





knowledge of the geology and hydrogeology of the terrain, careful planning and engineering, and diligence in the execution of drilling and fracking, no meaningful problems should arise.

Vegter (2012) gives an impartial view of both sides of the debate in his book *Extreme Environment* and shows how environmental exaggeration can harm emerging economies.

## Objectives of fracking

Most vertical wells do not produce gas until the permeability of the coal seam reservoir is enhanced through stimulation treatment. Stimulation of CBM wells is achieved by performing hydraulic fracturing. Fracturing is normally performed only once during the productive life of a well.

Stimulation or fracking of CBM wells is done to achieve the following objectives:

- Remediate damage to the reservoir caused by drilling and cementing fluids infiltrating the reservoir matrix and natural fracture system;
- Create new fractures in the coal matrix and prevent these from closing by injecting proppant to better access the natural fracture system of coal cleats and pores;
- Open natural fractures wider and keep open with proppant to enable flow of gas and water from the cleats and pores to the well; and
- Extending the life of low producing wells by performing a second and more severe stimulation.

Note that the primary purpose of CBM well stimulation is to connect the well to the natural fractures in the coal. In the case of shale formations where there are no natural fractures, the objective is to create a fractured rock reservoir to access the shale gas contained in pores and adsorbed onto organic material.

## Geology and properties of coal beds

### Formation

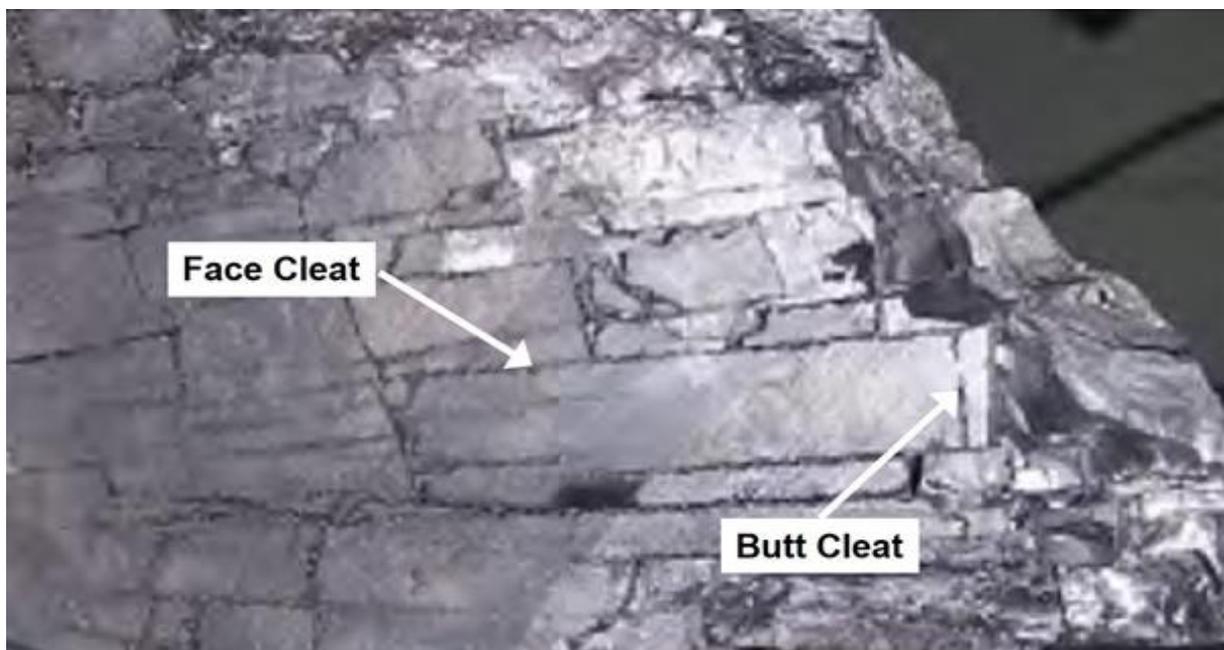
Coal is a combustible sedimentary rock formed from ancient vegetation which has been consolidated between other rock strata and transformed by the combined effects of biochemical decay, pressure and heat over millions of years. This process is commonly called coalification and involves the alteration of vegetation to form peat, succeeded by the transformation of peat through lignite, subbituminous, bituminous, to anthracite coal. The degree of transformation or coalification is termed the coal rank.

Coal occurs as layers or seams, ranging in thickness from millimetres to many tens of metres. It is composed mostly of carbon (55 to 95 %), hydrogen (3 to 13 %) and oxygen, and smaller amounts of nitrogen, sulphur and other elements. It also contains water and particles of other inorganic matter.

## Structure

All ranks of black coal are noted for the development of its jointing, more commonly referred to as cleat. This regular pattern of cracking in the coal may have originated during coalification. The burial, compaction and continued diagenesis of the organic constituents result in the progressive reduction of porosity and permeability. At this stage microfracturing of the coal is thought to be generated. The surfaces and spaces thus created may be coated and filled with mineral precipitates.

Cleats are fractures that occur in two sets that are, in most cases, mutually perpendicular. Through-going cleats formed first and are referred to as face cleats. Cleats that end at intersections formed later and are called butt cleats. Some of the characteristics of the structure of coal are shown in Figure 2.



**Figure 2: The structure of coal**

At surface conditions, cleats are typically  $<0.1$  mm in width and are scarcely visible with the naked eye (Laubach et al, 1998). Cleats in coal are much more intensely developed than fractures in adjacent non-coal rocks.

## Gas content

CBM is a gas, primarily methane, that naturally occurs in coal seams. It is formed during the conversion of organic material to coal and becomes trapped in cleats and micropores in the coal seam. Coal seams are, therefore, both the source and reservoir for CBM. The CBM is trapped in the coal seam in part by water pressure and in part by weak covalent Van der Waals forces. CBM exists in the coal seams in three basic states: as free gas, as gas dissolved in the water in coal, and as gas adsorbed on the solid surface of the coal.

Sorption is a physical or chemical process in which gas molecules become attached or detached from the solid surface of a material. Desorption is the process that occurs when free gas pressure drops, and adsorbed gas molecules start desorbing from a solid surface.

The amount of gas retained in a coal seam depends on several factors, such as the rank of coal, the depth of burial, the immediate roof and floor, geological anomalies, tectonic forces, and the temperature prevailing during the coalification process (Thakur, 2017). In general, the higher the rank of coal and the greater the depth of coal, the higher is the coal's gas content. Actual gas contents of various coal seams to economically mineable depths of 1200 m are up to 125 m<sup>3</sup>/t. Gas content in coal is not fixed but changes when equilibrium conditions within the reservoir are disrupted.

### Hydrostatic pressure

Pressure in sedimentary basins has two components, namely lithostatic pressure, which is the pressure caused by the weight of the overburden and hydrostatic pressure, which is an opposing pressure caused by reservoir fluid (Pashin, 2014). Intrusion of groundwater into coals is a common occurrence, and coal beds act as regional aquifers in some areas.

Water removal from the coal bed is the principal mechanism by which coal is depressurised, and understanding the hydrology of CBM reservoirs and the ways in which coproduced water can be managed is essential for a successful CBM project. Gas and water production over time is illustrated in Figure 3. The produced water often contains high concentrations of salts and other organic and inorganic substances solubilised from the coal bed. The disposal of these waters can present environmental problems.

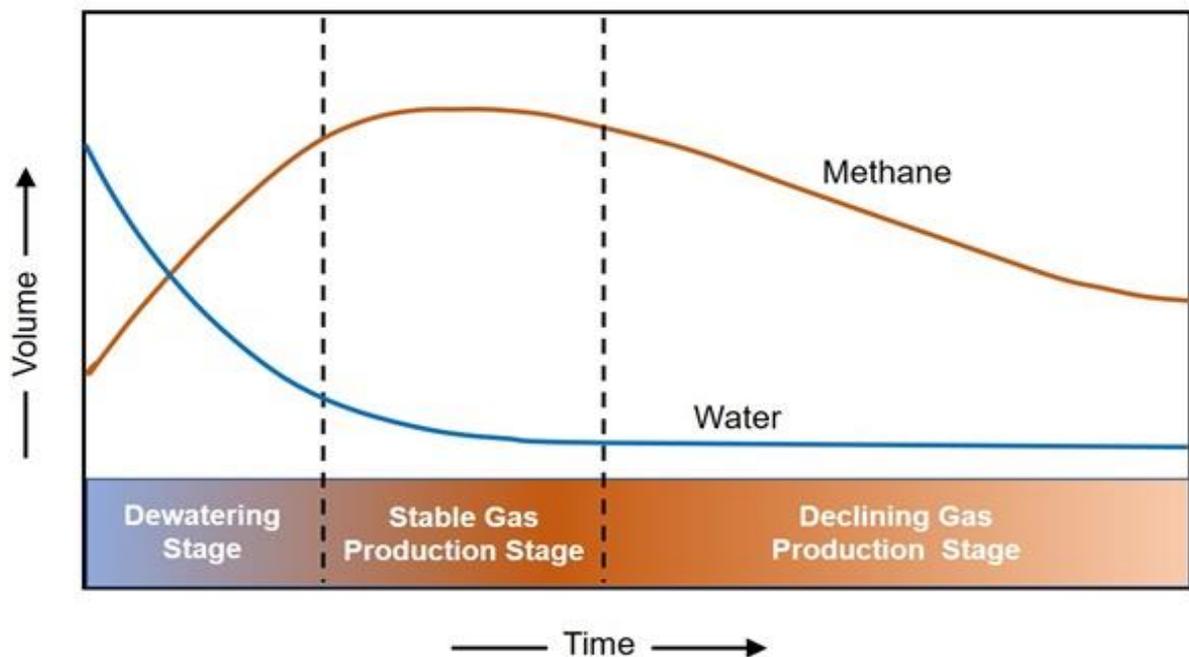


Figure 3: Gas and methane production over the life of a well

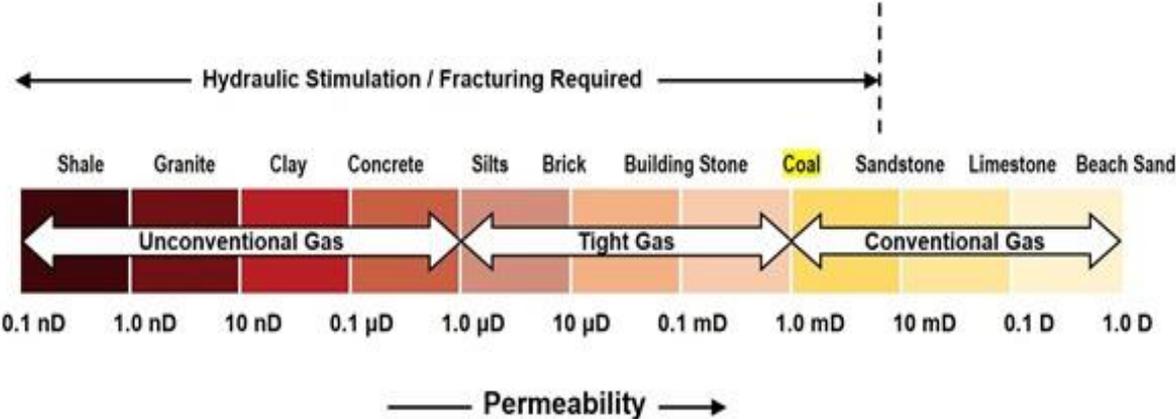
CBM production can take place only when the reservoir pressure is reduced sufficiently to allow the gas to desorb. Gas flow to wells drilled into the coal seam takes place through natural fractures and fractures created by fracking, not through the relatively impermeable coal matrix.

**Porosity and permeability**

Porosity is the fraction of the total volume of a rock that can hold gas or liquid, i.e. it is the percentage of the bulk volume of the rock that is not occupied by solid matter. The face cleat in coal is the major fracture that stores and conducts gases, with the butt cleat the minor fracture. Most of the porosity of coal comprises the space taken up by these fractures. The porosity of the cleat system in coals ranges from 1% to 5%.

Next to gas content, permeability is the most important coal reservoir property for CBM delivery. Permeability is a property of porous media such as coal, and is a measure of the capacity of the medium to transmit fluids. It depends on the driving pressure differential, the area of the specimen, and the viscosity of the fluid. However, permeability in coal-bed methane reservoirs is a transient property (Thakur, 2017). As gas is produced, the coal matrix shrinks, thereby widening cleat apertures and improving both porosity and permeability.

Permeability is measured by an arbitrary unit called the Darcy, D, which is named after Henry d’Arcy, who in 1856 devised a method of measuring the permeability of porous rocks. One Darcy is 1 cm<sup>3</sup> per second of a fluid having viscosity of 1 cP flowing through a 1 cm<sup>2</sup> cross-section of rock under a pressure gradient of 1 atm/cm. (Robertson & Chilingar, 2017). The Darcy scale is shown in Figure 4, with representative examples of rock and rock formations in the different ranges. Note that different ranks of coal will have different permeabilities and a range should be applied for each of the examples listed. As can be seen from Figure 4, the permeability of coal is such that light fracturing is required and therefore the term ‘stimulation’ is preferred.



**Figure 4: Permeability continuum** (Adapted from Simpson, 2019)

## The fracking process

### Opening comments

An introduction to fracking was given in Part 1 of this series of articles (Steyn, 2019). This covered the applications of fracking, described the chemicals and additives used in fracking fluid, and considered a method to classify fracking based on application, severity and impact.

In this section a brief description is given of some of the aspects of the stimulation of CBM wells by hydraulic fracturing.

### Well completion and perforation

Vertical well drilling is normally done with small footprint air rigs due to low cost and low environmental impact. Small cuttings pits are necessary to capture returned solids and formation fluids carried back by the air stream.

Casing is installed into the coal bed to total depth and cemented in place. Cementing the casing provides pipe support, zonal isolation to protect against cross contamination, and well control. Once the casing has been cemented in the hole, slotting can commence to gain access to the coal formation. One method involves the use of a jetting tool where friction-reduced water (slickwater) and sand are pumped at high pressure through opposing jets to abrasively remove casing and formation (Rodveldt, 2014). Slots can be cut most efficiently going down by slowly lowering the tool in the hole while pumping. Slot lengths should not exceed 35cm, prevent compromising the integrity of the casing. Another, more conventional method of gaining access to the coals seam is perforating the casing with explosive jet charges.

### Fracking in 4 stages

#### *Stage 1: Acid wash (Optional)*

This stage is not required in all cases and depends on the geology of the coal and the extent of blockage of the natural coal cleats by cement. However. It involves the pumping of a mixture of water and dilute acid such as hydrochloric or muriatic acid into the well and through the perforations in the wellbore into the coal face. This serves to clear cement debris in the wellbore and provide an open conduit for other fracking fluids by dissolving carbonate minerals and opening fractures near the wellbore.

#### *Stage 2: Propagate fractures*

This is also referred to as the pad stage and involves the pumping of slickwater or gelled water, without proppant material, into the well. The wellbore is filled with the water solution, fractures in the coalbed are opened and propagated, thereby creating pathways for the placement of proppant. Slickwater has fewer additives than gelled water, and is the preferred option in the USA.

### **Stage 3: Keep fractures open**

Stage 3 is also referred to as the prop sequence stage. It consists of several sub-stages of pumping water with proppant material (mostly fine mesh sand with spherical particles) into the fractures created in Stage 2 to 'prop' or keep the fractures open after the pressure is reduced. Proppant material may vary from a finer particle size to a coarser particle size throughout this sequence. The pressure of the fracking fluid is typically around 172 bar for this stage. On completion, the pressure is reduced, fracking fluid returns to the wellbore and proppant is locked in position in the fractures.

### **Stage 4: Flush**

Fresh water is pumped into the wellbore to flush out the fracking fluid, including flowback fluid from the fractures, to surface. This is normally stored in a lined pit, before disposal.

## **Potential impacts of fracking**

### **Opening comments**

Irresponsible fracking of coal seams has the potential to cause harm to the environment and the health and safety of operators and the community. I give a brief overview of some of the most mentioned potential impacts of fracking in the sections that follow.

### **Visual impact**

Fracking for the economic recovery of CBM is generally performed at depths of between 250m and 1200m. Most wells are fracked only once during their operating life of 20 to 30 years, and nobody gets to see the effect underground. However, the visual impact has to do with the number of wells required to effectively recover the CBM. Vertical wells are typically spaced at 400m to 500m intervals and this translates to many wells in a small area, as shown in Figure 5.



**Figure 5: Visual impact of many vertical wells in a small area**

The number of wells can be drastically reduced by using directional drilling along the coal beds. A significantly larger area can then be covered than with a vertical well, thereby reducing the visual impact. However, horizontal drilling is not applicable in all cases and depends on the number and thickness of the coal seams.

## **Spills**

A concern during fracking operations is the potential for spills or releases at the well pad site or during transportation. Prepared fracking fluid or chemical additives in their concentrated form pose a higher risk while being transported or stored on-site than when injected into the subsurface during the fracking process.

Sources of spills at the pad site include mechanical failures at the drilling/fracking rigs, storage tanks, pits, and even leaks or blowouts at the wellhead. Leaks or spills may also occur during transportation of materials, chemicals and wastes to and from the well pad. Soil, surface water and groundwater are the primary risk receptors. According to Holloway (2017), effective containment is a major factor in minimising the impacts on human health and the environment when a spill occurs. This can be further improved by using inherently safe and biodegradable additives in the fracking fluid.

## **Air pollution**

Air pollution can occur during every stage of CBM development, from exploration to construction, operation, maintenance and final closure. Heavy equipment is used during site preparation to clear and prepare the well pad site and to create new roads. Generators are set up, and there are emissions from vehicles and generators if they are diesel powered, as well as increased coarse particulate matter and dust from the new roads and increased truck traffic on the roads.

During normal operation and maintenance activities, methane can be released from pipes and machinery. Produced water also contains some dissolved gas which can be released to atmosphere. During exploration and upset conditions, significant volumes of methane is routed to a flare system where the gas is combusted to form carbon dioxide. All these aspects can be, and must be, carefully managed.

## **Silica Dust**

Silica dust is an emission source that is becoming more of a fracking industry concern. The fracking process requires large volumes of sand as proppant. Therefore, many truckloads of sand must be offloaded and transferred before being mixed with water and other chemicals and pumped down-hole. The dust produced by the handling of sand, which may contain up to 99% crystalline silica, is a health concern due to the risk of silicosis, a progressive and disabling lung disease. Sand stockpiles must be kept wet to reduce dust, and operators should be required to wear dust masks.

## Groundwater pollution

A common concern expressed by potentially affected parties about fracking is that the process creates fractures extending past the target formation to aquifers, allowing fracking fluids to migrate into the drinking water supplies (Holloway, 2017). This is unlikely because it would require the hydro-fractures to extend several hundred meters past the upper boundary of the coal seam. After completion of the fracking process, the flow of water and gas is toward the CBM recovery well, and not away from it.

The US Environmental Protection Agency (EPA, 2004) concluded, after a multi-year study, that the injection of fracking fluids into CBM seams poses little or no threat to higher lying aquifers of potable water. In a review of cases of contaminated boreholes, they also found no confirmed cases that are linked to fracking fluid injection or the subsequent underground movement thereof.

## Produced water impacts

Produced water from the coal bed, as well as flowback water from the fracking step, is commonly stored in pits or tanks on the wellfield before removal by truck or pipeline for reuse, treatment, or disposal. These options depend greatly on the quality of the water, which can vary from suitable for agricultural purposes to highly saline water. These pits and tanks are possible sources of leaks or spills.

Produced water may also be stored in evaporation ponds, with or without an HDPE liner system. Current best practice calls for a triple liner system in evaporation ponds with leak detection. Leaks of saline water into the subsurface will sterilise the soil and pollute upper aquifers in the long run.

Saline produced water should ideally be treated in a water treatment facility. A policy of zero pollution and waste is recommended. This implies that concentrated saline streams should be sent to evaporation ponds, or processed in a drying system to remove the salt from the water. A plethora of options are available, and each should be customised for the unique characteristics of the site and the produced water. Proper treatment and use of the produced water have proven to be highly beneficial

## Gas in water wells

Opponents of fracking love to cite cases of flammable gas in water wells as this makes for interesting reading. Although there have been many reported cases of gas in domestic water wells in the USA, almost all of these resulted from the unsafe storage of conventional natural gas in underground reservoirs, and none as a result of CBM recovery.

## Gas explosions

The lower explosive limit (LEL) of CBM occurs when approximately 5% by volume of gas is mixed with 95% by volume of air. This translates into a serious explosion and fire hazard, especially where the gas can migrate into a confined space such as a room

or an electrical vault. These hydrocarbon gases are often the result of leakage from gas pipelines. If the explosion (LEL) limit is met, a spark can quickly initiate a fire or an explosion.

A vast network of pipelines is normally part of any CBM development, and the risk of fires or explosions is always present. For this reason, the pipelines are normally buried underground to protect them from damage and methane detectors are used before any work is done. However, the risk of an explosion is minimal in open spaces because methane is much lighter than air.

### **Induced seismicity**

Pumping fluids in or out of the Earth's subsurface has the potential to cause seismic events. Fracking into a moderately sized fault at a sufficiently high rate and pressure may produce enough seismic energy to create measurable signals at instruments very close to the fracking site.

Seismic events, when attributable to human activities, are called 'induced seismic events.' Seismic events are dependent upon the sub-surface geology of the site. The biggest micro-earthquakes directly attributable to fracking have a magnitude of about 1.6 on the Richter Scale, which is insignificant (Holloway, 2017).

### **Subsidence**

The risk of subsidence is often mentioned when potential impacts of fracking are discussed, more so in the case of CBM production than for shale gas. The reason for this is twofold: CBM wells are much shallower than shale gas wells and significant volumes of produced water must be pumped from CBM wells in order to release the gas.

However, no direct correlation has yet been found between CBM wells and surface subsidence. Remember that coal seams suitable for CBM recovery are at least 250m deep and that the coal itself is not removed, but only the water contained in the coal.

### **Site remediation**

The common objective in the site remediation of drill pads and other infrastructure is to restore the site to its former condition and use (Holloway, 2017). Many countries require a mine closure plan which is updated at regular intervals. The closure plan should make provision for plugging of production wells, the removal of all pipelines, cables, tanks, other equipment on site and the remediation of any contamination. Closure plans must include an accurate estimate of the anticipated cost of closure and describe how provision is made to finance closure activities. Well sites and access roads cover a small percentage of a CBM wellfield and will quickly revert to their natural state after closure.

It is normally expected that gas companies continue with groundwater monitoring for a period of at least five years after closure to ensure that there are no latent environmental problems.

## Ranking of fracking intensity

Adams and Rowe (2013) proposed a terminology based on some of the physical aspects of fracking to allow clear differentiation between the many different types of hydraulic fracturing operations. This approach was described in more detail in Part 1 of this series of articles.

Based on this terminology, fracking of coal beds for CBM recovery can be classified as Type C(ap), meaning that additives and proppant are used in the fracking fluid. In comparison, fracking of shale seams for gas recovery would be classified as Type D(ap) because of higher pressures and more intensive fracking.

## Closing remarks

CBM reserves represent a major contribution to energy needs. However, gas recovery by fracking, requires responsible management to minimise any environmental effects. The industry is adapting, where possible, to fewer and more benign fracking chemicals to further reduce the impact of flowback and produced waters.

International economic, environmental, and technological advances over the past decade have led to the consideration of CO<sub>2</sub> sequestration together with CBM recovery. The idea is to geologically sequester CO<sub>2</sub> in coal seams, while at the same time recovering the methane already in them. The CO<sub>2</sub> would be injected via wells drilled into the coal, and the CO<sub>2</sub> would drive the methane out of the coal through other wells to the surface. This two-in-one idea is feasible because bituminous coal can store twice the volume of CO<sub>2</sub> than it stores methane. The net result would be less CO<sub>2</sub> in the atmosphere, no significant new methane added to the atmosphere, and enhanced recovery of methane to help pay for the process.

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