Invited review

An overview of the coal seam gas developments in Queensland

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A R T I C L E   I N F O

A B S T R A C T

The demand for natural gas in Queensland, Australia has historically been supplied from conventional reservoirs. However, depletion in conventional sources has led producers to turn to extensive supplies in Queensland's coal resources. These coal seam gas (CSG) developments not only represent new supplies for the domestic market in eastern Australia, they are also the first time that CSG (aka coal bed methane or CBM) has been liquefied to serve the expanding world LNG market. In order to make this development occur, considerable infrastructure had to be installed, with field developments still on-going. This AUD$60 billion investment precipitated a major overhaul of state regulations to provide not only a safe and clean operating environment, but also to allay the concerns of certain stakeholders.

The gas is primarily produced from thin high permeability coals in the Jurassic-age Walloon Coal Measures in the Surat Basin and from several relatively thick Permian-age coal seams in the Bowen Basin, of which the Baralaba Coal Measures and the Bandanna formation are the most important. There are numerous technical challenges with this production, such as fines production from the inter-burden clays, which can form a thick paste that is difficult to pump. Salt extraction by reverse osmosis, from associated water produced to depressurise the coal seams and enable the flow of gas, allows for the beneficial use of the water. Technical challenges also include mathematical modelling of the counter-current two-phase flow (gas and water) in the well annuli because conventional models in simulators only handle co-current two-phase flow in the well-bores. Also, the subject of on-going investigations is decommissioning of the large number of shallow wells over the next few decades in a safe and cost effective manner, with compressed bentonite being a promising option for well plugging.

As with any major commercial development, in addition to the technical challenges there have been social challenges as well. These include interaction and coexistence of extensive surface operations with an established agricultural sector, interactions between gas production and ground water aquifers in water-stressed areas, and the cumulative social and economic impacts of 3 large projects on a rural area.

Ultimately, the State of Queensland expects to produce more than 1800 BCF/annum, of which about 1400 BCF/annum will be exported as LNG. Depending on the demand and well productivity, up to 1000 CSG wells may be drilled per year for the next thirty years. A review of CSG resources, development, and challenges is presented in this paper to provide context for a stream of research findings that are emerging on the Queensland CSG experience.

1. Introduction

In January 2015, Queensland began exporting coal bed methane (CBM), known locally as coal seam gas (CSG), as liquefied natural gas (LNG) to Asian markets. This event marked the first time that CSG or any other 'unconventional gas' had been developed with the express purpose of underpinning an LNG export market. The volumes being converted to LNG are predicted to increase dramatically, with exports reaching 1400 BCF/yr by 2017. Along with LNG developments on the Northwest Shelf and northern Australia from conventional offshore gas, they are set to propel Australia to be the world's leading exporter of LNG by 2020. In this paper, the history

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of natural gas production in the state of Queensland is reviewed and the CSG developments are discussed in detail. It is a story of technological success on several fronts, with the application of leading technologies in a complex geological setting and the rapid establishment of extensive extraction, processing and transport infrastructure over a large geographical area in a relatively short timeframe. Such technologies include, for example, drilling and completion technology, which achieves commercial well rates, the management (reverse osmosis) of co-produced water, and introduction of GRE and polypipe in Australian gas production operations, amongst many others. There have also been near-term economic challenges, with localised inflationary pressures increasing projected costs combined with changes in the international market for LNG. This dramatic rise in oil and gas activity in a rural, agricultural region has occurred while government regulation has been evolving, in part, to respond to public concern around the environmental and social impacts of the expanding industry.

This overview paper begins by addressing the sources and producing horizons of the hydrocarbons. Then, it follows with an account of the history of natural gas production in Queensland, including how the emergence of CSG displaced the idea to import gas from Papua New Guinea (PNG) to make up a predicted domestic market shortfall, which led to a major new export industry. It provides an overview of challenges in the production process, including issues around associated water management, which are paramount in an agricultural area that has been subject to repeated prolonged droughts. The paper concludes with a description of the regulatory environment and a summary of the socioeconomic effects on the gas field region and the state. As this new CSG-to-LNG industry now shifts from a construction and development phase to a production and operational phase it is timely to review how it occurred, the challenges overcome and the prospects for the future. The lessons learned and discussed here may serve to help smooth the next CSG developments around the world that can supply the global demand for low cost lower carbon energy.

2. Geological setting and hydrocarbon habitat of the Surat & Bowen Basins

The Surat and Bowen basins, which host Queensland CSG resources, have a long and complex geological and petroleum generating history. These petroliferous basins contain multiple source rock horizons, including extensive coal deposits. Both liquid hydrocarbons and gas have been thermogenically generated, and the small fraction retained resides in reservoirs across a range of conventional and unconventional traps. In addition, there has been extensive biogenic gas generation (Hamilton et al., 2014; Golding et al., 2013; Al-Arouri et al., 1998), which continues today. Some two-thirds of the proved and probable (2P) CSG reserves occur in the Jurassic Walloon coals of the Surat Basin and the rest in the Bowen Permian coals.

The Permo-Triassic Bowen Basin forms the northern part of the Bowen–Gunnedah–Sydney Basin System of eastern Australia. The Bowen Basin development has been described by several authors (Baker and de Caritat, 1992; Raza et al., 2009; Fielding et al., 2001) to have been initiated by an extensional phase with the deposition of Permian to late Triassic sediments in two depocentres (Denison and Taroom troughs). These depocentres are separated by a basement high (the Comet Ridge) with a maximum thickness of ~10 km in the Taroom Trough (Fig. 1). Fielding (Fielding et al., 1997) describes three stages of the basin's formation: (1) an Early Permian period of extensional subsidence with associated volcanic activity; (2) an early Late Permian passive thermal subsidence phase; and (3) a Late Permian to Middle Triassic phase of foreland thrust load-induced subsidence. The depocentres were filled mainly by

continental alluvial sediments, punctuated by periods of marine incursion (Fielding et al., 1997) that had laterally extensive coal measures forming predominantly during the Late Permian as mountain building on the easting margin increased sedimentation and progradation of alluvial systems. Alluvial sedimentation, coupled with a changing climate, saw the end to coal accumulation. It continued into the Triassic and was finally terminated by basin inversion and deformation (Uysal et al., 2001).

The burial and uplift history of the Bowen and Surat basins, leading to hydrocarbon generation, has been modelled by numerous authors (Raza et al., 2009; Uysal et al., 2001; Boreham et al., 1999), who apply some assumptions about the geothermal gradient and paleo-heat flow. They all show the maximum Bowen Basin burial to occur at ~230 Ma with deepest burial in the northern end of the Taroom Trough. During this phase of burial, six source rock units and their stratigraphic equivalents have been recognised to account for the bulk of the thermally generated hydrocarbons in the Bowen Basin (Fig. 2): Moolayember Formation; Baralaba Coal Measures; Burunga Formation; Bandanna Formation; Flat Top to Buffel formations; and the Reids Dome beds (Boreham et al., 1996; Carmichael et al., 1997). CSG plays have occurred across a range of Permian age coals in the Bowen Basin, from more conventional anticline plays (e.g., Fairview and Peat/Scotia), to less conventional and lower permeability plays requiring new technology, such as horizontal drilling (e.g., Hillview, the Moranbah Gas Project) (Draper and Boreham, 2006; Miyazaki, 2005a).

Late Triassic sedimentation marked the initiation of the Surat Basin (overlying the Bowen Basin). There is current debate about the cause of increased accommodation space during Surat Basin formation, either as intracratonic sag (Gallagher, 1990) or as a pericratonic setting in a retro-arc position (Raza et al., 2009). The basin fill stratigraphy was proposed by Exon (1976), and it has subsequently been refined in several studies (Swarbrick, 1973; Jones and Patrick, 1981; Yago, 1996; Scott et al., 2004; Hoffmann et al., 2009). All of these studies describe six, major, fining, upward cycles of Mesozoic sedimentation. These cycles consist of fluvial channelized and over-bank deposits, including widespread coal formation within the Walloon Coal Measures, through to fine grained lacustrine sediments. The coal seams are laterally discontinuous, relative to the Permian coals, but their cumulative thickness in the sequence creates world class gas reservoirs (Ryan et al., 2012; Martin et al., 2013).

Surat Basin sedimentation lasted through to the mid-Cretaceous, where basin modelling of Raza et al. (2009), Uysal et al. (2001) and Boreham et al. (1999) show maximum burial of the Surat Basin to have occurred at ~100 Ma. This second period of burial saw Bowen Basin source rocks mainly generating gas, while at some locations Surat Basin source rocks entered thermogenic oil generation conditions. More than 90% of Bowen and Surat basin hydrocarbons were generated between the Cretaceous and the present day. For gas generation, in addition to the Baralaba Coal Measures and Burunga Formation mentioned before, the Buffel-Banana source rocks contribute more than 30% of the total gas in the Bowen and Surat basins (Shaw et al., 2000). It should be noted that the initial oil expulsion and migration (mainly from the Baralaba Coal Measures) may have been assisted by subsequent gas generation (both thermogenic and secondary biogenic), where gas generation helps expel previously generated oil from the source rock (Draper and Boreham, 2006). This Surat Basin burial period was followed by basin inversion that resulted in erosion of less than 1 km to greater than 2 km (Raza et al., 2009).

Shaw et al. (2000) showed that the volume of thermogenically generated hydrocarbons exceeds known reserves by some three orders of magnitude. They speculate that the missing hydrocarbons could be explained in four categories: 1) a large percentage remains
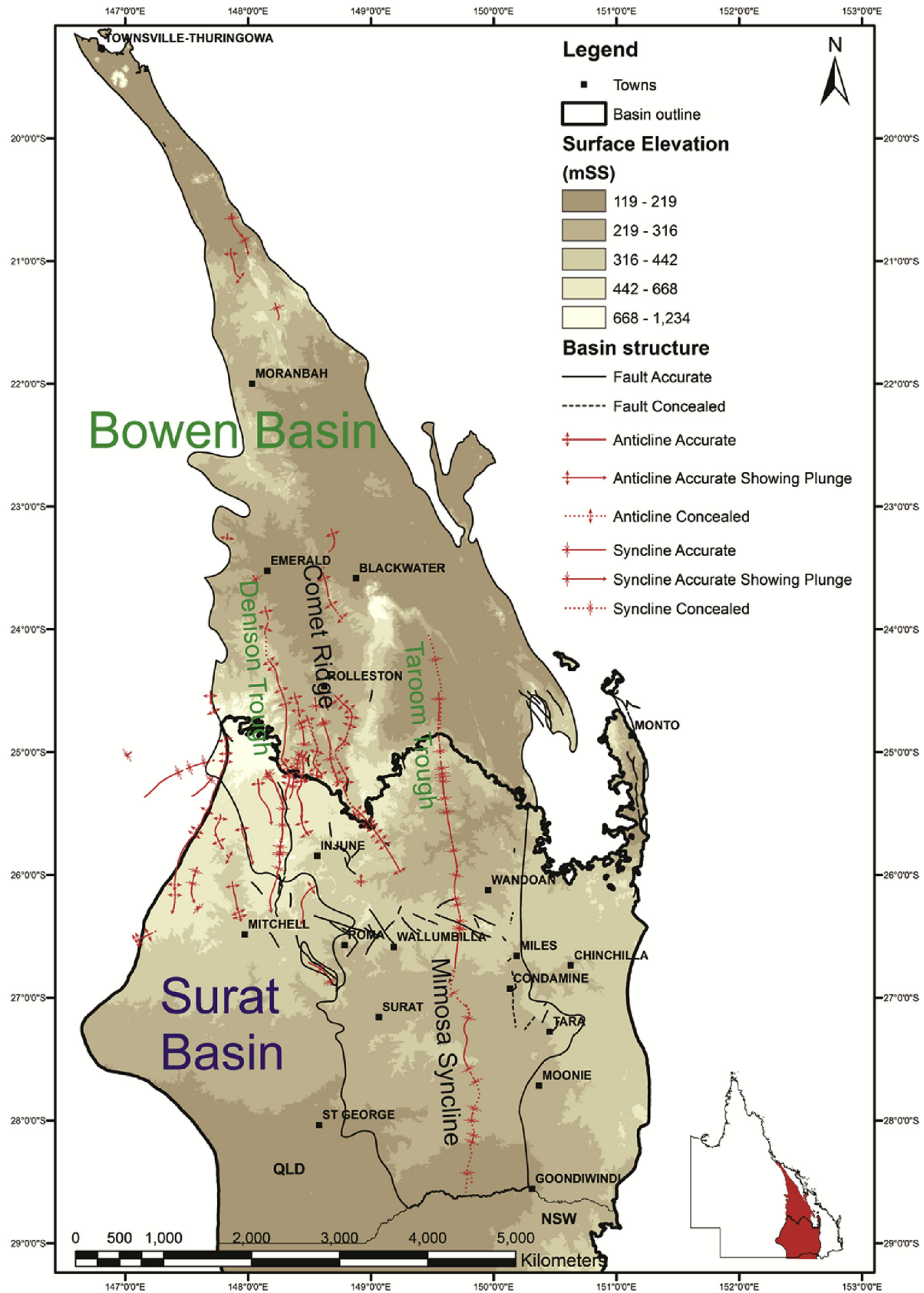
Fig. 1. Main structural features of the Surat and underlying Bowen basins.
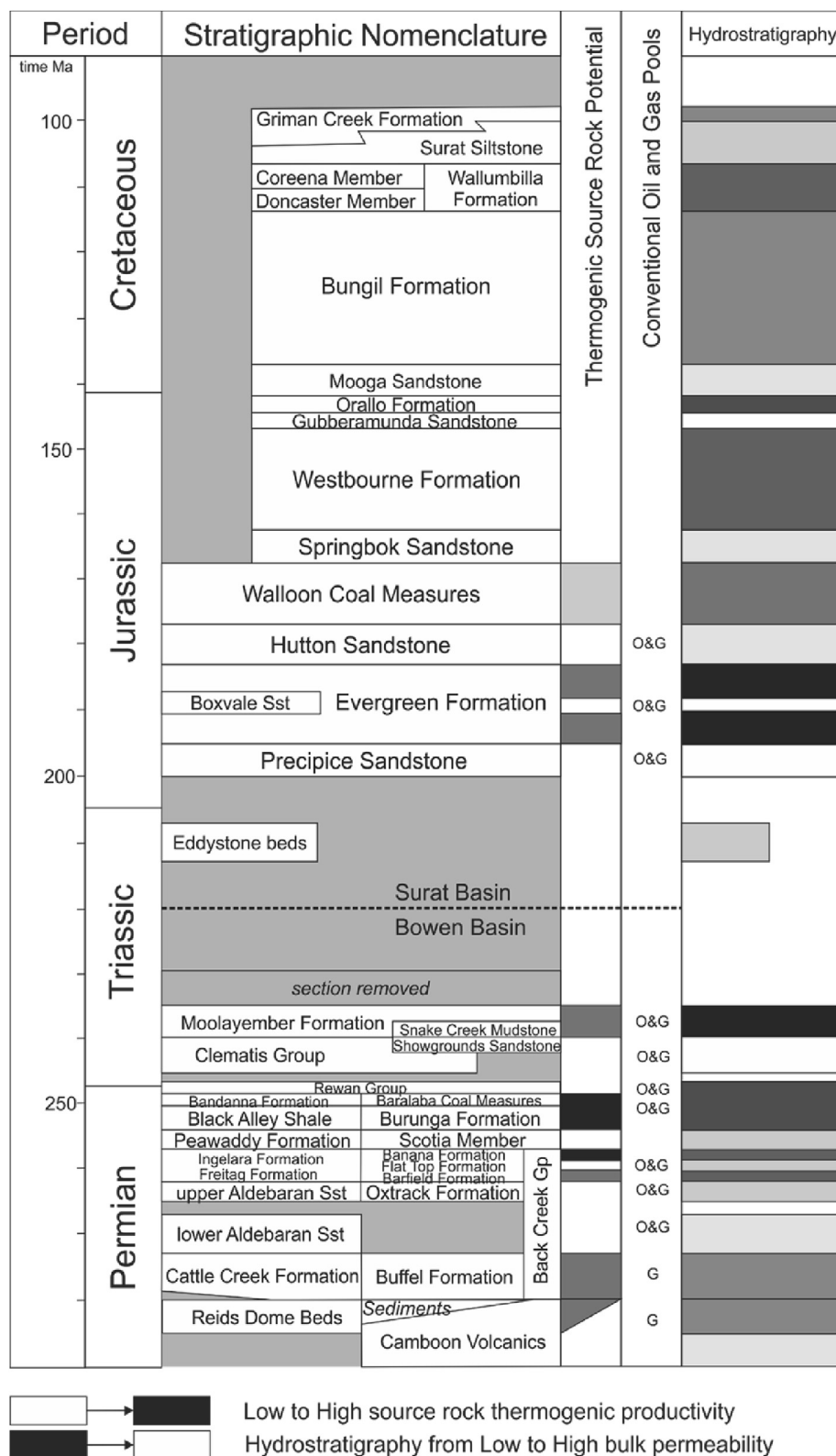
Fig. 2. Stratigraphic nomenclature of the Bowen and Surat basins with indications of source rock, conventional hydrocarbon reserves and hydro-stratigraphic significance of aquifers and aquitards (modified from Shaw et al., 2000; Korsch et al., 1998).

in the source rocks; 2) remaining undiscovered conventional hydrocarbons trapped within the basins; 3) the Great Artesian Basin aquifers, which contain large volumes of dissolved hydrocarbon in situ; and 4) large volumes of hydrocarbons that have been lost to the surface over geological time via migration of formation water and/or separate migration in the gas phase. It remains unclear how much thermogenic Permian gas initially migrated into the Walloon Coal Measures. However, the presence of ethane would suggest

that this process occurred to some degree, as the thermal maturity of these coals is only sub-bituminous rank.

In addition to the commonly considered thermogenic sources of hydrocarbon, there are also organic rich, sedimentary rocks that form sources of gas when subject to biogenic processes. This process is commonly thought to occur in the shallower parts of the sedimentary basin at temperatures less than 70 °C, where bacteria are more viable. Biogenic and thermogenic methane can be distinguished by their carbon and hydrogen isotope values. Biogenic methane, tends to have a value of $\delta^{13}C$ (the difference in the ^{13}C composition between the source rock and the generated methane) of the order of −60‰ because the microorganisms that generate biogenic methane prefer the ^{12}C bonds as they require less energy to break at the lower operating temperatures preferred by micro-organisms. But depending on particular circumstances biogenic methane can have a more broad range of values of $\delta^{13}C$, ranging from −40‰ to −110‰ (Faiz and Hendry, 2006). Consequently to properly define the biogenic/thermogenic mix it is frequently necessary to examine hydrogen isotope variations, δD, as well. On the other hand thermogenic methane tends to have a $\delta^{13}C$ value of the order of −40‰ to −50‰ (Faiz and Hendry, 2006; Papendick et al., 2011; Whiticar, 1999). Intermediate values of $\delta^{13}C$ are often interpreted to indicate a mixing of the two methane sources, which are due to secondary processes, such as water washing and thermal cracking (Al-Arouri et al., 1998). The complicated hydrocarbon generation history of the Bowen and Surat basins has led to estimation on the relative mix of thermogenic and biogenic methane currently in the Walloons Coal Measures. The measured values of $\delta^{13}C$ in the Walloons is of the order of −54‰ to −57‰ leading researchers (Faiz and Hendry, 2006; Papendick et al., 2011; Whiticar, 1999) to the conclusion that the majority of the gas is later stage biogenic rather than thermogenic but there are some indications of a remnant thermogenic signature, including the presence of ethane (Hamilton et al., 2014, 2015; Golding et al., 2013).

The complex geological circumstances that has led to the occurrence of significant CSG reserves in the Queensland Bowen and Surat basins also defines the variable nature of their occurrence (thick coals with thermogenic methane in the Bowen and thin multi layers coals interbedded with siltstone hosting mixed thermogenic and biogenic methane in the Surat) that defines the technical challenges and drives the need for innovative technology, robust resource management and adaptive regulation.

3. History of natural gas production in Queensland

Natural gas was first discovered and produced in Australia in the Hospital Hill water bore on the outskirts of the city of Roma in the Surat Basin in 1900. Describing a water well drilling incident on 16 October, 1900, Roberts (1992), refers to a gas "*blow-out*" in No. 2 water bore in a Jurassic reservoir at Hospital Hill (Cadman et al., 1998). This incident led to the drilling of several wells with one producing gas that was used for town lighting in Roma, from 1906 (Brisbane Courier, 1906). The supply lasted for only 10 days, after which the well stopped producing (Wolfensohn and Marshall, 1964). Non-commercial gas was again encountered in the area in 1927 and 1934 (Wolfensohn and Marshall, 1964). However, while obviously a gas-prone area, it was only in the 1960s that gas was commercialised from *conventional* gas accumulations. All of these gas (and oil) occurrences were from aquifers defined as being within the Great Artesian Basin (GAB).

Elsewhere, Gray (1967) documented reports of methane outbursts from water bores drilled in the Chinchilla area since the early 1900s. Gray reported that some water bores in the region were contaminated with methane gas according to historical government drilling log records from the GAB. Anecdotal accounts gathered by Gray indicate widespread instances of methane migration via water bores and natural features.

Occurrences of natural gas in ground water and periods of commercial gas production associated with coal basins are common and to be expected. For example, Miyazaki (2005b) has documented that in 1944, 11.5 MMSCF of CSG was produced from a well connected to the abandoned Balmain colliery underneath Sydney Harbour in NSW. This same well produced a total of 19.4 MMSCF of CSG between 1942 and 1950. Prior to that, in 1935, a well had been drilled into an unproduced coal seam in the Balmain colliery which had resulted in methane flows being tested, before abandonment (Miyazaki, 2005b).

By 1968, more than thirty conventional gas fields had been delineated on the Roma shelf, and enough gas had been proved up to justify building a natural gas pipeline to Brisbane (Cadman et al., 1998). Prior to construction of the 500 km pipeline to Brisbane, all of the gas being used in Brisbane, both for industrial customers and domestic households, was being generated as syngas (a mixture of hydrogen and carbon monoxide) from coal. This was being distributed through a local utility's pipeline network. These customers were rapidly converted to natural gas upon the completion of the Roma (Wallumbilla) to Brisbane gas pipeline (RBP) in 1968. Amongst the industrial customers were two large oil refineries that employed natural gas both as a fuel source for distillation columns and to generate hydrogen for hydrotreaters and hydrocrackers. The main domestic uses for gas were, and continue to be, cooking and heating water as the mild Queensland winters do not require homes to be centrally heated.

The gas production from the conventional fields in the Surat Basin steadily increased from an average of 10 BCF/yr in the 1970s to peak at 29.5 BCF in the 1994/95 fiscal year (Fig. 3). Production from Denison Trough (Bowen Basin) gas fields supplemented Surat production from 1988, supplying industrial users in Gladstone (via the Queensland State Gas Pipeline, QSGP). This gas plateaued around 16 BCF for some time, peaked in 2004/05 and declined after that (Fig. 3).

The Cooper and overlying Eromanga Basin are over 700 km west of Roma and sit across the South Australia (SA), Queensland border. Conventional natural gas had been discovered in the SA portion of the Cooper Basin in 1963 (Gidgealpa field). This gas was first piped to Adelaide from 1969, after the completion of the Moomba gas processing facility (northeast corner of SA). As the eastern Australia market grew and new fields were expanded, a Moomba-to-Sydney gas pipeline was completed in December 1976 (The Australian Pipeliner, 2007). Cooper (Eromanga) production remained roughly on a plateau throughout the 1980s, with additional discoveries, including in the Queensland portions of the basins. In the mid-late 1990s, pipeline expansion east into Queensland (via the South West Queensland Gas Pipeline − SWQGP) allowed for the connection of Cooper (and Eromanga) gas at the Moomba and newer Ballera processing plants to the existing Queensland 'Surat' supplies near Roma (which were by then in decline). By 1997, the SWQGP supplied industrial and residential markets in Brisbane and, by 1998, an additional 'Carpenteria Pipeline' also connected Queensland industrial users in Mount Isa (a large mining centre) (Santos Engineers, 2016).

Fig. 4 shows the location of the basins, major historic pipeline infrastructure and the boundary of the current Surat and Bowen CSG development area.

Annual production of Cooper/Eromanga (combined Queensland and South Australia) conventional gas plateaued between 1999 and 2001 at around 260 BCF and began to decline around 2002 (APPEA, 2013), by which time the conventional Surat Basin gas was already largely depleted. Therefore, new supplies of gas were needed.
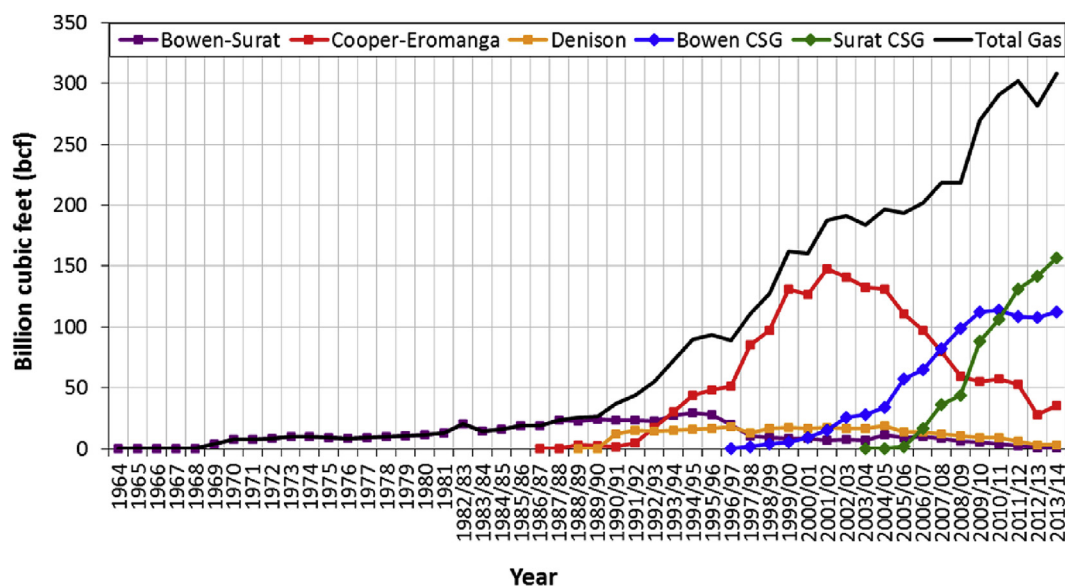
Fig. 3. Historical Queensland conventional and coal seam gas production (Queensland Government, 2015).

3.1. Gas market & infrastructure

Today, the majority of eastern Australian consumers (Townsville, Gladstone, Brisbane, Sydney, Melbourne, Adelaide, Canberra and northern Tasmania) are inter-connected via a gas pipeline grid. The gas has been primarily produced from conventional gas reservoirs in the Cooper and Eromanga basins in north-eastern South Australia and south-western Queensland, the Surat and Bowen basins in southern Queensland and the Otway and Gippsland basins, offshore from Victoria. The Northern Territory and Western Australia each have separate pipeline grids that are not currently connected to the rest of the Australian markets. Traditionally prices for gas on the east coast domestic market were typically of the order of A\$2-3/GJ with significant seasonal variation, with most demand being from the southern state of Victoria, as it is a colder area during the winter with significant population and manufacturing (Wood, 2013). The domestic (east coast) market has remained fairly steady at around 600 BCF per year, all supplied by domestic basins. Prices remained low, despite the decline in onshore gas production, because of factors such as material 2P reserves reported offshore in Bass Straight, or new supply from the Otway Basin, and/or possibly share-price pressures on smaller players to demonstrate production and reserves growth. Whatever the case, the long term outlook was (or should have been) always for a rising east coast price either due to increasing scarcity of supply and/or the need to find and profitably exploit the higher cost, more marginal resources, such as unconventionals.

Whilst CSG production had been a by-product of coal mining activity over many years, exploration for CSG, as a stand-alone resource, in Queensland commenced in the late 1970s. By 1990 around 30 CSG-specific wells had been drilled in the Bowen Basin. This development followed the success of similar developments in the United States of America. By 1995, approximately 160 wells had been drilled, mostly in the Bowen Basin, with commercial production commencing in 1996 for the domestic market in south-east Queensland.

One key domestic factor served to incentivise the exploration for large scale CSG/CBM in Queensland. In 2005, the Queensland Government acted to boost the State's gas industry via Chapter 5A of the *Electricity Act 1994*. Under that Act, Queensland electricity retailers were required to source 13% of their electricity from gas-

fired generation, subsequently rising to 15% in 2011 (Queensland Government, 2014). These factors served to increase the demand pressure and to help maintain a positive price outlook for domestic production, albeit with a price dip due to the Global Financial Crisis (GFC). Another factor was the aforementioned predicted shortage of domestic gas. From the late 1990s to around 2007, a consortium led first by Chevron and later by ExxonMobil proposed a PNG-Queensland gas pipeline to add supply in this predicted market shift. While these local market dynamics were in play, from approximately 1998, the global LNG price (c.i.f. Japan) rose steadily from around US\$4/GJ (approximately on par with historic domestic prices) to >US\$10/GJ by 2008/9 (Fig. 5) (Tasman, 2013). Ultimately, these dynamics and success in CSG seems to have negated the need for, or attractiveness of, new gas imports from PNG.

In fact, the first exploration wells completed in coal seams in Queensland occurred in Carra 1 in the Bowen Basin in 1976. While there was some earlier mine degassing undertaken in the coal mining sector, Department of Natural Resources and Mines (DNRM) noted that the first commercial production of CSG was in the Bowen Basin Permian Coal Measures (2016). This production began in 1996 at Dawson River (Baralaba Measures) near Moura, where permeabilities are reported to be relatively tight (10mD) leading to surface, in-seam developments. Dawson River was followed in 1998 by production from the Fairview area (Bandanna Measures). By 2002, this production had been added to from the Peat and Scotia fields (both Baralaba Measures), which, in common with Fairview, are reported to have structurally enhanced permeability due to their anticlinal setting.

Commercial gas production began from the Surat Basin, Walloon coal seams in 2006 from the areas west of and between Dalby and Chinchilla (Tipton West, Kogan and Berwyndale fields). By 2007, CSG production exceeded conventional gas production in Queensland, and by "*30 June 2008 certified reserves in the Surat Basin had surpassed those in the Bowen Basin*" (Qeensland Government, 2012). In 2011, the Surat Basin had overtaken the Bowen Basin as the chief supplier of natural gas in general, but of CSG in particular. In the 2014/15 fiscal year Queensland produced 469 BCF of gas, of which 430 BCF was CSG. This history, based on data reported by the Queensland Government (Queensland Government, 2015), is shown graphically in Fig. 6.
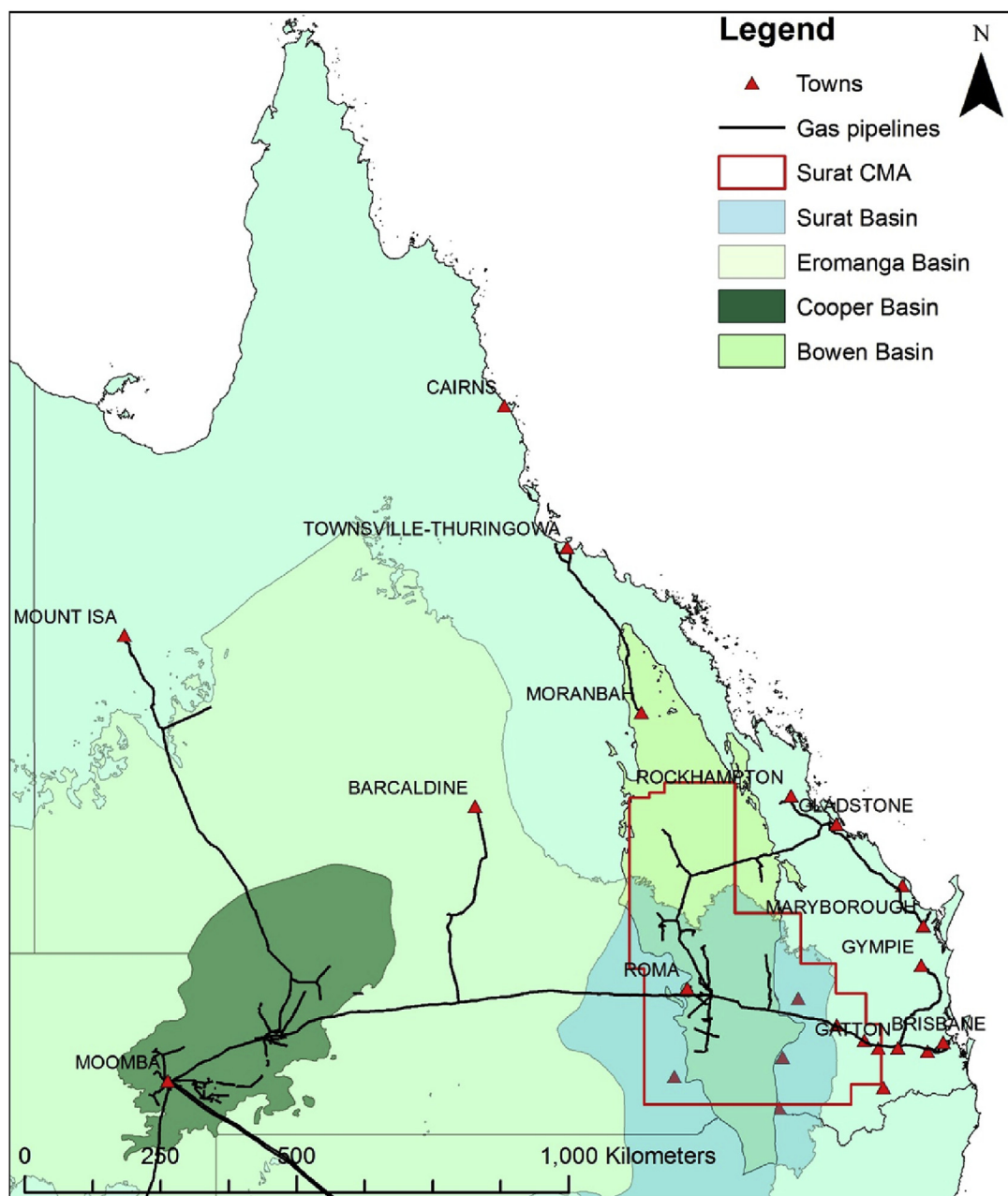
Fig. 4. Surat, Bowen, Cooper and Eromanga basins, cumulative management area (CMA) and gas pipelines.

3.2. Current status of CSG in QLD

As described earlier, the success of the early CSG explorers and producers led to the identification of a large and productive resource base in Queensland. The limited domestic market and low prices challenged the industry to seek new markets to monetise these resources. To that end, these early operators canvassed the idea of exporting the CSG as LNG and attracted the interest of large oil and gas companies. Following a period of mergers and acquisitions, this resulted in four major CSG production operations in place or under construction in Queensland, consisting of two consortia and two major oil companies. They are: Gladstone Liquefied Natural Gas project (GLNG) [Santos (operator, 30%), Petronas (27.5%), Kogas (15%), and Total (27.5%)], Australia Pacific Liquefied Natural Gas company (APLNG) [Origin (upstream operator, 37.5%), Conoco-Phillips (37.5%) and Sinopec (25%)], Queensland Curtis

Liquefied Natural Gas (QCLNG) [QGC operator, (a BG subsidiary, purchase by Shell recently finalised) with minor stakes in QCLNG owned by CNOOC and Tokyo Gas] and Arrow Energy (a company owned 50:50 by Shell and PetroChina). Three of the CSG companies have been in the process of building LNG plants on Curtis Island, near Gladstone, with the simultaneous construction of six trains, a world first (Macdonald-Smith, 2015). QCLNG commissioned its first LNG train in December 2014, and the second in July 2015. GLNG's first train began operations in the third quarter of 2015 and the first APLNG train commenced operation in late 2015. Both GLNG and APLNG are expected to commence operations on their second trains in 2016. The fourth group, Arrow Energy, had—by January 2016—not yet taken first investment decision (FID) on a large LNG project. However, the company has continued to appraise and develop gas resources in the Surat and Bowen basins and at this date looks likely to supply CSG to the other consortia's plants or for
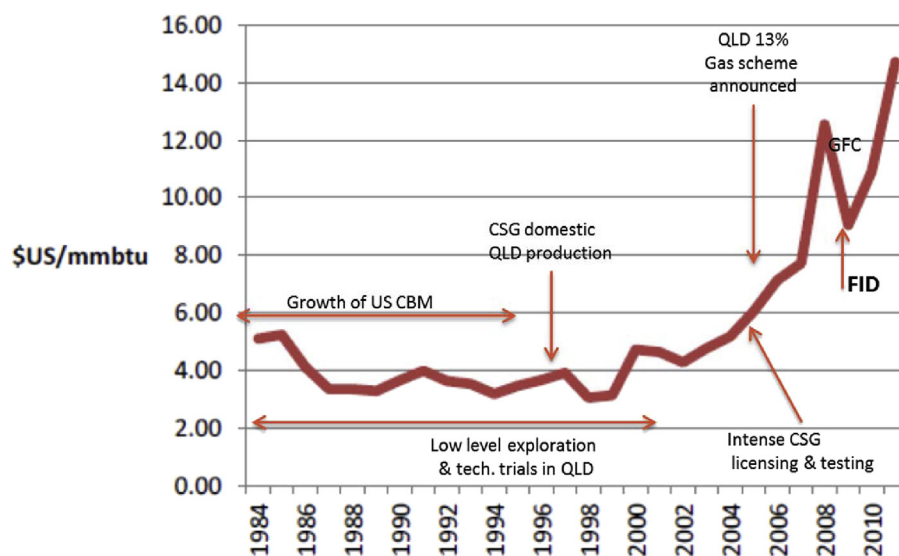
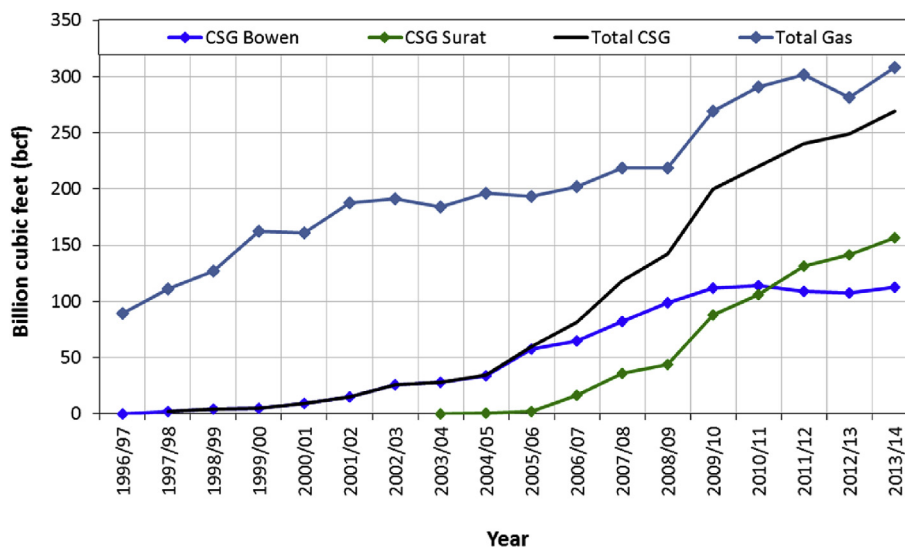**Fig. 5.** LNG prices cif Japan − modified after (Tasman, 2013).

Fig. 6. Historical Queensland approximate total gas and CSG production (Queensland Government, 2015).

domestic consumption.

As of (30/06/15) Queensland's 2P reserves of CSG were estimated to be 42,733 PJ (Department of Natural Resources and Mines, 2016), an increase from just 5 PJ in 1996. The Queensland CSG reserves currently represent over 81% of gas reserves in Eastern Australia (and 94.7% of all CSG reserves, the remainder being in NSW). The Queensland CSG reserves are held by 22 companies, with the majority of reserves under development in the three consortia working on CSG to LNG projects (Baker, 2013) as well as Arrow Energy. Reserves holdings are shown in Table 1.

3.3. Development

Initial CSG to LNG development strategies in Queensland were based on a number of appraisal pilots. They were also based on the assumption that a large number of wells would be required to meet market contracts. While initially uncertainty in the lateral variability of coal properties was recognised, successful pilots allowed

for production and facilities to be incrementally built adding confidence and early data on the degree of variability. Where early-stage models might indicate the need to drill with nominal spacings, ranging from 750 m to 1400 m between wells, this regularity and these estimates were modified by both production experience and by local, surface conditions requiring co-existence with farming operations. While Queensland CSG production would rank amongst the best CSG/CBM resources elsewhere, with mean rates between 1 and 2 MMscf/d and the best wells exceeding 20 MMscf/

Table 1
Reserves aligned to the four projects (GLNG, QCLNG, APLNG and Arrow Energy) as at 30 June 2015.

Project	2P Reserves (PJ)
1. GLNG (Santos operator)	5376
2. QCLNG (QGC operator)	10,326
3. APLNG	13,053
4. Arrow Energy	9494

d (Santos Engineers, 2016), *variability* in production from early wells began to suggest that lateral continuity of the coals, either as individual seams or as packages, was much more complex and less predictable than original expectations. Moreover, uncertainty in the key parameters such as gas content and permeability, fuelled an increasing realisation that better tools to assist in improving well placement were required.

When all of the currently planned LNG trains are in operation the total gas production from the LNG plants is expected to reach 1400 BCF/year. If Queensland's domestic demand for gas remains flat at the current 300 BCF/yr, this level of LNG production will mean that by 2017 the overall demand for gas is expected to increase to more than 1700 BCF/yr (more than five times current Queensland demand, noting that Queensland also exports gas to other States). With the current moderate domestic growth either in Queensland or other States, the total demand could reach around 1850 BCF/yr by 2025 (more than 6 times current domestic demand) — Fig. 7. It should however be noted that domestic demand outlook is highly uncertain and could decline. In any case, the overwhelming majority of the required gas will come from future CSG production. In line with this trend, it has been reported that up to 40000 CSG wells may eventually be drilled, of which over 8500 had been drilled as at September 2015 (exploration, appraisal and production wells). The additional 31,500 wells must be drilled over the next 15–20 years.

One of the by-products of CSG production is water production. The volume of water produced is dependent on the number of wells being drilled and on localised geological conditions. The historical water production from CSG wells since mid-2005 is shown in Fig. 8, along with the historical number of wells. There is a very close correlation between the number of CSG wells in production and the total water production rate. Work currently in progress at University of Queensland (Underschultz and Garnett, 2016) suggests that the amount of water produced as of mid-2015 is significantly lower than the volumes predicted in numerous third party studies undertaken pre-production—this is due to the uncertainty in production behaviour and operating conditions.

4. Well and facilities engineering

Well design, which is fit for purpose to the local geology is a key success factor in CSG development.

The well completion diagram for the Talinga No. 5 well as shown in Fig. 9, represents a typical vertical CSG well completion design. It contains a progressing cavity pump (PCP) installed on the tubing string. The PCP is designed to lift out the water, which dominates the early production life of the well. The gas and water are predominately separated downhole and the gas flows up the annulus outside the tubing, while the water is pumped up the inside of the tubing. In this case the wellbore is cased with 5.5 inch N80 casing and perforated in the productive coals, which in this case are the Kogan, Macalister and Taroom seams of the Walloon Coal Measures. In recently constructed wells it has become more typical to complete the well open hole, covering the productive horizon with a 7 or 8 inch slotted liner. Most of the wells to date are not fracture stimulated because the coal permeability and the well productivity are sufficient for good gas production levels. As at July 2014, approximately 8% of gas production wells had been hydraulically stimulated and Queensland's Department of Environment and Heritage Protection has further noted that this may rise to 10–40% of wells over time (Department of Environmental and Heritage Protection, 2014).

Bennett (2012) discussed the need for fit-for-purpose rigs to meet well design criteria and well safety requirements. This leads to the standardisation of well designs and equipment aligned to local government regulations and American Petroleum Institute (API) regulations. Vendors have been incentivised to meet company targets. This has led to an evolution in well design for the optimisation of gas recovery. They also emphasize the importance of adopting a culture of learning and flexibility to implement changes as design standards progress.

Different CSG reservoir horizons favour different completion strategies. In the Surat Basin, production from the large number of individual coal seams are co-mingled in a single vertical well. However, in the Bowen Basin a wider range of well types is employed depending on coal quality (permeability) and depth. This array of well types includes vertical and horizontal, hydraulically stimulated wells, as well as cavitation completions. Cavitation is the most common completion type in the higher permeability, Bowen CSG fields (e.g., Fairview & Spring Gully). Elsewhere, especially in the north of the Bowen Basin, surface to inseam (SIS) wells are sometimes drilled horizontally to intersect a vertical well as shown in Fig. 10. This has particular application in shallow coals that might be later subject to conventional coal mining. Therefore, to allow for future long-wall mining of this coal, legislation currently requires that, for the most part, SIS wells are required to use high density
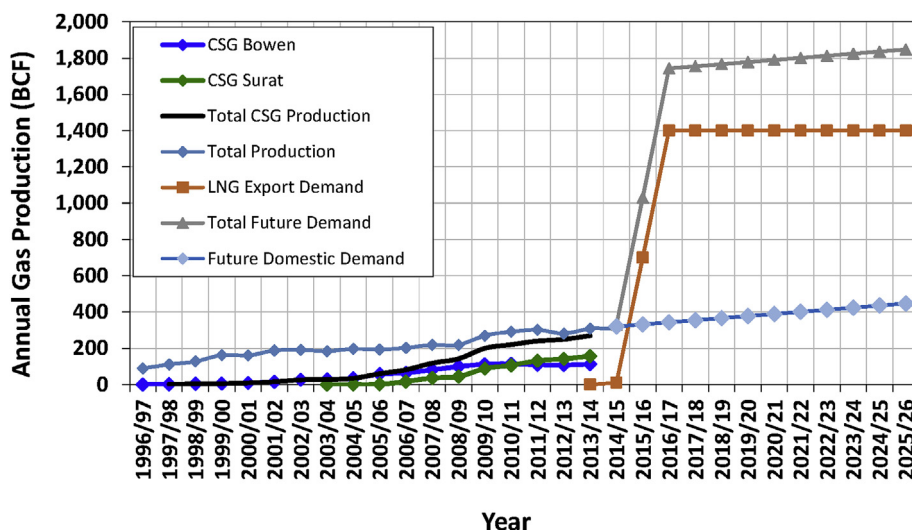

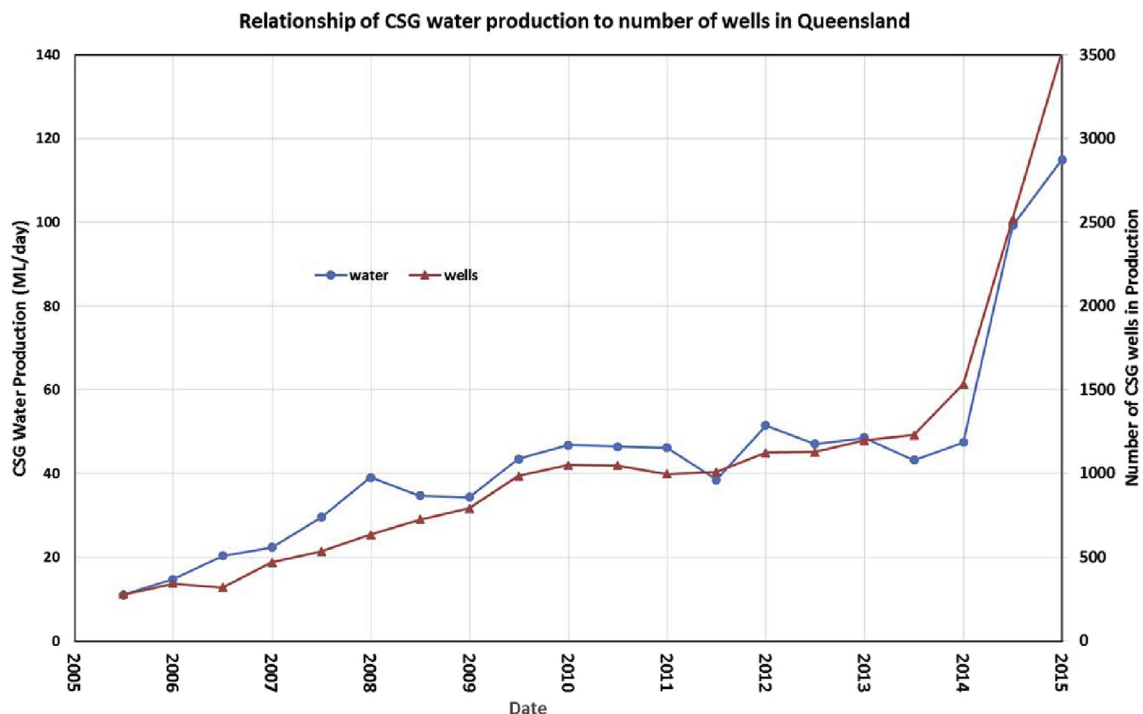**Fig. 7.** Queensland's historical and future gas "demand".

Fig. 8. Relationship of CSG water production to number of CSG wells (Queensland Government, 2015).

polyethylene (HDPE) pipe in the coal seams rather than steel (Bennett, 2012). In general most wells in both basins are drilled vertically and completed similarly to Fig. 9. To enhance production in low permeability reservoirs the coal seams may be under-reamed to create a cavity or fracture stimulated or drilled horizontally, perpendicular to natural fractures if they exist.

Reductions in drilling costs and increases in production in the Bowen Basin's Spring Gully field, located approximately 80 km north of Roma in Queensland, have been documented by Xu et al. (2015). The wells were previously developed with vertical wells and a cavitation completion or sometimes by hydraulic fracture stimulation. However, lower permeability areas of the field are now being developed with a shift to horizontal wells in the SIS arrangement. The CSG companies used SIS wells in 2012–13 to create significant improvements in productivity.

Smith et al. (2014) showed that the industry is learning and continuously improving using factory drilling approach to logistics, warehousing, well-site management, cementing, wireline, bits, solids control and directional drilling services. As described in this case study of QGC operations, between 2012 and 2014, the team incorporated LEAN initiatives (the identification and steady elimination of waste from operations) to drill and complete more than 1000 wells, some in as little as 2.15 days (drilling time) and 1.04 days (completion time). Therefore, the overall well cost has been significantly reduced. Other initiatives include the introduction of pad-based drilling (multiple horizontal wells from one well pad), which has significantly reduced the area of land occupied by well infrastructure (Carter, 2013). All the CSG companies have progressively introduced well design changes to improve gas production. Developing improved drilling and completion technologies to achieve commercial rates of gas production allowed a viable CSG industry to develop.

5. LNG facilities on Curtis Island

In order to liquefy methane at atmospheric pressure it must be cooled to −162 °C. Most liquefied natural gas (LNG) is cooled to this temperature and shipped at atmospheric pressure. The plants on Curtis Island are state of the art, and the technology is standard and well known. It is basically a refrigeration unit that cools the gas to the required temperature while lowering the pressure to atmospheric pressure. A typical LNG train is shown in Fig. 11. In the process shown in this figure, the gas is filtered to remove solids, stripped of carbon dioxide and water using the standard amine and glycol units and then cooled by contacting the gas first with liquid propane, followed by ethylene and liquefied methane. Finally it is pumped into storage tanks, where it waits to be loaded onto LNG vessels for shipping.

6. Technical issues faced in CSG wells

The companies continue to invest in research to achieve performance improvements and deal with the changing issues that arise as the industry matures. The focus on long-term and large-scale gas production expands research priorities into areas associated with the operation and maintenance of a complex well stock, and gas and water gathering systems, to deliver a highly stable and secure LNG contract shipment. This section highlights some key areas that are under investigations at The University of Queensland.

6.1. Geological variability and impact on field development

An over-riding theme is the higher than expected degree of inherent heterogeneity of lithology, continuity, connectivity and stresses within and between coal seams and also the variable interconnectivity between the coals and in the over- and under-lying aquifers and aquitards. This is being addressed via a complete review of the basin based on structural and stratigraphic 'first principles'. There is also collation and re-interpretation of the distribution of ground water compositions in all aquifers and there are novel developments in non-linear, geo-statistics and more efficient ways of modelling uncertainties (Vink et al., 2015; Tyson, 2015).
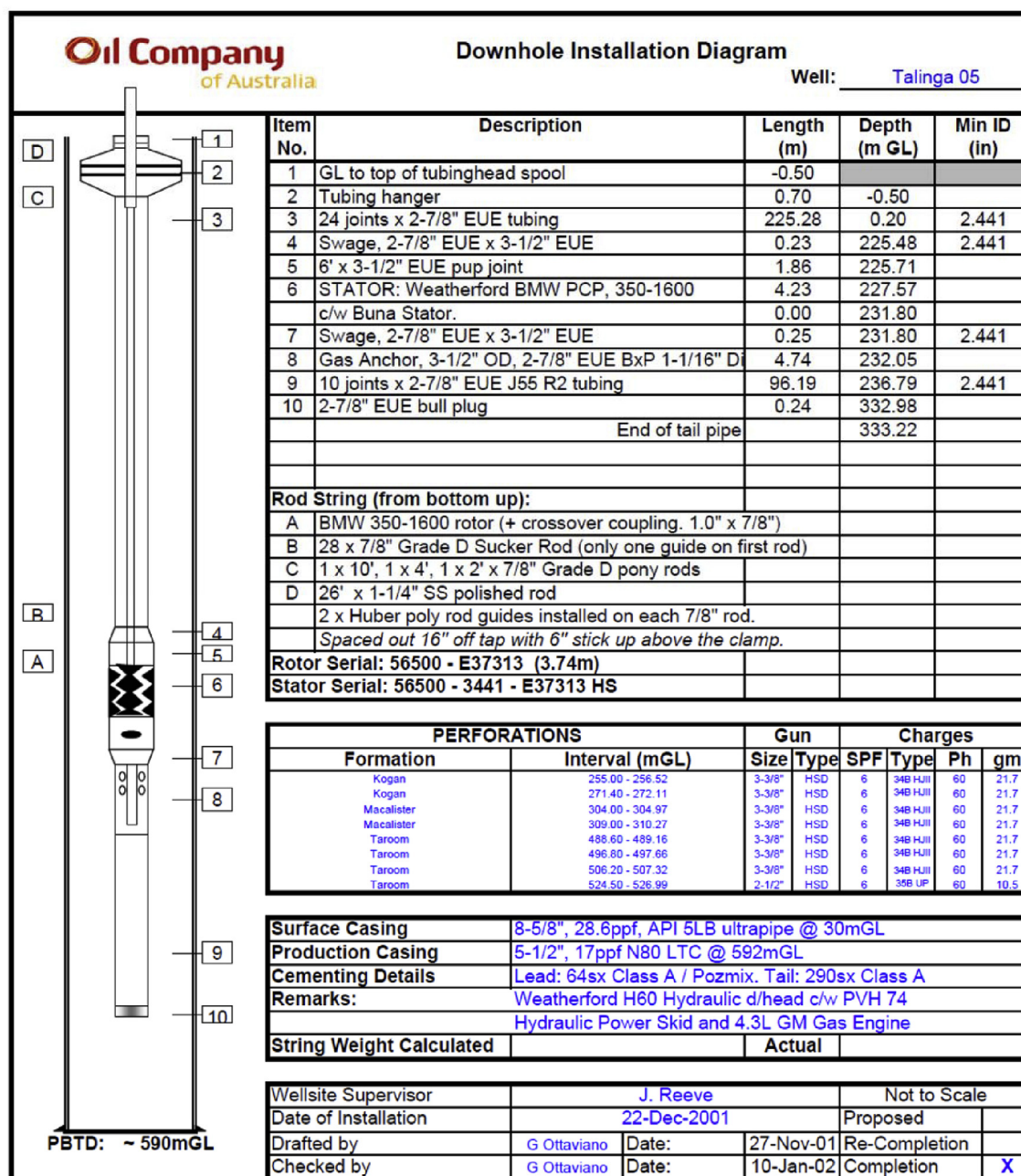
Downhole Installation Diagram

Oil Company of Australia

Well: Talinga 05

Item No.	Description	Length (m)	Depth (m GL)	Min ID (in)
1	GL to top of tubinghead spool	-0.50		
2	Tubing hanger	0.70	-0.50	
3	24 joints x 2-7/8" EUE tubing	225.28	0.20	2.441
4	Swage, 2-7/8" EUE x 3-1/2" EUE	0.23	225.48	2.441
5	6' x 3-1/2" EUE pup joint	1.86	225.71	
6	STATOR: Weatherford BMW PCP, 350-1600	4.23	227.57	
	c/w Buna Stator.	0.00	231.80	
7	Swage, 2-7/8" EUE x 3-1/2" EUE	0.25	231.80	2.441
8	Gas Anchor, 3-1/2" OD, 2-7/8" EUE BxP 1-1/16" Di	4.74	232.05	
9	10 joints x 2-7/8" EUE J55 R2 tubing	96.19	236.79	2.441
10	2-7/8" EUE bull plug	0.24	332.98	
	End of tail pipe		333.22	

Rod String (from bottom up):

A	BMW 350-1600 rotor (+ crossover coupling. 1.0" x 7/8")			
B	28 x 7/8" Grade D Sucker Rod (only one guide on first rod)			
C	1 x 10', 1 x 4', 1 x 2' x 7/8" Grade D pony rods			
D	26' x 1-1/4" SS polished rod			
	2 x Huber poly rod guides installed on each 7/8" rod.			
	Spaced out 16" off tap with 6" stick up above the clamp.			

Rotor Serial: 56500 - E37313 (3.74m)
Stator Serial: 56500 - 3441 - E37313 HS

PERFORATIONS		Gun		Charges			
Formation	Interval (mGL)	Size	Type	SPF	Type	Ph	gm
Kogan	255.00 - 256.52	3-3/8"	HSD	6	34B HJII	60	21.7
Kogan	271.40 - 272.11	3-3/8"	HSD	6	34B HJII	60	21.7
Macalister	304.00 - 304.97	3-3/8"	HSD	6	34B HJII	60	21.7
Macalister	309.00 - 310.27	3-3/8"	HSD	6	34B HJII	60	21.7
Taroom	488.60 - 489.16	3-3/8"	HSD	6	34B HJII	60	21.7
Taroom	496.80 - 497.66	3-3/8"	HSD	6	34B HJII	60	21.7
Taroom	506.20 - 507.32	3-3/8"	HSD	6	34B HJII	60	21.7
Taroom	524.50 - 526.99	2-1/2"	HSD	6	35B UP	60	10.5

Surface Casing	8-5/8", 28.6ppf, API 5LB ultrapipe @ 30mGL
Production Casing	5-1/2", 17ppf N80 LTC @ 592mGL
Cementing Details	Lead: 64sx Class A / Pozmix. Tail: 290sx Class A
Remarks:	Weatherford H60 Hydraulic d/head c/w PVH 74
	Hydraulic Power Skid and 4.3L GM Gas Engine
String Weight Calculated	Actual

Wellsite Supervisor	J. Reeve		Not to Scale
Date of Installation	22-Dec-2001		Proposed
Drafted by	G Ottaviano	Date: 27-Nov-01	Re-Completion
Checked by	G Ottaviano	Date: 10-Jan-02	Completion X

PBTD: ~590mGL

Fig. 9. Well Completion diagram for Talinga 5, coal seam gas well (Simeone and Corbett, 2003).

6.2. Relative permeability

Relative permeability of gas and water is one of the reservoir properties that controls the productivity of CSG reservoirs. Relative permeability can be used to determine if commercial gas production rates can be achieved and is a key parameter in reservoir simulation models that can play a significant role in determining the accuracy of such models. Gas-water relative permeability behaviour in coal cleats depends on the nature of fluids, local coal chemistry, minerals, surface morphology and local pressure conditions (Zhang et al., 2015). There are several methods to determine relative permeability including unsteady-state, steady-state, capillary pressure and numerical inversion methods. All of these approaches depend on the interpretation of experimental data in

laboratories (Zhang et al., 2015). However, it is noted that upscaling laboratory data to real reservoir conditions is subject to a great level of uncertainty (Müller, 2011), which in turn causes many uncertainties in prediction of gas production.

History matching is commonly employed in the industry to evaluate relative permeability and predict the field production. It involves matching simulation predictions with field results and adjusting input parameters. This technique requires an accurate numerical reservoir model to match the relative permeability. The relative permeability models that have been applied to CSG reservoirs were originally derived for conventional reservoirs and do not effectively represent the complex conditions. Therefore, a sound and comprehensive understanding of relative permeability is essential to modify the existing relative permeability models for
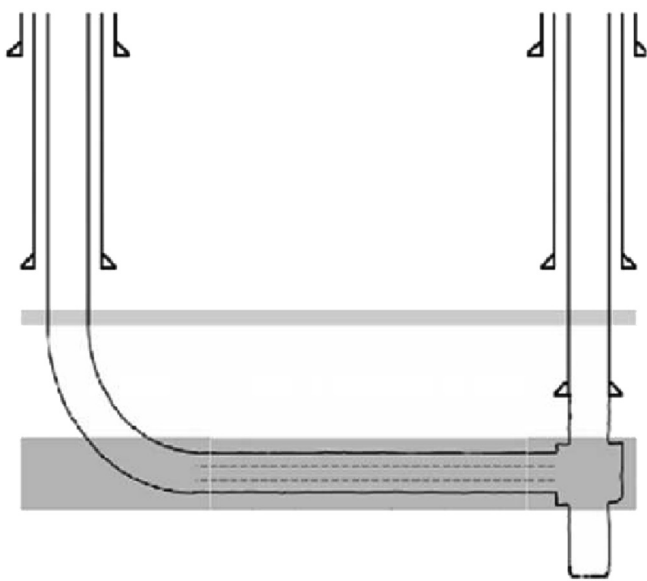
Fig. 10. Schematic of surface to inseam (SIS) well type (Bennett, 2012).

prediction of CSG wells.

While coal is generally assumed to be hydrophobic, the local conditions in a pore or cleat may create unique wetting characteristics. Previous studies have shown that wettability in coal is dependent on rank (Tampy et al., 1988; Keller, 1987), maceral composition (Arnold and Aplan, 1989), mineralisation (Gosiewska et al., 2002; Susana et al., 2012), functional group heterogeneity (Fuerstenau et al., 1983; Ofori et al., 2010), fluid pressure (Saghafi et al., 2014) and roughness (Drelich et al., 1996; Li et al., 2013). As

a result, capillary forces may permit water to bridge cleats and pore throats, potentially closing off sections of the reservoir to the wellbore and resulting in decreased production.

Mahoney et al. (2015) examined effects of coal rank and lithotype banding on coal cleat wettability with a series of artificially etched channels in a microfluidic Cleat Flow Cell (CFC) device. Relative contact angles on the coal surface of 110−140° were determined from images collected in the imbibition experiments. A trend of increasing contact angle with coal rank was observed. Zhang et al. (2015) performed a comprehensive review on relative permeability models, characteristics of relative permeability curves of coals and the influence of these curves on CSG production. They concluded that little work has been done on relative permeability of coals despite its importance in CSG related operation processes.

6.3. Fines

One of the issues that reduces profitability of some CSG wells is production of fine material, which mostly comes from smectite clays in the interburden strata between the coals. The smectites (principally montmorillonite) swell in contact with the (generally) brackish waters that are produced out of the coals. The swollen clays spall into the well bore, creating a very fine sludge that must be lifted out with the production water and gas. This sludge is viscous and difficult to pump. If the well is ever shut in the sludge tends to settle in the pump elastomers, causing the pump to seize and become difficult to re-start. One common solution to the re-start problem is to install a diversion valve in the tubing above the pump that opens when the well is shut in. This diverts the fines laden water from the tubing into the annulus during shut-in. Consequently, the fines are not allowed to accumulate in the PCP elastomers. This is a partial solution to one of the problems that
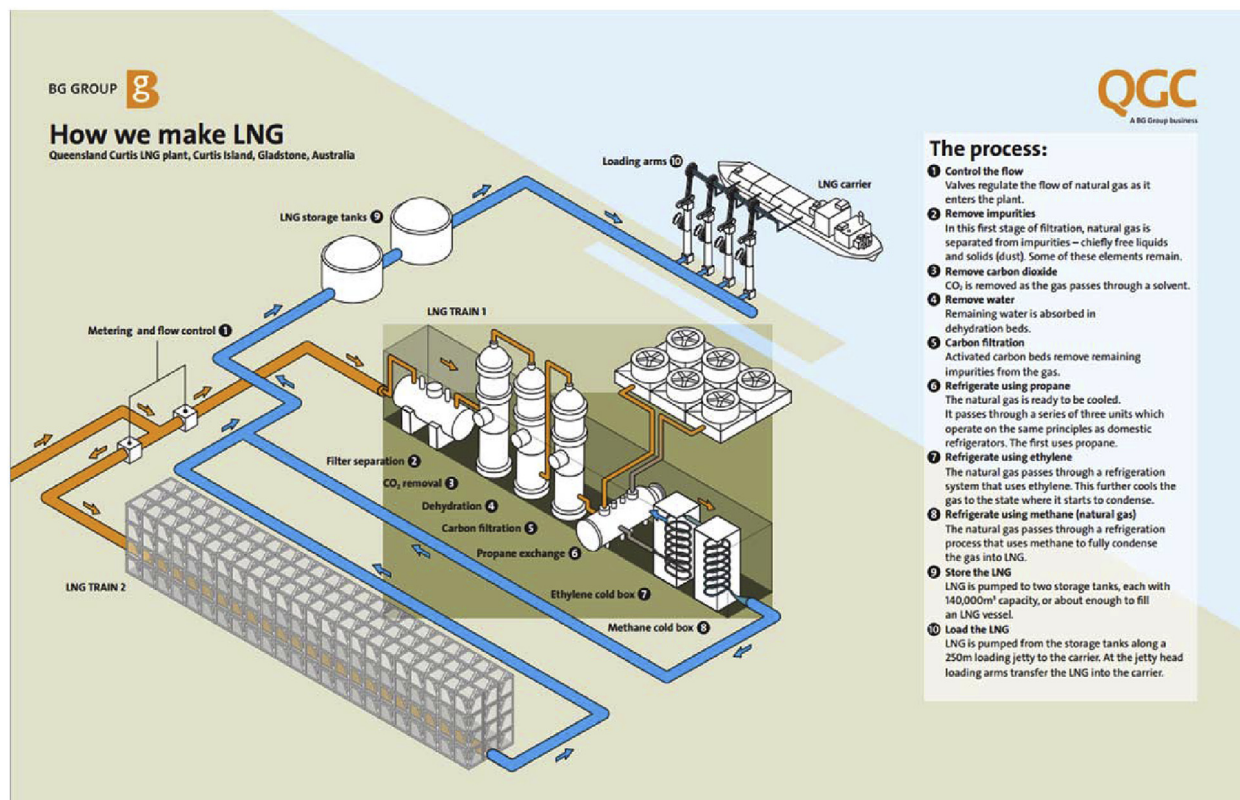

Fig. 11. Queensland Curtis LNG plant, Curtis Island, Gladstone, Australia (QGC, 2012).

results from fines production but ultimately the CSG companies would like to inhibit the production of fines altogether. Various solutions are being investigated, but at this time fines production remains an on-going problem.

6.4. Wellbore pressure profile

Using a numerical simulator to conduct history matching of early production data such as Bottom Hole Pressure (BHP) is a common practice in the CSG industry. It is used to predict a reservoir's producibility and thereby a well's production forecast. However, accurately forecasting the production from CSG wells, requires estimating the pressure profile in the flowing well. Currently, the conventional oil and gas industry uses a range of mathematical models and correlations to estimate the pressure drop for co-current two-phase flows in vertical wells. However, CSG wells are designed such that the upward flow of gas and downward flow of water in the annulus (between the tubing and casing) results in counter-current two-phase flow as shown in Fig. 12. Unlike the maturity of research in identifying flow regimes of co-current two-phase flows to evaluate the pressure drop, there is no information available on the flow regime of counter-current two-phase flows in annuli. Based on the flow map of counter-current flows in pipes, the flow regimes developed in a counter-current system in an annulus are expected to be significantly different to co-current flow regimes. Thus, the existing models used to predict pressure profiles in co-current wells do not adequately describe two phase flows in a CSG well-bore. A recent study by Firouzi et al. (2015) showed that pressure profiles of counter-current flows in annuli for the slug flow regime are appreciably different to those in co-current flows under the same conditions at high gas and water

flow rates. This difference may result in a large uncertainty in outcomes from well flow prediction tools when they are used with reservoir simulation studies to either forecast production or history match production data, and to reconcile various production zones in a well completed across multiple coal seams.

6.5. Slugging

Slugging is a concern in CSG wells as it can undesirably influence well performance. CSG wells can be subject to severe slugging due to the relatively large annulus required to host a pump (Gaurav et al., 2012). This is also a consequence of the nature of counter-current flow of gas and liquid, which is limited by the amount of gas and liquid flowing in each direction. Slugging causes variations in downhole pressure, which reduces the gas deliverability. Slugging also results in an inefficient downhole separation of gas and water in the CSG wells due to the liquid build up in the annulus. Due to low deliverability of CSG wells compared to conventional wells, one surface separator is employed to handle gas and liquid from multiple wells. The pressure fluctuations caused by variable slugging from multiple wells results in pressure back-out effects in the surface network which leads to inefficient productivity in the gas field (Gaurav et al., 2012). Identifying solutions to this problem requires better models of the counter-current two-phase flow in annuli that can be used to optimise down-hole pumps, as discussed in the previous section.

6.6. Well decommissioning

Oil and gas wells are required to be decommissioned (plugged and abandoned) when the production of these wells is no longer economical. Cement is the current standard method for plugging wells. However, this process has limitations because cement is expensive and prone to cracking and unsealing. The use of bentonite clay as an alternative plugging material is currently being investigated by the Centre for Coal Seam Gas at The University of Queensland. The purpose of this work is not only to reduce well decommissioning costs but also to create a more reliable plug that is self-healing. Bentonite is mostly composed of clay material that is predominantly a smectite clay mineral, usually montmorillonite (Ogden and Ruff, 1991). In reaction with water, sodium montmorillonite (the principal component of bentonite) shows a tendency to hydrate and expand while cement shows a tendency to shrink. Bentonite has higher plasticity than that of other clay substances, which stops permanent deformation. This property contributes to its potential as a good alternative for plugging wells.

Water wells in USA have been plugged and abandoned with bentonite chips for many years. The Wyoming Oil and Gas Conservation Commission (WOGCC) has also advocated the use of bentonite chips to plug seismic shot-holes (James, 1996). Ogden and Ruff (Ogden and Ruff, 1991) conducted laboratory investigations into the shear strength of bentonite when used as an annulus seal and as a grout. Their results showed that the seal made from granular bentonite has a greater shear strength to resist the hydrostatic push-out force relative to the seal made from the slurry grout. They measured the axial shear strength of granular bentonite versus time for plugs in an annulus between the steel casing and PVC. It was reported to be between 3.4 and 27.3 kPa. They also showed that average shear strength increased with setting time.

Towler and Ehlers (1997) studied the potential use of hydrated bentonite in plugging oil and gas wells both experimentally and theoretically. In their study a theory was proposed to predict the pressure that could be withstood by a hydrated bentonite plug,
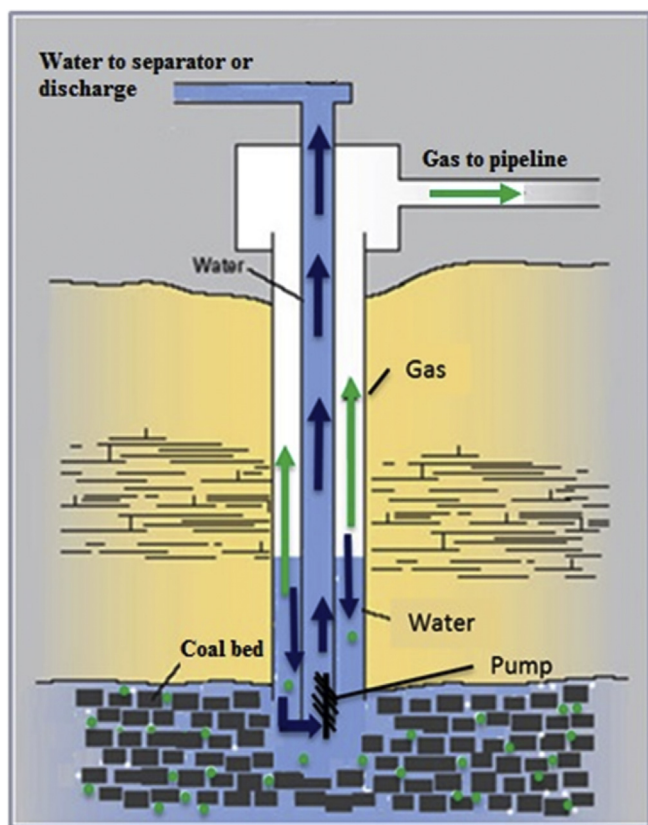

Fig. 12. Schematic of a coal seam gas well (modified from Integrating Research and Education:Cretaceous).

based on the frictional force between the casing walls and the bentonite plug. This pressure was found to be correlated to the height of the hydrated plug as a parabolic function. The predicted pressure was reported to be consistent with the results of their laboratory experiments on plug heights of 3–10 feet although their data exhibited a lot of scatter. Moreover, the reported parabolic relationship is in contrast to the work of Chevron researchers, who assumed that the relationship between the height of bentonite and the pressure it can seal is linear (Englehardt et al., 2001; Clark and Salsbury, 2003; Idialu et al., 2004). Recent analysis by Hywel-Evans and Towler (2015) suggests that the frictional strength is a parabolic function of plug height, while shear strength is linear with height, lending validity to Chevron's assumption for long plugs.

Englehardt et al. (2001) investigated the application of bentonite nodules to plug and abandon wells in California. A set of 19 wells in the Coalinga field was studied. Based on the successful results from this work, they obtained the approval of the Californian regulatory authority to proceed with the required plugging of many such wells in the San Joaquin Basin. That study is ongoing and as of 2015 Chevron has plugged more than 9000 wells with compressed bentonite nodules, proceeding at a rate of 400–1000 wells per year. Clark and Salsbury (2003) examined the application of compressed bentonite to plug one well in the Barrow Island field in Western Australia.

Towler et al. (2008) have proposed compressing the bentonite into bullet-shaped bars using a suitable binder. Chevron has alternatively proposed compressing the bentonite into fixed sized nodules (Englehardt et al., 2001). These methods of compressing the bentonite delay the hydration kinetics, allowing the bentonite to be deposited at the correct plug location before swelling occurs. In California Chevron usually fills the entire hole with compressed bentonite nodules.

A more detailed review of the studies conducted on plugging wells with bentonite is provided by Towler et al. (2015).

7. Key environmental challenges: methane emissions and produced water

A recent working paper from The University of Queensland's Centre for Coal Seam Gas (Garnett and Duncan, 2015), which sought to draw on extensive US experiences with CBM development highlighted four main areas of reported concern: (i) the nature and origin of methane in ground waters and of methane in the atmosphere, (ii) groundwater draw-down and management of produced water, (iii) risk of water contamination from CSG operations, and (iv) the possible impact of gas development on land subsidence.

7.1. Methane in groundwater and the atmosphere

For context, methane as a substance is non-toxic but can pose an explosive risk if present with oxygen and an ignition source in concentrations between the lower and upper explosive limits (5–15% by volume at room temperature and atmospheric pressure). Methane is also a greenhouse gas. There have been many studies and publications regarding global methane emission estimates from various sources, both natural and anthropogenic. Methane is thought to make up 16–20% of the total anthropogenic greenhouse gas emissions (Yusuf et al., 2012; Karakurt et al., 2012). While estimates vary between studies and over time (Yusuf et al., 2012; Karakurt et al., 2012; Kelly et al., 2015); the "ballpark" relative contribution for various source categories remains valid. From the published literature, the range of global anthropogenic methane emissions to the atmosphere that contribute to the overall 16–20% emission figure include: 19–21% from waste (primarily landfills and municipal waste water such as

sewage), 28–29% from energy production and utilisation (production and transport activities as well as industrial and retail uses), and 50–53% from agriculture. Natural sources of methane include wetlands, termites, wildfires, grasslands, coal outcrops and subcrops, and water bodies (Yusuf et al., 2012).

Because there are both natural and anthropogenic sources of methane it is important to look historically for evidence of methane in groundwater and the atmosphere in order to establish constraints on baseline conditions. This can be complicated by historical anthropogenic sources being potentially significant but unquantified. For example, there are several reports of gas seeps in Queensland, especially associated with artesian water bores, some of which date back to 1916 (Gray, 1967). Work by Day et al. (2014) and Kelly et al. (2015) found CSG emissions sources in Australia to be generally low. "*Of the 43 sites examined, 19 had emission rates less than 0.5 g/min and 37 less than 3 g/min; however, there were a number of wells with substantially higher emission rates up to 44 g/min*" (Day et al., 2014). Emissions that did occur were found mainly associated with:

- "*exhausts from engines used to power dewatering pumps,*
- *vents and the operation of pneumatic devices and*
- *equipment leaks*" (pg. 30) (Day et al., 2014).

The study acknowledged the limited sample size and the need to survey more wells. It reported mean emission rates representing around "*0.02% of total production*" for the sample set and noted that this figure was "*… very much lower than those that have been reported for U.S. unconventional gas production*" (Day et al., 2014).

There has been speculation that hydrocarbons in groundwater may be anthropogenic, induced by gas resource development. However, with hydrocarbon in groundwater known to be also naturally occurring and with significant non-CSG water extraction activities, it has led to debate on the relative share in provenance (natural or anthropogenic and CSG or other). Reports of hydrocarbon content in groundwater and seeping to the ground surface are an area that has recently been widely published in the peer reviewed literature and in the media. Much of the attention to hydrocarbons in groundwater is associated with concern about the environmental impacts of hydraulic fracturing (fraccing) and shale gas development (Darrah et al., 2014; Down et al., 2015; Llewellyn et al., 2015) using data derived from the USA. An extensive review of the USA unconventional gas industry (it is important to note that this is mainly shale gas) was conducted by the US Environmental Protection Agency (U.S. EPA, 2015), who concludes that contamination of drinking water resources is mainly due to:

- Surface spills of fracturing fluid and produced water
- Discharge of treated flow-back water
- Gas migration to aquifers via production wells
- Stimulating reservoirs that are also used for domestic water supply

However, they also set the context of these conclusions by stating "The number of identified cases where drinking water resources were impacted are small relative to the number of hydraulically fractured wells" (pg. ES-6).

For CSG in Australia, the CSIRO conducted laboratory analysis of water soluble organic compounds in Permian coals (Volk et al., 2011) to determine what organic compounds are likely to be naturally occurring in groundwater associated with coal zones. After an extensive literature search they conclude:

"*Where organic compounds have been found, these were often difficult to trace to their origin. Some of the detected compounds such as halogenated phenols clearly have no natural origin from coal. Others such as BTEX and PAH may be derived from coal*". (pg. 9)

The CSIRO completed a follow up study in 2014 on methodologies for detecting methane in water bores as well as an assessment of methane occurrences in groundwater across the Surat Basin (Walker and Mallants, 2014). They quote some 27 historical media reports between 1900 and 2001 of reported hydrocarbon in water bores across the Surat Basin. Complementing this study, the Queensland Gas Fields Commission report natural gas in soil at a number of locations prior to significant CSG development (Table 2).

Walker and Mallants (2014) refer to two data sets pertaining to the Surat Basin and present mapped distributions. One is dissolved methane measured in groundwater bores that was attributed to the Queensland Water Commission dataset (Queensland Water Commission, 2012). The other is free methane measured from groundwater bores that was sourced from a Geoscience Australia dataset (Feitz et al., 2014), which was collected to assist in the evaluation of greenhouse gas storage potential in the GAB.

It is clear that methane naturally occurs both dissolved and as a free phase in groundwater and often expressed at the surface in the form of natural gas seeps. Collecting data on these occurrences is important to establishing the base line conditions that can subsequently be compared to post production measurements.

7.2. Produced water

CSG production requires depressuring the coal seams, which generally results in producing water. The amount of water produced is proportional to the saturations and permeability of the coal as well as its internal connectivity and continuity and its connectivity to aquifers. The coals of the Bowen Basin generally produce significantly less water than those of the Surat Basin. Furthermore, the Surat Basin Walloon Coal Measures which represent the main production of the Queensland CSG industry, lie within the GAB. The GAB is a hydrological basin and is one of the largest groundwater reserves in the world and covers an area far larger than the CSG development areas. It contains a series of aquifers, which are used for abstraction, most with a high degree of spatial variability and vertical connectivity across the basin. Different aquifers within the GAB in different locations provide a water resource for the agricultural industry and for regional communities in the eastern states of Australia, as it underlies large low-rainfall and drought-prone areas. There is a long history of declining aquifer pressures through over-abstraction (Smerdon and Ransley, 2012), with the first interstate conference called in 1912 (Booth and Tubman, 2011). Within Queensland, aquifers within the GAB provide water to 35 towns and numerous farming and grazing properties for both stock and domestic use (Tasman, 2005). They also provide irrigation water for major crops, such as cotton, irrigated grains and horticulture (Delat, 2010). The GAB

also holds significant cultural and heritage significance for the indigenous communities, which it has supported for thousands of years as well as the agricultural communities that have developed since the mid-19th Century.

Community concern regarding the potential for the groundwater extraction required by the CSG industry to decrease the availability of water resources for agricultural production activities and to introduce contaminants into these GAB aquifers is at least partially offset by the availability of CSG associated water for beneficial use that has been amended by tailored water treatment options.

7.2.1. Produced water management

The volume of water production varies significantly over different spatial and time scales, reflecting the influence of geological and hydrological variation in the subsurface, and the pattern of industry development. Although highly uncertain, the cumulative water volume forecast in 2012 to be produced would peak at ~120 GL/yr (Klohn Crippen Berger (KCB), 2012) but water production decreases with time over the 30 yr production history. These early forecasts appear to be conservative (high), as the actual CSG water production to date is shown in Fig. 8 to be approaching 120 ML/day (~44 GL/yr) in 2015. Produced water shows significant, natural geochemical variation (100's to 1000's of ppm TDS) across the Basin (see Fig. 13). While some produced water is good quality that can be used directly for beneficial purposes, most requires treatment to some degree before use (Davies et al., 2015).

Although these ratios vary from basin to basin, in North America ~45% of CBM water has been disposed of in evaporation/infiltration ponds, ~15% goes to surface discharge, ~25% is re-injected into deeper saline aquifers and ~15% is treated and used on the surface. Queensland government policy requires that operators make beneficial use of produced water where possible e.g. recharging depleted aquifers, irrigation and substitution for other water use. Use of evaporation ponds will only be approved if all other options are not feasible (DEHP, 2012).

Almost all produced water from the Queensland CSG developments is intended for beneficial use, even if the water requires amendment before use. The water treatment required needs to be tailored to the end use. This can be accomplished through a full range of possibilities between using CSG produced raw water through to reverse osmosis (RO) treated water and various blends in between. RO treatment creates a second smaller waste stream of more concentrated salinity. While re-injection of co-produced water or a post-treatment brine stream into deep saline aquifers is used internationally, the approach has not been widely adopted in Queensland. With respect to the latter, the industry's preferred solution at present is to further concentrate the brine through to a crystallized solid salt product that is placed in regulated landfills (Davies et al., 2015).

7.2.2. Cumulative impacts on GAB pressure decline

The depressurising of the CSG reservoirs has the potential to temporarily reduce formation pressure in adjacent aquifers of the GAB. In the Surat Basin the peak in produced water extraction by CSG was predicted in 2012 (pre-production) to be roughly one-third of the total water extraction (Queensland Water Commission, 2012); however, current industry estimates would suggest this number to be as low as one sixth.

Cumulative impacts on groundwater by the CSG industry are estimated from regional groundwater flow modelling conducted by the Queensland Government. Estimates are based on assumptions about the volume and distribution of gas and water production and various static and dynamic geological

Table 2
Measured natural gas in soil (GasFields Commission Queensland, 2014).

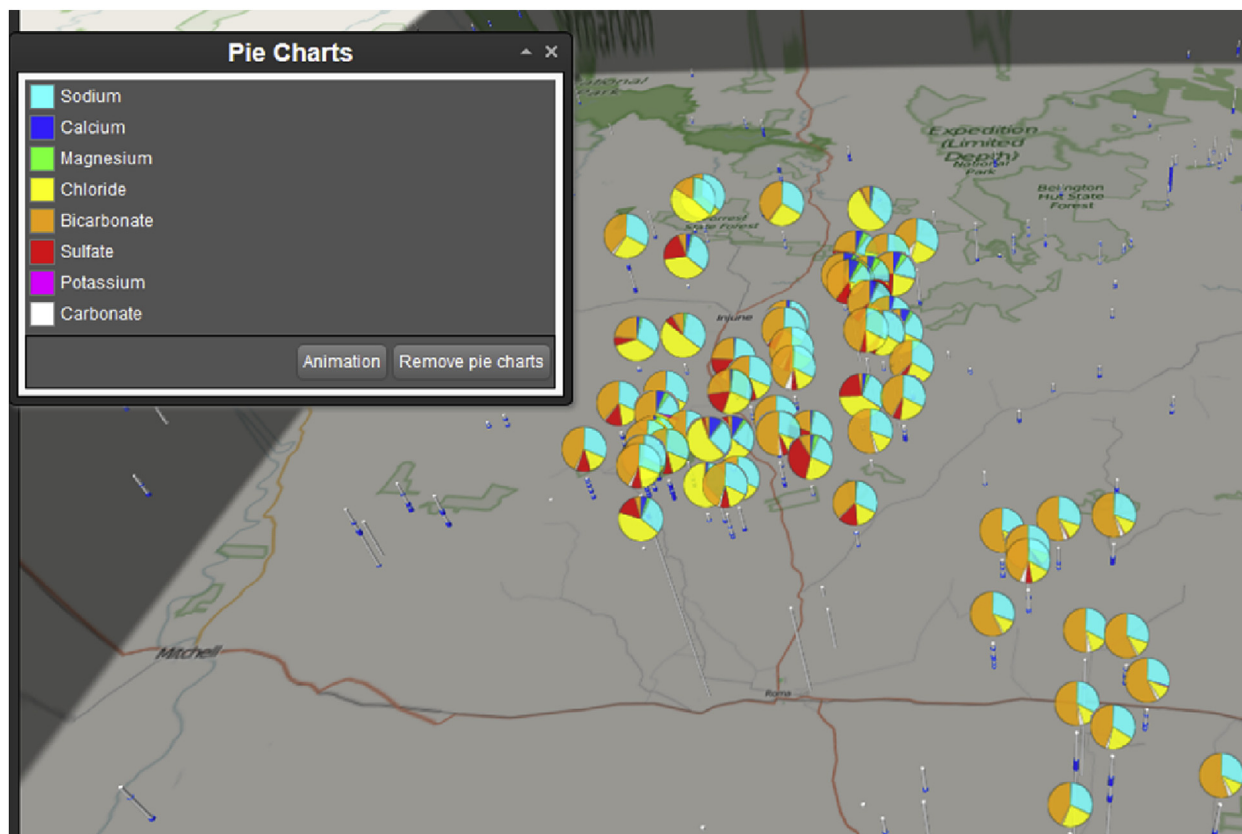| Year	Location	No of samples	Methane range [ppm]
1983	Giligulgul (Wandoan)	258	2.5–48
1987	Chinchilla	58	1.2–25.5
1988	St George	314	1.9–89.1
	Bungil (South of Roma)	322	0.1–48.7
1989	Kalima (near Roma)	158	1.7–14.8
	Chinchilla	150	1.7–22.1
1991	Glenmorgan	534	8.09–42.45

Fig. 13. Pie charts show the variation in groundwater chemistry across the central and north-western portions of the Surat Basin.
Source: The University of Queensland 3D Water Atlas.

implications and assumptions. The modelling results are published in an "Underground Water Impact Report" for the Surat Cumulative Management Area (Surat UWIR), with the first version published in 2012 (Queensland Water Commission, 2012). The model is used to characterise where trigger values are reached in the decline of groundwater levels. These levels are a 5 m decline in consolidated aquifers and a 2 m decline in unconsolidated aquifers. These areas are flagged as regions where GAB aquifers may be impaired by CSG development. The model also distinguishes between the timing of this predicted impact being felt within 3 years (immediately affected area) or over a longer period (long-term affected area). The trigger-value designation has implications for landholders in the region, resulting in make-good agreements, where CSG companies need to guarantee provision of water (or compensation) to agricultural landholders in specified, affected areas.

Besides the impact of water extraction from CSG development on the Walloon Coal Measures, the Queensland government's 2012 model suggests impact on the adjacent aquifers below and above, i.e., Hutton Sandstone and Springbok Sandstone, will have certain areas that will fit within these criteria, but this region of predicted impact substantially reduces stratigraphically further away from the Walloon Coal Measures. Since CSG production has begun, initial indications are that produced water from CSG operations is below the earlier forecasts. Recognising inherent uncertainty, the groundwater flow modelling is based on a 3 year cycle where the numerical model simulations are updated with recent data. Consequently, it is expected that predictions over time should have improved accuracy. The next generation groundwater flow model has been developed and the associated Surat UWIR will be released

in early 2016. The regulatory mechanisms associated with the groundwater flow model and the Surat UWIR are discussed further in Section 8.1.1.

8. Regulatory responses

The Queensland CSG industry commenced production for the domestic market in 1996. The opportunity to develop a CSG-LNG industry and service international energy markets led more recently to rapid expansion of production. The scale and pace of this expansion was unprecedented in Australia. While there had been a conventional oil and gas industry operating in the Surat Basin since the 1960's in traditional agricultural and high amenity areas, the expansion saw a significant increase in CSG operations in these landscapes. Consequently, the effectiveness of government regulation to ensure responsible development of the CSG industry came under increasing public scrutiny. The expansion of the CSG industry in Queensland has been the catalyst for a number of innovations in regulatory frameworks at both State and Australian Commonwealth levels. Some of these regulatory developments have been specific to the CSG industry while others have had broader application. This section summarises key initiatives at both state and federal levels.

8.1. Queensland Government initiatives

8.1.1. Surat Basin cumulative management area and the Office of Groundwater Impact Assessment

In response to concerns about the groundwater issues outlined above, Queensland's Office of Groundwater Impact Assessment

(OGIA) was created in 2012.[1] OGIA is an independent entity[2] with responsibility for advising the Queensland government on the nature and extent of impacts on the groundwater systems. It also, establishes baseline data, maintains a groundwater database, provides ongoing monitoring and prepares underground water impact reports (UWIRs) for cumulative management areas (CMAs). Legislation allowing the government to declare a CMA had been introduced in 2010 as government had recognised that in an area of concentrated CSG development where the tenures of multiple operators overlap, the effects on groundwater from individual projects would be cumulative and would require an understanding of the whole system. This legislation constructed an adaptive management framework for addressing the cumulative groundwater impacts of the CSG industry. The aim is that regulatory conditions and industry responsibilities are able to be revised as scientific knowledge improves with increasing data on groundwater extraction rates and volumes.

Prior to 2012, each CSG company had prepared a groundwater flow model for their development area. The effectiveness of individual company attempts to model the cumulative impact of all projects was limited as commercial sensitivities meant that each company only had access to their own confidential geological and hydrological data. The industry had endeavoured to develop an assessment of cumulative impact on groundwater resources (University of Southern Queensland, 2011), —essentially a 'summing' of the different impacts identified through the individual company models, rather than a synthesised result based on the interaction of all data. Integration of data from all four companies operating in the CMA was enabled by the regulatory framework underlying the OGIA modelling. The government modelling process has estimated the impacts on bores employed for stock (e.g., cattle and sheep) and domestic use due to drawdown by the CSG industry. It has also addressed drawdown impacts on aquifer discharge springs, which are protected ecological communities under Australian environmental legislation. The model has also informed the design of the groundwater monitoring network. The results of the modelling are published in the Underground Water Management Impact Report for the Surat Cumulative Area (Queensland Water Commission, 2012).

A key feature of this regulatory response is that OGIA uses the modelling results to allocate responsibilities to individual companies for the installation of monitoring bores, and to assess baseline bore conditions. Where water levels are predicted to drop in wells used for stock and domestic water supply, there are instances where OGIA will allocate responsibility among CSG companies. These instances are (a) outside CSG tenured areas—that is, on farms that have no CSG wells but the bore is affected by the industry drawing down on an aquifer at another location or (b) in areas of overlapping tenure—that is, where multiple companies have CSG wells on a farm and there would otherwise be debate over which company is responsible for the lower water level. In these instances, OGIA will allocate responsibility for negotiating a 'make good agreement'. The 'make good agreement' is an agreement contract between the landholder and the company regarding how the impact on the landholder's water bore is to be addressed. This can take the form of monetary compensation, deepening of the water bore into a lower, productive aquifer, drilling of a new water bore, or providing alternative access to water.

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[1] The responsibilities of OGIA were initially carried out by the Queensland Water Commission, an independent statutory authority, for the period 2010–2012.

[2] Created under the *Water Act 2000 (Qld),* housed within the Queensland Department of Natural Resources and Mines with administrative support, and funded through an industry levy.

8.1.2. Coal Seam Gas (CSG) compliance unit

The LNG Enforcement Unit (renamed the CSG Compliance Unit in 2012) was created in the early phases of the recent CSG industry expansion in 2010. The aim was to provide "an integrated one stop monitoring and enforcement service." (Qeensland Government, 2010). This initiative provided a strong government presence, by placing government staff in the gasfields region to address public enquiries, investigate complaints, and conduct activities to monitor compliance. The current CSG Compliance Unit is staffed by Department of Natural Resources and Mines employees but works in partnership with other agencies, such as the Department of Environment and Heritage Protection and the GasFields Commission Queensland.

The Unit includes the regional presence of the Petroleum and Gas Inspectorate, responsible for petroleum and gas safety; the Groundwater Investigation and Assessment Team, responsible for assessing and monitoring groundwater impacts; and an engagement team, responsible for land access issues and community and industry engagement. Complaint investigation, assisted dispute resolution and proactive compliance auditing and inspections are key activities (Department of Natural Resources and Mines, 2015).

8.1.3. GasFields Commission Queensland

Amid a growing public discourse about possible impacts on groundwater, agricultural productivity, and local communities, CSG development in Queensland became a controversial public issue. In 2011, the Queensland Government recognised the need to provide formal processes and organisational structures to give a range of stakeholders a clear voice on CSG related matters. The Surat Basin Engagement Committee (SBEC) was established to facilitate dialogue between the community and the CSG industry and to resolve issues of concern (Queensland Government, 2011). Participants of the SBEC were drawn from local government, peak agricultural bodies, landholder groups, senior government executives, senior executives from the CSG companies, the oil and gas industry peak body (APPEA) and the Queensland Resources Council (QRC—the resource industry peak body). While this Committee had an advisory role to government, it lacked formal powers to obtain information or make recommendations.

In 2013, the GasFields Commission Queensland (GFCQ) was formed as an independent statutory authority with powers, additional to and much broader than the powers of government departments, to *require* information and data. The Commission's legal powers under the *Gasfields Commission Act 2013* are numerous. They include powers to request any information relating to the onshore gas industry from government entities and the power to request documents or information from landholders, onshore gas operators or their contractors. Additionally, the Commission may publish any information about the CSG industry. That expands on its original role of facilitating engagement, to offer a new layer of transparency and accountability. The GasFields Commission has provided key advice on the implementation of land access laws.

8.1.4. Land Access Framework

The access of petroleum and gas companies to private land for the purposes of exploration and production activities has historically been managed under the relevant Queensland Petroleum Acts and Regulations. In addition, since 2010, all resource companies entering private land must comply with conditions set out in the Queensland Government's Land Access Framework. That framework includes the Land Access Code 2010 (hereafter referred to as: Land Access Code), which was developed to suggest how resource companies communicate with landholders and negotiate compensation agreements (Conduct & Compensation Agreements—CCAs) and to regulate how resource companies must act

while on private land.

These laws were subject to review in 2012, amid landholder complaints about conduct, lack of dispute resolution, and process. To date, few CCA negotiations have progressed to the Land Court [confidential research interview]. To some, that can suggest success in aspects of the act, of which Land Access Code is a part. However, others indicate that resolution in court can be a tortuous process for a busy landholder contending with drought and ongoing, time consuming interchanges with CSG companies [confidential research interview (Cavaye et al., 2016)].

Alternative dispute resolution has been employed as a route for resolving disputes. CSG companies prefer to resolve issues prior to legal proceedings, and landholders are faced with significant legal costs if they proceed to court. Despite a record of few, formal legal proceedings being initiated post-CCA, the independent reviewers of the Code suggested several amendments. Those amendments include making good conduct legally enforceable, using a standardised process around land access negotiations (pre-CCA), providing better information to landholders, and offering an 'opt-out' option for landholders. The government responded with a Six Point Action Plan with the implementation of changes overseen by a multi-stakeholder committee.

8.1.5. Development programs for impacted communities

Public debate has escalated in recent times regarding the amount of financial benefit that communities experience from the extractive industries operating in their areas. Rolfe et al. (2011) noted that changes during the last 30 years in resource company operations, workforce management and procurement activities have decreased the amount of direct economic benefits for local communities. Input-output modelling of 2009–2010 data showed that the state capital, Brisbane, gained ~47% of the total economic stimulus associated with the whole of the Queensland resources sector at that time, while generating only 0.006% of the royalties. During this period, the Darling Downs area where CSG development had commenced, generated 4.1% of total royalties, and gained 2.6% of the total economic stimulus (Rolfe et al., 2011). The contribution to royalties from CSG development in the regions is expected to have increased greatly since 2010, as production levels continue to increase from 2014 (Tasman, 2012) but the amount of local direct benefit is still disproportionate. That is, the development is in the Darling Downs, but the benefits are landing mainly in Brisbane and in the regional centre of Toowoomba, which is 100 km from Brisbane and is a gateway to the CSG area.

To ensure that the regions receive greater direct benefit, the Queensland government introduced specific programs to fund infrastructure investment within resource communities including the Royalties for the Regions (R4R) program (2012–2014) followed by the Royalties for Resource Producing Communities (2015–2016). Local Government Authorities (LGAs—the equivalent to US county or UK shire governments) apply for funds under these programs and must secure further financial contributions, e.g., from industry, the coffers of the LGA itself, associations, or other state and commonwealth agencies. LGAs within the gas fields regions have received funding under the $495 million R4R program for various projects including roads, upgrades to water and sewerage systems, and flood levee construction.

8.1.6. Regulator conditions: from rule-based to principle-based regulation

The environmental impact statements (EISs) submitted to the Queensland government for each of the four CSG projects (covering upstream field development, pipelines, and LNG plants at Gladstone) address not only possible environmental impacts but social and economic ones, as well. As such, the EISs include a social impact assessment (SIA) and a social impact management plan (SIMP). The Coordinator-General (C-G) assesses most EIS's and places conditions on a project's industry proponent to mitigate the identified environmental and social impacts. For one CSG project, the C-G imposed over 550 conditions during its approval process on a wide range of aspects of the construction and operations.

For example, under the rule-based approach, a 'condition' imposed on an early project might specify that a CSG company build a prescribed number of houses, based on detailed assessment of housing needs. Other rule-based conditions set 'target' levels e.g., Company A would provide "*as a guide, 75 per cent or other percentage concluded from the project's Integrated Project Housing Strategy*". Other examples include target levels of Aboriginal employment and local spending, the requirement to establish community shopfronts in specific locations to facilitate community access to information on CSG development and operations, and even specifications regarding the issues that the company needed to report to a Regional Community Consultative Committee (The Coordinator-General, 2010).

The rule-based approach to regulation, puts the onus on government to accurately forecast and address public concerns, while companies 'tick the box' on the government's list of conditions to show compliance. The rule-based approach was abandoned in 2012 with the change of Queensland government, which sought to reduce the volume of government regulation. The new government adopted a principle-based approach (Queensland Government, 2013) to regulation of social impacts, which put the onus back on the CSG companies to assess the needs of affected communities, identify desired outcomes and propose effective strategies to achieve those outcomes. The Queensland CSG companies were given the option to comply according to the regulations under which they started their project construction or to adopt the new, more flexible, outcomes-based approach. The companies opted for a hybrid approach. They elected to complete the requirements specified in their social impact management plans (SIMPs). The rationale was that those tasks were well progressed at that point, and completing the tasks represented reaching a well-defined target. The companies adopted the new principle-based guidelines for their reporting beyond the end of the 5-year SIMP period (Caddies, 2016).

8.2. Australian federal government initiatives

In Australia's federal system of government, the states have jurisdiction over onshore extractive industries. However, to overcome inconsistencies in state regulations, and in response to concerns raised by federally-funded natural resource management groups and other parties, the federal level of government (the Australian Government) moved to exert greater control over CSG development. The Australian Government used existing powers under the *Environment Protection and Biodiversity Conservation Act (EPBC) 1999* (Cth) to expand its influence on development approvals.

Changes made under the EPBC Act in response to CSG development were twofold. The first was the establishment of a specialised scientific advisory committee, the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC). The IESC provides advice to the Australian Government regulators on the potential impacts on water resources from proposed CSG and coal mining developments.[3] Under

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[3] The IESC replaced an Expert Panel, which the regulatory agency (Department of Sustainability, Environment, Water, Population and Communities) had established in 2011 to specifically consider the water management issues associated with the Queensland CSG projects.

an inter-governmental agreement, (the National Partnership Agreement on Coal Seam Gas and Large Coal Mining Development) state governments have also agreed to seek expert advice from the IESC where CSG or coal mining developments are likely to have significant impact on water resources.

The second key federal government response was to expand the definition of 'matters of national environmental significance' (MNES) that trigger the application of the EPBC Act to development projects. This change defined 'water' as an environmental impact area, referring to both surface and ground water. Assessment of the Queensland CSG projects under the EPBC Act preceded the above amendments to the EPBC Act. As a result, the federal Environment Minister could impose conditions only in relation to impacts on matters such as threatened plant or animal communities. Consequently, conditions in relation to water resources were restricted to those that would protect ecosystems dependent on GAB groundwater discharge springs. Now that 'water' more generally has been added as a MNES, a CSG project will almost always trigger the EPBC Act. This allows the federal Minister to impose extensive conditions to protect all water, including organisms, ecosystems and hydrology.

9. Effects on community and social licence to operate

The effects of three (with the then prospect of a fourth) simultaneous CSG to LNG developments in the region were added to other challenges in Queensland. These challenges included, prolonged drought, then major flooding, and the imposition of local government restructuring. This succession and juxtaposition of events led people in the affected communities to begin thinking and speaking in terms of 'cumulative impacts'. Cumulative impacts arise from one or more projects that are large relative to the receiving region, are instituted quickly relative to the capacity of governments and communities to respond, and are managed by multiple corporations and regulated by multiple government agencies, i.e. responding to the impact is hindered by a fragmentation in governance (Franks et al., 2013; Uhlmann et al., 2014). These cumulative impacts are outlined below in relation to public perceptions, effects on farmers, effects on small businesses in the towns, and effects on the region. The nature of development and the effects being seen suggest that the southern Queensland gasfield region may be facing the 20–30 year, boom-bust-recovery cycle previously seen in gasfield communities of the western United States (Smith et al., 2001).

Previous sections have described the process of gaining governmental approval—what is often referred to as the 'social license to operate'—for major projects. Gaining social approval is important as protest action can compromise project timelines. Gaining a social license was particularly made difficult for the CSG industry in Queensland as CSG development accelerated soon after release in 2010 of a controversial documentary on US shale gas development, 'Gasland'. Prior to Gasland, CSG development was predominantly portrayed in the media as an economic development opportunity (Mitchell and Angus, 2014). Gasland seemed to resonate with certain sentiments and concerns in Australia, leading to the CSG industry in Queensland being portrayed as an environmental and human health threat. Differences between the two forms of 'license'—government's versus social—creates pressure for government to change regulation so that elements perceived publicly as essential to the 'social license to operate' are specifically enforced by government. Additionally, expectations that form a social license can be different with some views more prevalent in the urban centres where most of Australia's population (and voters) resides, and the rural regions where the CSG development is occurring (UQ Centre for Coal Seam Gas, 2013). Urban media tended

to be focused on environmental and human health threats (Mitchell and Angus, 2014), whereas rural concerns pertained to groundwater quality and quantity, the increased levels of traffic—due to construction vehicles as well as workers and contractors commuting to work sites, and issues around access to—and conduct on—farming properties by CSG company staff and contractors who are drilling wells or installing pipelines and other infrastructure (The Australian Pipeliner, 2010). As the CSG construction period ends, dominant community concerns have changed to concerns about small business viability, as many small businesses invested heavily to grow to service demand during the three-year, peak construction period.

The extent and distribution of profits accumulated locally during the height of construction have been difficult to discern. Growing wealth is not evident in material terms e.g. expensive cars or houses, as media stories about the North American experience suggest, such as with CBM development in Kansas in 2003 (Hegeman, 2003). Research interviews and anecdotal evidence indicate that some farmers with income from CCAs in relation to CSG infrastructure on their properties are investing in property outside the region. The net income for farms in the district of Chinchilla (population of about 7000) in 2009 and 2010 fiscal years was zero, when totalled across the 70–80 farm businesses (Australian Taxation Office, 2015a). For the 2011 fiscal year, major flooding contributed to a net loss of $2 million. For fiscal 2012, net farm business income for the district rose to $8 million before dropping to well under $1 million dollars for 2013. The average net farm income for the district had been between $1 million and $1.5 million per year for 2001 to 2006 (Australian Taxation Office, 2015a). These figures suggest an additional influx of up to $7 million in compensation or other construction related income in 2012, or nearly $50,000 per farm. However, this income was not distributed evenly across farms in the district. Some farms had more wells or infrastructure being put in place, while others had more flood damages. Additionally, the farms are different sizes with different mixes of crops and livestock. Despite such unevenness, the boost in farm income from the CSG industry CCAs is evident.

At the same time, farmers without CCAs were dealing with diminished income from either drought or flood (average net annual income per farm in Chinchilla was $12,500 between 2001 and 2007 (Australian Taxation Office, 2015b)). These financial stresses were combined with a demand on a farmer's time and attention to negotiate with CSG companies about access to their land, and subsequently facilitating and monitoring that access while continuing daily farm activities. Extended research interviews with 47 farmers with CSG infrastructure on their properties have revealed an estimated one day per week being spent in dealing with CSG company staff and operations on their property, though this figure has not been substantiated by outside measurements (Cavaye et al., 2016).

Although farmers are the historical power base in this region (De Rijke, 2013), they are not the only residents, nor are their farms the only businesses in the region. Chinchilla district, as one example in the heart of the CSG development, has had roughly 100 farm businesses, and the town centre has hosted from 150 to 200 small businesses in the period 2001 to 2010 (Australian Taxation Office, 2015b). During this decade, total net business income for the community grew gradually to reach $5 million per year. In 2011, as CSG construction was launched in earnest, that figure boomed to $30 million (Australian Taxation Office, 2015b), multiplying by a factor of six. It climbed further to $35 million in 2012 (Australian Taxation Office, 2015b) and then is reported by representatives of local business organisations (e.g., Toowoomba Surat Basin Enterprise and the chamber of commerce in the neighbouring town of Miles) to have dropped dramatically in 2014 (Australian Taxation

Office figures are not yet available). During the CSG construction boom, the number of businesses in Chinchilla grew from 200 to 300. Such rapid growth in local businesses, though many, may be quite small. There was also an influx of labour contracted to work on the CSG construction, suggesting migration to the area. These factors contributed to localised inflation from a booming town economy.

The rapidity and magnitude of these changes can be seen to have significant cumulative effects. Rifkin et al. (2015) found three key cumulative effects. Together these effects suggest at least temporary downward pressures on the level of social capital in the region. Social capital represents the strength of relationships and trust among residents. Social capital has been linked to the viability of small businesses in rural regions, as business owners benefit from knowing their customer base, knowing their vendors, and knowing potential staff (Cohen and Prusak, 2001).

The specific cumulative socioeconomic effects noted include movement—the migration of people into the region, temporarily or permanently; migration of older residents out of the region—-selling their farms and houses in an inflated market; and movement within the region—from town to countryside or vice versa. Between the Australian census years of 2006 and 2011, more than 50-percent of the population changed residence in the town of Dalby, the largest town in the local government area and location of local government offices (the 'county seat' in US terminology). There was also movement in social and economic class, such as older pensioners cashing in and poorer residents being forced to move out of town centres by rapidly rising rents (a doubling of rents in some towns) (Rifkin et al., 2016).

Physical movement of the population was accompanied by a growth in diversity. Diversity here refers in part to a greater diversity in culture, with overseas migrants coming to work in service industries as local residents took up CSG industry jobs. There was also growth in diversity in the skills base of the population, via both migration and training. There was growth of diversity in retail offerings and in the housing stock. A growth in human diversity can contribute to greater social capital provided that new relationships are forged, but that may take time. Studies in North America suggest that recovery of what is referred to as 'community coherence' following a resource boom can take 15–20 years (Krannich, 2012).

The impacts of population movement and a growth in diversity were accompanied by issues related to the expectations in these communities concerning the distribution of benefits and burdens. These concerns centred on the timing of construction work (start and end), locations (e.g., workers living in town or in camps), and extent of this construction and related work, who received contracts from the CSG industry and its primary contractors, and whether outcomes agreed with prior understandings. There were also concerns about the perceived fairness with which benefits were distributed, such as there being a lack of clarity among town residents about how the industry allocated its community investment funds. Concerns about fairness have been compounded in this region because the dollar amounts and conditions of CCAs with individual landholders are kept confidential. So, there is a large stream of income into the region, where residents do not know who is receiving how much or why they are getting it. This sort of dynamic can be seen to contribute to a rise in distrust among residents, something that corresponds with a downturn in social capital.

One can conclude that towns at the heart of the CSG development in Queensland are likely to have suffered from a decline in social capital, a loosening of ties among residents due to outward migration, inward migration, and factors that can be seen to stimulate mutual distrust. That implies a loss—though not necessarily permanent—of a measure of the 'small town' feeling that is attributed to these rural areas and is iconic in Australian views of its rural agricultural regions (Everingham et al., 2015). Such a decline in social capital, evidence suggests, has been accompanied by a substantial inward flow of wages and business income, albeit over a short period: 2011–2014. It has not yet emerged what level of local revenue the operations phase of these CSG projects will yield. Additionally, it is not clear how much of the funds from the construction boom will remain in the region to fuel the local economy. There is anecdotal evidence (from research interviews) - from the agricultural investment field, from landholders, and from a farm organisation − of investments that residents are making outside the region as a risk mitigation strategy. While net local benefits may still be hard to discern without further research, local change has been a certainty, with CSG development having been its catalyst. Communities are now experiencing a different suite of effects as the CSG projects transition from construction to operations and staffing for development of new wells proceeds at a slower rate than during the initial establishment phase.

10. Conclusions

The development of CSG in Queensland has been brought about by the coincidence of many geological, technical and non-technical factors and by the adaptation of industry, government and society.

A series of small conventional fields briefly flourished, feeding gas to Brisbane from the late 1960s to the 1980s but the conventional fields are now all in decline. The infrastructure from this activity together with the geological endowment of CSG and the gas market opportunity underpinned the CSG industry decision to explore for CSG in the Surat and Bowen basins in Queensland. CBM developments at the beginning of the 1980s in the USA saw new technologies and commercial success. After more than 10 years of exploration and over 160 wells, the first commercial CSG was put in production in 1996 for domestic consumption.

The Australian gas market is, however, small, with little scope to support the mega-projects needed for relatively high-cost, low margin unconventional gas. Throughout the early 2000's, regional LNG prices rose and the *outlook* for LNG futures rose at least 3-fold. At the same time, the Queensland government stimulated local gas demand in the power sector. These factors along with success in several technology trials led to significant exploration and appraisal efforts and eventually the sanctioning of 3 major CSG-LNG projects in Queensland in 2010 and 2011. The current, 2P estimates of over 40 Tcf reserves represent an increase of almost 10-fold in under 10 years.

While the gas resources belong to the State and are accessed and exploited by gas companies under State licence, the gas field developments co-exist with an important agricultural sector in a water stressed area. The main Walloon coal seams (in the Surat Basin) are encased within the Great Artesian Basin on which the region depends heavily for its water. The developments are large and aerially extensive and will require 25,000–40,000 wells to be drilled by 2025–30.

There are concurrent and inter-linked technical and social challenges, which the industry, the regulator, and society have had to work through. They continue to do so in an adaptive way. This learning process has built on an inter-play of insights from geological sciences, petroleum engineering and social sciences. It has involved improving the understanding and optimisation of gas production in complex formations, at the same time as understanding and minimising impacts on ground water. Additionally, there has been engagement with rural communities for a better understanding of the socio-economic impacts, along with new regulatory structures and instruments. Nowhere else has LNG been tied entirely to CSG/CBM. The areas now under development are

probably the most monitored and best understood with respect to regional ground water systems in the world—and improvements are still coming. There is a new industry, which is a major employer and taxpayer, one that works continuously to hold its 'social licence'. Future challenges remain in sustaining the sector, not least its production predictability, cost structures, community impacts and environmental performance. Work continues within the industry, regulatory and research sectors to improve in these areas.

Acknowledgement

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