations and thus loss of pay zone. These fractures also impact the hydraulic fracture treatment when fracking rock volume, leading to less broken shale surface area and thus loss of production. Also, a study of the production mechanisms in gas shales and main production divers was conducted to model the productive fracture spacing and surface area, reviewing a data from a case study.

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CHAPTER (1)

INTODUCTION

1.1. Background and context:

1.1.1. Tight Gas Shale:

1.1.1.1. Geological Formation:

Tight Gas shale formations are considered to have a combination of low matrix permeability, ranging from nano to microdarcy, and a small matrix porosity of 2 – 8 %. These formations have fine-grained strata with a high complexity and variable mineralogy of different clay minerals, such as chlorite, illite and smecite. Additionally, the mineralogy of such shales also includes calcite, silica, calcareous silts and/or quartz [1].

Tight gas shales have a high degree of thermal maturation and organic matter that lead sufficiently to generate gas. Different dominant characteristics are associated with these shales; highly associated surface area per unit mass, constituents of colloidal shape, and laminated anisotropy. These formations also show an elevated energy surface, giving tendency of promoting of gradually organic and mineralogy transformations and highly geochemical interactions. Furthermore, the interactions of their sediments with the present quantity of micro-organisms and depositional environment changes locally, resulting in all scales, have highly unique heterogeneous characteristics [2].

1.1.1.2. Mechanisms of Natural Gas Storing:

There are typically several mechanisms by which the natural gas is trapped and stored in tight shales: **(1)** Gas could be dissolved and adsorbed into kerogen matter [3], **(2)** Gas could be trapped freely in a small matrix pores, **(3)** Gas could be trapped freely in micro-cracking pores, **(4)** Gas could be stored freely in fractures that are hydraulically created during process of stimulation, and **(5)** Gas could be trapped and stored freely in a complex network of pores raised from organic material [4, 5]. **Figure (1.1** below**)** shows typical gas storing mechanisms, with respect of total gas content and organic matter.

1.1.1.1. Process of Shale Gas Extraction:

Tight gas shale reservoirs have intentionally a very ultra-low permeability and matrix porosity. These reservoirs most occasionally require methods that improve their permeability to extract the natural gas stored, and thus improve production efficiency. The conventional method that is commonly used to achieve this is a hydraulic fracturing with combination of horizontal drilling [6].

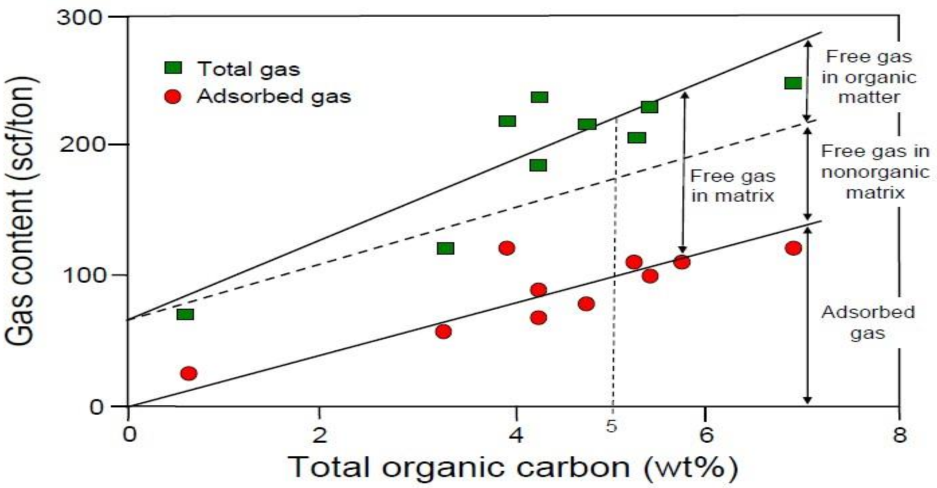

Figure 1.1: Typical processes by which natural gas is trapped and stored in tight Shale formations [3, 4, 5].

1.1.2. Hydraulic Fracturing:

1.1.2.1. Basics and Process:

The development of the hydraulic fracturing process with a combination of inclined horizontal drilling has successfully achieved a great stimulation process to enhance gas flow in most of ultra-low permeability reservoirs e.g. *tight gas shale*. Briefly, the process involves a fluid pumping (*water-rich*) under a certain pressure into the reservoir holes to create rock fracturing. This fluid consists of rich quartzite sands, called *Proppant* that functions as a proper opener of the generated fractures (see **Figure 1.2**). Additionally, the fracking fluid has some chemical additives such as *acids* that function to help initiating rock fracking [7].

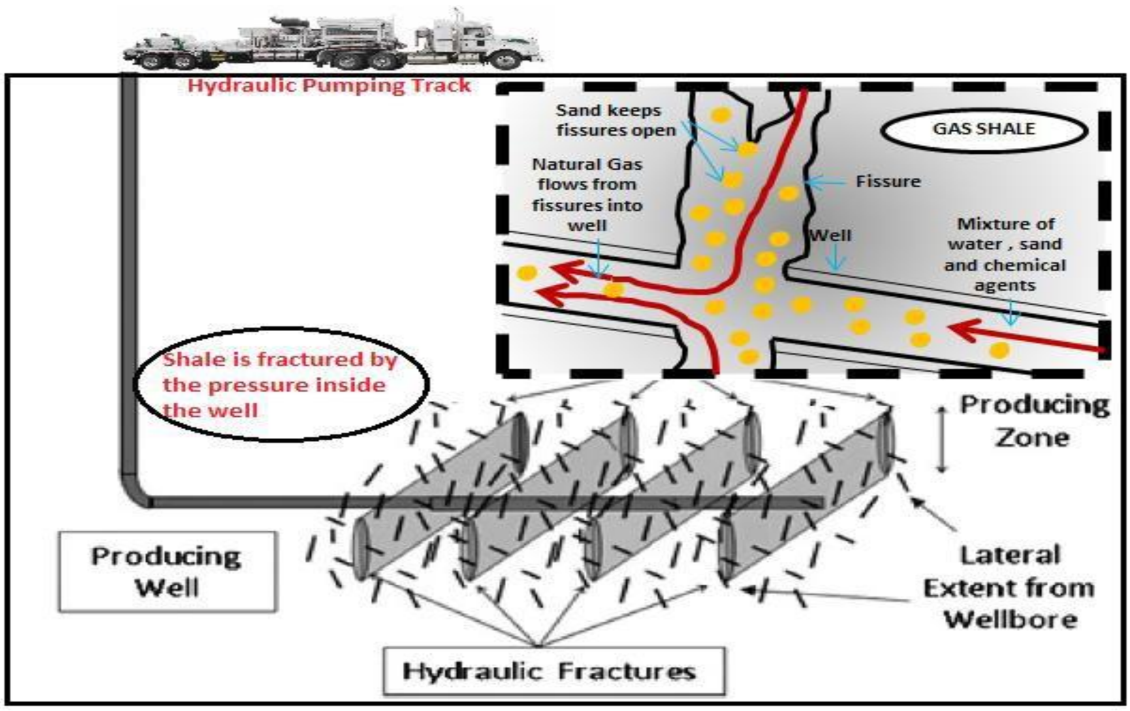

Figure 1.2: Schematic diagram of hydraulic fracturing in gas shale formations [7].

1.1.2.2. Mechanics of Rock Fractures:

The local *in-situ* stress, pore pressure of fluids and rock strength that is required to initiate the rock failure, are considered to be the dominant aspects by which the propagation of stimulated fractures are controlled. Moreover, there are many geomechanical theories and models used to predict the modes of hydraulic fracturing and fracture treatment design as a result of increasing pore pressure and stress changes, such as Perkins, Kern and Nordgren (PKN) , Geertsma and de Klerk (GDK), Mohr-Griffith failure and Mohr-Coulomb frictional models and theories, etc [8]. However, there are many research studies are now conducted using these models and theories to predict the mechanisms of fracturing in tight gas shales; these studies are found to be still secretive and thus are beyond the scope of this research.

Modes of rock fractures are categorised as *opening or extensional Mode (I)*, *shear or slide Mode (II)* or combination of both, known as *Hybrid process*, and *tearing Mode (III)*. **Figure (1.3)** shows types of genetic fractures modes. *Mode I fractures or opening mode* appears as a result of opening the fracture against the least principle stress ($_{3}$), exerting on the intact rock material. This means that the fracture tensile stress should be higher than the least principle stress (*exceeding the least principle stress*). Due to the fact that zero tensile strength is addressed to the most of rocks, giving tendency to that in order to form tensile fractures in the rock, no need too much tension (*indeed, almost 1/10 of young's modulus for rock material*). The conventional (*natural or stimulated*) hydraulic fracture, are defined in terms of tensile Mode (*Mode I*), without any signature of shear movement, as shown in **Figure (1.3, A)**. Briefly, the mechanics of forming hydraulic fracture under tensile stress is due to the increase of the injection fluid under pressure in the pores. As the pore fluid pressure is increased, overcoming the compressive stresses (*normal stresses*) [8]. This fracture will then open in tension. On Contrast, both Slide and tearing modes (*Modes II and III respectively*) result from the rock compression, leading to shear movement and fractures in the rocks (see **Figure 1.3, B and C**), but these modes typically differentiate in terms of fracture propagation, relevant to the subjected stress. In Mode II, known as a *slide mode*, the propagation of the fracture is parallel to the maximum principal stress ($_{1}$). This scenario can be an alternative one for systems resulting in high shear stresses in a hydraulic fracture. In Mode III, known as *tearing or anti-plane shear mode*, the propagation of the crack or fracture is perpendicular to the maximum principal stress. The reactivation concept of the pre-existing natural faults and fractures during hydraulic fracturing, i.e. those of influenced by high stresses failure, is induced by Mode II (*shearing*). Briefly, when the pore fluid pressure increases, (to a level below the pressure required to create tensile fracture), near pre-existing faults and fractures, it will lead to shear slippage, reactivating such faults and fractures and thus inducing micro-seismicity i.e. artificially induced shearing slip on pre-existing faults and fractures [8]. Meanwhile, it is worth to note that pre-existing natural faults and fractures (*due to Mode II*) may intersect with the newly formed hydraulic fractures (*due to Mode I*), leading to fluid leak-off and therefore form a complex network of conductive fractures with different geometries in tight gas shales.

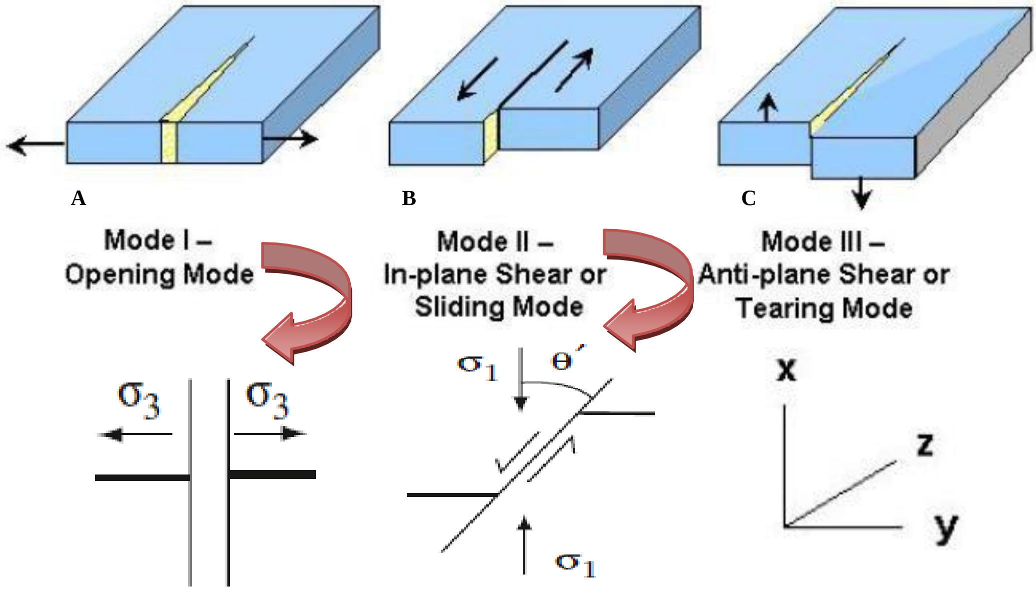

Figure 1.3: Schematic diagram of principle of fracture modes:
A) Tensile or opening mode (*Mode I*), **B)** Shear or slide mode (*Mode II*), and **C)** Tearing or anti-plane shear mode (*Mode III*). ( ) is dihedral angle [8].

1.1.2.3. Characterization of Geomechanics and Fluid flow:

From geomechanics perspective, the process of pre-existing faults and fractures reactivation is most likely linked to processes of the sub-surface hydrocarbon migration and thus trapping fill. There is, however, strong evidence that the matter of combination between pre-existing faults and fractures and hydraulic fractures will have tendency to increase production surface area and thus enhance permeability in some of U.S gas Shales during stimulation mechanisms [9]. Moreover, this evidence can be evenly applied to the active faults and fractures in tight gas shales and thus provide high gas flow [10]. On the other hand, if these fractures and faults are not subjected to stresses and induced failure systems; there will be no conduits for the fluid to flow. The latter case most frequently occurs when fractures act as a sealing post-discharge due to precipitation processes such as healed deposited minerals in cracks in Barnett U.S Shales, causing permeability destruction. This case gives tendency for pore fluid pressure to increase which may again leads to fault to be reactivated and thus improve permeability and fluid flow. This process is considered to be cyclic continuously [10].

1.2. Dissertation Outline:

This study tries to capture and understand the geomechanics of hydraulic fracturing in tight gas shales. Critical reviews have been conducted in this study to investigate the effects of different parameters on fracture initiation and deformation mechanisms in gas shales, and how might a gas production from such shales be consequently affected. This dissertation has four objectives which are addressed and outlined in each chapter as follows:

Chapter (2) provides an improved understanding of the components of mechanical stratigraphy and material behavior of tight gas shales. This includes; heterogeneity, stress dependence, mechanical anisotropy, geomechanical properties and brittle-ductile couplets behavior and dispersion behavior.

Chapter (3) provides an improved understanding of hydraulic fracturing technology in tight gas shales. This includes the followings: multi-stage hydraulic fracturing technique, selection and concepts of fracturing fluid, and the most successfully used post-frac diagnostic techniques e.g. Near-Wellbore and Far-Field Fracture Monitoring Techniques.

Chapter (4) is a proposal for the exploration of stimulation mechanisms of fracture initiation and breakdown as revealed by Induced Micro-Seismic Events in tight gas shale reservoirs. This extensively includes the key mechanisms by which hydraulic fractures and pre-existing fractures and faults are generated and propagated. It also provides an improved understanding of geomechanics principles of fracturing i.e. tensile and shear fracturing conditions and basics of *in-site* stress state, fracture orientation and growth. It also attempts to make interpretations for stimulation mechanisms and induced micro-seismicity, by simply making some implications and analyses of geomechanics and by reviewing a case study from
U.S shales in order to understand the principles of geomechanics for fracturing. Finally, it also discusses the relevance of induced micro-seismicity to tight gas shale compositions.

Chapter (5) presents the influences of pre-existing natural fractures and faults in shale gas production – case of U.S. shales. This includes the evaluation of the relevancy of pre- existing natural fractures and faults to gas production from tight shales and their effects on the hydraulic fracture treatment efficiency. It also provides a brief review of production mechanisms and techniques used to modeling gas production in such shales.

It also provides a brief understanding of production drivers and their implications and dedications to shale gas production, using a case study from U.S Barnett gas shales.