chapter 1

Unconventional Gas – What is it?

1.1   Introduction

Dry natural gas is naturally occurring methane extracted from the petroleum produced from oil and gas wells. Wet natural gas refers to naturally occurring petroleum gas (largely methane with lesser amounts of ethane) and gas liquids (such as butane, propane and molecularly heavier hydrocarbons). Wet natural gas is generally more valuable than dry natural gas based on the higher calorific value of wet gas.

The Society of Petroleum Engineers (SPE[1]), American Association of Petroleum Geologists (AAPG[2]), Society of Exploration Geophysicists (SEG[3]), World Petroleum Council (WPC); and Society of Petroleum Evaluation Engineers (SPEE) have worked over many years to standardise the definitions of petroleum resources and how they are estimated, culminating in the jointly developed Petroleum Resources Management System in 2007 (SPE-PRMS). The definitions and guidelines in the SPE-PRMS are designed to provide a common reference for the international petroleum industry. The Australia Security Exchange (ASX) is considering its requirements for how listed companies report resources, including the adoption of, or adapting the SPE_PRMS. The Glossary of Terms Used in Resources Evaluations included as Appendix A in the SPE-PRMS has therefore been adopted, with minimal alteration, for this report.

Unconventional resources are defined in the SPE-PRMS as follows:

"Unconventional resources exist in petroleum accumulations that are pervasive throughout a large area and that are not significantly affected by hydrodynamic influences (also called "continuous-type deposits"). Examples include coal seam gas (CSG[4]), basin-centred gas, shale gas, gas hydrate, natural bitumen (tar sands), and oil shale deposits. Typically, such accumulations require specialised extraction technology (e.g. dewatering of CBM, massive fracturing programmes for shale gas, steam and/or solvents to mobilise bitumen for in-situ recovery, and, in some cases, mining activities). Moreover, the extracted petroleum may require significant processing prior to sale (e.g. bitumen upgraders)."

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1   The SPE is the peak international professional representative body for petroleum engineers. The SPE has a very active local branch in South Australia.

2   The AAPG is the peak international professional representative body for petroleum geologists The Petroleum Exploration Society of Australia (PESA) is the AAPG's local affiliate. PESA has a very active local branch in South Australia.

3   The SEG is the peak international professional representative body for exploration geophysicists. The Australian Society of Exploration Geophysicists (ASEG) is the SEG's local affiliate. The ASEG has a very active local branch in South Australia.

4   CBM is synonymous with Coal Seam Methane (CSM) and Coal Seam Gas (CSG). CSG is the more widely used term in Australia.

The relationship of unconventional to conventional resources is illustrated by a resource triangle (Figure 1.1), modified from the figure published by Chan (2011[5]). Unconventional gas resources are shown down the right side of the triangle. Coal gasification has been added to the base of the triangle as suitable coals can be converted to synthesis gas ('syngas') either underground (in-situ) or through mining and surface processing. Synthesis gas can then be further processed to manufacture high value synthetic diesel (liquid synfuel) and fertilizer. Oil shale and coal gasification resources differ from the other unconventional gas resources in that the enhancement of host rock reservoir quality through either de-pressurisation (as for shallow Coal Seam Gas, CSG) or hydraulic fracture stimulation (as for shale gas, shale oil and CSG) is not the key to yield significant volumes of synthesis gas. Rather, thermal energy is the key to creating synthesis gas from oil shale and coal gasification.

Very large volumes of petroleum exist in unconventional reservoirs, but their commercial recovery often requires a combination of improved technology and higher product prices.
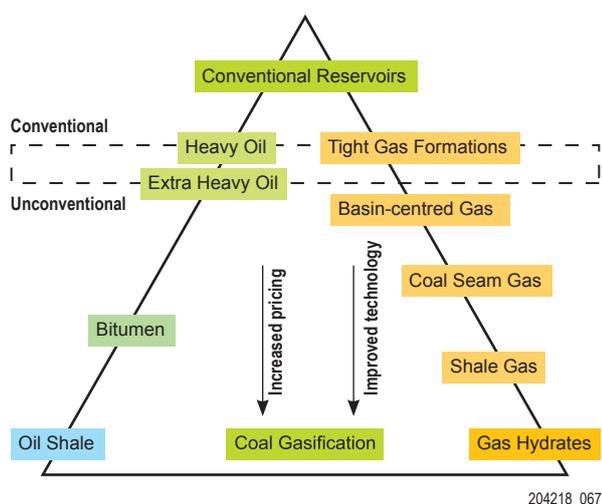

Figure 1.1   *Resource Triangle - modified from Chan (2011) and Holditch (2009)*

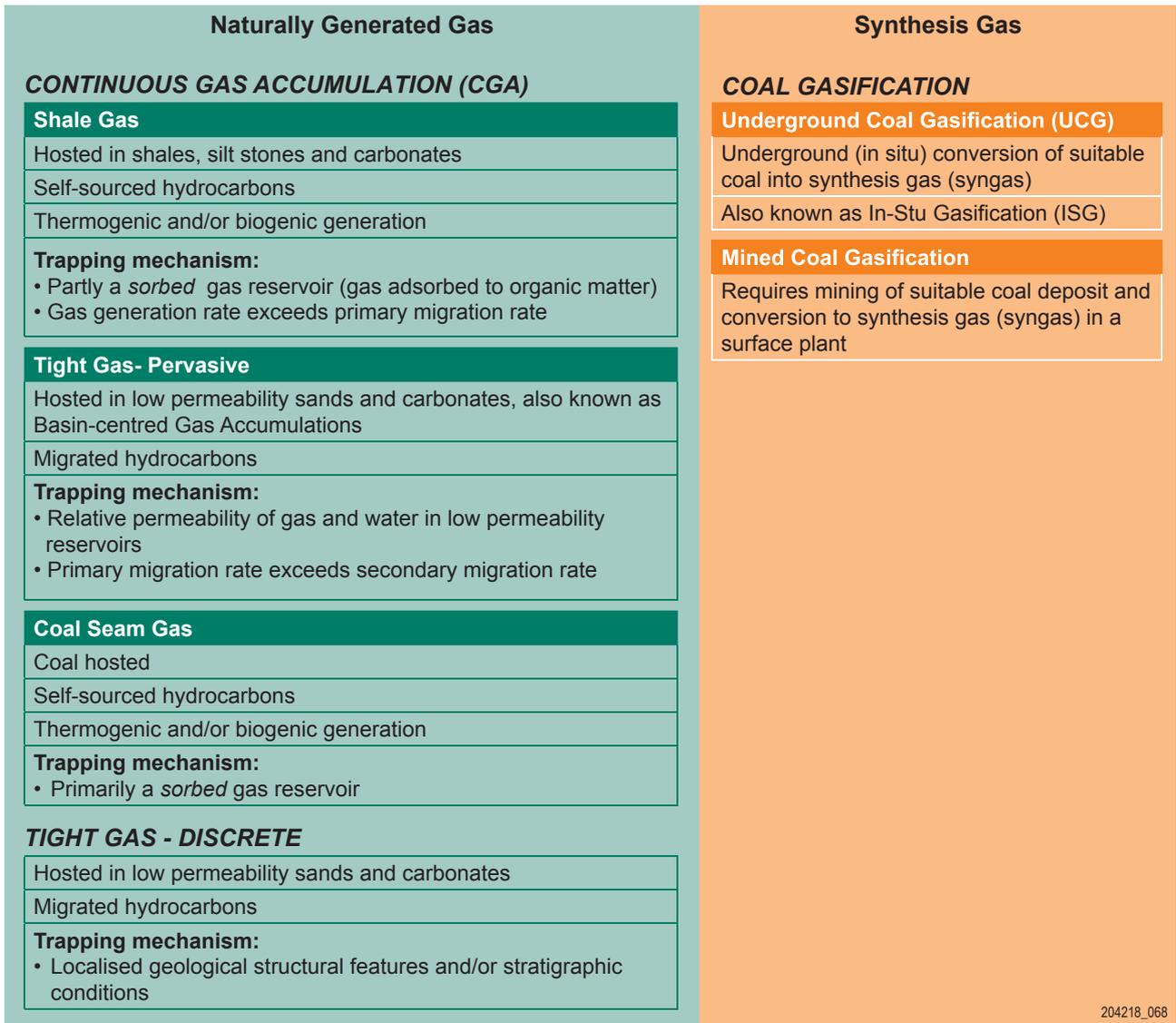## 1.2 Definitions and Generic Play Descriptions

The basic characteristics of each of the unconventional gas resource categories, with the exception of gas hydrates, are summarised in Figure 1.2. Unconventional gas resources have been divided into two broad types – those in which gas has been generated by natural thermogenic and/or biogenic processes[6], and those in which gas (synthesis gas) is synthetically generated underground or in a surface plant with a thermo-chemical process.

1.2.1 Reserve and Resource Definitions

The SPE-PRMS resources definitions, together with the classification system, are intended to be appropriate for all types of petroleum accumulations regardless of their in-place characteristics, extraction method applied, or degree of processing required. Consequently, both unconventional and conventional resources share the same classification framework for petroleum resources shown in Figure 1.3.

Despite sharing resource definitions, different approaches exist for the evaluation of in-place volumes and for evaluating development and production programs of unconventional resources. New techniques are required for unconventional resource and reserve estimation due to the differences in hydrocarbon accumulation and extraction, described:

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5   Chan, P., Unconventional Resources Estimation – Introduction, Chapter 8 in Guidelines for the Application of the Petroleum Resources Management System, November 2011. Download from: www.spe.org/notes/wp-content/uploads/2010/12/ADS_Final.pdf

6   Biogenic gas is formed at shallow depths and low temperatures by microbial decomposition of sedimentary organic matter. In contrast, thermogenic gas is formed at deeper depths by: (1) thermal cracking of sedimentary organic matter into hydrocarbon liquids and gas (this gas is co-genetic with oil, and is called "primary" thermogenic gas), and (2) thermal cracking of oil at high temperatures into gas ("secondary" thermogenic gas) and pyrobitumen. Biogenic gas is very dry (i.e. it consists almost entirely of methane). In contrast, thermogenic gas can be dry, or can contain significant concentrations of "wet gas" components (ethane, propane, butanes) and condensate (C5+ hydrocarbons). These definitions come from a subsidiary of Weatherford (See: www.gaschem.com/determ.html)

Naturally Generated Gas	Synthesis Gas
CONTINUOUS GAS ACCUMULATION (CGA)	**COAL GASIFICATION**
Shale Gas Hosted in shales, silt stones and carbonates Self-sourced hydrocarbons Thermogenic and/or biogenic generation **Trapping mechanism:** • Partly a *sorbed* gas reservoir (gas adsorbed to organic matter) • Gas generation rate exceeds primary migration rate	**Underground Coal Gasification (UCG)** Underground (in situ) conversion of suitable coal into synthesis gas (syngas) Also known as In-Stu Gasification (ISG) **Mined Coal Gasification** Requires mining of suitable coal deposit and conversion to synthesis gas (syngas) in a surface plant
Tight Gas- Pervasive Hosted in low permeability sands and carbonates, also known as Basin-centred Gas Accumulations Migrated hydrocarbons **Trapping mechanism:** • Relative permeability of gas and water in low permeability reservoirs • Primary migration rate exceeds secondary migration rate	
Coal Seam Gas Coal hosted Self-sourced hydrocarbons Thermogenic and/or biogenic generation **Trapping mechanism:** • Primarily a *sorbed* gas reservoir	
TIGHT GAS - DISCRETE Hosted in low permeability sands and carbonates Migrated hydrocarbons **Trapping mechanism:** • Localised geological structural features and/or stratigraphic conditions	

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Figure 1.2   *Unconventional gas resources – basic characteristics by type.*

- Conventional resources exist in discrete petroleum accumulations related to a localised geological structural feature and/or stratigraphic condition (typically with each accumulation bounded by a down-dip contact with an aquifer) that is significantly affected by hydrodynamic influences such as the buoyancy of petroleum in water. The petroleum is recovered through wellbores and typically requires minimal processing prior to sale.

- Unconventional resources exist in hydrocarbon accumulations that are pervasive throughout a large area and that are generally not significantly affected by hydrodynamic influences
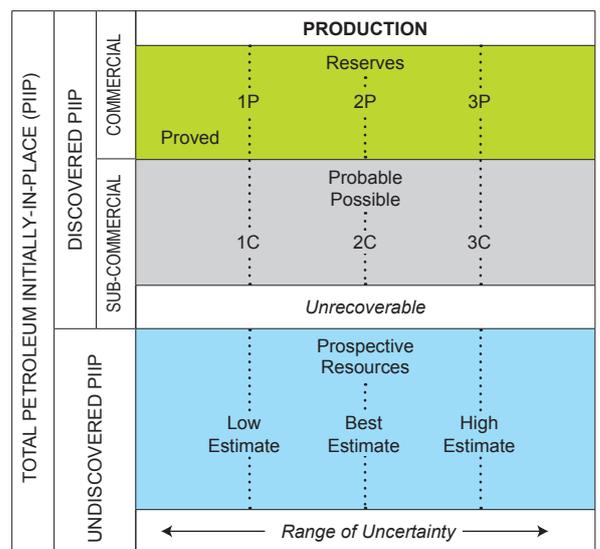
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Figure 1.3   *Resources Classification Framework.*
(Society of Petroleum Engineers – Petroleum Resources Management System (SPE-PRMS) 2007).

(also called "continuous-type deposits"). Such accumulations require specialised extraction technology, and the raw production may require significant processing prior to sale.

1.2.1.1 Prospective Resources

As in conventional resource assessments, those quantities of petroleum estimated, as of a given date, to be potentially recoverable from 'Undiscovered' accumulations are classified as Prospective Resources (shown in blue at the bottom of the Resources Classification Framework in Figure 1.3). A chance of discovery and a chance of development are both associated with Prospective Resources.

1.2.1.2 Contingent Resources

Those quantities of petroleum that are estimated, as of a given date, to be potentially recoverable from 'Discovered' accumulations, yet the applied project(s) are not yet considered mature enough for commercial development due to one or more contingencies, are classified as Contingent Resources (shown in grey at the centre of the Resources Classification Framework in Figure 1.3). For unconventional reservoirs, the accumulation may be classed as 'Discovered' based on evidence other than a flowing well test (e.g. sampling and/or logging). A 'Discovered' resource type may be identified in very large areas from the results of prior drilling and the use of analogs to determine production potential.

1.2.1.3 Reserves

Those quantities of petroleum anticipated to be commercially recoverable by application of development projects to 'Discovered' accumulations from a given date forward under defined conditions are classified as Reserves (shown in green at the top of the Resources Classification Framework in Figure 1.3). Reserves must satisfy four criteria: they must be discovered, recoverable, commercial and remaining (as of the evaluation date) based on the development project(s) applied. Typically, an unconventional resource can be classified

as a Reserve after pilot programs have confirmed the technical and economic potential of a project(s). Reserves should be allocated once capital has been assigned for development.

An estimate of the associated uncertainty must be included for an assessment of unconventional resource potential. As in conventional resource assessment, a low/best/high case probability is allocated based on the estimated uncertainty.

1.2.2 Continuous Gas Accumulations

A continuous gas accumulation is a gas accumulation that is pervasive throughout a large area and which is not significantly affected by hydrodynamic influences. Such accumulations are included in unconventional resources. Examples of such deposits include "basin-centred" gas, CSG and shale gas (Figure 1.4. from Beach Energy, amended from Schenk and Pallastro, 2002[7]).

1.2.3 Shale Gas[8]

Shale gas is produced from organic-rich mudrocks, which serve as the source and reservoir for the gas. Shale oil is also sourced from organic-rich mudrocks but at shallower depths and lower maturity levels. Text Box 1 (see page 21) provides a description of how organic matter accumulated in sediments is converted to petroleum gases and liquids. Shales have very low matrix permeability (Text Box 1), and therefore natural or hydraulically induced fracture networks are required to enable the flow of gas at economic rates. Shales have diverse reservoir properties, and a wide array of drilling, completion, and development practices are being applied to exploit them.

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7   Beach presentation in which Figure 1.4 is made public can be downloaded from: http://bpt2.live.irmau.com/IRM/Company/ShowPage.aspx/PDFs/2337-36623505/BeachEnergyLimitedPresentations

8   Adapted from Jenkins, C., 2011, Shale Gas, Chapter 8.6 in Guidelines for Application of the Petroleum Resources Management System, SPE. Download from: www.spe.org/industry/docs/PRMS_Guidelines_Nov2011.pdf
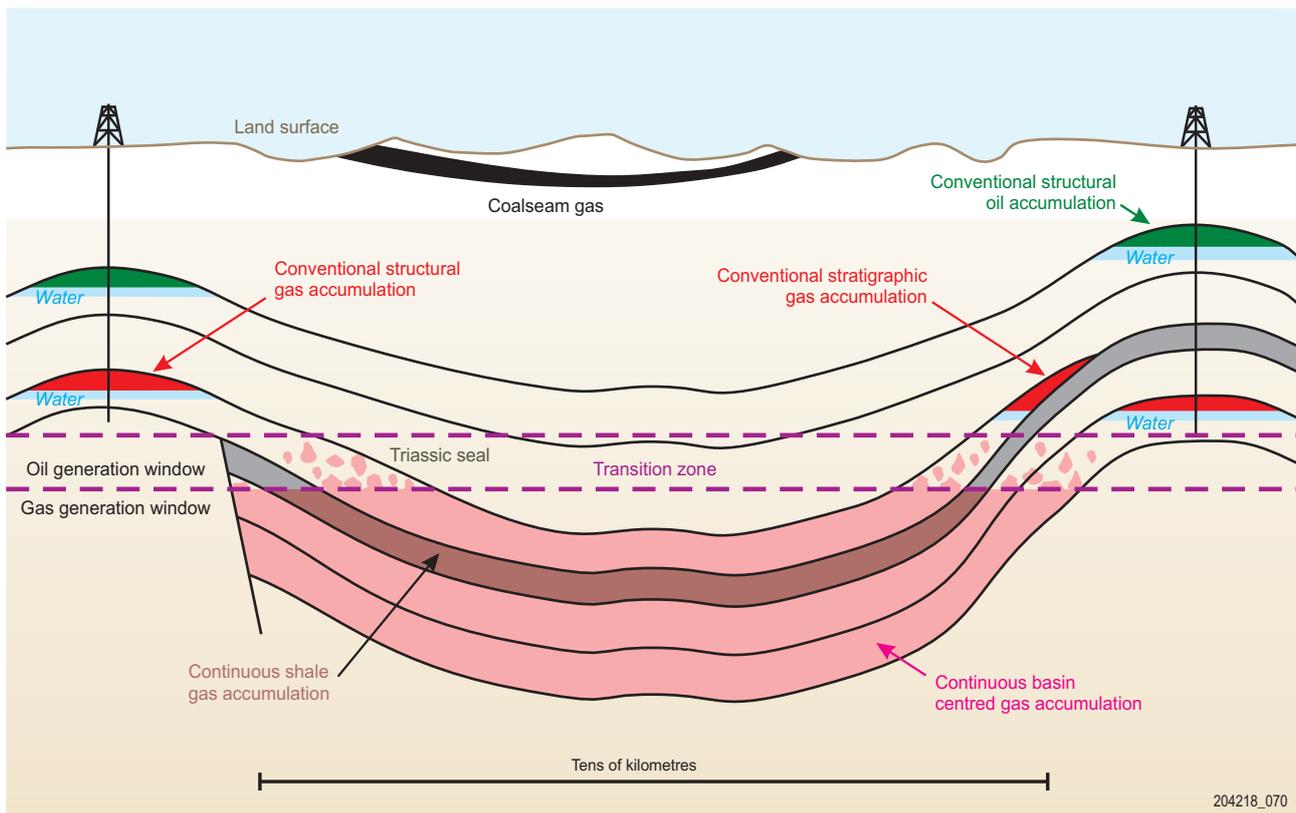
Figure 1.4 *Schematic diagram showing conventional and unconventional oil and gas accumulation types (source: Beach Energy Limited. Amended from Schenk and Pallastro, 2002)*

Total organic carbon (TOC, refer Text Box 1) values are high in biogenic shales (often greater than 10 weight percent), but relatively low (greater than 2 weight percent) in thermogenic shales where a fraction of the organic matter has been converted to hydrocarbons.

Many of the successful shale gas plays in the USA occur in oil prone source rocks that have generated and retained large volumes of oil that has subsequently been cracked to gas at higher thermal maturities.

Rocks containing significant amounts of silica-rich -rich minerals are generally, characteristically brittle and susceptible to natural and hydraulically-stimulated fracturing. "Healed" natural fractures are a common feature of productive thermogenic shale gas plays. Brittle rocks more effectively fracture than more ductile clay-rich rock (when hydraulically stimulated). Hence, shale gas targets can be ranked based on prospective: Stimulated Reservoir Volume (SRV); the proportion of solid organic matter

that has been thermogenically converted to gaseous and liquid petroleum; and the proportion of very valuable gas liquids and oil that is recoverable from wells. In contrast, biogenic gas in shallow shales that have not reached temperatures needed to sustain thermogenetic conversion of plant remains to petroleum are commonly less brittle, and generally less susceptible to fracture stimulation.

The rapid commercially successful expansion in North American shale gas development results from advances in drilling and completions technology, and in particular: horizontal drilling; light-sand, slick-water fracture stimulation; and micro-seismic monitoring of hydraulic stimulations.

Lateral well lengths have increased, along with the number of stimulation stages that are pumped per well. It is now common for extended reach lateral wells to be 1500 m long with 15 to 20 fracture stages.

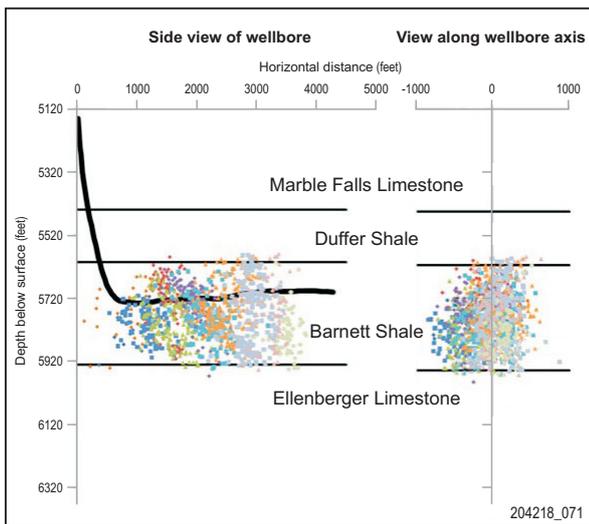This substantially increases SRV, accelerating drainage. Micro-seismic is used to monitor

Figure 1.5 *Micro-seismic diagram of typical hydraulic fracturing job in the Barnett Shale, USA (Stanford University, 2011)*

the stimulations to understand fracture geometries and estimate SRV. High resolution seismic motion sensors record micro-movements of rocks before, during and after pumping fracture stimulation fluids to provide a basis to locate pre-stimulation 'natural' seismicity, induced seismicity during stimulation and post pumping seismicity that manifests rocks re-adjusting to conditions of both well shut-in and well production. A micro-seismic diagram of typical hydraulic fracturing job in the Barnett Shale, USA is provided as Figure 1.5.

Induced fractures propagate in the direction of maximum compressive stress so laterals are oriented perpendicular to maximum compressive stress. Optimised well spacing depends on multiple factors including: gas-in-place; permeability; SRV; and costs.

Long-offset lateral wells are commonly landed in the most brittle intervals of the shale to most effectively initiate fractures and to maximise SRV. Laterals are carefully placed to avoid structural complexities such as significant faults identified from: nearby wells and the interpretation of reflection seismic. Current leading practice to optimise lateral wells in shale gas reservoirs entails the recording and evaluation of three-dimensional (3D) seismic cubes.

Thermogenic shale gas reservoirs are generally found at depths >1000m and production may be dry or wet gas. Thermogenic shale gas wells generally exhibit steep production declines of 30 to 80% or more in the first year after which production rates flatten substantially indicating transient flow (linear flow from matrix into fractures). Because matrix permeability is so low in these reservoirs it may be tens of years before pressures begin to decrease substantially away from induced fractures. As a result, even though up to half the gas in thermogenic shale gas reservoirs may be adsorbed gas, only a small fraction of this gas will be produced over the life of the well.

Initial production (IP) gas rates for fracture stimulated horizontal wells are typically greater than 1 Million cubic feet per day (MMcf/d) with corresponding expected ultimate recoveries (EURs) of more than 1 bcf.

While IPs up to 10 MMcf/d are known, a typical Montney shale gas well from British Columbia in Canada flows 3 to 5 MMcf/d on start-up from long-reach, multi-stage fracture stimulated zones[9].

In 2012, Santos Moomba 191 vertical well flowed 2.6 MMcf/d at system pressure from fracture stimulated shales of Permian age in the south-western extent of the Nappamerri Trough in the South Australian Cooper Basin.

Shales that are less thermally mature (in the oil or wet-gas window) generally have lower IPs and EURs due to relative permeability effects and the difficulties related to moving liquids through very small pore throats. However IP is significantly enhanced if the shale is overpressured (eg. Eagle Ford Shale in Texas).

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9   Johnson, Mike, Davidson, Jim, and Mortensen, Paul (2010), A perspective on Canadian shale gas, National Energy Board, (Contact: Mike.Johnson@neb-one.gc.ca), Derived from: National Energy Board, 2009. A primer for understanding Canadian shale gas. Available at: www.neb-one.gc.ca. Download from: www.worldenergy.org/documents/congresspapers/248.pdf

The Geology of Continuous Petroleum Plays

The following is a description of the origin of continuous petroleum plays now being economically developed with extended-reach wells that drain multiple zones that have been hydraulically fracture stimulated.

Rocks that originate from the burial of sediments rich in biological remains (especially algae and other plants) and dominated with clay-sized minerals have the potential to become petroleum source rocks. When buried to sufficient temperatures over geologic time:

- solid organic matter naturally converts to petroleum gases and liquids;

- the pressure within micro-pores in shales increases; and

- when the increased pressure exceeds the yield strength of the rock - micro-fractures develop.

This natural process opens up migration paths (fracture permeability) for generated petroleum to be migrated within and expelled from source rocks.

Where oil and gas expulsion from source rocks occurs at an interface between source rocks and more naturally permeable and porous reservoir rocks, petroleum can buoyantly migrate until it is accumulated in a natural trap. Trapped petroleum accumulations are oil and gas exploration targets.

Why Naturally Micro-fractured Shales Are Brittle

The micro-fractures naturally formed in source rocks will narrow as rock cements grow into fractures and when the pace of petroleum generation declines to a level insufficient for the associated micro-pore pressure increase to prop open and extend micro-fracture fabrics.

Fracture healing cements dominated by quartz (silica dioxide) constitute a brittle natural rock fabric that is susceptible to further natural and hydraulic fracture stimulation.

Inter-bedded quartz-rich shales, siltstones and sandstones that contain considerable residual petroleum represent good fracture stimulation candidates to produce oil and gas. Higher pressures developed with increasing burial depth and generation of petroleum also contributes to higher initial productivity of shale reservoirs.

Biogenic shale gas reservoirs tend to have significantly lower production rates and EURs than thermogenic shales because of their shallow depths, lower gas contents, and the need to dewater the fractures before producing the adsorbed gas.

Initial gas rates and EURs for shale gas wells are highly variable and difficult to predict, with values often varying by one to two orders-of-magnitude across any given area. Assessments by the USGS (2011[10]) conclude

a log-normal distribution of shale gas well EURs, the top decile of wells drilled is critical to the overall economic success of any project.

1.2.4 Pervasive Low Permeability (Tight) Gas Reservoir Plays[11]

A low permeability tight gas reservoir play is "a reservoir that cannot be produced at economic flow rates nor recover economic volumes of natural gas unless the well is

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10 Charpentier , Ronald. R., and Cook, Troy. A. Methodology for Assessing Continuous Petroleum Resources, USGS Open-File Report 2011–1167, Downloaded from: http://pubs.usgs.gov/of/2011/1167/OF11-1167.pdf

11 Adapted from Aguilera, R, 2011, Tight Gas Formations, Chapter 8.4 in Guidelines for Application of the Petroleum Resources Management System, SPE. Download from: www.spe.org/industry/docs/PRMS_Guidelines_Nov2011.pdf

stimulated by a large hydraulic fracture treatment or produced by use of a horizontal wellbore or multilateral wellbores" (Holditch, 2006). Tight gas plays are generally divided into: (1) basin-centred gas accumulations; and (2) gas reservoirs that occur in low-permeability, poor quality reservoir rocks in conventional structural and stratigraphic traps. The primary definition used in the PRMS guidelines (2011) assumes that tight gas plays, including sandstones and carbonates, are characterised by permeabilities of less than 0.1 millidarcy (md).

A basin-centred gas accumulation is an unconventional natural gas accumulation that is regionally pervasive and characterised by low permeability (generally ≤ 0.1 md), abnormal high pressure[12], continuous gas saturation that does not depend on buoyancy trapping gas above a spill-point at a clear down-dip gas-water contact. Hydrodynamic studies are useful in determining whether a tight gas resource is a basin-centred accumulation or a conventional structural or stratigraphic low-permeability trap. It is important to determine this as the estimates of gas-in-place volumes and mobile gas are much larger in a basin that contains a basin centred gas accumulation instead of discrete conventional gas traps.

The integration of geoscience and engineering is essential in exploring for and assessing tight gas resources. Folding, faulting, natural fracturing, in-situ stresses, multilayer systems, mineralogy and petrology, connectivity and continuity, permeability barriers, and interbedded coals and shales are just some of the aspects that

must be taken into account when evaluating tight gas resources (Aguilera et al., 2008).

Exploration methods focus on the location of natural fracture swarms, closures and "sweet spots" of higher matrix permeability. Wells are drilled perpendicular to open natural fractures to maximise the intersection of permeable fabrics that can be produced. If more than one set of open fractures is present, a properly designed slanted, horizontal, or multilateral wellbore can maximise gas production and recovery by intersecting as many fracture sets as economically possible. Hydraulic fracture stimulation (single or multi-stage) is necessary to produce tight gas reservoirs via vertical, slanted and horizontal wells.

In 2011, Beach Energy's Holdfast-1 vertical exploration well in the Nappamerri Trough of the Cooper Basin was fracture stimulated over an interval of both tight gas and shale gas and flowed up to 2 MMscf/d. This is a milestone result for at least the tight gas play in the Cooper Basin.

1.2.5 Coal Seam Gas (CSG)[13]

Coals are the rocks that result from the accumulation and burial of land plant remains and lesser amounts of non-organic minerals. CSG is produced from coal, which serves as the source and reservoir for the gas. CSG is generated from coal either by biogenic (methanogenic bacteria[14]) or thermogenic processes.

The primary mechanisms for gas storage in CSG reservoirs are: 1) adsorption upon internal surface area, primarily associated

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12 Abnormal high pressure in a geologic formation is generally defined as pore pressure at a depth that exceeds a water pressure gradient of 0.431 psi per ft (9.75 kPa/m) for fresh water and more for saltier (denser) water. When impermeable rocks such as shales are buried rapidly, pore fluids cannot always escape and then support the total overlying rock column (overburden), leading to abnormally high formation pressures. Also referred to as overpressure or geopressure, abnormal high pressure can also result from the generation of petroleum within a source rock that lifts pore pressure.

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13 Adapted from Clarkson, C. R., and Barker, G. J., 2011, Coal Bed Methane, Chapter 8.5 in Guidelines for Application of the Petroleum Resources Management System, SPE. Download from: www.spe.org/industry/docs/PRMS_Guidelines_Nov2011.pdf

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14 Methanogenic bacteria can generally survive at depths corresponding to temperatures up to 70° Celsius. That is a rough estimate for the sterilization of methanogenic bacteria. Hence, in general, biogenic methane is preserved at depths corresponding to higher-than-sterilization temperatures, but little more if any additional biogenic methane is created below the sterilization depth.

with organic matter; 2) conventional (free-gas) storage in natural fractures; 3) conventional storage in matrix porosity; and 4) solution in bitumen and formation water. The term "sorption" is used to encompass adsorption of gas on the internal surface area of coal and solvation of gas by liquid/solids[15] in the coal matrix. Generally free gas is negligible compared to sorbed gas storage and is usually ignored in CSG reservoirs because of low fracture-pore volumes and high pre-production water saturations. The exception is for some dry CSG reservoirs in which free-gas storage may be more significant. Solution gas is usually ignored. Adsorbed gas storage is by far the most important storage mechanism in most CSG reservoirs.

The geothermal (heating) history and composition of coals determine the total surface area available for gas to be adsorbed within a coal. Over geologic time, all rocks are generally exposed to ever higher temperatures with increase depth of burial. Coal fabrics evolve with increasing heating over time to ever higher rank. High-rank coals have surface areas on the order of 100 to 300 m^2/g, whereas conventional reservoirs typically have surface areas less than 1 m^2/g. The immense ratio of surface area to volume in the coal matrix means that a large surface area is available to attract gas molecules through molecular forces resulting in adsorption. The controls on sorption include organic matter pore structure and composition, pressure, temperature, moisture, thermal maturity, mineral matter content and gas composition. Sorption on coal is a nonlinear function of pressure.

Gas and water flow through the coal to the wellbore via natural micro-fracture fabrics called "cleats". Cleats form in coals as a result of natural dewatering with burial, and generally form orthogonal micro-permeability paths perpendicular to bedding. These sub-vertical fabrics generally

take two forms: (1) "face" cleats are more continuous and represent effective paths of permeability; and (2) "butt" cleat which are more discontinuous and terminate into the face cleat.

If coals are undersaturated (in-situ gas content < in-situ storage capacity), the reservoir needs to be dewatered. This means single phase water flow will occur through the cleats (fractures) until a critical desorption pressure is reached, and gas will start to flow. If the coals are saturated then two-phase flow (water and gas) will occur from the start of production.

For some CSG reservoirs, gas composition may change during depletion. For example, carbon dioxide content may increase with depletion as surface of coal fabrics has a greater affinity for carbon dioxide than methane, and gives up carbon dioxide in greater amounts as the reservoir is depleted. Sweet spots due to enhanced natural fracturing can occur in CSG plays.

The two-phase flow nature of most CSG plays means that well spacing, well geometry and well orientation are designed to accelerate dewatering, to increase effective permeability to gas, initiate gas production, and reduce the time to peak gas production.

It is useful to differentiate between shallow and deep CSG at the least because deep CSG does not require de-watering, and does not usually require water handling operations that are in general associated with in shallow CSG development.

1.2.6 Coal Gasification[16]

Gasification is a process where any carbon based material, such as coal, is transformed into thermal energy without burning it. The core of the gasification system is the gasifier, a vessel where the coal feedstock is reacted

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15 Solvation of gas is equivalent to dissolution of gas (in liquids and solids such as bitumen in the coal matrix)

16 Adapted from Gasification Technologies Council, 2011, Gasification, an Investment in our Energy Future, Gasification Technologies Whitepaper. Download from: www.gasification.org/uploads/downloads/Final_whitepaper.pdf

with oxygen at high temperatures. The conditions inside the gasifier break apart the chemical bonds of the feedstock to create "synthesis gas" (syngas). The syngas consists primarily of hydrogen and carbon monoxide, and depending on the specific gasification technology, smaller quantities of methane, carbon dioxide, hydrogen sulphide and water vapour.

The ratio of carbon monoxide to hydrogen depends in part upon the hydrogen and carbon content of the feedstock and the type of gasifier used, but can also be adjusted downstream of the gasifier through the use of catalysts. This ratio is important in determining the type of product to be manufactured: electricity, chemicals, fuels, hydrogen. For example, a refinery would use a syngas consisting primarily of hydrogen, important in the production of ultra clean transport fuels. Conversely, a chemical plant uses syngas with roughly equal proportions of hydrogen and carbon monoxide, both of which are basic building blocks for the broad range of products that they produce, including fertiliser and plastics. Typically 70 to 85% of the carbon in the feedstock is converted into syngas.

The raw syngas produced in the gasifier contains trace levels of impurities. After the syngas is cooled virtually all the trace minerals, particulates, sulphur, mercury and unconverted carbon are removed using commercially proven cleaning processes common to the chemical and refining industries. More than 90% of any mercury in raw syngas can be removed using relatively small and commercially available activated carbon beds. Carbon dioxide can also be removed in the syngas clean-up stage using a number of commercial technologies, and can then be utilised or stored. More than 99% of sulphur is removed and recovered either as elemental sulphur or sulphuric acid.

Most solid feed gasifiers produce a solid residue composed primarily of the mineral component of the feedstock. This solid residue is non-hazardous and can be used in roadbed construction, cement

manufacturing or in roofing materials.

1.2.6.1 Underground Coal Gasification (UCG)/In-situ Gasification (ISG)[17]

Underground coal gasification (UCG) also known as in-situ gasification (ISG) of coal takes place underground, generally below approximately 370 m. The underground setting provides both the coal feedstock source as well as pressures comparable to that in an above-ground gasifier, and at a depth less attractive for mining owing to the cost to remove cover.

With most UCG facilities, two wells are drilled on either side of an underground coal seam. One well is used to inject air or oxygen (and sometimes steam) into the coal seam to initiate the gasification reactions. The second well is used to collect the syngas that is formed from the gasification reactions and to transport it to the surface for additional processing and use (Figure 1.6).

The UCG reactions are managed by controlling the rate of oxygen or air that is injected into the coal seam through the injection well. The gasification process can be halted by stopping the injection of the oxygen or air. After the coal is converted to syngas in a particular location, the remaining cavity (which will contain the left over ash and other solid residue from the coal) may be flushed and then flooded with water and the wells are capped. However, there is also growing interest in using these cavities to store carbon dioxide that could be captured
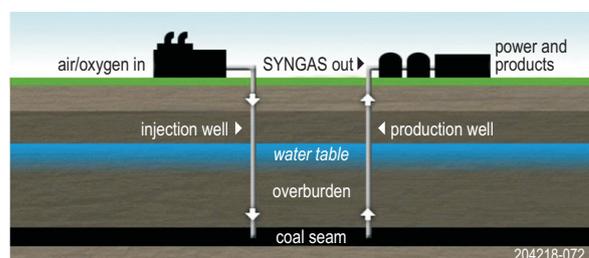

Figure 1.6 *Underground coal gasification (figure sourced from www.gasification.org)*

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17 Adapted from information provided on the website of the Gasification Technologies Council. For more information visit: www.gasification.org

from the above-ground syngas processing (i.e. water shift reaction to produce high hydrogen concentration syngas). Once a particular section of a coal seam is exhausted, new wells are drilled to initiate the gasification reaction in a different section of the coal seam.

The syngas that is produced from UCG is the same as that produced by above-ground gasification processes—it can be combusted in a gas turbine to produce electricity or further processed to produce chemicals, ultra clean transport fuels, or fertilizers.

UCG does face a number of challenges including but not limited to:

- Coal seams may not be suitable for UCG because of composition, thickness, geologic complexities or hydrologic conditions;

- Decommissioning will most usually entail injection of gases and/or fluids to minimise potential hazards of subsidence, and the sustainable and economic availability of water to flush the reaction cavity can be a limiting factor; and

- Pending experience in profitable UCG projects in the context of competitive Australian energy markets, UCG project economics are somewhat uncertain;

- Site selection needs to be done properly to avoid potentially harmful short-term and long-term impacts including but not limited to: groundwater desiccation; groundwater contamination; surface subsidence; permanent damage to local and regional biota; and the sterilisation of land access for the multiple-use of land for other activities.

These issues can be mitigated through careful project design, site selection, and monitoring. UCG has enormous potential for harnessing the energy of coal resources that would otherwise be too expensive or difficult to reach.

1.2.7 Value-Adding Processes and Products

Given suitable product price, syngas, and the thermal energy associated with syngas can be used for power generation plus the manufacture of synthetic fuels. Additional details are provided in the proceeding text.

1.2.7.1 Coal-to-liquids (CTL)[18]

Rising fuel costs and a desire for energy independence have revived interest in the production of liquid transportation fuels from coal. Commonly called coal-to-liquids (CTLs), or Fischer-Tropsch (FT) liquids, after the German inventors of the primary chemical conversion process (indirect liquefaction), CTL can help increase fuel supply diversity and energy security.

In CTL, clean syngas from coal gasification is converted to a liquid hydrocarbon or alcohol. The FT process is one possible CTL path. FT catalysts are used to facilitate the formation of hydrocarbons or alcohols from the carbon monoxide and hydrogen in the syngas. The end-product of the process can be determined by changing the catalyst, feed composition, and reactor conditions such as internal temperature and pressure. The main products of the FT process are typically straight-chain, saturated hydrocarbons (paraffins), from which gasoline and diesel can be refined. Fuel gases like methane and liquefied petroleum gas (LPG; mostly propane and butane) are usually also formed in small amounts by CTL but are generally discouraged by the process designers. Waxes are also formed, but can be "cracked" to shorter, liquid forms. Different catalysts can facilitate the formation of alcohols like methanol, ethanol and propanol that can be used as fuel or fuel additives.

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18 For additional details of CTL, visit: www.netl.doe.gov/technologies/coalpower/gasification/gasifipedia/6-apps/6-3_coal-to-liquids.html

1.2.7.2 Methanol to Gasoline (MTG)

MTG is another alternative path for CTL production. In this process, syngas is reacted to form methanol, from which gasoline is then formed. Developed by Mobil throughout the 70s and early 80s, a first-of-its-kind plant was built in New Zealand in 1985, where it successfully produced gasoline for 10 years. The process has been continuously refined since then to its current state as a viable alternative to conventional gasoline sources.

1.2.7.3 Coal-to-Synthetic Natural Gas and Hydrogen[19]

In addition to liquid fuels, gasification can be used to produce gaseous fuels like synthetic natural gas (SNG) and hydrogen. SNG is equivalent to natural gas, which is mostly methane, and can be substituted for it in natural gas applications. Hydrogen is predicted by some to be the energy carrier of the future because it is extremely clean when reacted with oxygen (producing water) and has a high energy density by mass. Hydrogen can be used to feed fuel cells or combusted in a hydrogen turbine to generate electricity. Hydrogen could also power fuel cell vehicles. Although there are technical and commercial[20] challenges to overcome, a clean coal gasifier to produce hydrogen would be a key component of a hydrogen economy.

1.2.7.4 Chemicals and Fertilizers[21]

Modern gasification has been used in the chemical industry since the 1950s. In coal-to-chemicals, syngas from coal gasification is fashioned into a number of useful chemical building blocks, like methanol or acetyls for example. Ammonia and urea are significant products of coal-to-chemicals for use in fertilizers.

One of the earliest and most notable coal-to-chemicals plants in the United States is owned and operated by Eastman Chemical Company and based in Kingsport, Tennessee, where the plant produces methanol and acetyl chemicals, produced from methanol and carbon monoxide through a reaction called carbonylation. Acetic acid and acetic anhydride are commonly used in pharmaceutical and industrial applications and can be processed into products like paints, fibres, photographic film, tool handles and more. Methanol also has important uses, as a fuel or fuel additive, for example.

1.2.7.5 Power Generation (Integrated Gasification Combined Cycle)[22]

Integrated gasification combined cycle (IGCC) uses gas (syngas) and steam turbines to generate electricity. Integration of the gasifier, gas turbine, and steam turbine (for reclaiming lost heat in the exhaust) allows for high efficiencies. In fact, current designs can rival the most advanced pulverized coal plants in efficiency, while research and development leading to technological advances in integration, turbine design, and supporting processes should increase IGCC efficiency even further.

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22 For additional details of power generation with integrated gasification combined cycle technologies, visit: www.netl.doe.gov/technologies/coalpower/gasification/gasifipedia/6-apps/6-2_IGCC.html

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19 For additional details of coal to synthetic natural gas and hydrogen, visit: www.netl.doe.gov/technologies/coalpower/gasification/gasifipedia/6-apps/6-4_synthetic.html

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20 For some details of costs associated with the manufacture of SNG, visit: www.iea-etsap.org/web/E-TechDS/PDF/S01-Coal%20gasification-GS-gct.pdf

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21 For additional details of fertilizers and chemicals, visit: www.netl.doe.gov/technologies/coalpower/gasification/gasifipedia/6-apps/6-5_chemicals.html