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The risk of migratory methane emissions resulting from the development of Queensland coal seam gas

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Table of Contents

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The University of Melbourne Energy Institute is an access point for industry, government and community groups seeking to work with leading researchers on innovative solutions in the following areas: new energy resources; developing new ways to harness renewable energy; more efficient ways to use energy; securing energy waste; and framing optimal laws and regulation to achieve energy outcomes.

About the Authors

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Executive summary

In sedimentary basins migration of methane and other fluids occurs naturally in response to multiple factors. Natural methane surface seeps are well known in many gas provinces. The pathways for such seeps can be enhanced and new pathways created through subsurface resource developments, leading to so-called induced migratory emissions. Distinguishing induced migratory emissions from natural emissions is important for a range of considerations, including resource recovery efficiency and safety, carbon budgets and environmental impacts.

As a companion to a more extensive paper on the measurement and reporting of methane emissions of unconventional gas[1], this paper reviews the current understanding of migratory emissions associated with CSG developments in eastern Australia. The paper forms part of series of contributions from the Melbourne Energy Institute's Sedimentary Basin Management Initiative aimed at providing new approaches to optimising the value of subsurface sedimentary basin resources.

The current paucity of publicly available data makes it impossible to definitively assess the impact of coal seam gas (CSG) production has had, if any, on the creation of new migratory emissions pathways and the enhancement of known methane seeps, such as in the Condamine River in Queensland. Similarly, in the absence of thorough baseline data, the cumulative impacts of water production from various aquifers for multiple purposes would compromise unique attribution of cause and effect in any observed enhancement of such seeps.

Where multiple resource use impacts the hydrostatic pressure of key aquifers, the consequences for subsurface gas flows needs particular consideration. For example, hydrostatic pressure reduction in the Condamine Alluvium, largely for agricultural use, and depressurization of the Walloon coals for gas recovery, both enhance the prospects for gas exchange especially in zones where the two aquifers are connected. In the case of the Condamine, to better resolve these issues it is crucial to characterise the local hydrogeology. Specifically, continuity of the upper aquitard in the Walloon coals, is of importance as it prevents free gas from moving towards the surface and reduces the connectivity between the Condamine Alluvium and the Walloon coal aquifers. In several locations the aquitard is known to be thin or absent.

Natural faults and fractures with enhanced permeability are natural fluid migration pathways. Known gas seeps such as the Condamine are understood to be associated with ancient fault lines. As with aquifers, hydrological connectivity in permeable faults can be altered by subsurface resource developments in ways that impact hydraulic gradients and reduce confining pressures. Characterising the distribution and character of such potential pathways is essential to mitigating risk.

[1] Melbourne Energy Institute, 2016, A review of current and future methane emissions from Australian unconventional oil and gas production

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Fractures induced by hydraulic fracturing ('fracking') can introduce new migration pathways beyond the coal measures into overlaying and underlying formations if the fracturing job is poorly executed. This risk maybe enhanced if the surrounding geology is not well understood.

Water bores and coal exploration bores are potential sources of methane emissions and it has been acknowledged that the existence of methane in water bores can be the consequence of gas migration from the coal seams due to depressurisation. Well integrity is an important long-term issue not only in dedicated oil and gas wells but also in existing bores that were not designed to prevent migratory emissions.

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1. Introduction

The MEI report

> *"A review of current and future methane emissions from Australian unconventional oil and gas production (September 2016)"*

describes several ways that methane from unconventional oil and gas production may be emitted into the atmosphere.

This present companion report

> *" The risk of migratory methane emissions resulting from the development of Queensland coal seam gas (September 2016)"*

focuses on the potential emission sources known as 'migratory methane emissions'.

In this report, migratory methane emissions are defined as where, as a result of unconventional oil and gas development, methane may migrate upward and laterally out of its original reservoir. Migratory methane may eventually reach the Earth's surface and enter the atmosphere possibly at a considerable distance away from the site of original oil and gas drilling or other disturbance.

Coal seam gas (CSG) is a relatively new approach to accessing subsurface gas resources, representing one of the new “unconventional” approached. Coal seam gas developments have rapidly expanded in Australian coal basins, allowing the development of new export capacity. A key issue in any new approach to accessing sub-surface resources is understanding unintended consequences, such as migratory emissions. Assessments of induced emissions need to be framed against the backdrop of natural emissions. For example, the migration of gas and other fluids is a natural process in sedimentary basins, that for example leads to accumulations of conventional gas fields. In many sedimentary basins it is well documented that methane seeps naturally to the surface.

The nomenclature "unconventional oil and gas" covers a range of oil and gas reservoir types. To date, overseas migratory emissions research has focused mainly on shale reservoirs in the United States. That research found that well integrity is a potentially serious problem in unconventional gas basins such as the Marcellus Shale. Although not yet developed, Australia has large shale formations. While Australian stakeholders should to be mindful of such research, this report deals specifically with the issue of migratory emissions from CSG basins.

This report does not cover in depth the process of how gas is released from the coals targeted by the coal seam gas industry. This topic has been studied and reviewed by various stakeholders including industry, government, and researchers (e.g. Rice (1993), Levine (1996), Laxminarayana and Crosdale (1999), Mastalerz, Glikson et al. (1999), Hildenbrand, Krooss et al. (2006), Scott, Anderson et al. (2007), Flores, Rice et al. (2008), Strąpoć, Picardal et al. (2008), Moore (2012), Hamilton, Esterle et al. (2012).

In this report, the concept of coal seam gas production is described followed by a discussion of five enablers that can help gas to migrate to the surface.

In Australia, CSG developments have been mostly focussed in Queensland, in the Surat and Bowen basins, where concerns about induced migratory emissions have been raised by the visible seeps in the Condamine River. The focus of this report is therefore the Condamine region.

2. The concept of coal seam gas extraction

Gas can be present in coal seams in commercial quantities only if there is enough pressure to keep the gas adhered (adsorbed) to the coals. When it is, gas can be released by dewatering the coal seams which decreasing the water pressure in the coal seams. The released gas is extracted through a grid of wells. Gas will only start flowing when the pressure in the coals is reduced to a critical level that typically involves extraction of significant volumes of water from the coal seam formation (see Section 3.2). The level of depressurisation required depends on the pressure exerted on the coal by the surrounding rock and water.

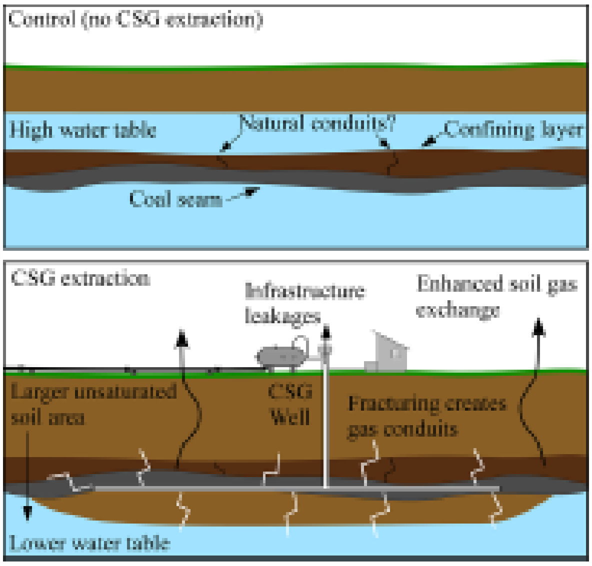
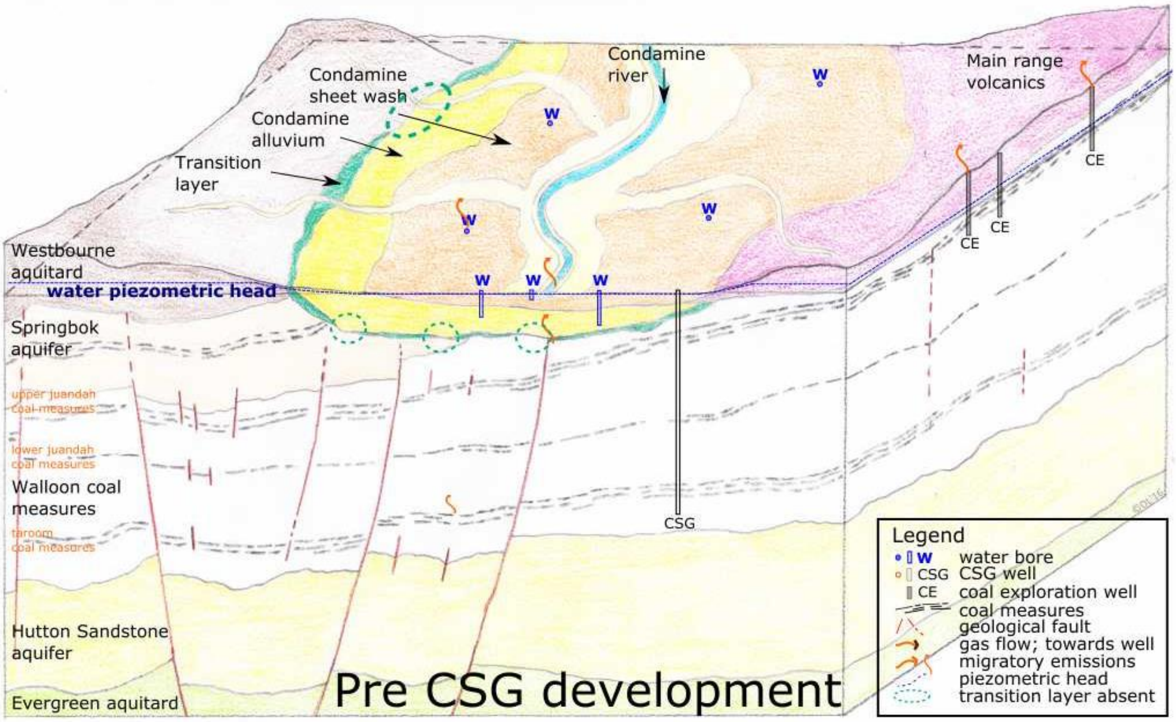


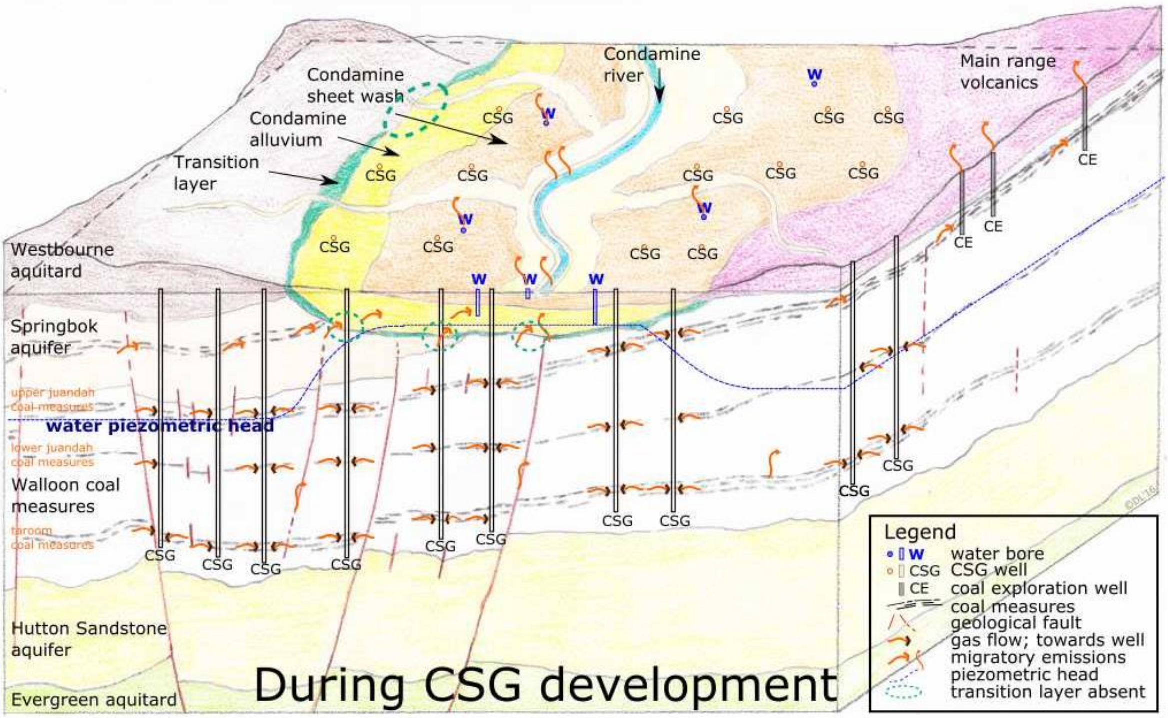
Figure 1. Migratory methane emissions.
Top figure: Water table and coal seams where no CSG extraction is underway.
Bottom figure: Depicts coal seam dewatering, hydraulic fracturing and migratory methane emissions.
Tait et al. (2013)

Extracting coal seam gas arguably poses more significant environmental risk than extracting gas from conventional reservoirs (sandstones, carbonates, or even deep shales) for two reasons: the gas resides in coal and is at shallow depths (less than 1000 metres below the surface).
The possibility of gas migrating to the surface has been raised as a potential risk (for example, Tait, Santos et al. (2013)). Figure 1 depicts the process of depressurising a coal seam and extracting the water, which can enable gas to flow toward possible gas migration pathways.

Figure 2 (three parts) provides schematic geological cross-sections depicting possible gas migration pathways and the evolution of the potentiometric surface of the Walloon coal aquifer for the before, during, and after CSG-production phases.

Since the aquifers are in hydraulic connection with each other, gas may migrate to the surface via stratigraphic pathways, via faults, or using the changing pressure gradient that results from coal seam dewatering and depressurisation. Migratory emissions may be minimal without any disturbance along existing natural geological conduits, but migration of gas along natural conduits may increase significantly when aquifers are depressurised, thereby changing the hydraulic gradients and reducing the confining pressure on the gas.





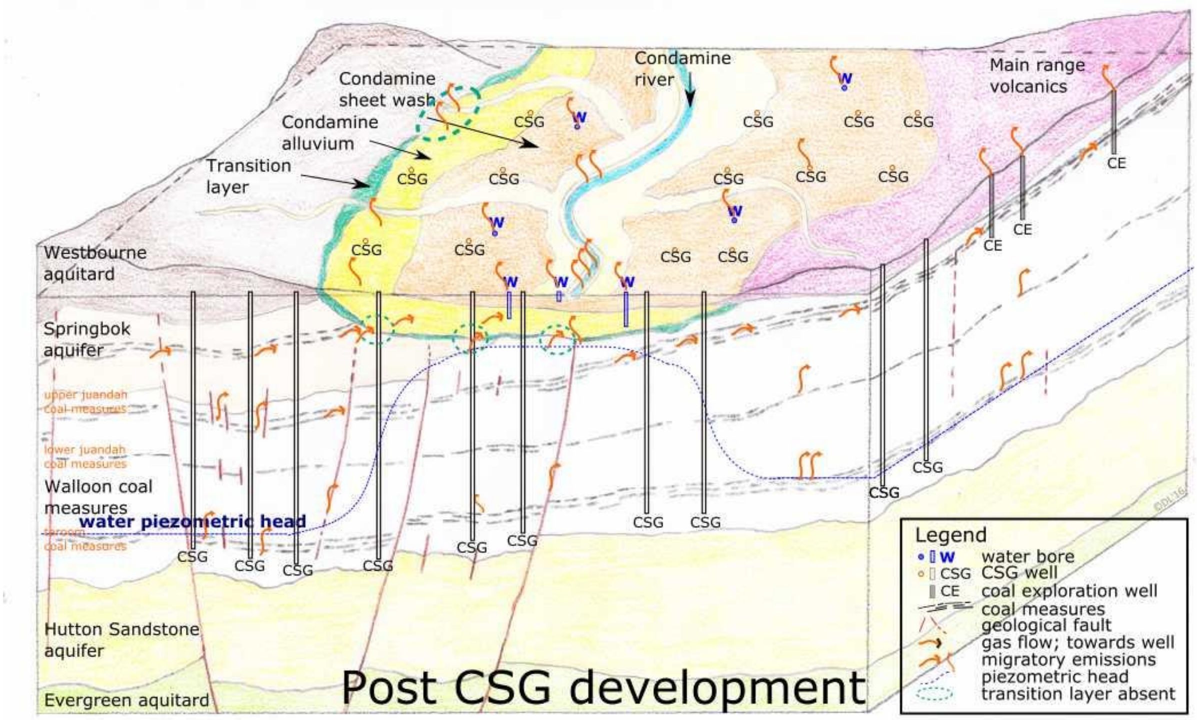


Figure 2: Schematic geological cross-section depicting the impact of the CSG development stages in a multi-user basin. Methane pathways and methane emissions are shown in orange. Brown arrows show gas flow to wells, an orange arrow show potential migratory emissions. Faults are shown in red. The piezometric head (potentiometric surface) of the Walloon coals is shown in blue. Dashed green circles show where the transition layer is absent.
CE: Coal exploration wells. W: Water wells. CSG: CSG dewatering and gas production wells.

3. Possible migratory pathways for methane in the Bowen and Surat Basins

In this section we review information pertinent to our understanding of natural and induced migratory emissions in Australia's two main CSG basins, the Bowen and Surat basins, with a particular focus on the Condamine region.

Australia has natural methane seeps, such as

- the "Burning Mountain" coal bed in New South Wales (Fleming (1972))
- the seeps near Alberton in the Gippsland Basin (O'Brien, Tingate et al. (2013))
- the offshore Terrigal gas seeps in the Sydney basin.

The Gasfields Commission Queensland has published a list of Queensland gas seeps[2].

[2] http://www.gasfieldscommissionqld.org.au/resources/gasfields/fact-sheets/historical-evidence-of-landscape-gas-seeps-in-qld.pdf

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Methane emissions from some seeps around the Condamine River are reported to have recently intensified[3], but are not regularly monitored. We are unaware of any reports of significant methane seeps in the Condamine river prior to the commencement and seeps prior to CSG development, except anecdotal evidence (DNRM Queensland Government 2012). Gray (1967) describes a gas blowout in a water bore some 10km south east of Brigalow (30km south east of Chinchilla) that lasted 40hours. It occurred while drilling through the formations of the Injune Creek Group (that include the Walloon coals). This indicates free gas within the Injune Creek Group. To closest reported 'microseeps' to the Condamine river are anomalously high soil methane concentrations in soil samples at 2m depth, related to a soil gas surveys 5km south of the Condamine river between Glenmorgan and Surat Geochemical Exploration Services Inc. (1991). They are referred to as microseeps but are not comparable to the Condamine river seeps in their current state. A description of the Condamine seeps can be found in Section 5, including references and recommendations from reviews by the Queensland government, Norwest (commissioned by Origin), and the Chief Scientist to the Queensland Government.

The next sections discuss the possible migratory emissions pathways in detail.

3.1. Migratory emissions enabled by the geological stratigraphy

This section describes the stratigraphy (the sequence of rock formations) of the main Queensland CSG-producing areas and how this stratigraphy may allow gas to migrate to the surface.

At present, the Queensland coal seam gas industry has two main targets:

- the Bandanna formation in the Bowen Basin
- the Walloon coal measures in the Surat Basin.

[3] http://www.abc.net.au/news/2016-02-14/condamine-river-mysterious-bubbling-intensifying-landholders-say/7139676

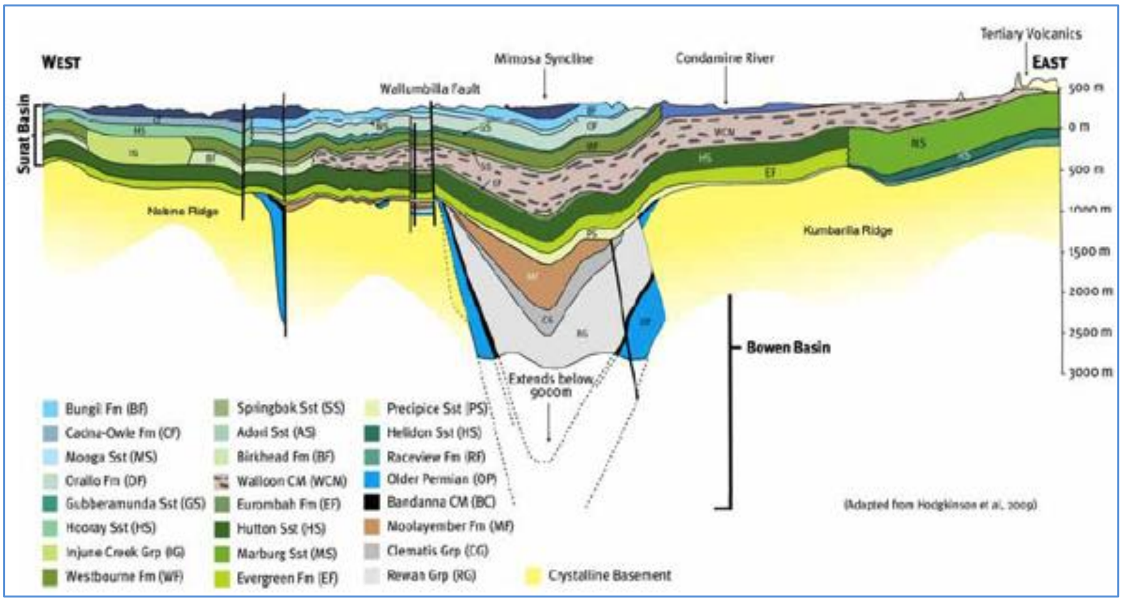

Figure 3: Schematic geological cross-section depicting the Surat Basin overlying the Bowen Basin. (Queensland Water Commission (2012) from Hodgkinson, Preda et al. (2009).

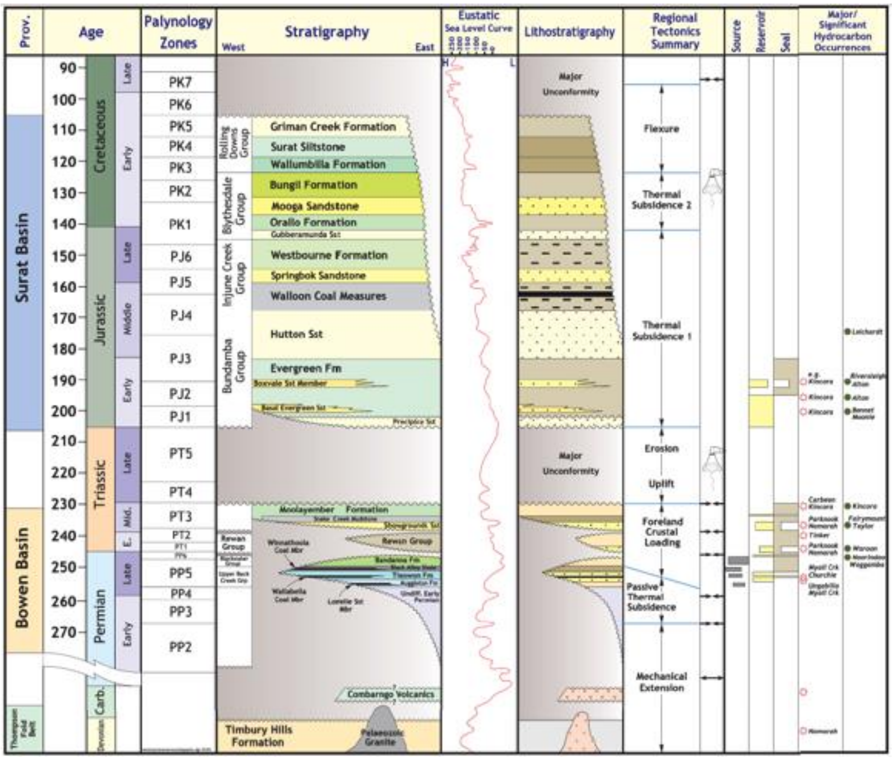

Figure 4: Stratigraphy of the Surat and Bowen Basins. (Norwest (2014)

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Figure 3 shows a schematic geological cross-section of the Surat Basin and the underlying Bowen Basin. Figure 4 shows the stratigraphical sections of the Surat and Bowen Basins, showing the sequence of formations deposited on top of each other.

The Bandanna formation is overlain and underlain by thick formations (called 'aquitards') that are not likely to allow flow of gas and/or water. The permeability of these aquitards is very low and they are a proven seal to conventional oil and gas reservoirs in the Bowen Basin. They are likely to act as a gas-migration inhibitor where they are continuous. Faults are most likely present (Section 3.3) and could act as preferential conduits for flow; however, given the proven seal characteristics from existing petroleum exploration studies, migration through this unit is considered to be less likely.

The Walloon coal measures are overlain by the Springbok sandstone and the Westbourne formation (Green, Carmichael et al. (1997)). The latter is a sequence of siltstone and mudstones that is between 100 and 200 metres thick (Exon (1976)).

In the area around the Condamine River and its tributaries, this sequence is overlain by the Condamine Alluvium (Exon (1976), Queensland Water Commission (2012), DNRM Queensland Government (2016)). The Condamine Alluvium is an unconfined aquifer that is actively recharged by rainfall. Its deposits incise into the Walloon coal measures, cutting through the Springbok Aquifer.

Some studies introduce a base layer in the Condamine Alluvium, called the ‘transition zone’, which consists of alluvial clays and weathered coal measures (Figure 5). This layer is present in some areas but absent in others (Dafny and Silburn (2014)). This heterogeneity makes is difficult to develop a conceptual model based on homogeneous hydrological properties, which has implications for the ability to reduce hydrological uncertainties (Dafny and Silburn (2014)).

The Queensland Water Commission (2012) states that, in general, the thickness of the transition zone is around 30 metres, but there are areas where alluvial sands (i.e. very porous material) sit on top of the coal measures. This report also shows that in the area around Dalby, and further downstream of the main Condamine River towards Chinchilla this layer is less than five metres thick.

This report also includes a map of the Upper and Lower Walloon Coal measures aquitard, defined as mudstone-siltstone layers that separate the Walloon coal measures from the underlying Hutton Sandstone and the overlying Springbok Sandstone, respectively. (The Upper Walloon Coal measures aquitard is a different formation than the so called transition zone defined at the bottom of the Condamine Alluvium.) The maps show that in the area south and west of Miles, the Upper Walloon coal measures aquitard have a thickness of less than five metres (Figure 6 and

Figure 7). The report indicates there is a high chance of the Walloon coals being in direct contact with the Condamine Alluvium and that “a higher degree of interconnectivity is expected in these areas”. Klohn Crippen Berger (2011) reports similar results to the Queensland Water Commission in their conceptualisation study for the Healthy HeadWaters program. In the central area of the Surat Basin, formation-pressure data suggest that hydraulic communication between the Hutton Sandstone (below the Walloon coals) and deeper Precipice Sandstone via the Evergreen aquitard is also possible (Hodgkinson, Hortle et al. (2010)). The Evergreen formation is a seal for conventional oil elsewhere.

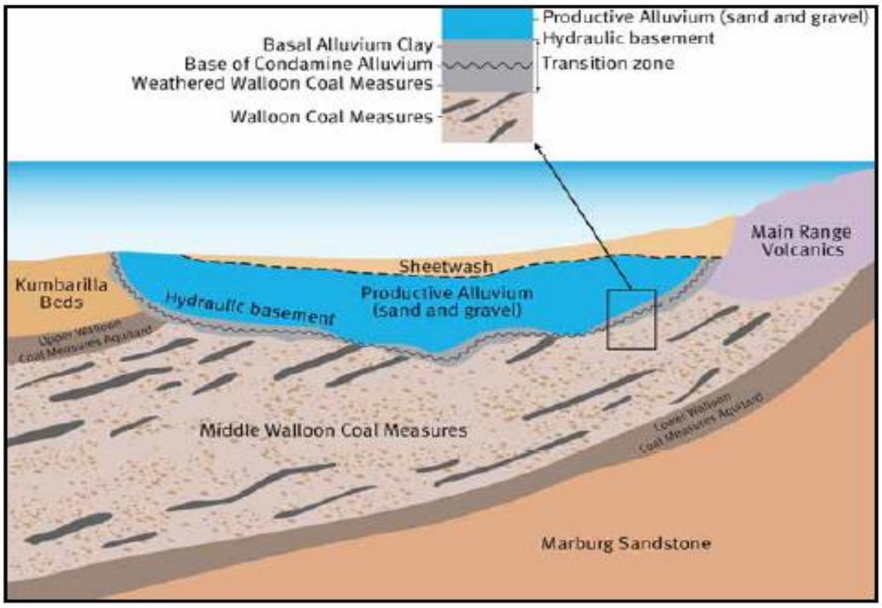

Figure 5: Schematic showing the transitional layer in-between the eroded Walloon coal measures and the Condamine Alluvium (Queensland Water Commission (2012))

The Queensland Water Commission report also states that there is very limited data available that describes the permeability of the Condamine Alluvium transition layer, or the Walloon coal upper aquitard. Given these layers are key flow-inhibition layers, more data needs to be collected to establish their effectiveness as aquitards, in particular in areas where they are inferred to be very thin. In a significant update of the Water Commission report (DNRM Queensland Government (2016), the Office for Groundwater Impact Assessment, states that there is at least a 30m vertical separation between the base of the Condamine Alluvium and targeted coal seams (Office of Groundwater Impact Assessment (2016)). However, it also mentions coals present within 10m below the transition zone in observation bores.

Taking into account the fact that the Walloon coal measures are dipping at a slight angle due to the presence of the Undulla Nose (an area where formations are dipping down and a known coal seam gas 'sweet spot' (Hamilton, Esterle et al. (2012)), it is possible that the coals are in direct contact with the overlying strata. The risk of gas flowing into the overlying porous formation during depressurisation as a consequence of the stratigraphy is therefore believed to be real. If flow is currently possible due to the natural geological heterogeneity, then it remains possible as more coal seam gas is produced from the coals (Section 3.2).

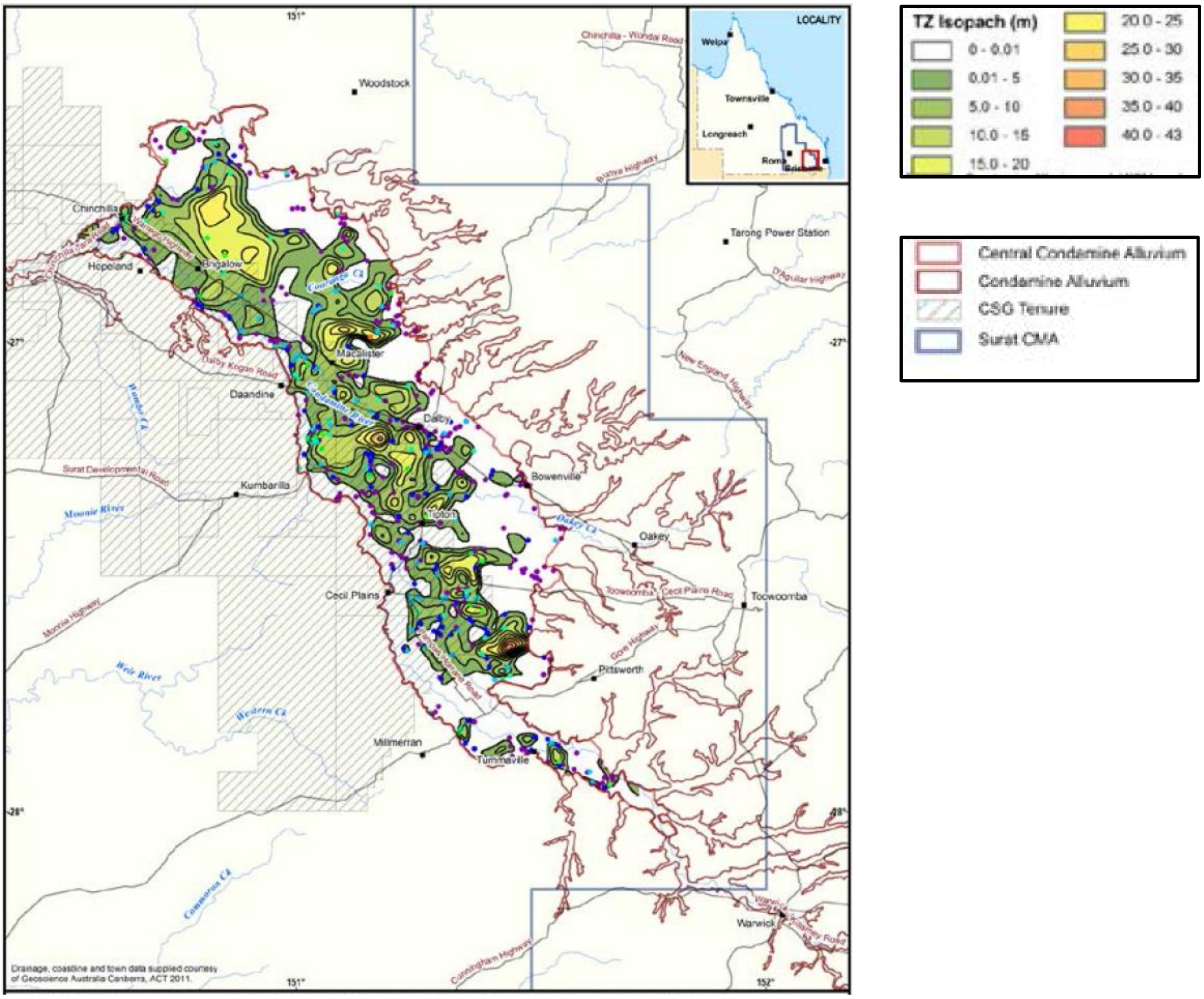

Figure 6: Inferred thickness of the transitional layer around the area of Chinchilla, Dalby and Toowoomba based on water bore data. Darkest green < 5 metres DNRM Queensland Government (2016).

Methane emissions are also possible through the Walloon coal seams themselves at locations where the formation is exposed at the surface. (These areas are known as coal ‘outcrops’; they are called ‘subcrops’ when the formation is situated at a depth beneath the surface). Day, Dell’Amico et al. (2013) suggested that a natural-seep field-survey should be carried out in an area where the Walloon coals outcrop/subcrop. However, the survey area chosen by Day, Ong et al. (2015) covers subcropping Walloon coals and does not overlap with the Walloon coal seam outcropping area. The Walloon coals outcrop north and northeast of the coal seam gas development area (Klohn Crippen Berger (2011)). In terms of monitoring, it may be useful to install monitoring stations in the coal outcropping area in order to investigate if coal seam depressurization increases methane emissions after heavy precipitation events. Although the outcrops have mostly already lost their gas because they are in contact with the atmosphere, gas can reach the atmosphere from deeper parts of the formations via these outcrops.

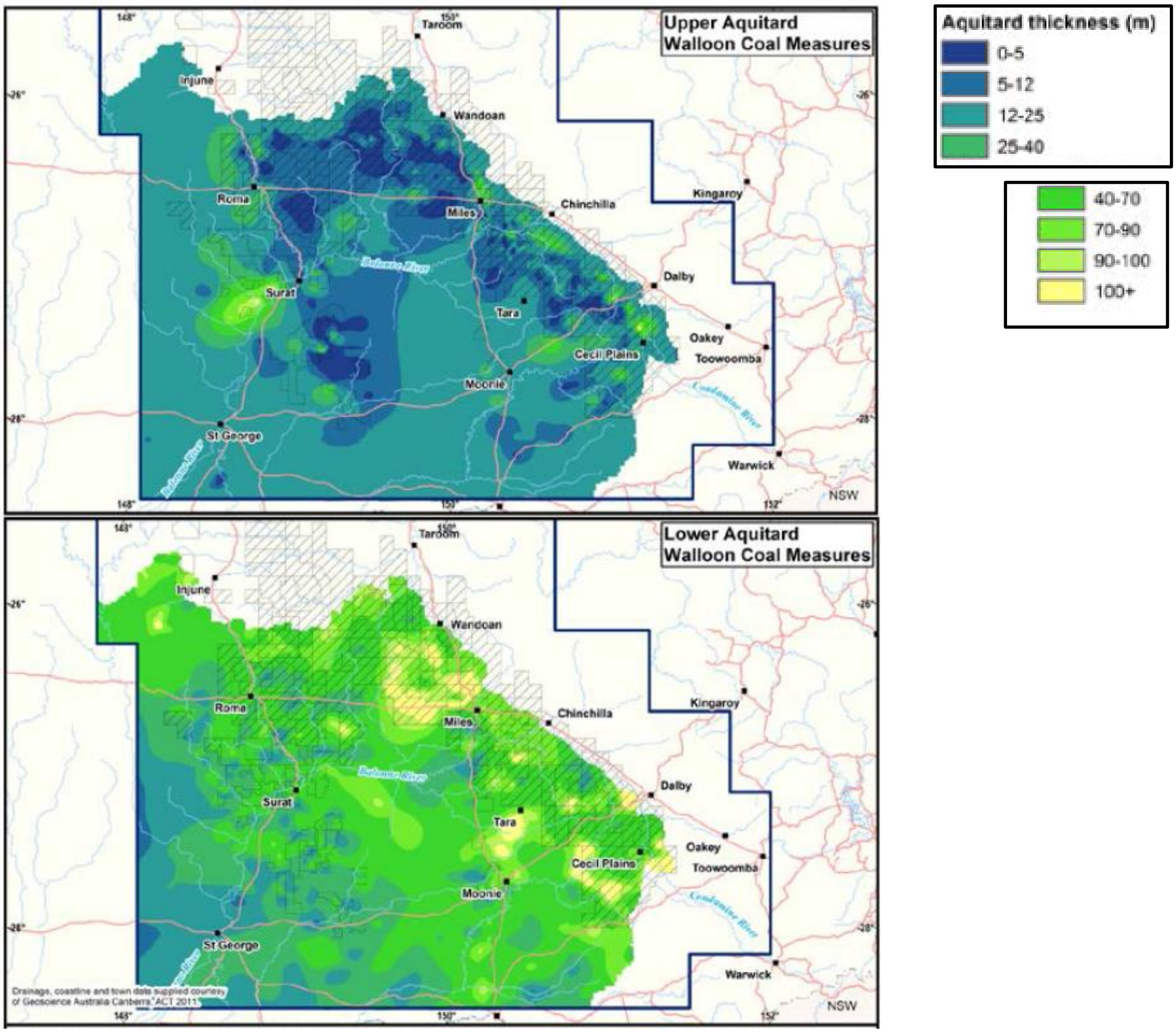

Figure 7: Thickness-map of the Upper and Lower Aquitard overlying and underlying the Walloon coal measures, respectively. The area to the south and west of Miles has very limited cover of the Upper Aquitard.
Dark blue < 5m, yellow < 100m DNRM Queensland Government (2016). to yellow light to dark green shading: thickness < 5 metres, 5-20 m, 21-40 m, > 40 m DNRM Queensland Government (2016).

3.2. Migratory emissions enabled by aquifer pressure gradient

This section describes how methane emissions can reach the surface using the pressure gradient that exists in the subsurface. An aquifer has a pressure gradient that is usually vertical (i.e. increasing with depth). When a geological formation is depressurised, the pressure gradient within the formation changes, as does the pressure gradient between formations. This has consequences for the overall pressure gradient and its direction, which in turn can impact gas movement. Solubility of the gas phase also plays a big role in the ability for gas to move: gas solubility increases linearly with increasing pressure. Depressurising decreases pressure, thereby reducing the solubility of the gas phase linearly. Eventually gas may reach 'ebullition pressure', the pressure at which gas is moving freely to zones of equal or lower pressure. In order to assess the methane migratory risk in relation to pressure gradient changes, an understanding is required of the extraction and recharge rates of the various aquifers and the connectivity between aquifers.

Groundwater in the Condamine Alluvium is intensively extracted for agriculture. In total, 64,250 megalitres (ML) is extracted each year (DNRM Queensland Government (2016)) for agricultural purposes. This volume exceeds annual recharge, estimated to be only 35,000 ML/yr (SKM (2002)). Since the 1960s, the water level in the Condamine Alluvium has declined by six metres in the area around the Condamine River, and up to 26 metres in areas further away from the river.

Hillier (2010) demonstrates that there is a hydraulic connection between the Condamine Alluvium and the Walloon coals. This is based on:

- the increase in dissolved salts in alluvial bores in the direction downstream of the Condamine River. This can only be explained by flow from a more saline aquifer (Walloon coals) to a less saline aquifer (Condamine Alluvium). The flow of water is from below as well as from the side.
- the different groundwater levels found in the Walloon coals and the Condamine Alluvium: because the water level in the Walloon coals is approximately 20 metres higher than the water level in the Condamine Alluvium (Queensland Water Commission (2012)), the hydrostatic head is higher, which should induce a flow from the Walloon coals to the Condamine Alluvium[4].

Iverach, Cendón et al. (2015) confirm local connectivity between the Condamine Alluvium and the Walloon coals using a combination of groundwater methane concentration, $\delta^{13}C$-isoptopic composition, groundwater tritium and dissolved organic carbon.

Many models have been built to estimate the volume of water that would be extracted from the Walloon coals over the lifetime of the coal seam gas developments (Table 1). These models all show that three to six times more water will be extracted from the Walloon coals than from the Condamine Alluvium.

As water is extracted from the Walloon coals, water will flow from the Condamine Alluvium to the Walloon coals. The impact on the actual water level is estimated to be small due to the very high storage-coefficient characteristic of the Alluvium, being a very good aquifer with high

[4] It is noted the Office of Groundwater Impact Assessment (2016) concludes that differences in groundwater levels persist suggesting flow is limited.

porosity. Nevertheless approximately 1,160 megalitres of water per year is projected to flow from the Alluvium to the coals for at least the next 100 years (DNRM Queensland Government (2016))[5].

Water extraction estimates for the Condamine Alluvium and Walloon coals					
	Extraction		Recharge		Information Source
	Average (ML/y)	Peak (ML/y)	Total (ML/y)	Walloon coals -> Condamine Alluvium (ML/yr)	
Condamine Alluvium	64,250				DNRM Queensland Government (2016)
	55,000		35,000		Queensland Water Commission (2012)
			36,000	Eastern flank: 1,604	SKM (2002), Hillier (2010)
				Western flank: 441	SKM (2002), Hillier (2010)
Walloon Coals	70,000				DNRM Queensland Government (2016)
	75,000				Industry data (2012)
	98,000				Preliminary, Queensland Department of Natural Resources and Mines (DNRM) based on Industry data (2012)
		125,000 (first 3 years of full CSG production)			Queensland Water Commission (2012)
	127,500 (2010 to 2050)	175,000 (ca.2020)			Scenario 2, based on 2012 gas production (Klohn Crippen Berger (2012))
	112,500 (2010 to 2050)	180,000 (ca.2030)			Scenario 1, based on Environmental Impact Statements and inferred expansion (Klohn Crippen Berger (2012))
		200,000 (ca. 2020 to 2025)			University of Southern Queensland and RPS Aquaterra (2011)
		213,000 (year unknown)			Centre for Water in the Minerals Industry (2008); based on an LNG production rate of 28 million tonnes per year

Table 1: Overview of modelled extraction and recharge rates for the Condamine Alluvium and Walloon coals aquifers.

[5] The Healthy HeadWaters program does not provide an estimate of how much water will flow from the Condamine Alluvium to the Walloon coals.

The water extracted by the coal seam gas industry is not part the Murray-Darling plan, but through this mechanism has an indirect impact on the Condamine Alluvium, which will be subject to the new Sustainable Diversion Limits that limit extraction in 2019 under the Murray-Darling Basin management plan.

A significant body of work by the Queensland Department of Natural Resources and Mines has been released into the public domain at a late stage of our review (Consultation draft of the Underground Water Impact Report by the DNRM Queensland Government (2016) and a hydrogeological investigation report by the Office of Groundwater Impact Assessment (2016)). These reports will greatly assist in the understanding of groundwater management and aquifer connectivity. Conclusions from this work suggests that in general the connectivity between the aquifers is low (in particular based on hydrochemical data and pumping tests), albeit data in the area where the transition zone is absent remains very limited. The same report however forecasts a 1,160 ML/y flow from the Condamine Alluvium to the Walloon coals.

We hypothesise that migratory methane emissions could significantly increase with continued depressurisation of the coals seams. Water extraction from the Condamine Alluvium used for agricultural purposes will reduce the hydrostatic pressure, making it easier for gas to flow upward. Dewatering and depressurisation of the Walloon coals, thereby desorbing gas, together with the continued water extraction from the Condamine Alluvium, would enhance gas flow from the Walloon coals through the transition zone into the alluvium. This could significantly increase gas releases from weak or porous zones such as the Condamine River.

Over the long term, it is assumed that the Condamine Alluvium will lose water volume to the Walloon coals. In other words, if the Walloon coals are extensively depressurised, it would reverse the current pressure gradient, and allow water flow from the Condamine Alluvium to the Walloon coals. This could make a pressure assisted migratory route harder (gas may still rise through the stratigraphy). However, if the reduction in hydrostatic pressure in the Condamine Alluvium due to water extraction is greater than the hydrostatic pressure reduction in the Walloon coals due to depressurisation, gas will continue to migrate, and exacerbate migratory methane emissions.

Given the heterogeneous geology and the dynamics of aquifer depressurisation, the lack of an integrated high resolution geological hydrological model makes an assessment of the risks of migratory emissions very difficult.

3.3. Migratory emissions enabled by faults and natural fractures

This section describes how subsurface faults and natural fractures can be pathways that assist gas to migrate from coal seams to the surface.

Coals exhibit natural fractures in the form of cleats (face and butt cleats). Cleats can form through compaction during the burial process and coalification, or they can form as a consequence of strain applied to the coals by tectonic events (on a much longer timescale). Dawson and Esterle (2010) define four types of cleats. Cleat spacing is shown to be inversely proportional to cleat length. In other words: fractures within coals can be very close together but their length will be very limited. Fractures that are longer, and may penetrate the entire seam will be more sparsely spaced. Laubach, Marrett et al. (1998) propose a relationship between the width of the opening of the cleats (the aperture), the number of cleats, and the maximum permeability, based on hundreds of measurements in the San Juan Basin (Moore (2012)). Coals can therefor exhibit varying permeability: Coals seams in the area known as the Undulla nose have higher permeability than elsewhere (WorleyParsons (2010). This was also concluded by the Healthy HeadWaters coal seam gas feasibility study (Klohn Crippen Berger (2011)). In general the industry finds coal seams are less permeable than anticipated (DNRM Queensland Government (2016))

Coal seams are not continuous. Besides coals seams ending because no coals were deposited, faults can offset coals seams. Horizontal drilling experience has seen wells 'losing' the coal seam when a well was drilled through an unexpected fault (e.g. Fairview-117H, Tipperary Oil and Gas and Santos (2005)).

APLNG (2010) and WorleyParsons (2010) state that there is evidence that coal permeability declines near regional faults such as the Leichhardt and Moonie faults. This may reduce the ability of gas to use these faults as migration pathways.

Faults have been interpreted from seismic data (Norwest (2014)), a standard procedure in the oil and gas industry. It is unknown how well the faults are resolved on seismic close to the surface (imaging faults close to the surface is difficult). Likewise, it is unknown how many shallow faults that gas field operators have identified from seismic information. It is also unknown how much methane is being naturally emitted from faults. Lafleur and Fest (in preparation, 2016) examine possible gas flux from faults south of the Condamine River, but it is not known if emissions may be exacerbated over the lifetime of coal seam gas field production.

Bearing in mind the geological heterogeneity described above (Section 3.1), the changing hydrological properties and the potential faults (e.g. the fault relevant to the Condamine seep according to CSIRO[6]), conduits are likely to be very localised features where geological and hydrological properties permit the easiest path for gas to flow to the surface.

3.4. Migratory emissions enabled by man-made hydraulic fractures

Hydraulic fracturing (i.e. fracking) involves high-pressure fluid injection with the primary objective to open or increase permeability of a subsurface reservoir. Hydraulic fracturing can be used during coal seam gas production as a way to increase the permeability of the coal seams, but it is not known in how many wells the method has been applied. It certainly is not necessary in every well.
The orientation of the fractures depends on the stress regime that exists in the basin. To initiate

[6] http://www.abc.net.au/news/2016-02-14/condamine-river-mysterious-bubbling-intensifying-landholders-say/7139676

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(or enhance) a fracture, the fluid pressure needs to exceed the minimal stress component (Hubbert and Willis (1972)). The fractures will then propagate perpendicular to the direction of the minimal stress.

In-situ stress data from the Bowen Basin suggests that the vertical stress component in the upper kilometre is in most cases the minimal principal stress direction (Hillis, Enever et al. (1999)). For hydraulic fracturing, this means that fractures are very likely to propagate in a horizontal direction. Brooke-Barnett, Flottmann et al. (2015) show that the Surat Basin is under a similar stress regime, but much more variable. Flottman, Brooke-Barnett et al. (2013) show that hydraulic fracturing applied in the top 500 metres will induce horizontal fractures, whereas deeper fracturing will most likely result in more vertical fractures.

Vertical-induced fractures introduce possible gas migration pathways beyond the coal measures into overlaying and underlying formations. In areas where vertical fractures are planned, their lateral extent needs to be well understood in order to limit the creation of possible pathways.

The publication of hydraulic fracture lengths and the estimated distance of the fracture tip to adjacent formations in a centralised database, would increase understanding of the impact of hydraulic fracturing. This would be particularly useful where vertical fractures are anticipated.

3.5. Methane emissions assisted by wells and bores

This section describes how wells and bores may assist both non-migratory and migratory methane emissions.

Well integrity depends on the ability of the well casing and the cement between casings to withstand degeneration. There are numerous studies that have raised concerns about well integrity, poorly decommissioned wells, poor enforcement of the well regulatory system or a regulatory system playing catch-up to an expanding industry (e.g. Dusseault, Gray et al. (2000), Miyazaki (2009), Bair, Freeman et al. (2010), Wojtanowicz and Kinik (2011), Bishop (2013), Ingraffea, Wells et al. (2014), Boothroyd, Almond et al. (2016)).

Boothroyd, Almond et al. (2016) conclude that 30% of the abandoned, decommissioned onshore oil and gas wells in the United Kingdom are leaking gas, with the onset of leaking occurring within as little as ten years after abandonment. These wells are conventional gas production wells, and emissions are not significant. Poor well decommissioning, however, can result in large emissions.

Watson and Bachu (2007) describe instances where a rapidly-expanding gas-field expansion resulted in corner-cutting to reduce drilling time and maximise project progress.

Ingraffea, Wells et al. (2014) point out that although wells that had been more recently drilled show less cement or casing impairment, this may be because of time lag: recently drilled wells simply have seen less analysis and less time to deteriorate and therefore have an incomplete record compared to older wells. The researchers analysed over 32,000 wells in the U.S state of Pennsylvania and found that

1.9% of these wells showed integrity loss. Unconventional wells (drilled predominantly in the Marcellus shale) show up to a six-times higher degree of integrity loss than conventional wells (9.8% versus 1.5%). This does not seem to relate to immaturity of the industry because wells before 2009 show a degree of integrity-loss similar to wells drilled after 2009.

Darrah, Vengosh et al. (2014) show that noble gas isotopes can be used to identify contamination of drinking water due to cement failure. In their study, poor cement jobs and casing failures are linked to contaminated drinking water wells overlying the Marcellus shales and the Barnett shales.

Using Notice of Violation records, Vidic, Brantley et al. (2013) find integrity issues in 3.4% of unconventional wells in Pennsylvania drilled into the Marcellus shale over the period 2008 to 2013.

Deteriorating cement and zonal isolation is also identified as a problem in the San Juan Basin (U.S.), where coal seam gas is produced. Chafin (1994) note that uncemented annuli over the coal-bearing formation created the migration path.

In their report on the Condamine River seeps, Norwest (2014) notes that a similar pathway is possible in poorly-completed or poorly-maintained wells, emphasising the potential for enhancing connectivity between coal seams and shallower aquifers via the well annulus. A simple method is known as 'Bradenhead pressure monitoring', involving monitoring the pressure between sections of well casing can be used to indicate well anomalies.

Norwest (2014) and Apte, McCabe et al. (2014) note that coal-exploration wells in Queensland are a potential source of methane emissions, especially as many have not been plugged. With ongoing depressurisation of the coal seams, old unplugged coal-exploration bores are likely to emit more methane in future.

Similarly, water bores can be a source of methane emissions. Water bores are not designed to accommodate the effects of depressurising coal seams. Klohn Crippen Berger (2016) report free-gas in water bores that may originate from coal seams, even in cases where there is no appreciable decline in the water table. It is noted that methane in the water bores is a safety hazard, compromises water quality, can damage pumps, and impacts the yield.

In a welcome development, the gas-producing company Origin is implementing a water-bore monitoring program, acknowledging there is a lack of subsurface data[7]. This program aims to provide a baseline assessment and will monitor the effects of precipitation and drought, groundwater recharge, and changes in reservoir pressure. In addition DNRM Queensland Government (2016) reports that by the end of 2016 most monitoring points will be installed for a water monitoring network. Current data suggests that the water pressure in the coals is declining, but the decline is in line with expectation of the CSG industry.

[7] http://www.aplng.com.au/pdf/factsheets/Baseline_Assessments.pdf

4. How analogous is the U.S. San Juan Basin to Australian CSG fields?

In order to understand possible methane emissions resulting from Australian coal seam gas production, it is useful to look elsewhere for analogues. The San Juan Basin, located in the U.S. state of New Mexico and straddling the border with Colorado, is a prime candidate. The coals in the San Juan Basin are fairly shallow at depths of 300 to 700 metres, and the basin has been producing for more than twenty years (since 1989). This is also the area that has the highest methane emissions in the United States, recorded by satellite measurements (see Figure 11).

Since 1989, New Mexico has produced approximately 11,000 petajoules of coal seam gas, mainly from the San Juan Basin (EIA (2015)). By 2009, nearly 8,000 coal seam gas wells had been drilled in the basin, and nearly 40,000 oil and gas wells in total. (Figure 8, Figure 9 and Figure 10)

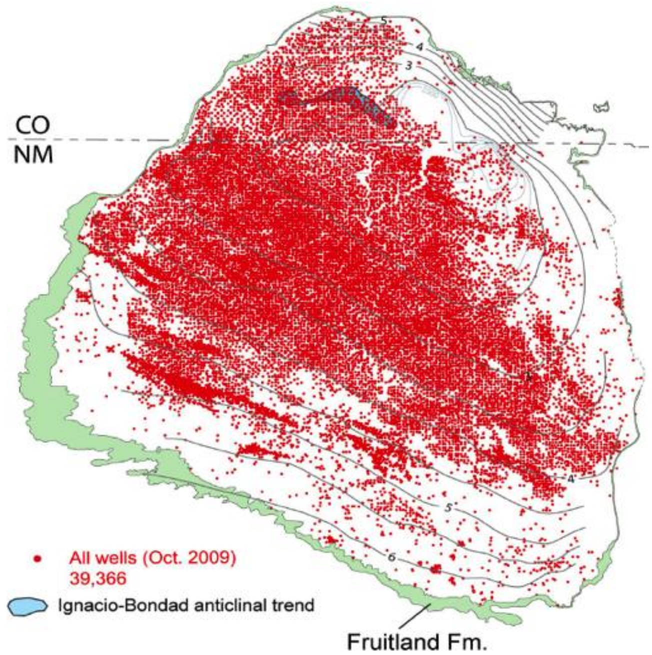

Figure 8: All oil and gas wells drilled in the San Juan Basin by the year 2009. Area shown covers an area approximately 100 kilometres by 100 kilometres. (Fassett (2013))

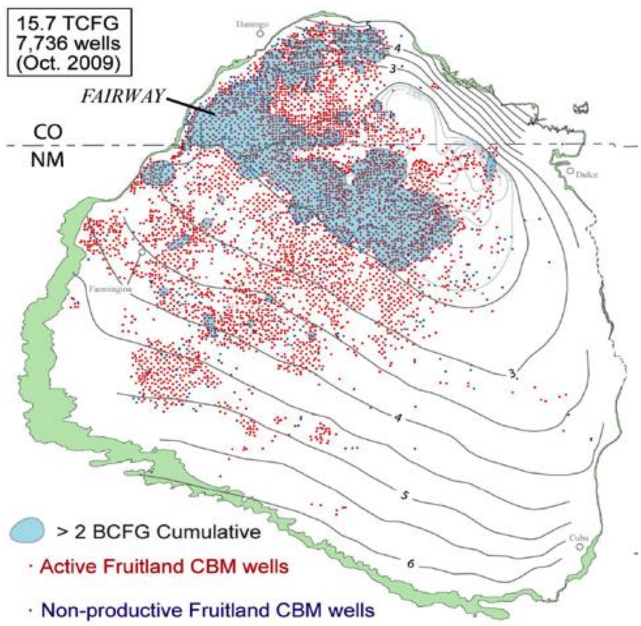

Figure 9: CSG wells drilled in the San Juan Basin by the year 2009. Area shown covers an area approximately 100 kilometres by 100 kilometres. (Fassett (2013))

The geology of the San Juan Basin has been extensively studied (Wray and Colorado Geological Survey (2000) and references therein). There are historic accounts of various natural gas seeps in the San Juan Basin. In the 1990s there appeared to be evidence suggesting that coal seam dewatering had led to an increase in natural surface seeps (Wray and Colorado Geological Survey (2000). Their research did not reveal any new gas seeps that were not already recognised, nor revealed it whether seeps can be initiated or prevented by depressurisation for coal seam gas production.

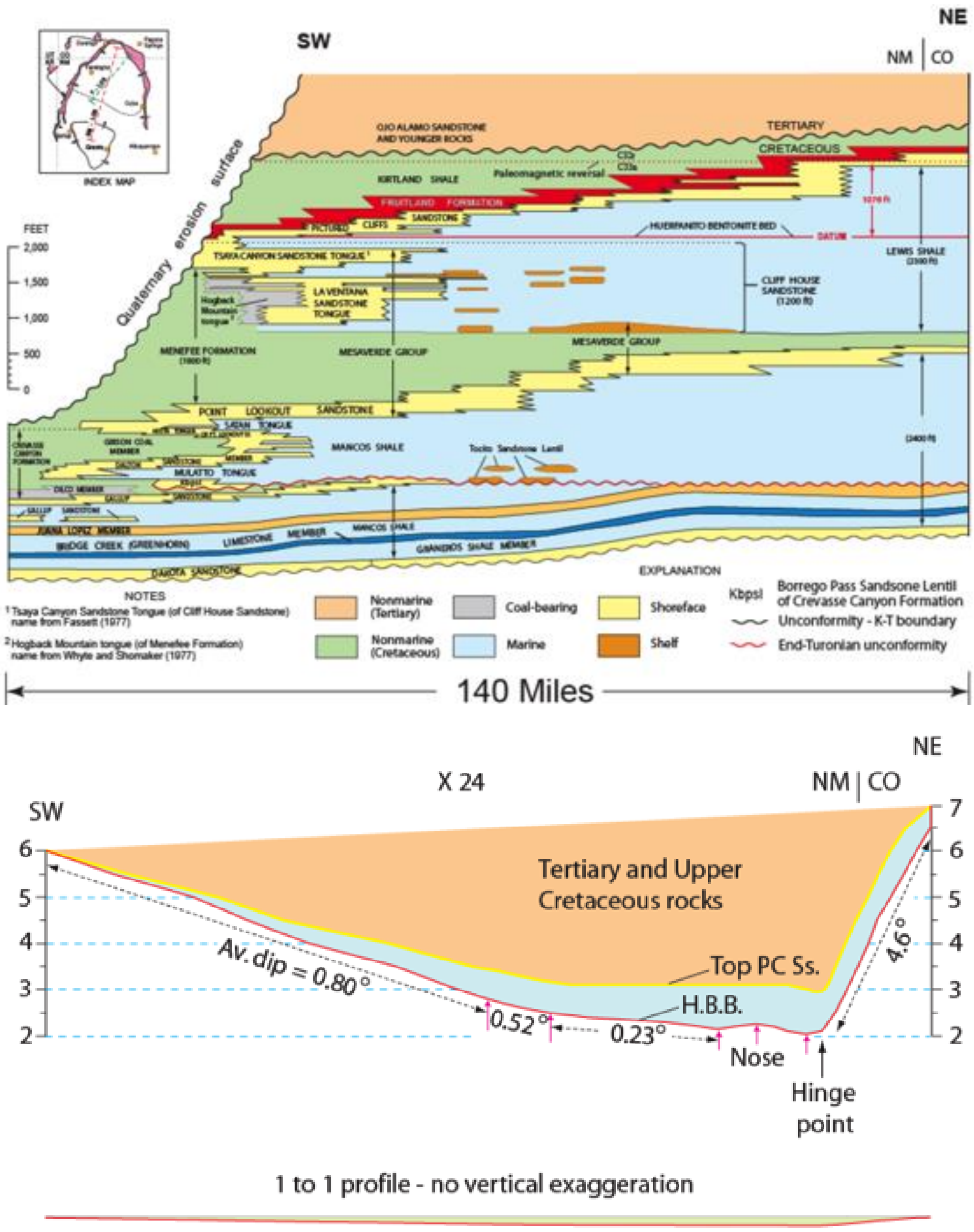

Figure 10: ***Top*****: SW-NE cross-section of the stratigraphy of the San Juan Basin. In red the Fruitland formation bearing the coal seams. The Fruitland formation lies at depths between ~300 to 700 metres.** ***Bottom*****: SW-NE cross-section of the San Juan basin, extending 12,000 km2. The Fruitland formation is 'draped' on top of the layer labelled "Top PC Ss." (Top Picture-Cliffs Sandstone), dipping at a very small angle in the Southern section (<1°) and slightly higher angle in the North (4-5°). Vertical axis is height above sea level of the base of the basin ('000 feet). From Fassett (2013).**

Oldaker (2015) presented a correlation between higher than normal precipitation and major methane emission events. Downhole video evidence, well packer testing and water quality and age testing (Snyder, Walter et al. (2003)) suggested that seeps are not due to increased coal seam gas production (Oldaker (2015)). However, as early as 1991, it was recognised that improperly cemented wells can act as conduits when coal seams are depressurised (Chafin (1994), Norwest (2014)). Pressure monitoring throughout the lifetime of a well (known as Bradenhead pressure monitoring) can be used to determine if gas or water flow can occur between well casing points and if well cementing has been inadequately performed.

Kort, Frankenberg et al. (2014) showed that the emissions from the Four Corners area of the U.S. (i.e., the San Juan Basin) can be observed from space (Figure 11). The researchers concluded that these emissions are most likely a result of fossil fuel production in the area, but stopped short of pointing to one specific industry. The researchers ruled out hydraulic fracturing as the main cause of the emissions given that technology is yet to be widely applied in that basin.

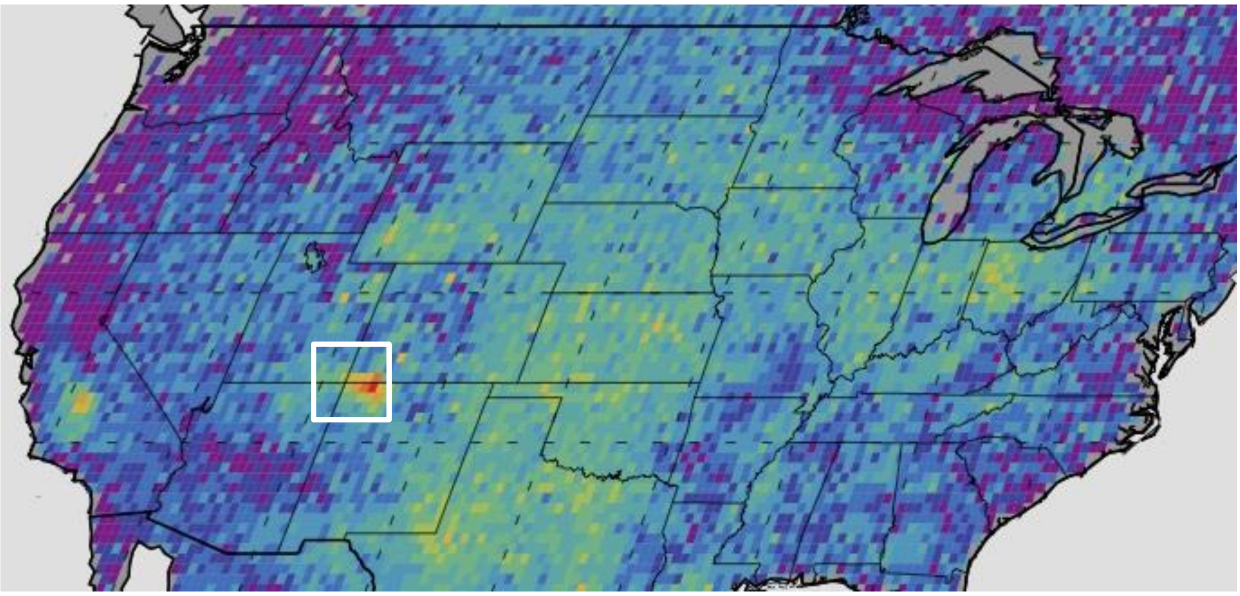

Figure 11: Column-averaged methane mole fractions from spectra collected by the SCIAMACHY satellite instrument, from 2003 to 2009 gridded at 1/3° resolution (Kort, Frankenberg et al. (2014)). The white rectangle depicts the Four Corner region.

As early as 1995, the Colorado Oil and Gas Conservation Commission concluded that the dewatering of the coal seams was the most likely explanation for the rise in emissions, leading to exacerbation of the emissions of the 'natural seeps'. Similar to the Bowen and Surat Basins of Queensland, the San Juan Basin had no baseline study. Since then however, the Colorado Oil and Gas Conservation Commission has commissioned an array of monitoring actions[8].

The centralised database for reporting and addressing complaints and spills of the Colorado Oil and Gas Conservation Commission is a good way of registering, monitoring and solving complaints

[8] See http://cogcc.state.co.us/library.html#/areareports

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and issues. It also has a wealth of data and reports on monitoring, measurements and studies carried out in the state Colorado.

The geology of the San Juan Basin is different to the eastern Australia basins. The coals that are targeted in the San Juan Basin are situated in the Fruitland formation that lies in a synclinal structure (Figure 10). They are overlain by thick non-marine Kirtland Shale and underlain by the Pictured Cliffs sandstone (itself a productive gas reservoir) and the Lewis shale.

The San Juan Basin is also home to various conventional gas reservoirs. This makes differentiation of possible causes of methane emissions difficult. Nevertheless, Australia could learn much from recently-released data (such as Kort, Frankenberg et al. (2014)), previously-recorded incidents and governance.

5. The Condamine River gas seeps

This section describes gas seeps occurring in Queensland's Condamine River near a CSG-producing area.

In May 2012, a landholder contacted the Queensland Government's LNG Enforcement Unit regarding gas seeps in the Condamine River, west of Chinchilla (Figure 12).

An initial investigation by the DNRM Queensland Government (2012) focused on public safety and environmental damage. The relevant permit-holder and gas-producing company, Origin, subsequently commissioned Norwest Energy to investigate (Norwest (2014)). Isotope analysis conclusively showed the source of the gas to be the Walloon coal and/or the Springbok sandstone, and not, for example related to decaying vegetation in the river bed.

Norwest stated that gas can be released from the underlying coals and reach the surface aided by either man-made pathways or natural pathways.

Man-made pathways can be created through water extraction from water bores or converted coal exploration bores, through coal seam dewatering, or through uncased well sections or deteriorating zonal isolation well sections between different formations.

Norwest (2014) states that apart from natural extreme precipitation events and associated falling and rising water tables, natural methane seeps can also be driven by the erosion of aquitards, past (Jurassic unconformity, where Walloon coal measures are overlain by the Cenozoic Condamine Alluvium) and present (bed erosion and shifting sediments) (Norwest (2014)).

Faulting can also assist gas migration. Faults may extend into overlying formations, and are interpreted as such from seismic (Figure 13, Figure 14, Norwest (2014)). It is not known which faults are conduits (allowing migration) or barriers (preventing migration). Professor Barrett of the Gas Industry Social and

Environmental Research Alliance (GISERA) states that the methane from the Condamine seeps comes to the surface along a small fault that intersects with the river[9].

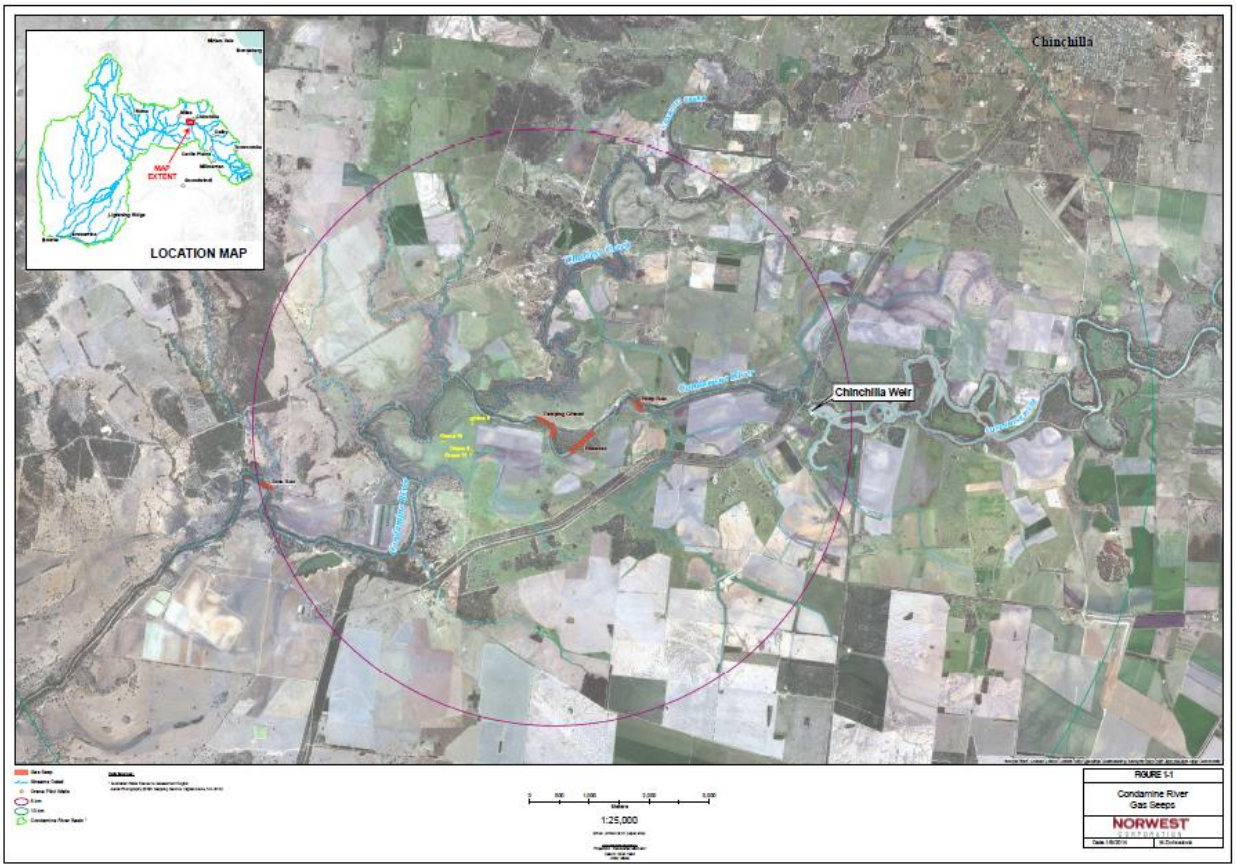

Figure 12: Location of the methane seeps west of Chinchilla (Norwest (2014)).

In 2014, Origin stated that it would conduct a seismic survey and drill eight monitoring bores in order to monitor pressure and groundwater level in real time APLNG (2014).

9 http://www.abc.net.au/news/2016-02-14/condamine-river-mysterious-bubbling-intensifying-landholders-say/7139676

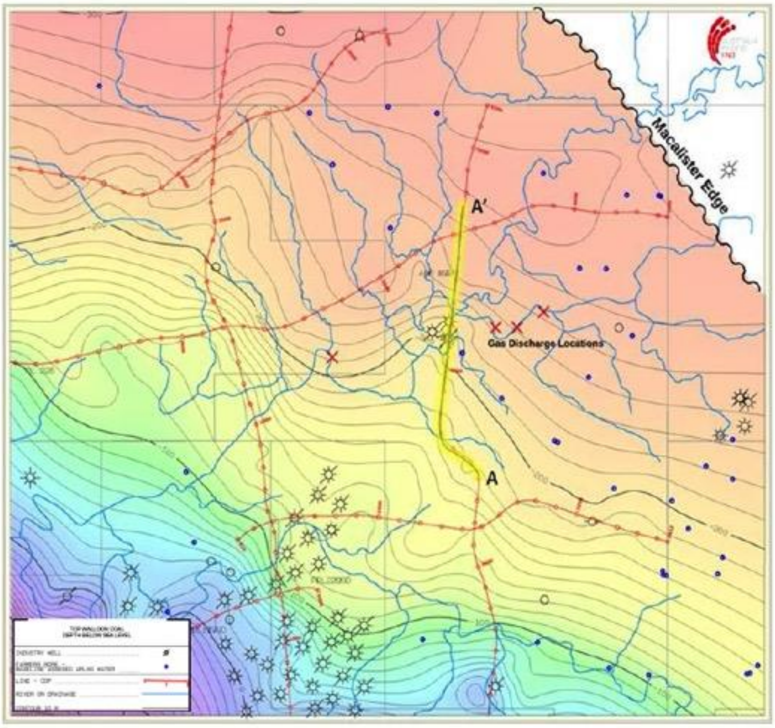

Figure 13: Depth map of top of Walloon coals around Chinchilla, Queensland (Norwest, 2014)

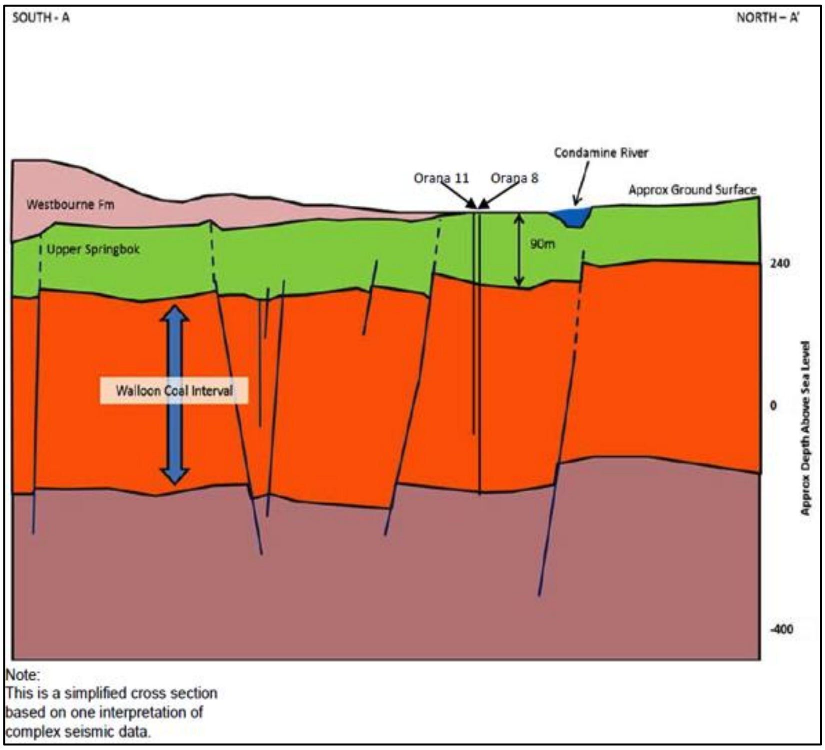

Figure 14: Simplified cross-section along AA' line in Figure 13.
Some faults are interpreted to extend into shallower formations (Norwest (2014).

In an independent review of the Condamine seeps coordinated by the Chief Scientist to the Queensland Government, Apte, McCabe et al. (2014) concluded that the seeps were still poorly understood. Apte, McCabe et al. (2014) recommended that the integration of a hydrological model with a high-resolution geological model would allow the impacts of stratigraphic heterogeneities on gas and water flow to be examined. Apte, McCabe et al. (2014) echoed Norwest's recommendation that a centralised geo-referenced database for gas data and water quality measurements would assist in understanding the impacts of natural variation and human activities. Apte, McCabe et al. (2014) also emphasised the need for more monitoring of emissions, and measurement of methane fluxes, over an adequate length of time (several years). The technology to do so is available and the numerous studies done in the U.S. San Juan Basin are considered to be the scientific standard (Section 4).

6. Sedimentary basin management plans needed

In the Queensland CSG-producing areas, there seems to be no clear understanding of the potential impacts of current and future human activities on the various aquifers. It is not clear how well the risks of gas-migration pathways are understood and being communicated to stakeholders. From the reports referred to above, it is clear there are insufficient data on permeability, lateral continuity of formations, and methane fluxes. For the Condamine area and in the wider Surat Basin, there is no integrated geological-hydrological model that allows for the analysis of the risk of gas migration.

Sustainable and well-managed extraction of commodities such as water and fossil fuels from sedimentary basins requires a holistic sedimentary basin management plan (Rawling and Sandiford (2013)). Without understanding the workings of a sedimentary basin that may provide multiple services, it is impossible to foresee the consequences of human interventions.

Dafny and Silburn (2014) and Apte, McCabe et al. (2014) have pointed out that significant gaps remain in terms of subsurface understanding. Additional field data needs to be acquired to narrow down uncertainties around the spatial extend of the Condamine Alluvium and the transitional layer and the properties of the transitional layer. None of the hydrological models include all the hydrological processes that play a role (Dafny and Silburn (2014)).

In cases where there are competing demands on sedimentary basins such as provision of water and fossil fuels, there is a need for an integrated geological-hydrological model. This model would assess the implications of formation heterogeneity, irregular formation thickness, coal seam dewatering and depressurisation, and water extraction by all users. We acknowledge the computational challenges of such a complex model.

7. Conclusion

This report highlights the potential for migratory methane emissions to occur in Queensland's coal seam gas basins. Due to a lack of available data, the likelihood of migratory emissions occurring as a direct consequence of the gas extraction, at present or in the future, is difficult to assess. Current Australian methane-emissions estimation methods largely ignore this potential source of emissions.

The heterogeneity of the geology in the area where the Condamine Alluvium exists, increases the risk of migratory emissions occurring. The emissions could significantly increase with continues depressurisation of the coal seams while multiple users are extracting water from various aquifers.

Migration of methane along existing natural faults and fractures is possible and may increase with continued depressurization even when the leakage rates today may be minimal without disturbance.

Water bores and coal exploration bores are known sources to methane emissions and the presence of free methane can be the direct consequence of the depressurisation of the coal seams. The well integrity of dedicated gas wells and other existing bores that were not designed to prevent migratory emissions is an area of concern.

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