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This document was created in response to a Freedom of Information request made to CSIRO.

FOI Number: FOI2018/33

Date: 1 June 2018

Request: Correspondence between CSIRO and GISERA which relate to the bubbling or gas leakage of the Condamine River in Queensland from 1 May 2016 to 1 May 2017.

First and last versions of documents produced by GISERA outlining research conducted by or for GISERA into the causes of bubbling or gas leakage in the Condamine River in Queensland

Document(s): 1-35

For more information, please refer to CSIRO's FOI disclosure log at www.csiro.au/FOILog

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[redacted]

From: O'Sullivan, Michelle (Energy, Pullenvale)
Sent: Monday, 23 May 2016 2:09 PM
To: Barrett, Damian (Energy, Black Mountain); Guo, Hua (Energy, Pullenvale); Harris, David (Energy, Pullenvale); Hartley, Patrick (Energy, Clayton); White, Stephen (Energy, Newcastle)
Cc: Rodrigues, Karl (Energy, North Ryde)
Subject: Energy submissions for the EER report to ET - for your review due COB Friday 27th May

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[redacted]

s22 [redacted]

Key external relationships/business development

s22 [redacted]

- Over the past month Damian Barrett has conducted numerous media interviews regarding GISERA research into the Condamine River. These interviews stem from a TV interview on The Project (channel 10) and 'went viral' including CNN, BBC, Washington Post and The Guardian.

s22 [redacted]

Michelle O'Sullivan
Executive Manager – Business Unit Operations
Energy
CSIRO
s47F [redacted]
PO Box 883 Kenmore QLD 4069
www.csiro.au

Please note I do not work on a Wednesday.

Document 2

[redacted]

From: Barrett, Damian (Energy, Black Mountain)
Sent: Thursday, 10 November 2016 7:02 PM
To: Rees, Gavin (latrobe.edu.au) - Contact
Cc: Cham, Tsuey (CorpAffairs, Dutton Park)
Subject: Re: Condamine work

Hi Gavin

Firstly, apologies for delay in getting back to you. I know its been a while! My only excuse is the work load of the last couple of months. Currently, GISERA is in the process of bringing together a fact sheet on the Condamine River gas seeps using material from within and outside CSIRO. I've been in touch with Matt previously about what material we will include and he has been quite supportive in describing the work Origin have been doing. We've had a bit of a delay over the last few weeks in completing this task but it is a priority now.

I would like to include reference to the latest findings of your work in the fact sheet so that it is maximally up to date. We are citing all sources of information we use. Is it possible to get a copy of your report and then we can have a discussion about various points (or do both concurrently). Early next week would be advantageous if you are agreeable. I'll be re-checking with Matt that he is happy for any of the seeps results be made public before this material is released.

Happy to discuss further if you'd like more information.

Many thanks

Cheers...Damian

Dr Damian Barrett
Research Director - Onshore Gas (Energy Business Unit)
Director Gas Industry Social and Environmental Research Alliance
CSIRO
P: [redacted]
P:
E:

Adjunct Professor
Centre for Water in the Minerals Industry
Sustainable Minerals Institute
University of Queensland, Brisbane

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[redacted]

Document 3

[redacted]

From: Barrett, Damian (Energy, Black Mountain)
Sent: Wednesday, 16 November 2016 5:00 PM
To: Rees, Gavin (latrobe.edu.au) - Contact
Subject: Re: Condamine work

Thanks Gavin. Like all good research it raises more questions. Its a very comprehensive piece of work and I am very pleased how it has come along. I am confident there will be more work to come in this space

Cheers...Damian

From: Gavin Rees
Sent: Wednesday, 16 November 2016 2:31 PM
To: Barrett, Damian (Energy, Black Mountain)
Subject: RE: Condamine work
Probably cant put a time scale on it. They are relatively slow growing bugs, but we don't really know how long it would take to enrich given populations. My guess is that we would not be seeing something on the scale of day/weeks.
I am under the impression that dissolved methane is always enriched at the main seep sites, although its likely to vary over time. I don't know anything about growth response of the methanotrophs to methane concentration. This was our first look at the bactos, but hope to do some more in the future.
Gavin

From: Damian.Barrett[redacted]
Sent: Wednesday, 16 November 2016 12:34 PM
To: Gavin Rees
Subject: Re: Condamine work
HI Gavin
Thanks for sending the report through. A quick question: The presence of elevated methanotrophs in the vicinity of the seeps. Can we attribute any timescale to that? i.e. does this reflect a long-term adjustment of microbial population structure in response to methane being present over decades or is it a rapid adjustment by the population to the build up of methane concentration in the river water during periods of low flow?
Cheers...Damian

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Duplicate

[redacted]

Document 4

[redacted]

From: Barrett, Damian (Energy, Black Mountain)
Sent: Monday, 28 November 2016 4:53 PM
To: Raiber, Matthias (L&W, Dutton Park); Cham, Tsuey (CorpAffairs, Dutton Park)
Cc: Creagh, Ben (CorpAffairs, Dutton Park)
Subject: Re: Condamine river fact sheet

Hi Mathias

That paper has added a complication to the source of methane. I think its results are indicative of methane diffusion or deeper regions west of the seeps. However, at the Condamine bubbling, the coal is shallow and the fractures are present. So I have changed that par to read:

"CSIRO's isotopic analysis of methane gas collected from the main bubbling site in the Condamine River shows that the origin of the methane is from bacterial metabolism of coal. Other research suggests that methane in groundwater of the Condamine River alluvium may originate from the Walloon Coal Measures or adjacent geological formations in the Surat Basin. However, conflicting data also exists suggesting virtually no migration of methane from the Walloon Coal Measures into the alluvium, at least at sites west of where bubbling occurs in the Condamine River. What is apparent, is that the methane seeps do not originate from biological sources in the river sediments. "

I think this reflects the ambiguity of isotopic measurements west of the bubbling but still preserves what we know. Let me know if you have any objection going with that statement

The figure looks fine to me, but I'll see if Tsuey can place it across both columns.

Cheers..Damian

[redacted]

[redacted]

From: Barrett, Damian (Energy, Black Mountain)
Sent: Sunday, 27 November 2016 11:59 AM
To: Raiber, Matthias (L&W, Dutton Park); Cham, Tsuey (Comms, Dutton Park)
Cc: Creagh, Ben (Comms, Dutton Park)
Subject: Re: Condamine river fact sheet
Thanks Mathias.

All - Here is the final version of the fact sheet. I just have one point of clarification:

Mathias - I agree with your point about the narrowing and thining of the Condamine Alluvium. I've added this as text to the fact sheet. I also note your point about groundwater chemistry showing CSG-water in the alluvium long before development. I have added this sentence "Groundwater chemistry data in the Queensland Government database show that Walloon Coal Measure groundwater was found in the alluvium here long before CSG started". Do you have a reference for this statement or is it based on your analysis of the DNRM geochem database? If you have a reference, please supply. If not, I am happy to go with this sentence provided that it is what you see in your analysis of the DNRM data. Please confirm on Monday.

Tsuey - With this final version can you please add a reference to the GISERA methane seeps report (where noted) and change the Norwest Reference to the MDFRC reference (where noted). Mathias will provide the final cross section figure on Monday. Once this is done and the fact sheet formatted its ready to go as per steps laid out last Friday. I'll check with Matt K the release of the CSIRO work done for Origin.

Let me know if you'd like to discuss.

Cheers...Damian

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Document 5

[redacted] s22

From: Barrett, Damian (Energy, Black Mountain)
Sent: Monday, 5 December 2016 12:50 PM
To: Cham, Tsuey (CorpAffairs, Dutton Park)
Subject: Re: Condamine River seeps Fact Sheet v7

Hi Tsuey

Thanks for finalising the fact sheet and getting it into the light of day.

In relation to the comment "There is no public health or safety risk caused by the methane concentrations measured in the area of these or any other seeps in the Surat Basin CSIRO has measured"; this statement is carefully constructed to (1) refer to methane concentrations only, (2) refer to both the Condamine River seeps and other seeps measured by the CISRO/GISERA Methane Seeps project (which I have not cited), (3) refers to the Qld Dept of Health study (cited) and (4) refers to the Qld DNRM Condamine River Gas Seeps study (not cited) which stated: "...results indicate that there is no safety risk or evidence of environmental harm occurring in the immediate area from the Condamine River gas seeps." I only cited the one reference due to space restrictions but the statement is a synthesis of this other material. I am happy to see all these references cited if that makes the statement more strongly supported in the fact sheet.

In relation to the independent review of the Condamine River Gas Seeps Investigation: Thanks for sending that through. I haven't seen that before. On reading it there is general agreement between the Review and the fact sheet. There are some minor differences (e.g. the review states gas pathways include "...natural geologic pathways (such as faults and permeable layers), water wells and old coal exploration wells" there is no evidence at all of water wells and old coal exploration wells in the vicinity of the Condamine River bubbling). The review is also out of date on some of its recommendations as these are being addressed in the GISERA/CSIRO methane seeps project and the CSIRO/MDFRC work done on the Condamine River. I don't think we need to change anything in the Fact Sheet to cover off these minor differences.

Cheers...Damian

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[redacted]

[redacted] s22

From: Barrett, Damian (Energy, Black Mountain)
Sent: Wednesday, 1 March 2017 10:16 AM
To: Proctor, Nicola (CorpAffairs, Newcastle); Beringen, Helen (CorpAffairs, TownsvilleATSIP)
Subject: Condamine River Fact Sheet
Attachments: CSIRO Condamine River Factsheet 010317_Final.Edits.pdf

Hi Nicola and Helen

Attached is the final version of the Condamine River Fact Sheet which Tsuey was working on with me to be released. It contains a couple of very minor edits and then is ready to go on the website. I have been waiting for Origin Energy to put a report up on their website but, in my view, we are ready to go with this. Once the release is imminent we will just need to let our industry partners know that it is happening.

Many thanks

Cheers...Damian

Dr Damian Barrett
Research Director - Onshore Gas (Energy Business Unit)
Director - Gas Industry Social and Environmental Research Alliance (GISERA)
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Adjunct Professor
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Sustainable Minerals Institute
University of Queensland, Brisbane

Methane seeps in the Condamine River

This fact sheet presents the current state of scientific knowledge on methane seeps in the Condamine River including natural and human causes, and the human and environmental health and safety impacts of methane escaping from underground. This fact sheet has been developed by CSIRO researchers with expertise in the hydrogeology, geology, ecology and biogeochemistry and from multiple sources to summarise what we currently know about these methane seeps.

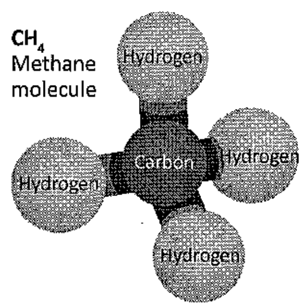
Key points

- Depressurisation of the Walloon Coal Measures during CSG production could generate horizontal migration of free methane gas. However, this flux of methane is likely to be small because of the shallow dip of the coal beds and the distance to gas production fields.
- Hydraulic fracturing is unlikely to be the cause of bubbling in the Condamine River because to date there has been no hydraulic fracturing by the CSG industry in these production fields.
- Variation in bubbling of the Condamine River may be caused by:
  - an increase in river water flow; moving sand and sediments that previously sat over the seeps and limited their seepage.
  - groundwater receding from the Condamine River alluvium since the 2011 floods has reduced pressure over the Walloon Coal Measures near Chinchilla, allowing trapped gas to expand and rise to the surface.
  - CSG industry activity in production fields 5 to 6 km away has reduced pressure in the coal seams leading to ~~some~~ possible up-dip flow of gas into the network of fractures and thereby into the Condamine River.
- CSIRO research has found no evidence that these seeps have any adverse environmental impact on the plant or animal life of the river and its surroundings. To date, there is no public health or safety risk caused by the methane concentrations measured in the area of these or any other seeps in the Surat Basin that CSIRO has measured.

Capturing methane

Methane is a colourless, odourless, non-toxic gas. It is the main component of coal-seam gas (CSG), a gas taken from underground coal seams. The gas is lighter than air, so rises into the air when released. Methane originates naturally from biological sources (lakes, rivers, wetlands), agricultural sources (cultivation, ruminants), and geological sources (coal seams). Methane may also be released by humans when digging for coal from mines, producing Liquefied Natural Gas (LNG) from CSG and from city waste (land fill).

CH_4 Methane molecule



Methane is a potent greenhouse gas with a warming potential about 28 times that of CO_2 when considered over a 100 year lifetime in the atmosphere[1].

Sedimentary basins around the world that contain coal or organic matter naturally leak methane to the atmosphere. About a third of the 200 million tonnes of methane released to the atmosphere annually comes from these geological sources, which are derived from ancient organic matter deposited over millions of years and turned to coal under high temperature and pressure conditions underground. The fossil fuel industry including natural gas, coal and oil contribute between 15 and 22% of total global methane emissions[2].

Where leaking methane can be captured, it can be used as fuel to generate electricity. On combustion, methane produces carbon dioxide and water vapour, which trap heat in the atmosphere less than the original methane.

1 Kirschke et al (2013), Three decades of global methane sources and sinks, Nature Geoscience, doi:10.1038/ngeo1955

2 Schwietzke et al (2016), Upward revision of global fossil fuel methane emission based on isotope database, Nature 538, pp 88- 91 doi: 10.1038

Geology of the Condamine River region

The Surat Basin is situated in southern-central Queensland and is part of Australia's Great Artesian Basin. The Surat Basin contains the Walloon Coal Measures with large quantities of methane gas that are being extracted for LNG production. The Condamine River, near Chinchilla in southeast Queensland, is situated on the eastern edge of the Surat Basin.

The Surat Basin formed tens to hundreds of millions of years ago[3]. It consists of multiple aquifers (typically consisting of sandstones) and aquitards (typically dominated by claystones, siltstones and mudstones)[4]. The Walloon Coal Measures rise at an angle of about 1 degree to the surface from the west and meet the alluvial sediments deposited by the Condamine River (the 'Condamine River alluvium'). The layers of porous and non-porous rock above the Walloon Coal Measures intersect the surface and can be seen as outcropping rock formations along the river channel. The Condamine River has eroded the landscape over aeons, and the Surat Basin formations are intersected with numerous faults that have dissected and fractured these underground formations[5].

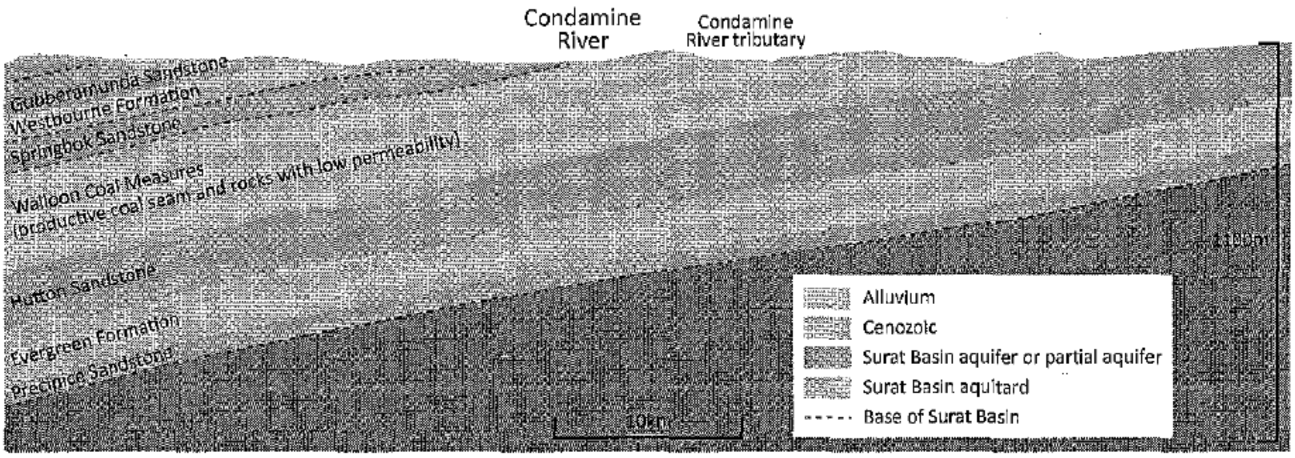
Geology of Walloon Coal Measures

Researchers have used seismic surveys, drill core data and other direct measurement techniques to create an image of the subsurface geometry and structure of the Walloon Coal Measures and other aquifers and aquitards beneath this region of the Condamine River.

This work has identified complex folding, faulting and deeply fractured rock layers beneath the surface[6]. These fractures can form natural links between coal seams and the surface via fissures and cracks that formed millions of years ago.

The Walloon Coal Measures in the vicinity of the Condamine River, near Chinchilla, Queensland, is a highly permeable underground environment which allows methane to flow easily[7]. In this part of the Condamine, the alluvium is very narrow and thin, and the Walloon Coal Measures are much shallower and closer to the base of the river than elsewhere within the catchment. The combination of fractured formations and permeability beneath the Condamine River allows migration of methane to the surface. The fractured geology also show structures underground at shallow depths where gas may accumulate in traps. These traps can collect methane under pressure (e.g. hydrostatic pressure from the alluvium above). As this pressure is eased the methane in these traps can expand and find its way to the surface. This could explain variation in methane fluxes we see at some places in the Condamine River.

In the vicinity of the Condamine River where bubbling occurs, it is possible that depressurisation of the Walloon Coal Measures during CSG production could generate some horizontal migration of free methane gas. However, with the shallow strike of these formations and the 6 to 10 km distance to gas production fields, this flux of methane is likely to be small.



Conceptual geological cross section of the Surat Basin and Condamine River alluvium near Chinchilla

3 Jell, P.A. (2013), Geology of Queensland, Queensland Geological Survey, pp 928.

4 State of Queensland (2016) Underground Water Impact Report for the Surat Cumulative Management Area, The Office of Groundwater Impact Assessment, Department of Natural Resources and Mines.

5 Esterle, JS, Hamilton, SK, Ward, V, Tyson S, Sliwa, R, (2013), Scales of Geological Heterogeneity within the Walloon Subgroup and its Coal Measures. February 2013. Final report of Activity 1.3 of the Healthy Head Waters Coal Seam Gas Water Feasibility Study. Department of Natural Resources and Mines.

6 Hamilton S.K., Esterle, J.S. & Sliwa, R. (2014) Stratigraphic and depositional framework of the Walloon Subgroup, eastern Surat Basin, Queensland, Australian Journal of Earth Sciences, 61:8, 1061-1080, DOI: 10.1080/08120099.2014.960000

7 S.K. Hamilton, J.S. Esterle, S.D. Golding (2012) Geological interpretation of gas content trends, Walloon Subgroup, eastern Surat Basin, Queensland, Australia, International Journal of Coal Geology 101, 21–35

Both CSIRO and the Gas Industry Social and Environmental Research Alliance (GISERA) are undertaking research to locate and measure these natural methane seeps, including the gas appearing as bubbling in the Condamine River. While the bubbling in the Condamine River is spectacular, it is only one location of many in this region where methane is being released at the surface. The other locations are cracks and fissures that are not visible and CSIRO researchers are using sensors to locate and measure the flow of methane at these locations[8,9]. CSIRO has also undertaken research on the potential impacts of the bubbling methane on the biogeochemistry and aquatic ecology of the Condamine River.

Natural and human causes of methane leakage

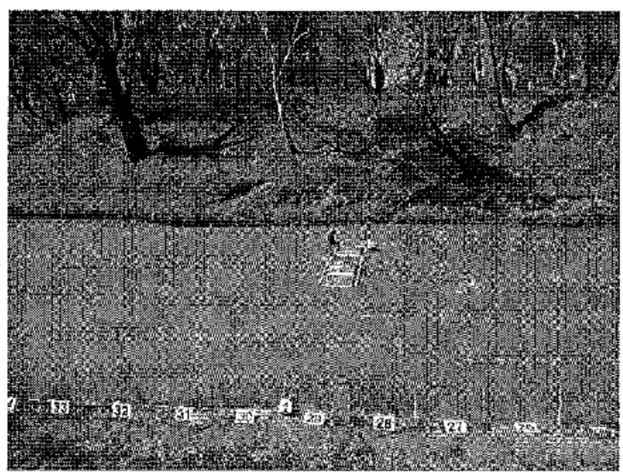
In addition to the natural underground formations and fissures which can form migration pathways for the methane to the surface, human activities such as drilling water bores, extracting gas, and exploring for gas and oil can allow methane to escape. Some of these activities (e.g. drilling of water bores or coal exploration holes) have created further pathways for gas to rise to the surface[10].

The presence of methane in water bores has been documented well before development of the region's CSG industry as far back as 1919[11]. Since the early 1900s, there has been natural gas in water bores in nearby Roma, which have led to well blowouts and occasionally caught fire. Methane in water bores in the Surat and Bowen basins has also been documented in drilling reports from the 1960s and 1970s.

CSIRO's isotopic analysis of methane gas collected from the main bubbling site in the Condamine River[12] shows that the origin of the methane is from bacterial metabolism of coal. Other research suggests that methane in groundwater of the Condamine River alluvium may originate from the Walloon Coal Measures or adjacent geological formations in the Surat Basin[13]. However, conflicting data also exists[14] suggesting virtually no migration of methane from the Walloon Coal Measures into the alluvium, at least at sites south-east of where bubbling occurs in the Condamine River. What is apparent, is that the methane seeps do not originate from biological sources in the river sediments.

The bubbling of methane from the Condamine River area has increased three-fold since ongoing measurement began in early 2015[15], but has declined again recently. There may be many reasons for this variation in methane flow to the surface through the Condamine River. CSIRO researchers provide three possibilities for this variation in methane flow:

1. that an increase in flow in river water has scoured the river bed moving sand and sediments that previously sat over the seeps and limited their flow
2. that groundwater receding from the Condamine River alluvium since the 2011 floods has reduced pressure over the Walloon Coal Measures near Chinchilla, allowing trapped gas to expand and rise to the surface
3. that CSG industry activity in production fields 5 to 6 km away has reduced pressure in the coal seams leading to possible up-dip flow of gas into the network of fractures and thereby into the Condamine River[16].



Scientists measuring methane gas using rising chambers from Condamine River (Source: Brad Sherman)

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8 Day, S., Dell'Amico, M., Etheridge, D., Ong, C., Rodger, A., Sherman, B., Barrett, D.J. (2013) Characterisation of regional fluxes of methane in the Surat Basin, Queensland – Phase 1: A Review and Analysis of Literature on Methane Detection and Flux Determination. CSIRO, Australia

9 Day, S., Ong, C., Rodger, A., Etheridge, D., Hibberd, M., van Gorsel, E., Spencer, D., Krummel, P., Fry, R., Mark Dell'Amico, M., Sestak, S., Williams, D., Loh, Z., Barrett, D. (2015) Characterisation of regional fluxes of methane in the Surat Basin, Queensland: Phase 2: A pilot study of methodology to detect and quantify methane sources. CSIRO, Australia.

10 Walker, G.R., Mallants, D., Methodologies for investigating gas in water bores and links to coal seam gas development (2014). CSIRO. Australia

11 Gray, A.R.G. (1967) Natural Gas Occurrence in the Brigalow Area, March 1967. Queensland Government Mining Journal. 68, 394 - 396

12 Sherman B.S. and Ford, P.W. (2014) Condamine River Coal Seam Gas Emissions: Final Report. CSIRO, Water for a Healthy Country Flagship, Australia

13 Iverach, C.P., Dioni I. Cendón, Stuart I. Hankin, David Lowry, Rebecca E. Fisher, James L. France, Euan G. Nisbet, Andy Baker & Bryce F. J. Kelly (2015) Assessing Connectivity Between an Overlying Aquifer and a Coal Seam Gas Resource Using Methane Isotopes, Dissolved Organic Carbon and Tritium. Scientific Reports. DOI: 10.1038/srep15996

14 Owen, D.D.R., Shouakar-Stash, O., Morgenstern, U. & Aravena, R. (2016) Thermodynamic and hydrochemical controls on CH_4 in a coal seam gas and overlying alluvial aquifer: new insights into CH_4 origins. DOI: 10.1038/srep32407

15 CSIRO flux measurements https://www.aplng.com.au/topics/coal-seam-gas/condamine-river-seeps.html

16 Norwest report, Executive Summary, p.17-18

It is well known that water and gas extraction activities reduces pressure in underground coal seams and aquifers, thereby releasing methane. Experiments undertaken by the CSG industry that involve shutting down gas wells in these production fields have shown pressure changes due to gas industry activity in the vicinity of the Condamine River, but only a few per cent of the current methane flows in the Condamine River can be explained by these activities. Furthermore, the very low angle of dip (about 1 degree) of the Walloon Coal Measures would preclude large-scale transport of gaseous methane underground. Hydraulic fracturing is not the cause of this increase in bubbling in the Condamine River because there has been no hydraulic fracturing by the CSG industry in these production fields.

Impact on health and environment

CSIRO has found no evidence that the seepage of methane from the Condamine River area has any adverse environmental impact on the plant or animal life of the river and its surroundings[17]. While higher concentrations of methane are present in the river up to 8 km downstream the river seeps, temperature, electrical conductivity and turbidity are not affected. Nitrogen, ammonium, phosphorus and organic carbon concentrations in the vicinity of the seeps are not different to other parts of the river and are typical of Australian inland rivers. Phytoplankton, zooplankton and macroinvertebrates are unaffected by the presence of the seeps; although, bacterial and fungal populations were higher which is to be expected given that methane is the food source of methanogenic bacteria.

There is no public health or safety risk caused by the methane concentrations measured in the area of these or any other seeps in the Surat Basin CSIRO has measured[18,19]. Analysis shows the gas is very pure, composed almost entirely of non-toxic methane, with traces of carbon dioxide and nitrogen. There is no evidence of volatile organic compounds or dangerous hydrocarbons in the seeping gas. Metals, such as silver, cadmium, chromium, mercury, lead, aluminium, iron and manganese, were either at the threshold of detection or within the range expected for inland Australian rivers.

Methane is only dangerous if concentrated in enclosed spaces to levels where it is explosive, and there are safety risks if it is deliberately lit. In the Condamine River the seeps can only be lit when the river is not flowing and where flames are supported by additional combustible material.

Ongoing monitoring

CSIRO has been undertaking research on gas seeps in the region for more than three years. Scientists have used remote sensing, isotopic analyses, field surveys, computer modelling and other techniques to map methane sources and understand the processes that lead to methane emissions.

CSIRO will continue to independently measure and monitor methane from geological sources and from other origins including old coal exploration wells from the 1960s, fugitive emissions from the gas industry, and methane emissions from cattle and agriculture. In addition, the Queensland Government is monitoring water quality and gas levels to identify any environmental harm or safety concerns, and reviewing relevant research to ensure a high level of scientific rigour and independent research is maintained.

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17 Rees GN, Nielsen DL, Cook RA, Petrie R, Watson GO, Davey C, Oliver R, Lorenz Z (2016) Condamine River: Ecological study. Report to Origin Energy.

18 State of Queensland, Department of Natural Resources and Mines (2012) Summary Technical Report - Part 1 Condamine River Gas Seep Investigation.

19 State of Queensland, Queensland Health (2013) Coal seam gas in the Tara region: Summary risk assessment of health complaints and environmental monitoring data.

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Document 7

[redacted]

From: Barrett, Damian (Energy, Black Mountain)
Sent: Thursday, 9 March 2017 5:29 PM
To: Close, David
Cc: Aryana, Amir (Energy, North Ryde)
Subject: Re: Condamine Seeps and Chinchilla - Shallow Gas studies

Hi David

Great to hear from you.

I think it is an excellent initiative to bring together all the relevant expertise around the Condamine River Gas seeps and beyond. Happy to be involved and pull together the relevant people in CSIRO to attend. Let me know when is the most suitable time for you and I'll get on to it.

I've included our acting Research Director for Onshore Gas on this email too because it would be worth inviting a select group in CSIRO across the unconventional gas and environmental research areas.

Let me know if there are any specific points you'd like to discuss further.

Cheers...Damian

Dr Damian Barrett
Research Director - Onshore Gas (Energy Business Unit)
Director Gas Industry Social and Environmental Research Alliance
CSIRO
P: [redacted]
P:
E:

Adjunct Professor
Centre for Water in the Minerals Industry
Sustainable Minerals Institute
University of Queensland, Brisbane

[redacted]

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[redacted]

[redacted] s22

From: Barrett, Damian (Energy, Black Mountain)
Sent: Thursday, 23 March 2017 12:48 PM
To: Proctor, Nicola (CorpAffairs, Newcastle); Beringen, Helen (CorpAffairs, TownsvilleATSIP)
Subject: Condamine River Gas sheet

Hi Nicola and Helen

You can go ahead and put the condamine river fact sheet up on the GISERA webs site. I've made Origin people aware of this happening this week.

Cheers...Damian

[redacted]

From: Barrett, Damian (Energy, Black Mountain)
Sent: Thursday, 20 April 2017 5:29 PM
To: Howard, Will
Subject: Re: Office of the Chief Scientist paper on methane and fugitive emissions [SEC=UNCLASSIFIED]

G'day Will

Great to hear from you!

Yep, I can provide comment for you on the paper you attached regarding fugitive emissions and our CSIRO research.

In fact, we are just in the process of pulling together a 'fact sheet' to synthesise the current science on fugitive emissions in relation to the onshore gas industry. This will have the look and feel of the fact sheet we produced in relation to the current state of the science of the gas bubbling in the Condamine River in Queensland (https://gisera.org.au/wp-content/uploads/2017/04/GISERA_MethaneSeepsCondamineRiver_4ppFactsheet_170310.pdf). We are trying to get this finished and released before the end of May 2017.

Are you thinking of making your paper public? It occurred to me that, if that was the case, it might be worth coordinating? Happy to chew over the idea with you if you are interested.

Cheers...Damian

Dr Damian Barrett
Research Director - Onshore Gas (Energy Business Unit)
Director Gas Industry Social and Environmental Research Alliance
CSIRO
P: [redacted]
P:
E:

Adjunct Professor
Centre for Water in the Minerals Industry
Sustainable Minerals Institute
University of Queensland, Brisbane
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[redacted]

Project Order
Proforma 2012

1. Short Project Title (less than 15 words)

Methane seepage fluxes, Surat Basin, Queensland

Long Project Title	Characterising the regional fluxes of methane seepage in the Surat Basin, Queensland
GISERA Project Number	Gas 1315
Proposed Start Date	June 2013
Proposed End Date	November 2017
Project Leader	Stuart Day

2. GISERA Research Program

- ☐ Biodiversity Research
- ☐ Marine Research
- ☐ Land Research
- ☐ Water Research
- ☐ Social & Economic Research
- ☒ GHG Research

3. Research Leader, Title and Organisation

Stuart Day
CSIRO Energy Flagship
Newcastle

4. Summary (less than 300 words)

This research proposal aims to address significant uncertainties associated with background seepage of methane and their detection and measurement in the Surat Basin, Queensland. By seepage we refer to the diffusive flux of methane to the atmosphere through the land surface and water bodies, the localised flux of methane *via* connectivity pathways consisting of leads, faults and outcrops and the flux from agricultural wells and bores. It does not consider the fugitive emissions of methane occurring as part of open cut and underground coal mines or emissions occurring from infrastructure (wells, compressors, associated water reticulation, or gas pipelines) associated with CSG production.

The research will provide:

(1) A desktop review and analysis of remote sensing imaging and direct detection (ground based flux) methods to quantify methane sources and fluxes;
(2) A field trial of methods at (a) a remote sensing pilot site, and (b) a ground based direct detection and monitoring pilot site. The remote sensing pilot will test the acceptable method(s) developed in Task 1 for deployment within a defined test area and ability to detect methane seeps more broadly in the Upper Condamine River catchment. The ground detection and monitoring pilot will test *in situ* measurement of on-ground methane fluxes at up to two pilot sites. Isotopic chemical tracers will assist in distinguishing coal methane seeps from biogenic methane sources. Each pilot is contingent on results from Task 1 and the client's input at decision points in the project; and,
(3) broad scale application of methods to a larger region in the Upper Condamine River catchment. This research will provide baseline monitoring data of methane seepage fluxes over different seasons. The final design is contingent on results from Tasks 1 and 2, their successful application and the client's input at decision points.

4b. Summary (variation – Methane emissions enhanced modelling

The atmospheric "top-down" approach provides continuous and independent monitoring of emissions. The atmospheric measurements and modelling in GISERA has been spread across a 3 year period to obtain a baseline on sources at the regional scale using fixed monitoring stations. The atmospheric monitoring, originally proposed to be one baseline station, will be enhanced to a network of 2 CSIRO stations and at least one industry station, all linked to the same concentration scales. This network will continuously monitor small differences in methane concentrations across the main CSG production area of the Surat Basin which will

be interpreted by atmospheric modelling to infer the locations and fluxes of the main gas sources, with defined uncertainties. In addition, measurements in the network of gases such as carbon dioxide and carbon monoxide (to help attribute emissions to sources including those unrelated to CSG such as combustion), and evidence of known methane sources coming from the ground surveys, will be included in the modelling and result in a greater level of detail and confidence about the methane budget, including fugitive emissions. New and existing "bottom-up" information on point sources from inventories and from infrastructure based monitoring will be included as it comes to hand. These data may be provided from industry and other sources but specific emission data will also be provided throughout the project by targeted ground surveys, which were used successfully during Phase 2. A modelling framework will be developed to derive the main source areas and emissions using forward simulations and inverse methods. Improved confidence in the emissions estimates will be obtained by combining results from the top-down and bottom-up approaches.
This approach of combining world's best science in measurements and modelling will lead to a workable system with broad application to monitoring regional gas emissions.

The following table provides a summary of the aims, methods, outputs and outcomes of this project:

Research Aim	Research Methods	Outputs	OUTCOMES
Year 1			
Task 1. A literature review of the science on all methods and technologies of CH_4 measurement in light of their applicability to quantifying fluxes and their variations at a range of spatial and temporal scales in the Surat Basin, Queensland.	Desktop study of scientific literature with, potentially, limited numerical modeling using synthetic or limited datasets to demonstrate feasibility of methods and their applicability to the measurement of diffuse CH_4 fluxes from a range of potential sources (including but not confined to terrestrial outcrops, preferential pathways, alluvium losses, river fluxes, biogenic sources, agricultural wells, and other infrastructure not part of CSG development fields).	A report advising on the scientific capabilities of all forms of CH_4 detection and measurement methodologies to be used in the Surat Basin to quantify fluxes and sources of background emissions.	A comprehensive assessment of the application of methods of CH_4 detection and measurement to an important sedimentary basin in which CSG development is underway.
Task 1.The development of agreed plans for a pilot program for measuring CH_4 fluxes on at least one study site.	Scoping of a pilot program of application of methods for CH4 flux measurement and its sources.	The report is to include a plan for deployment of these activities as part of a pilot study (Task 2) and year one of an ongoing baseline-monitoring program (Task 3).	A fully scoped plan for analysis of CH4 fluxes and sources for an important sedimentary basin in which CSG development is underway.
Task 2. Based on successful development of a plan pilot program, deploy appropriate technology for the measurement and sourcing of CH_4 from sources in the Surat Basin.	Deploy CH_4 measurement technologies as agreed in Task 1 (including, but not limited to, FTIR spectroscopy, laser, atmospheric concentration measurement, inverse atmospheric transport modeling, eddy covariance measurement, Flux chamber measurement, hyperspectral imaging, and/or isotope sampling) at pilot test site(s). Establish value of applied methodologies and identify	A report on the application of specified CH_4 methods at the pilot test site(s), the value of measurements and analysis and recommendations for development of the pilot test into a baseline-monitoring program.	A scientifically defensible pilot program to demonstrate the value of application of CH_4 measurement methodologies in the Surat Basin for the purpose of developing a long term monitoring program as CSG development occurs.

	uncertainties/gaps in their application. Scope plan for deployment of methods for one year to establish baseline monitoring		
Year 2			
Task 3. Based on successful demonstration of value of the pilot program, deploy appropriate technology for CH_4 measurement and sourcing for the purpose of initiating a baseline monitoring study.	Application of the demonstrated methods to long term monitoring conditions. Analysis of the variation in CH4 fluxes from various sources in time and space. Analysis of the attribution of sources of CH4 fluxes to biogenic/thermogenic origins. An assessment of the value of baseline monitoring of background CH_4 fluxes.	A report on the long-term application of specified technologies for measurement of CH_4 fluxes and their sources in the Surat basin, Queensland, including an assessment of the degree of variation in fluxes on a range of space and time scales and specifications for ongoing operation of a baseline monitoring program.	The foundation of a baseline monitoring program, its methods and quantified uncertainties that will underpin an ongoing, long term monitoring program for the Surat Basin.

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Gas Industry
Social & Environmental
Research Alliance

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Task	Milestone Number	Milestone Description	Funded by	Participant Recipient	Start Date (mm-yy)	Delivery Date (mm-yy)	Fiscal Year	Fiscal Quarter	Payment $
Task 1	1.1	Report on review and analysis of literature on detecting and measuring diffuse sources of methane seeps and proposal for discrete testing at pilot sites in Task 2	GISERA	CSIRO	1.07.2013	31.08.2013	13/14	1	s22 [redacted]
Task 2	2.1	Remote sensing pilot studyf	GISERA	CSIRO	1.09.2013	08.09.2014	14/15	2	
Task 2	2.2	Ground detection pilot study	GISERA	CSIRO	1.10.2013	30.11.2014	14/15	2	
Task 3	3.1	• The continuous monitoring results – installation, commissioning and operation of the two field stations. • Preliminary data available.	GISERA	CSIRO	1.07.2014	30.11.2015	15/16	2	
Task 3	3.2	• Modelled development and analysis of continuous data. • Periodic monitoring and field validation • Trial of remote sensing technologies.	GISERA	CSIRO	1.12.2015	30.11.2016	16/17	2	
Task 3	3.3	• Delivery of final report for Remote sensing baseline study and Ground detection baseline study	GISERA	CSIRO	1.12.2016	30.11.2017	17/18	2	
Task 4	4.1	Prepare new data from new and emerging monitoring stations including Hopelands (Origin), from field surveys including EC fluxes, and of gas tracers	GISERA	CSIRO	30.11.2015	30.11.2016			
	4.2	Evaluate data from 4.1 for ability to determine the local and	GISERA	CSIRO	30.11.2015	30.11.2016			

Task	Milestone Number	Milestone Description	Funded by	Participant Recipient	Start Date (mm-yy)	Delivery Date (mm-yy)	Fiscal Year	Fiscal Quarter	Payment $
		regional sources of methane. Screen data for non-CSG sources such as livestock and combustion emissions.							s22 [redacted]
	4.3	Use the selected data in forward modelling and improved inverse modelling to better constrain local and regional methane sources.	GISERA	CSIRO	1.7.2016	1.8.2017			
	4.4	Report on results of enhanced modelling of additional data and the inferred emissions (can be combined with final report, Task 3.3).	GISERA	CSIRO	1.12.2016	30.11.2017			

6. Other Researchers

Researcher	Time Commitment (project as a whole)	Principle area of expertise	Years of experience	Organisation
Damian Barrett	0.05	Environmental science and resources sector	>20	CSIRO
Stuart Day	0.30	Methane sensing and detection	25	CSIRO
David Etheridge	0.50	Atmospheric trace gas composition and fluxes	20	CSIRO
Brad Sherman	0.20	Methane flux measurement in aquatic environments	>12	CSIRO
Ashok Luhar	0.40	Atmospheric transport modelling	20	CSIRO
Zoe Loh	0.40	Concentration measurements and interpretation	5	CSIRO
Colin Allison	0.35	Isotopes and tracers	20	CSIRO
Cindy Ong	0.30	Remote sensing	>20	CSIRO
Andrew Roger	0.10	Remote sensing	11	
Mark Dell 'Amico	0.25	Methane sensing and detection	25	CSIRO
Robyn Fry	0.1	Methane emissions	10	CSIRO
Steve Zegelin	0.30	High level skills in flux tower deployment and operation, and related soil and atmospheric measurements	>30	CSIRO
Eva van Gorsel	0.25	Micrometeorology and fluxes	15	CSIRO
Technical Assistant	0.80	Remote atmospheric monitoring, calibrations, data management	5-20	CSIRO

6b. Other Researchers (variation 2 – Methane emissions enhanced modelling)

Researcher	Time Commitment (project as a whole)	Principle area of expertise	Years of experience	Organisation
David Etheridge	0.18	Atmospheric trace gas composition and fluxes	20	CSIRO O and A
Zoe Loh	0.12	Atmospheric measurements, calibration, data handling	10	CSIRO O and A
Ashok Luhar	0.20	Inverse modelling	20	CSIRO O and A

Mark Hibberd	0.13	Forward modelling	25	CSIRO O and A
Darren Spencer	0.10	Instrumentation	10	CSIRO O and A
Paul Marvig	0.10	Field measurements	30	CSIRO Energy
Stephen White	0.20	Atmospheric chemistry	10	CSIRO Energy

7. GISERA Objectives Addressed

This research will determine the flux and sources of background seeps of methane to the atmosphere which is an important determinant of the GHG footprint and a baseline for estimation of fugitive emissions from industry

8. Program Outcomes Achieved

See section 13

9. Program Outputs Achieved

Details are provided in *Section 15. Project Objectives and Outputs*

10. What is the knowledge gap that these research outputs will address?

There is currently no information on the size and source of background methane seepage to the atmosphere from the Surat Basin. This project will provide important baseline information on the characteristics and magnitude of methane seepage.

10b. What is the knowledge gap that these research outputs will address? (variation 2 – Methane emissions enhanced modelling)

Measurement of surface to atmosphere fluxes is an accurate way of quantifying emissions of gases from a wide range of sources. Fluxes on the scale of 1 metre can be directly measured by chamber techniques and from to 100-1000 metres can be inferred from concentrations combined with modelling of individual source plumes. However, the limited scale and discontinuous nature of these techniques means that sources can be missed or their emissions incorrectly estimated, especially for sources which are distributed or diffuse and sporadic in time such as those likely to exist in the Surat Basin.

Broad scale atmospheric techniques on the other hand are continuous in time and can infer emissions across a large area from concentrations and atmospheric transport modelling. The limitation of this "top-down" approach is that multiple sources can be merged unless additional information is available.

This project will enhance the capability of GISERA baseline atmospheric monitoring by introducing into models additional data that is becoming available, such as

-new measurement stations (Hopelands, Origin) that can improve the spatial resolution of the model-inferred sources

-new tracers that can potentially discriminate methane from non-CSG sources such as livestock, vehicles and power stations

-a greater array of point or small scale source information from field surveys and infrastructure monitoring.

11. How will these Research outputs and outcomes be used in State Government and other water managers to achieve Adaptive Management of Water Resources?

The outputs of this project form the basis of a further project on estimation of methane fugitive emissions by coal seam gas development in the Surat Basin, Queensland.

12. Project Development

The Jurassic and Permian coal beds of eastern Australia have become an increasingly significant source of Australian gas production. Geochemical and isotope data indicate that the considerable stores of methane in these shallow coal seams are the result of CO_2-reduction methanogenesis from microbial activity occurring since uplift of eastern Australian geologic basins during the late Cretaceous and Tertiary (Faiz and Hendry 2006). The known 2P gas reserves in these seams amount to over 35,000 PJ, of which ~92% occur in the Surat and Bowen Basins (Kaye et al 2012).

Methane is a powerful 'greenhouse' gas contributing more than 20 times the global warming potential of CO_2 on a per mass basis. It is the most abundant organic compound in the earth's atmosphere. The total annual source of methane to the atmosphere is estimated to be about 580 Tg/year (Denman et al, 2007) largely from wetlands, lakes, rice cropping and ruminant animal production, biomass burning, landfill, and waste with about 6% from coal mining activities. Natural geological sources may account for about 10% of the total methane source (Lassey et al., 2007; Etiope et al., 2008).

Important geological sources of methane enter the atmosphere through natural seeps and fissures occurring in terrestrial and marine settings. The potential natural sources of methane to the atmosphere from sedimentary basins include surface exposed outcrops of shale and near-surface coal and *via* connectivity pathways along faults, cleavages, and alluvial sediments associated with rivers. 'Background' methane fluxes (i.e. those not associated with the CSG production) occur through biogenic processes in wetlands, swamps, rivers, and dams. In some locations, further background sources of methane are agricultural bores, feed lots, old exploration wells, landfill, wastewater and biomass burning. Fluxes from all of these sources are often episodic, ephemeral and difficult to observe.

It is possible that, in the Surat Basin, Queensland, all of these sources of methane to the atmosphere exist and it is important to be able to distinguish among them to determine those potentially susceptible to CSG production. Baseline data on the fluxes, sources, pathways and variations in natural methane seeps is required to separate 'background' or 'baseline' emissions from other human induced variation in methane emissions particularly in gas production regions such as the Surat Basin. Any perceived variation in methane production from seeps in this region are potential conflict points with communities and hence risks to the gas sector's production if there is a perception, even incorrectly, that the industry is responsible for this variation.

This project will address pathways of methane emissions that are considered 'non-anthropogenic'; that is, natural connectivity between coal seams and coal bearing aquifers and the atmosphere as a result of links occurring between these sources and the surface and will separate these sources of methane from biogenic sources such as decomposition of organic matter and feed lots. It will also consider methane emissions from agricultural wells. Consideration of the impacts of CSG field development on potential connectivity and preferred pathways of methane to the atmosphere will be part of future studies and their mitigation and are not considered in this study. Detection and quantification of fugitive emissions from CSG production will be part of another study to be undertaken by CSIRO (Day et al 2012).

Currently, there is virtually no information on baseline methane seeps in the Surat and no existing study has examined the impacts of coal seam gas development on these background fluxes of methane. Nor have these studies investigated potential impacts of gas field development (both positive and negative) on these fluxes.
This project aims to generate for the first time a comprehensive quantitative estimate of baseline methane emissions from soils, rivers and agricultural infrastructure at a regional scale in the Surat Basin. The project is designed in Tasks that increment knowledge toward this aim. Both the client and research agency have input into decisions during the project on the emphasis and timing of Tasks. The approach is to examine a range of methods and their applications in a phased manner. At the conclusion of the two years, the result will be a comprehensive study of the location and flux of methane seeps (terrestrial and aquatic), the governing processes and sources of methane and the establishment of a baseline against which ongoing monitoring can occur.

12b. Project Development (variation – Methane emissions enhanced modelling)

This project builds on the atmospheric monitoring for a methane emission baseline of the Surat Basin region to provide more definitive results on methane sources and their emissions.
GISERA Phase 2 incorporated prior estimates of methane emissions in the Surat Basin in modelling to predict the likely perturbations of atmospheric concentrations for present emissions estimates and for a growth scenario. Two stations have recently been installed in optimum locations to monitor these possible baseline signals.
The enhancement proposed here brings in new information that is becoming available since the Phase 2 concept. In addition to the baseline concentrations, ground survey concentration and flux data from Task 3, the enhanced project will include new station monitoring data (greenhouse gases and tracers from ground based stations including new air quality stations such as Hopelands, Origin)and information from collaborators such as the University of Melbourne and industry based monitoring. The aim is to give more detailed and better resolved estimates of source area, type (large infrastructure sources such as gas processing plants and power stations, feedlots, coal mines, significant seeps) and emissions.

13. Project Objectives and Outputs

The three Tasks of this research program build a hierarchy of knowledge whereby later Tasks use information and understanding developed in the earlier Tasks to underpin further work.

The **first Task** consists of a survey, review and analysis of literature on methane detection and measurement. The literature will be assessed on its applicability to develop customised methods for application to the task of quantifying methane sources and fluxes from seeps in the Surat Basin. Utilising the collective, internationally recognised skills within CSIRO, methods for remote sensing imaging, spectroscopy, atmospheric concentration, flux and source detection will be reviewed and a best strategy based on these methods will be proposed for deployment in the Surat Basin in Tasks 2 and 3. Proposals for limited discrete testing of remote sensing and ground detection methods at pilot sites will be completed and evaluated by the client. From this, agreement will be reached on how to proceed with either a remote sensing pilot, a ground detection pilot or both in Task 2. The proposals will include a review of methods for monitoring fluxes to determine baseline sources and potential natural variation. A report will advise on the best methods for deployment of a pilot study flux and establishment of a broader scale application of methods.

The **second Task** will utilise the strategy from Task 1 to deploy a pilot study of methane sources in the Surat basin. The pilot study will be field trial(s) of (a) a remote sensing pilot, and/or (b) a ground based detection and monitoring pilot. The remote sensing approach will test laser and imaging methods. The ground based detection will test the use of atmospheric concentration and flux measurements as inputs to determine the capability of atmospheric transport modelling to determine fluxes of methane on a range of spatial scales. Limited ground based gas geochemistry sampling for isotopic analyses and dissolved methane concentrations will be used to determine whether pilot site methane losses are of biogenic or coal origin and potentially assist with locating the source of the methane.

Finally, the **third Task** will apply a broad scale application of methods to assess regional methane sources (based on Task 2 results) based on remote sensing methods. An option exists to apply these methods to develop a survey of regional methane sources within the Surat basin from which a register of methane sources would be developed for the Condamine. Ongoing ground based monitoring of pilot sites will provide a baseline of methane seepage fluxes and their seasonal variations as the basis of an ongoing monitoring program.

13b. Project Objectives and Outputs (variation - Methane emissions enhanced modelling)

- Analyse and prepare additional data from new and emerging monitoring stations in a network across the Surat Basin for a more definitive source estimation.

- Quantify contributions from sources through forward modelling using existing and new information on inventories and that from infrastructure based monitoring.
- Develop an inverse modelling framework to better constrain the main source areas and emissions using data from the new and emerging monitoring stations and information from forward modelling.

Outputs include:

- A modelling methodology to better estimate sources using data from a variety of measurement systems.
- Report and a journal publication describing the methodology and results

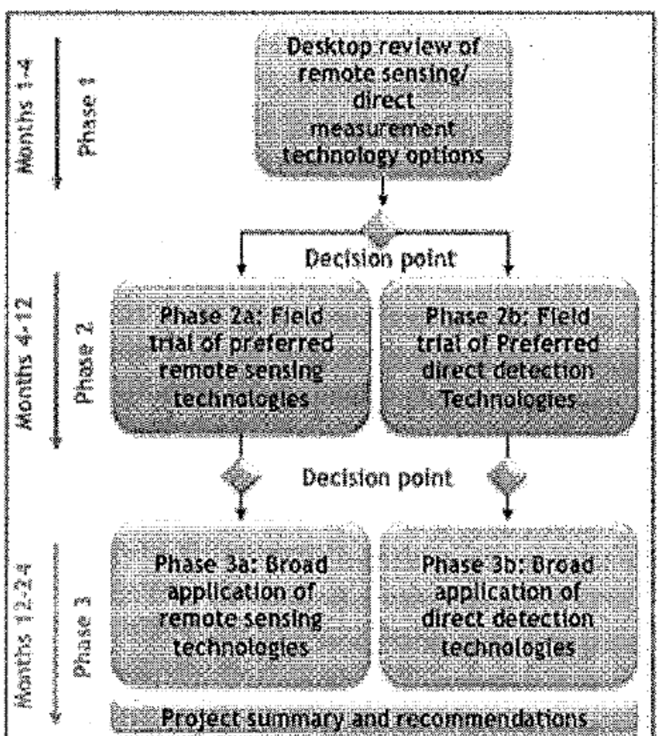
14. Project Plan

The program of work applies existing CSIRO capability to review methods and develop an integrated measurement program of methane sources and fluxes. CSIRO already has expertise in this domain through a well established program of work on coal seam methane fugitive emissions for the coal mining industry and more recently work on fugitives related to coal seam gas production.

The proposed work involves a comprehensive analysis of methane sensing and measurement methods followed by implementation of measurement activities at pilot sites and extensive deployment within the Surat Basin.

The **aim** of this research program is:

To refine methods of methane detection, locate existing significant seeps, identify sources of methane, characterize the flux of gas and develop a scientifically robust baseline of methane fluxes from seeps.



The challenge is to identify methane that has migrated from a coal seam reservoir to the surface *via* seepage and separate these fluxes from other sources (e.g. biogenic methane). The research is designed to proceed in three Tasks with decision points separating each Task. The decision point is designed to ensure shared negotiation/decision making occurs between the Research Advisory Committee, APLNG and CSIRO prior to embarking on Tasks 2 and 3 in order to ensure deliverables are aligned with the best deployment of methods. The decision points also take into account the exploratory nature of the research in recognition of the significant uncertainties surrounding background methane seepage in the Surat Basin. It is possible that parts of Tasks 2 and 3 could be undertaken in a parallel fashion based on mutual agreement between APLNG and CSIRO.

14.1 Project Schedule

ID	Task Title	Task Leader	Scheduled Start	Scheduled Finish	Predecessor
Task 1	Review & analysis of literature	Stuart Day	1 July 2013	31 August 2013	
Task 2.1	Remote sensing pilot study	Stuart Day	1 October 2013	8 Sep 2014	
Task 2.2	Ground detection pilot study	Stuart Day	1 July 2014	28 Feb 2015	
Task 3.1	· The continuous monitoring results – installation, commissioning and operation of the two field stations. · Preliminary data available.	Stuart Day	1 July 2014	30 Nov 2015	
Task 3.2	· Modelled development and analysis of continuous data. · Periodic monitoring and field validation · Trial of remote sensing technologies.	Stuart Day	1 Dec 2015	30 Nov 2016	
Task 3.3	· Delivery of final report for Remote sensing baseline study and Ground detection baseline study	Stuart Day	1 Dec 2016	30 Nov 2017	
Task 4.1	New data prepared	David Etheridge	30-11-2015	30-11-2016	

Task 4.2	Data screened, assessed	David Etheridge	30.11.2015	30-11-2016	
Task 4.3	Models developed and applied to new data	Ashok Luhar	1.7.2016	1-8-2017	
Task 4.4	Report prepared	David Etheridge	1.12.2016	30-11-2017	

Task 1

TASK NAME: Survey, review and analysis of literature

TASK LEADER: Stuart Day

OVERALL TIMEFRAME: It is proposed to finish Task 1 in 4 months.

BACKGROUND: xx. The first Task consists of a literature review and analysis of methane detection and measurement methods with the aim of tailoring a set of methods to the specific problem of locating and quantifying methane seeps in the Surat Basin. The review will also consider the sensitivity of methods to the task of detecting and quantifying fluxes. This Task will reduce the very significant uncertainties associated with this problem and provide a sound basis for Tasks 2 and 3. The review will include two components: (a) remote sensing methods (FTIR and laser spectroscopy and hyperspectral imaging/spectroscopy methods) and (b) direct ground based detection (mobile Piccaro CRDS analyser + GPS). The most suitable approach will depend on the type of sources (terrestrial or aquatic), the flux and area of seepage and the resulting atmospheric concentrations (under differing meteorological conditions). Existing remote measurement methods for methane detection work well for concentrated point sources (e.g. pipeline leaks) but function poorly when used to detect and measure diffuse low concentration fluxes such as seeps. The research task being tackled in this project is to design, tailor, develop and adapt methods to this problem.

TASK OBJECTIVE: Review and analyse literature on methane detection and measurement. Development of tailored methods for application at pilot sites in the Surat Basin, Queensland.
TASK OUTPUTS & SPECIFIC DELIVERABLES: The output from Task 1 will be a report containing proposals for discrete testing of methods at pilot sites for use in Task 2 and the design of measurement protocols to quantify the variability in baseline sources and ongoing monitoring at monitoring sites.

PROGRESS REPORT: The final draft report was submitted to APPEA on 18 December 2013. The literature review has gone through the mandatory internal review process and is now publicly available on the GISERA website http://www.gisera.org.au/publications/tech_reports_papers/ghg-emission-proj-1-lit-review.pdf.

Task 2.1

TASK NAME: Remote Sensing method pilot study

TASK LEADER: Stuart Day

OVERALL TIMEFRAME: It is proposed that Task 2 be undertaken over 8 months and be finished at 12 months.

BACKGROUND: Task 2 consists of utilising knowledge gained in Task 1 to deploy methods at pilot test sites. Prior to deployment at pilot sites, model testing is required to ensure the best application of methods. Due to the highly uncertain nature of methane seeps in this region, a significant amount of interpretation and testing of numerical models will be required as part of the review process. It is important that characterization of the drivers of methane fluxes and their response processes can be understood and interpreted by source modelling. The review of methods will consider the measurements and numerical modelling requirements for work undertaken at three scales or 'footprints' of methane loss to the atmosphere:

1) Localised (1 - 10 m) flux chamber measurements and interpretation of methane sources
2) Landscape (100 - 1000 m) eddy covariance measurements from which methane fluxes are determined
3) Regional (100 - 10,000 m) inverse derivation of methane fluxes using atmospheric transport modeling methods based on the observed concentrations.

The pilot studies will be applied to methane sources using a combination of methods identified, developed, tested and refined in Task 1 and model testing in Task 2. Ground based methods potentially include atmospheric concentration measurements with accompanying meteorology and chamber measurements to both calculate fluxes and obtain samples for pilot isotopic analyses.

TASK OBJECTIVE: The remote sensing pilot will examine Fourier Transform Infrared (FTIR) spectroscopy, Laser spectroscopy and hyperspectral imaging/spectroscopy methods to determine suitability for ground based or airborne measurements of seeps. A range of new, cheaper sensors are appearing on the market and these will be evaluated along with existing methods to determine best approach for this application. This will require resolving a suite of technical difficulties and questions associated with each method and testing them against diffuse, low concentration sources of methane in the atmosphere.

TASK OUTPUTS & SPECIFIC DELIVERABLES: Report on application of methods at pilot sites and recommendations for establishing baseline measurements

PROGRESS REPORT: The interim report for Phase 2 (which only relates to the remote sensing component) has been through the mandatory internal review and was submitted to Rick Wilkinson at APPEA on 11 November 2014.

Task 2.2

TASK NAME: Ground detection pilot study

TASK LEADER: Stuart Day

OVERALL TIMEFRAME: It is proposed that Task 2 be undertaken over 8 months and be finished at 12 months.

BACKGROUND: Task 2 consists of utilising knowledge gained in Task 1 to deploy methods at pilot test sites. Prior to deployment at pilot sites, model testing is required to ensure the best application of methods. Due to the highly uncertain nature of methane seeps in this region, a significant amount of interpretation and testing of numerical models will be required as part of the review process. It is important that characterization of the drivers of methane fluxes and their response processes can be understood and interpreted by source modelling. The review of methods will consider the measurements and numerical modelling requirements for work undertaken at three scales or 'footprints' of methane loss to the atmosphere:

1) Localised (1 - 10 m) flux chamber measurements and interpretation of methane sources
2) Landscape (100 - 1000 m) eddy covariance measurements from which methane fluxes are determined
3) Regional (100 - 10,000 m) inverse derivation of methane fluxes using atmospheric transport modeling methods based on the observed concentrations.

The pilot studies will be applied to methane sources using a combination of methods identified, developed, tested and refined in Task 1 and model testing in Task 2. Ground based methods potentially include atmospheric concentration measurements with accompanying meteorology and chamber measurements to both calculate fluxes and obtain samples for pilot isotopic analyses.

TASK OBJECTIVE: The on-ground pilot will utilise observations of atmospheric methane concentration as data constraints in models to determine fluxes from locations and their potential variation in response to known drivers. Inverse methods will be trialled at these pilot sites to obtain best estimates of source fluxes of methane and their variability. Inverse modelling is the most scientifically rigorous approach to examining the mechanisms driving variation in background methane fluxes. The modelling undertaken will form the bases for a scientifically robust interpretation of measurements and longer application of methods in Task 3 to establish baseline fluxes and their variations.

If the pilot site consists of methane fluxes from water bodies, the work will build on existing research undertaken in CSIRO in the Condamine River. Methane fluxes from aquatic systems with free water surfaces (e.g. river weir pools, farm dams) will be quantified using floating chambers used in one of two modes:

1) For low fluxes typical of natural waters the head-space gas is recirculated through a high precision gas analyser (Picarro CRDS) following the protocols used by CSIRO for similar research in water supply reservoirs;
2) For high fluxes (i.e. vigorous bubbling), a once-through system currently being developed and trialled by CSIRO will be employed in which gas captured by a chamber is diluted by ambient air drawn through the chamber and subsequently analysed using a high precision gas analyser.

Initial sampling is to be conducted at a coarse spatial resolution to identify important spatial gradients in fluxes. Subsequent sampling will be undertaken at higher spatial resolution to reduce uncertainty in the overall areal mean flux to within satisfactory levels. Adequate characterisation of instantaneous fluxes from a weir pool experiencing decomposition of catchment-supplied organic matter can be completed in 1-2 days of sampling (depending on spatial scale; 1 day of sampling should be sufficient for volumes < 2000 ML). Characterisation of seasonal variability requires 3 to 4 sampling experiments and would be undertaken in Task 3. Interannual variability is likely to be very high in systems subject to flooding on an irregular basis as flood waters will supply large amounts of organic matter that will degrade rapidly over the first year but may continue to fuel methanogenesis at a lower rate for several years. Characterising interannual variability would require ongoing monitoring following Task 3.

At the pilot sites, flux chamber measurements, combined with **limited** isotopic analyses will be used to differentiate reservoir methane from other potential sources. Once started the isotope observations will enable planning for potentially more detailed sampling based on cost and importance (in Task 3). More extensive sampling and detailed work is planned in Task 3 depending on results from the pilot sites. Terrestrial sites may include soil-air space sampling and soil water sampling. Aquatic sites will include chamber measurements of fluxes, samples of bubble methane and associated samples of river water to measure dissolved methane concentrations. The geochemistry of these samples will assist with establishing sources of methane and flux measurements will determine quantities of methane generated per unit time.

Measurements of samples will consist of limited isotopic composition (such as $^{13}CH_4$, CH_3D, $^{14}CH_4$), CH_4 concentration in air, soils, water and direct from source, and a suite of geochemical elements as potential tracers to identify sources.

In aquatic sites, we will also conduct the following sampling and measurements:
- Collect and analyze (by ICPMS) water samples for basic geochemical constituents to characterize possible groundwater exchanges with the river.
- Collect and analyze water samples for 13C isotopes, alkalinity and TIC.
- Collect gas samples and analyze for composition (C_1-C_5, O_2+Ar, N_2, CO_2, $d^{13}C$ - CH_4, d^2D - CH_4)

Collect and analyze water samples to characterize the spatial variability of dissolved methane and compute any associated fluxes.

TASK OUTPUTS & SPECIFIC DELIVERABLES: Report on application of methods at pilot sites and recommendations for establishing baseline measurements

PROGRESS REPORT: The final report for Phase 2 (which includes the remote sensing and ground detection components) has been through the compulsory internal review. It is now undergoing an external review with an expected completion date of 31March 2015.

Task 3

TASK NAME: Broad scale application of methane detection

TASK LEADER: Stuart Day

OVERALL TIMEFRAME: It is proposed that Task 3 will be undertaken over 12 months and begun at the end of the first year to coincide with the culmination of the pilot remote sensing imaging of seeps.

BACKGROUND: The third Task will extend the tested remote sensing methods from Tasks 1 and 2 at a more broad scale in the Surat Basin (Upper Condamine River catchment) to assess regional methane sources and fluxes. Using the most suitable remote sensing methodology from Task 1 and 2, a survey to cover the Surat Basin will be undertaken to enable identification of the location of sources of methane. The survey method will need to be sufficiently wide and frequent to ensure that all material sources of methane are located and documented. If successful this approach would allow development of a register of methane sources. The register of significant methane sources provides further information for a baseline to establish ongoing monitoring or for more intensive examination of selected locations in the future. The approach and methods will be developed in consultation with industry representatives to ensure the measurement program compliments existing sampling already undertaken by industry and to meet industry needs.

TASK OBJECTIVE: The third Task will also extend monitoring at the aforementioned pilot sites in order to begin developing an ongoing set of baseline measurements used to determine day-to-day, season-to-season and year-to-year variation in methane fluxes. This activity will reduce the considerable uncertainties associated with background methane fluxes in the Surat Basin and contribute to the establishment of a sound baseline. This component extends and refines the direct concentration and flux measurement techniques developed and applied in Task 2.

TASK OUTPUTS: Report on development of baseline measurements and plan for ongoing monitoring

SPECIFIC DELIVERABLES: The scientific review in Task 1 will provide robust knowledge as to the best selection of detection and measurement methods for this particular region.

The data provided by this project will provide an important baseline data set that allows an objective, quantitative comparison of methane fluxes and concentrations to be undertaken in the future as CSG production in the Surat Basin accelerates.

Outcomes from this work to APLNG, the CSG sector and communities include a comprehensive and scientifically rigorous analysis of background methane fluxes and the establishment of a baseline for an important part of the Surat Basin, Queensland, in which CSG development is occurring and against which ongoing monitoring can conducted.

Through this program of research, a critical unknown in CSG production will be reduced thereby contributing to maintaining and improving environmental stewardship by the industry.

References used in Task section:

Day S, Connell L, Etheridge D, Norgate T and Sherwood N (2012) Fugitive greenhouse gas emissions from coal seam gas production in Australia. CSIRO Australia, 27 pp.

Denman, K. L., et al. (2007), Couplings between changes in the climate system and biogeochemistry, in Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon et al., chap. 7, pp. 499 – 587, Cambridge Univ. Press, Cambridge, U.K.

Etiope, G., K. R. Lassey, R. W. Klusman, and E. Boschi, 2008: Reappraisal of the fossil methane budget and related emission from geologic sources. *Geophysical Research Letters 35: L09307.*, 35, L09307.

Faiz M and Hendry P (2006) Significance of microbial activity in Australia coal bed methane reservoirs – A review. *Bulletin of Canadian Petroleum Geology.* 54, 261 – 272

Kaye L, Barrett DJ, Vink S, Roux E, Murray C-E, White J, Robbins S (2012) Coal Seam Gas, Coal and Agriculture: Water Implications. Report for ACARP Project C21006. *Australian Coal Association Research Program.* 139 pp.

Lassey, K. R., Etheridge, D. M., Lowe, D. C., Smith, A. M., Ferretti, D. F. Centennial evolution of the atmospheric methane budget: what do the carbon isotopes tell us?. Atmospheric chemistry and physics. 2007; 7:2119-2139.

Task 4.1

TASK NAME: Prepare new data

TASK LEADER: David Etheridge

OVERALL TIMEFRAME: 30.11.2015-30.11.2016

BACKGROUND: Data from Ironbark and Burncluith stations should be available and complemented by additional tracer gas measurements from the new industry air quality monitoring stations (including Origin's Hopelands). Field surveys will be undertaken and data made available.

TASK OBJECTIVE: Compile and calibrate new station concentration data to include with Ironbark and Burncluith. Compile emissions and flux information from field surveys (from Phase 2 and from new tasks) to inform modelling.

TASK OUTPUTS & SPECIFIC DELIVERABLES: Calibrated data sets of greenhouse gas concentrations and tracer gases across a network of stations in the Surat Basin. Data base of locations and emissions strengths of known sources to inform forward and inverse modelling.

Task 4.2

TASK NAME: Screen and evaluate data

TASK LEADER: David Etheridge

OVERALL TIMEFRAME: 30.11.2015-30.11.2016

BACKGROUND: Station data from Task 4.1 available.

TASK OBJECTIVE: To screen and filter data and develop techniques to identify confounding local sources such as livestock, vehicles, power plants and fires, using multiple species concentrations, tracer gases and information on wind trajectories. Identify the underlying main source signals in the screened data.

TASK OUTPUTS & SPECIFIC DELIVERABLES: Screened data sets from the ground based atmospheric monitoring network, which will then be used for modelling. Main source locations identified.

Task 4.3

TASK NAME: Develop and apply models

TASK LEADER: Ashok Luhar

OVERALL TIMEFRAME: 1.7.2016-1.8.2017

BACKGROUND: This task requires source locations and emissions strengths from field surveys; Screened and evaluated concentration data from Task 4.2; Meteorological and flux data from Ironbark and Burncluith stations and emerging industry stations (Origin's Hopelands).

TASK OBJECTIVE: Develop the modelling framework for the Surat Basin, using TAPM (CSIRO meteorological and dispersion model) in forward and inverse modes. Use predicted concentration fields from forward modelling simulations of prior source estimates from Phase 2 as initial conditions. Constrain atmospheric transport with meteorological and flux station data. Include known sources in the model and compare with observations over the GISERA monitoring period. Identify and estimate emissions from main source areas not previously known or identified in field surveys. Attribute source type using multiple gas species and follow up ground surveys.

TASK OUTPUTS & SPECIFIC DELIVERABLES: A modelling capability to infer methane sources across the Surat Basin with more definitive information on source locations and types than would be available from the baseline atmospheric monitoring and modelling in Phase 3. Reports, presentations and a draft journal publication on the technique and the findings.

Task 4.4

TASK NAME: Report on enhanced monitoring.

TASK LEADER: David Etheridge

OVERALL TIMEFRAME: 1.12.2016-30.11.2017

BACKGROUND: Successful progress on Tasks 4.1-4.4

TASK OBJECTIVE: To report on atmospheric concentration monitoring network, field surveys, modelling framework and inferred source information from enhanced monitoring and modelling program.

TASK OUTPUTS & SPECIFIC DELIVERABLES: Report on enhanced monitoring and modelling project to GISERA, possibly combined with final report (Task 3.3).

Gas Industry Social & Environmental Research Alliance

15. Budget Justification

The budget for this project has been agreed between APPEA, APLNG and CSIRO. APPEA identified the project as one of particular public and industry interest and has, on behalf of the industry and via APLNG, contributed whole-of-industry funds to the project. APPEA funds appear 'via APLNG' because APLNG is a member of GISERA, APPEA is not. The Research Advisory Committee and Management Committee have approved this budget.

16. Project Governance

The project leaders and APPEA/APLNG representatives will meet at least 1 month prior to delivery of milestone reports to discuss project management issues and no less than on six monthly intervals. There are three 'decisions points' in the project plan that enable input from industry representatives, the GISERA Research Advisory Committee and CSIRO researchers as to the specific direction of research work conducted in this project. Decisions will be made by mutual agreement between researchers and industry representatives, and will be offered for and will require ratification by the GISERA Research Advisory Committee.

17. Communications Plan

GISERA will manage communications in accordance with GISERA's Alliance Agreement (available at: http://www.gisera.org.au/contract.html) and Communications Strategy.

18. Risks

Capacity to deliver this project will be managed by CSIRO. Risks in delivery will be mitigated using the breadth of skills across the organisation. Communication risks will be mitigated by adherence to the communications protocols outlined in the GISERA Communications Strategy and the GISERA Alliance Agreement. CSIRO will undertake all project management tasks and will consult with APLNG on decisions points and contingencies in the work program.

19. Intellectual Property and Confidentiality

<table>
<tr><th>Background IP (clause 10.1, 10.2)</th><th>Party</th><th>Description of Background IP</th><th>Restrictions on use (if any)</th><th>Value</th></tr>
<tr><td></td><td>CSIRO</td><td>All atmospheric transport modelling, inverse modelling methods, prior remote sensing methods for methane detection, CH_4 flux measurement methods (aquatic and terrestrial) and eddy covariance techniques used in this study.</td><td>None</td><td>$</td></tr>
<tr><td></td><td></td><td></td><td></td><td>$</td></tr>
<tr><td>Ownership of Non-Derivative IP (clause 11.3)</td><td colspan="4">CSIRO</td></tr>
<tr><td>Confidentiality of Project Results (clause 15.6)</td><td colspan="4">Project results are not confidential.</td></tr>
<tr><td>Additional Commercialisation requirements (clause 12.1)</td><td colspan="4">Not applicable</td></tr>
<tr><td>Distribution of Commercialisation Income (clause 1.1)</td><td colspan="4">Not applicable</td></tr>
<tr><td rowspan="4">Commercialisation Interest (clause 1.1)</td><td colspan="2">Party</td><td colspan="2">Commercialisation Interest</td></tr>
<tr><td colspan="2">Australia Pacific LNG</td><td colspan="2">None</td></tr>
<tr><td colspan="2">CSIRO</td><td colspan="2">None</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td></tr>
</table>

20. Approval from Project Parties

In signing this document you are committing your organisation to provide the specified funds, personnel and the required in-kind contributions.

Australia Pacific LNG

SIGNED for and on behalf of — Australia Pacific LNG, exercising authority delegated by the GISERA Management Committee

by ....
in the presence of

....
Signature of witness

....
Name of witness

....
Date

CSIRO

SIGNED for and on behalf of — CSIRO, exercising authority delegated by the GISERA Management Committee

by ....
in the presence of

....
Signature of witness

....
Name of witness

....
Date

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Document 11

Methodologies for Investigating Gas in Water Bores and Links to Coal Seam Gas Development

Glen R. Walker and Dirk Mallants

September, 2014

For: Queensland Natural Resources and Mines

CSIRO Land and Water Flagship

Citation

Walker, Glen R., and Mallants, Dirk (2014) Methodologies for Investigating Gas in Water Bores and Links to Coal Seam Gas Development. CSIRO, Australia.

Copyright and disclaimer

Important disclaimer

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Acknowledgments

The authors would like to acknowledge the funding from the Queensland Government CSGCU. Useful discussions were held with a number of people. In particular, David Free and Ross Carruthers gave much useful information on the topic and provided data, media clippings, technical reports and scientific papers. Discussions were also held with Matthias Raiber, Linda Stalker, Brad Patterson, Stuart Day, Jim Underschultz, Sanjeev Pandey, Isaac Santos, Tsuey Cham, Randall Cox, Andrew Moser, Simon Gossmann, Andrew Volcich and Patrick McKelvey, most of whom also supplied references and papers. Further information was supplied by Bryce Kelly and Jane Coram. Dhananjay Singh supplied the baseline data from the Office of Groundwater Impact Assessment. Phil Davies produced the maps of methane analyses. Many thanks to all of the above.

Executive summary

Introduction

Methane in water bores is a major concern in areas of coal seam gas (CSG) development. There are risks associated with ignition and asphyxiation in closed spaces around bores that create real concern. There are also other risks, such as gas lock in pumps, colour and odour impacts from water quality changes, toxicity due to other gases and build up of gases affecting the integrity of the bores.

To address these risks, there is a need for an appropriate monitoring, management and response strategy, commensurate with the risks. Responsibilities for these strategies are variably divided between the industry, government and private concerns. This report deals with the state of the art of methods for investigating gas in water bores and analysis of resulting data world-wide and historical presence of gas in water bores in the Surat and Bowen basins. Information from this report is to be used to investigate and respond to reports of increased gas content in individual water bores across a large area in Queensland. For such work to be effective, a good understanding of the processes for and limitations of measuring gas in water bores is critical.

Methods for undertaking investigations into gas in water bores

Methane is a colourless, odourless and non-toxic gas, but is an asphyxiant at a concentration of over 50 per cent in air. It is the largest component of the gas causing concern in water bores in the Surat and Bowen basins. Methane in water bores may be present as "free gas" and/or "dissolved gas". Methane usually only exsolves from a still solution, if the concentration of methane in the fluid exceeds its dissolved gas saturation point or solubility. Gas solubility varies with temperature, salinity, and pressure: it decreases with increasing temperature and salinity and increases with increasing pressure. Coal seam gas-derived methane will often co-exist with other gases such as short chain hydrocarbon gases such as ethane, propane and butane, as well as carbon dioxide, nitrogen and hydrogen sulfide. The relative abundance of such hydrocarbon gases (and their isotopic signatures) may be used to determine the gas source.

For methane, the measurement is that of dissolved gas or as a free gas derived from a water sample in the bore. Ideally, the sample should be collected from deep within the bore close to the screen either by low flow pumping or an in situ device such as a diffusion sampler. However, the logistics of any sampling survey and the need for consistency means that techniques involving sampling at the bore head are used. Appropriate techniques reviewed include the inverted bottle method as used for both free and dissolved gas and gas extraction samplers. Unfortunately, measured concentrations are sensitive to the exact sampling protocol, the device used, the analysis technique, and even the water temperature, salinity, and pressure. A study in Alberta, Canada, suggested that discrepancies in presence of free gas in water bores was due to different sampling methods used by different firms conducting the sampling.

Methane concentrations have been shown to be highly variable in space and time. This variability can be related to real processes that cause methane concentrations to go up and down. Some studies have shown that sampling error and analytical error also contribute to this variability; this suggests that a certain number of duplicate samples should be part of any larger survey, perhaps one in ten, or repeated sampling at a single site to provide standard deviation information.

For a better understanding of the impact of coal seam gas extraction and depressurisation on methane in the groundwater resource as a whole, a more systematic sub-regional and regional strategy is required.

This will allow the identification of gradual or sudden changes, irrespective of cause, and understanding of periodic changes of methane that may not be of concern.

When analysing methane data, careful consideration should be give to the following issues:

- methane occurs naturally in groundwater and in the vapour phase of the unsaturated zone, especially in areas where there is coal seam gas;
- methane concentrations will have been exacerbated by depressurisation caused by pumping for water and conventional gas development over time, as well as exploration for oil and gas before any coal seam gas development occurred;
- changes in methane may be due to a range of causes other than coal seam gas development. In many cases overseas, investigation of complaints have found that poor maintenance of water bores resulted in microbially-mediated methane production as a cause of changes in water quality. Presence of nearby landfill sites may be another source of methane;
- the coal seam gas development is somewhat different from many other industries due to the number of extraction wells required at relatively close spacing, the areal extent of the development and the number of companies involved;
- variability with time of measured methane concentrations due to sampling and analytical error and processes leading to presence of methane in the water bore; and
- variability of concentration of methane and related constituents within each of the different sources of methane.

A strategy, designed to address this plethora of issues, will need a sampling and analysis methodology that is robust enough to provide consistent measurements with sufficient sensitivity to detect trends in time and spatial patterns. Overseas experience with various sampling protocols have shown that to consistently and reliably measure concentrations with sufficiently low variability, requires focus on training, adherence to strict protocols, including split and duplicate samples, and consistency in the information recorded. For example, in the San Juan Basin in the USA, such a rigorous approach has lead to the situation where it could be shown that apart from a few bores, the coal seam gas development has not had a measurable impact on the methane levels regionally. In Alberta, Canada, where different trained consultants were used, large inconsistencies between results were found, despite considerable guidance being given by regulators. Best overseas practice often has data stored on an audited transparent database, a practice that helped identify and resolve inconsistencies between different firms measuring methane.

The sources of methane, transport processes from those sources to the well, pathways through which this transport occurs and transformations that might occur along the way have been reviewed. This forms a basis for understanding how chemical and isotopic data might inform us about the causes of gas occurrences and possible mitigation measures.

Most methane in water bores is of biogenic or thermogenic origin. The general relationship is that gas sources grade from biogenic to thermogenic with depth. Biogenic methane production is the most common of the processes in shallow groundwater systems and involves bacterial decomposition of organic matter in the absence of oxygen through either fermentation of organic matter or reduction of carbon dioxide. These processes can occur under conditions found in both near ground surfaces, such as in wetlands, as well as at depths to several hundred metres below ground surface. Shallow sources include organic-rich soils, landfills and manure/sewage storage systems. Thermogenic methane is formed by the thermal breakdown of complex hydrocarbons resulting from decomposition of organic material largely originating in ancient shales. Thermogenic gases typically originated at great (several 1000s of m) depths; however, over geologic time these gases may have migrated far from the original source area and subsequently accumulated at shallower depths. Thermogenic methane may be associated with a wide range of heavier hydrocarbon gases such as ethane and propane, as either gases or heavier long chain hydrocarbons found in crude oil liquids, and hydrogen sulfide. The ratio of methane to ethane and propane is a commonly used method to distinguish between microbial and thermogenic gases.

Coal seam gas extraction in water-saturated coals involves pumping groundwater from a well to decrease the water pressure until methane desorbs from the coal. The methane first dissolves in water. When the water pressure is decreased sufficiently for methane to exist largely as a free gas phase, the gas migrates to the point of lowest pressure which is the production well. However, the pumping for production is not the only way to create the pressure reduction needed for gas to form. Dissolved methane can exist in the groundwater near a water bore. When the water bore is pumped, water pressures in both the bore and the adjacent formation are decreased. Such a decrease in pressure can lead to methane degassing as water is drawn into the bore. Pressure declines due to pumping are exacerbated if the pumping rate is increased or if adjacent areas of abstraction start to overlap and interfere with each other or if pumping continues long-term. These declines in pressure could lead to enhanced methane degassing and migration from increasingly larger areas around the bore.

Methane migration can also be affected by water, oil and gas developments, i.e. when water bores or gas production wells provide conduits through the different geological layers. Such borehole breaches present a number of opportunities for leakage of fluids in the vertical direction. Experience in the USA has indicated that older wells producing oil and gas from deep conventional reservoirs are more likely to provide gas migration pathways to the surface than shallower and newer coal seam gas wells. For example, in the La Plata County part of the San Juan Basin, approximately 20% of the conventional wells required remedial cement or were plugged and abandoned, while during the same period, approximately 3% of the coalbed gas wells were found to require remedial cementation or were plugged and abandoned.

The ability to identify the causes of any high concentrations of methane in water bores or changes requires measurements of other constituents besides methane. For example, methane from coal seam gas or other deep geological sources can be distinguished using isotopes of hydrogen and carbon of methane and associated wet gas components. Because water from different sources may mix before arriving at the water bore, a measurement of other hydrochemical signatures of water may help distinguish these further. Other useful measurements are (i) the stable carbon isotope ratio of dissolved inorganic carbon, which may be used to identify any bacterial consumption of methane that has occurred between the source and the bore and (ii) the radioactive carbon isotope (^{14}C) which identifies a younger source of carbon originating from shallower groundwater unrelated to coal seams targeted for CSG extraction. The ability to conduct such forensic analysis obviously adds expense to any baseline or ongoing monitoring program and makes it difficult to tailor the program so that cost is commensurate with risk.

Occurrence of gas in water bores in Surat and Bowen basins

There has been a long history of methane, both in dissolved form and as a free gas, detected in existing water bores or during drilling for water in the Surat and Bowen basins, dating back to the beginning of the twentieth century around Roma. Since then, there have been several occurrences of gas being reported during drilling, in bores, or gas in bores igniting. Gases from micro-seeps at the land surface have been measured in the region in the 90's. Gas companies have been required by the Water Act to collect and analyse baseline samples and for the results to be sent to the Queensland Government. The collated results are presented here and show that methane is present in water bores across the region. The methane is found at higher concentrations above features such as faults and above known gas reservoirs. The concentrations of gas vary in time according to atmospheric and other others factors.

Ongoing studies in Surat and Bowen basins

There are a number of recent and current projects investigating issues related to methane in water bores. Perhaps, the most notable has been the study of gas bubbling in the Condamine River. Norwest has conducted a study which showed that the source of the gas was from deeper aquifers, but could not rule out any specific pathways or causes for any increase in gas bubbling. It is only through further monitoring and studies that these will become clearer. Some baseline studies of methane and associated chemistry are also conducted by research institutions on behalf of land-holders. Here we report on the measurement of atmospheric methane being done in three studies by different institutions. While such studies are generally aimed at accounting for greenhouse gases, the patterns with respect to time and space can help target management options at reducing methane emissions and also support our understanding of methane pathways to the land surface. Finally, the understanding of broader chemistry from the perspective of carbon storage and recovery, inter-aquifer leakage, organic contamination of groundwater and the study of methane production all provide useful baseline information for methane in water bores. In particular, a recent program by Geoscience Australia and the Queensland Government for the purposes of carbon capture and storage has many relevant measurements for baseline and forensic interpretation. There does appear to be good coordination between the hydrochemical studies although coordination on methane-specific aspects could be improved.

1 Introduction

The Coal Seam Gas Compliance Unit (CSGCU) in the Queensland Department of Natural Resources and Mines (DNRM) is responsible for investigating complaints associated with impacts to water bores from coal seam gas (CSG) development in the Surat and Bowen basins in Queensland. Increasingly the complaints are related to increased gas in bores causing problems with the operation of pumps in sub-artesian bores and causing blockages in distribution lines from artesian bores.

The CSGCU has contracted CSIRO to undergo a literature review to support decision making around the issue. Broadly, the review should address the issue of an accepted methodology for sampling, analysis, and data interpretation to address risks associated with gas in water bores. If a methodology could be accepted, it is believed that it would help to resolve uncertainties and disputes associated with gas in water bores in coal seam gas development areas. More specifically, the report includes:

- The occurrence of gas in water bores prior to the commencement of the coal seam gas industry in Queensland;
- Methods for undertaking investigations into gas in water bores including:
    - hydrochemical methods;
    - sampling techniques to collect representative groundwater samples of dissolved or free gas;
    - dissolved or free gas composition analyses including stable isotope composition; and
    - field measurement of in situ total dissolved gas pressure and volume;
- Methods for determining methane gas migration potential including gas migration processes and mitigating factors affecting vertical / lateral gas migration;
- Investigations undertaken into gas in water bores to date in Australia and in particular the Surat and Bowen basins including assessment of the occurrence, volume, stable isotopic composition and source formation of the gas.

An information sheet, "Methane Gas in Water Bores" (CSIRO, 2014) has been developed in conjunction with the review.

In addressing the topics above, the review recognises that:

1. Methane is the dominant gas of concern. Methane is associated with smaller concentrations of other gases and hydrocarbons. Some of these, such as H_2S (hydrogen sulfide), may create issues of odour ("rotten egg" smell) and toxicity. Others are useful for understanding the source of methane;
2. The risks of methane in water bores are broader internationally than problems with pumps and distribution lines;
3. Sampling is one component of a monitoring strategy aimed at addressing these concerns through the identification of risks, measurements of any relevant changes in state, identification of the causes of these changes, identification of likely mitigation strategies and determination of whether the mitigation strategies have been successful;
4. Understanding the variability in space and time of gas concentrations in water bores is necessary to underpin investigations of gas occurrence in groundwater aquifers; well constructed and tiered

baseline surveys provide key information to relate gas occurrence to appropriate sources and pathways; and that

5. Coal seam gas is not the only cause of increased methane in groundwater.

The review addresses each of the topics and sub-topics in the following order:

1. Methods for undertaking investigations into gas in water bores. Under this topic, the following sub-topics are discussed:
   a) A brief overview of the properties of methane, the major concerns of methane in water bores and mitigation measures to address these;
   b) Sampling of dissolved and free gas;
   c) Developing a monitoring strategy beginning with a baseline survey;
   d) Sources of methane, transport of methane from source to the water bore and transformations along the way;
   e) Impacts of water and gas development on increased methane; and
   f) Conducting a forensic analysis.
2. Occurrence of gas in Surat and Bowen basins: This topic provides a historical perspective of methane in water bores within the Surat and Bowen basins; along with other evidence of gas in water bores before coal seam gas development occurred.
3. Relevant studies in Surat and Bowen basins, and elsewhere in Australia: This topic provides an overview of projects currently being undertaken to address the issue in Queensland and Australia.

This review has been aided by many excellent analyses on the topic internationally. In particular, the paper by Jackson et al. (2013) was provided with the terms of reference. The authors of this paper were also senior authors on many of the analyses on the topic, information which supported this review.

2 Methods for undertaking investigations into gas in water bores

2.1 Properties of Methane and Associated Risks

Natural gas is typically accumulated in a subsurface reservoir - any rock formation with adequate porosity, fractures, or sorption potential that can store liquid or gas hydrocarbons. The different forms of natural gas are generally categorised into conventional and unconventional gas. Conventional gas is obtained from reservoirs that largely consist of porous sandstone formations capped by impermeable rock. The gas can move to the surface through the gas wells without the need to pump. Unconventional gas is generally produced from complex geological systems that prevent or significantly limit the migration of gas and require innovative technological solutions for extraction. The difference between conventional and unconventional gas is the geology of the reservoirs from which they are produced.

There are several types of unconventional gas such as coal seam gas, shale gas and tight gas. Coal seam gas is entirely adsorbed into the coal matrix. Movement of coal seam gas to the surface through gas wells normally requires extraction of formation water from the coal cleats and fractures. Shale gas is generally extracted from a clay-rich sedimentary rock which has naturally low permeability. Tight gas is trapped in ultra-compact reservoirs characterised by very low porosity and permeability.

Methane is the largest component of the gas causing concern in water bores in the Surat and Bowen basins. It is a colourless, odourless and non-toxic gas, but is an asphyxiant at a concentration of over 50 per cent in air. Many of the specific properties of methane can be found in Stalker (2013).

Methane in water bores may be present as "free gas" and/or "dissolved gas". One of the analogies used to differentiate these two forms is that of the soda bottle. While the lid is sealed, pressure keeps the gas dissolved in the liquid. Removing the lid causes a drop in pressure, allowing the previously dissolved gas to form bubbles (exsolve[1]) and rise to the liquid surface as free gas.

Methane usually only exsolves from a still solution, if the concentration of methane in the fluid exceeds its dissolved gas saturation point or solubility (Jackson et al., 2013). For a sample at the land surface, the solubility at normal levels of atmospheric pressure is 24.7 mg/L (or 34.6 ml/L) at 20 °C and 20.7 mg/L (or 29 ml/L) at 30 °C (Wiesenburg and Guinasso, 1979; Hirsche and Mayer, 2009).

Gas solubility decreases with increasing temperature and salinity and increases with increasing pressure. The effects are non-linear in all cases. A temperature difference of 20 °C (between 10 and 30 °C) for fresh water (zero salinity) results in a difference in solubility of 10 mg/L. At 20 °C, methane solubility ranges from 25 mg/L for fresh water to 19.3 mg/L at 40,000 mg/L salinity (Figure 1).

Hirsche and Mayer (2009) cite the example of a 360 m column of water leading to a methane solubility of 863 mg/L at 25 °C. Pressure effects can lead to water degassing as it is brought from depth to atmospheric pressure at the surface. This is similar to removing the lid of a soda bottle resulting in free gas coming to the surface.

---

[1] Gas to separate out from groundwater and form a free phase

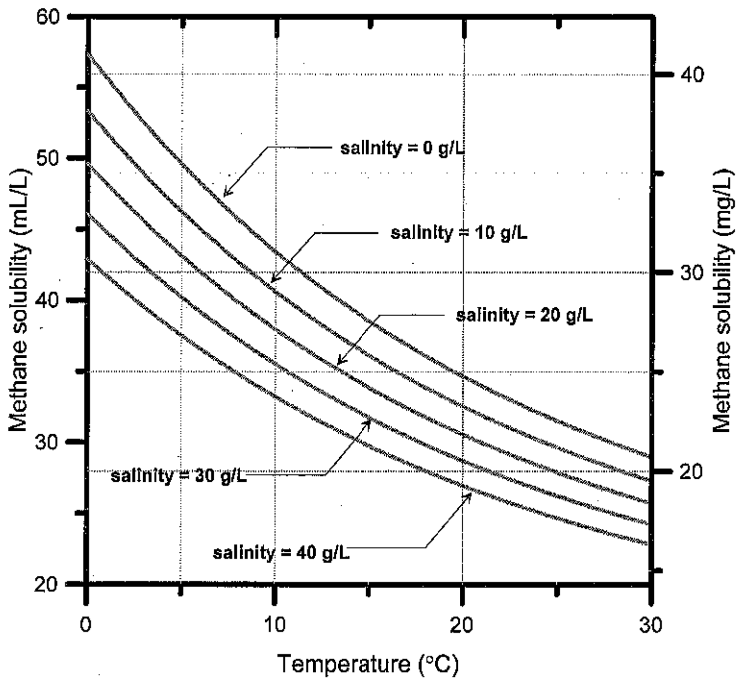

Figure 1 Methane solubility as function of temperature and salinity at atmospheric pressure (Based on data from Wiesenburg and Guinasso, 1979).

Agitation due to pumping and movement through samplers can lead to free gas release at under-saturated conditions. This is similar to shaking or heating a soda bottle, which causes more gas to bubble out.

Because it is odourless, methane can accumulate undetected in bores and bore enclosures that are not properly vented. Methane is extremely flammable and can be easily ignited by heat, sparks or flames. Methane is explosive at volumes of 5 per cent to 15 per cent (50,000 ppm to 150,000 ppm) in air. Methane is also an asphyxiant at a concentration of over 50 per cent in air. Although methane will rise, it can displace oxygen in confined spaces and hence such spaces can become vulnerable. Such risks can be mitigated through monitoring and proper ventilation. There are a number of useful sources of information on this (National Groundwater Association (NGWA), 2013a; NGWA, 2013b; Indiana Department of Natural Resources; Pennsylvania Department of Environmental Protection (DEP), 2011; Griffiths, 2007). Gas may also leak from the bore into the shallow sub-surface and then leak into closed buildings (Pennsylvania DEP, 2013). Some water quality issues can be treated with some form of treatment plants (Figure 2).

The bubbling of gas in water bores can also lead to other concerns. For example, it can affect pumps as the gas bubbles can lead to a "gas lock", in which the gas bubbles adhere to the impeller and impede the water flow. Harris et al. (2012) reported on the need to replace bore pumps due to the motors burning out as a result of "cavitation" when the dissolved gas comes out of solution. Pump shrouds or sleeves could be used or the type of pump changed (Figure 3; NGWA, 2013a). The shroud or sleeve is a tube open only at its base enclosing the submersible pump.

Gas bubbling can affect water quality in at least two ways. First, bubbles cause sediments that accumulate at the bottom of water bores to move through the water column, which in turn leads to water being used going from being clear to being "coloured, turbid, slimy, and smelly". Secondly, in certain circumstances, it can lead to the conversion of dissolved sulfate into "odiferous, noxious, and toxic" sulfides (Gorody 2012).

Under the most extreme circumstances, build-up of pressure may be great enough to dislodge the entire bore casing and pump assembly. At lower pressure, the water column can be gas lifted and promote artesian flow. It is not unusual to detect significant, yet short-lived, changes in water quality during such events, resulting from the mixing of deeper aquifer fluids with those of the shallow aquifer regimes.

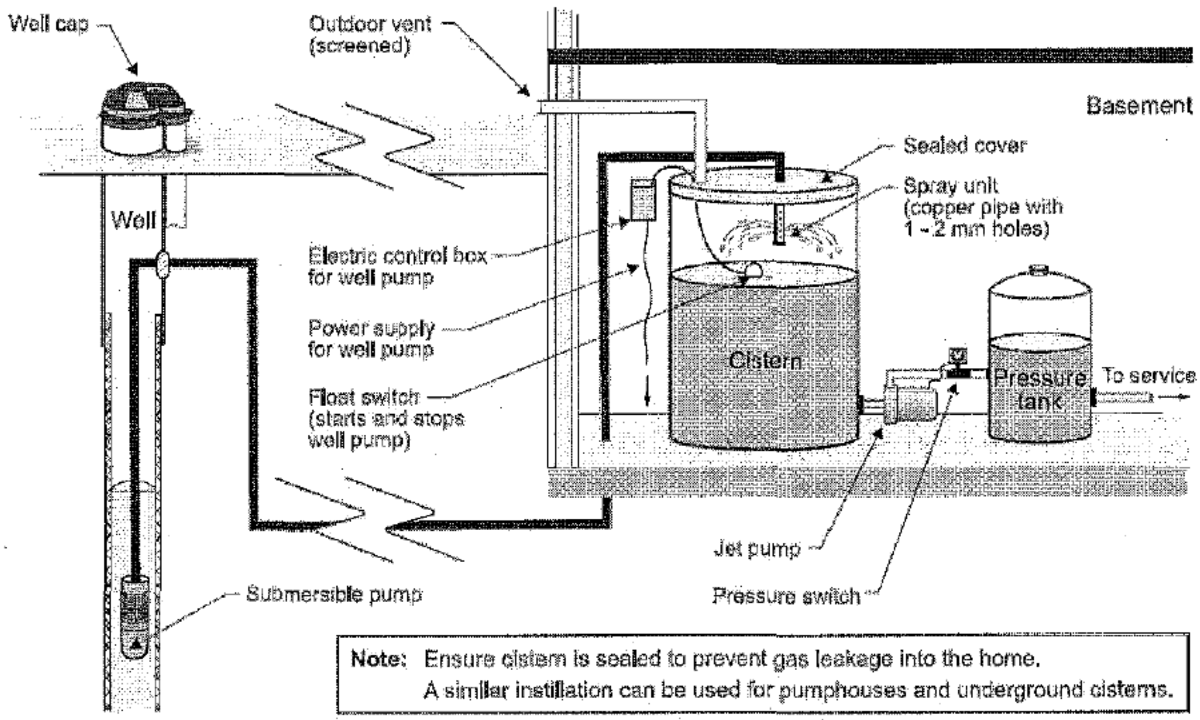

Figure 2 An aeration and ventilation system (Source: Agrifacts, 2006).

Alberta Environment's investigations indicate that, in the majority of complaints it investigates, the cause of water quality issues is not due to oil and gas activity (Armstrong et al., 2009). Inadequate water bore maintenance or the age of the bore is often determined to be the cause (Armstrong et al., 2009). Bacteria, such as iron and sulfate-reducing bacteria, can build up in bores that are not properly maintained, resulting in slime growth. In other cases, such bubbling may be natural or caused by pressure reductions from nearby bores. Dealing with water quality generally involves understanding and dealing with the causes of water bore nuisance aspects.

Coal seam gas-derived methane will often co-exist with other gases[2] such as short chain hydrocarbon gases including ethane (with its molecular formula C_2H_6, abbreviated as C_2), propane (C_3H_8, abbreviated as C_3) and butane (molecular formula for butane and its structural isomer 2-methylpropane is C_4H_{10}, abbreviated as C_4), as well as carbon dioxide and hydrogen sulfide. The last can lead to problems of odour, toxicity, and corrosion of casings and pipes (Moore, 2012).

Fortunately, methane gas is readily detected. Methane is sometimes recognizable as an effervescing[3] gas in the bores. In some cases, the release of methane in a water bore may be recognized by a sound similar to that of boiling water. Harris et al. (2012) report on anecdotal evidence from landowners referencing 'gassy' bores,' burping' bores, flaring bores and rumours of lighting farmhouses from the gas produced from the

[2] CSG contains 94-98% methane (Sydney Catchment Authority, 2012). The Santos CSG is typically 94% methane, 4% nitrogen, and 1% carbon dioxide (Santos, 2009a)

[3] The escape of gas from an aqueous solution and the foaming or fizzing that results from a release of the gas

water bore. Griffiths (2007) reports that ' The usual evidence of gas is spurting water at a tap that is turned on quickly after it has not been used for a while and a milky colour to the water during the first few seconds.' Any of these should cause the bore owner to obtain a measurement of free gas and/or dissolved gas. Such measurements are described in the next section.

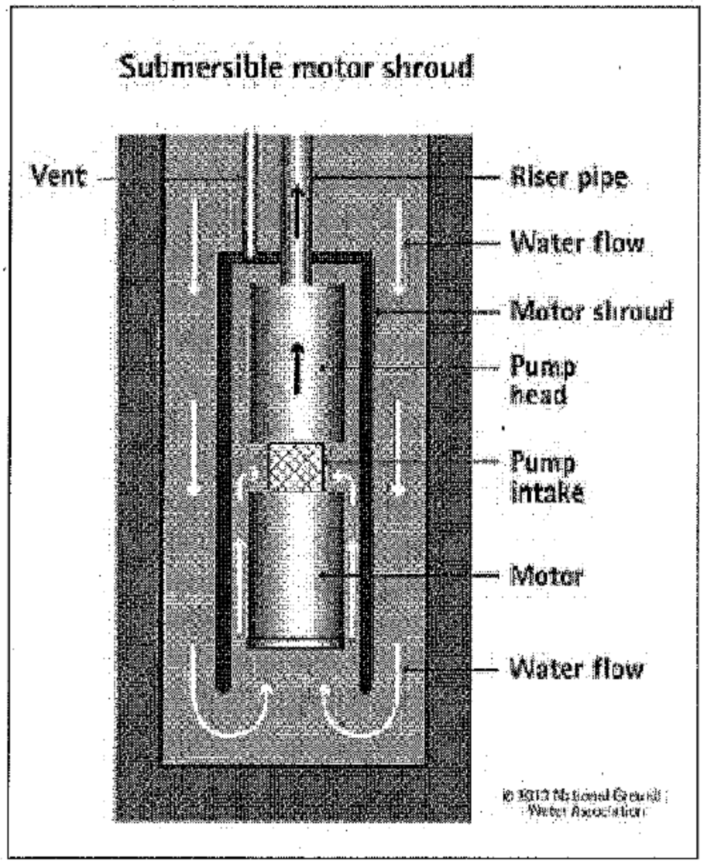

Figure 3 Schematic showing a pump shroud to avoid gas lock (Source: NGWA, 2013b).

As shown later, methane has been found in water bores in the Surat and Bowen basins over the last 100 years. In many cases, it has been something that locals have learnt to deal with. However, there has been an increasing number of potential ways in which methane can occur in shallow groundwater and water bores. Any sudden or widespread increases in methane in bore water may reflect problems that need to be addressed.

2.2 Sampling of Methane in Water Bores

In 2006, the Alberta Energy Resources Conservation Board issued Directive 035. This directive mandates that coal seam gas operators offer to test all active water bores within a 600 m radius of a proposed coal seam gas bore under given conditions. A Science Review Panel (Science Review Panel, 2008) found that there was a clear discrepancy between different environmental consulting firms conducting the sampling and analysis in the fraction of bores sampled that produce free gas. For instance, as of December 2007, the firm that conducted the largest number of tests (979) found free gas in 24% of the bores sampled. Other firms report even higher fractions. In contrast, the firm that conducted the second largest number (892) found free gas in only 2% of bores sampled. The Panel noted that many of the samples were collected in overlapping geographic areas and therefore such a large difference in the fraction of bores producing free gas is unlikely to be due to chance. This suggested that the sampling methods may have a significant effect on whether or not free gas is observed and subsequently analysed.

The objective of the sampling strategy has a large impact on the type of sampling and analysis being undertaken. In the above case, the sampling focussed on identifying whether gas exsolution may occur during pumping (is there any dissolved gas present), rather than determining the dissolved gas concentration. This would help determine if there were any likely risks associated with the build-up of gas. Hence, the methods encouraged more rapid pumping and sampling methods that would more likely cause gas to exsolve. Also, the coal seams producing the gas were above the water table. Thus, the result has been heavily influenced by the sampling and analysis method (Armstrong et al., 2009).

This section will describe sampling methods, while the next section deals with the monitoring strategy. Generally, the following steps need to be considered as part of sampling and analysis: 1) purging of the bore, 2) taking the sample itself, 3) transportation and storage, and 4) analysis. For this report, we will be considering the first three steps. Geoscience Australia (Sundaram et al., 2009) has developed some detailed protocols for groundwater sampling in Australian conditions. There are a number of international documents dealing with sampling methods, including those used in Alberta (Hirsche and Mayer, 2009), and the USA (Koterba et al., 1995; Stolp et al., 2006). Taken together, these provide descriptions of a wide range of techniques and the pros and cons of each. We will not describe detailed protocols here but refer the reader to these documents. It is also worth noting that methane is not usually the only constituent sampled, but others will be as part of any monitoring or required for forensic analysis, as described later in the report.

2.2.1 SAMPLING OF DISSOLVED GAS

Purging/sampling

The methods for purging and subsequent sampling are important to provide consistent analyses. Criteria for choosing any given method include i) it must be comparatively simple while ensuring reliable and accurate results, and ii) accessibility to the bore itself. Sampling can occur at above-ground access points, or by using down-hole sampling devices. Techniques where pumps and other sampling equipment can be placed down the bore are preferred over above-ground sampling; the latter techniques are known to suffer from pumping-induced pressure changes that may affect the dissolved gas concentration due to degassing during pumping (Hirsche and Mayer, 2009).

Caution must be exercised when pumping bores prior to sampling. Especially pumping of gassy bores leads to de-gassing and therefore might not be safe. In such situations, snap (ProHydro, 2014) or diffusion sampling techniques are recommended.

For some existing production water bores, it may be necessary to use existing pumps and this restricts the range of methods. Purging is necessary (depending on the use of the bore) as any stagnant water in the bore is likely to have degassed, and chemical reactions in the bore are likely to modify some of the other chemical parameters. Usually, purging involves removal of 3 casing volumes of standing water, if possible (ASTM, 2012). Field parameters such as pH, temperature and EC are monitored during the process and help provide a guide to whether a sufficient volume has been pumped; stabilisation of such parameters is used to indicate sampling can begin. Purging based on stabilisation of these parameters is more suitable for bores with low yields or in cases where the landowner will not allow purging of three bore volumes.

The process of pumping, well recovery and bringing the sample to the surface is likely to lead to degassing. Figure 4 shows the response of the total dissolved gas pressure to pumping. The measurement of total dissolved gas pressure is an in situ measurement. Where possible, it has been recommended as part of the monitoring and analysis program (Roy and Ryan, 2011).

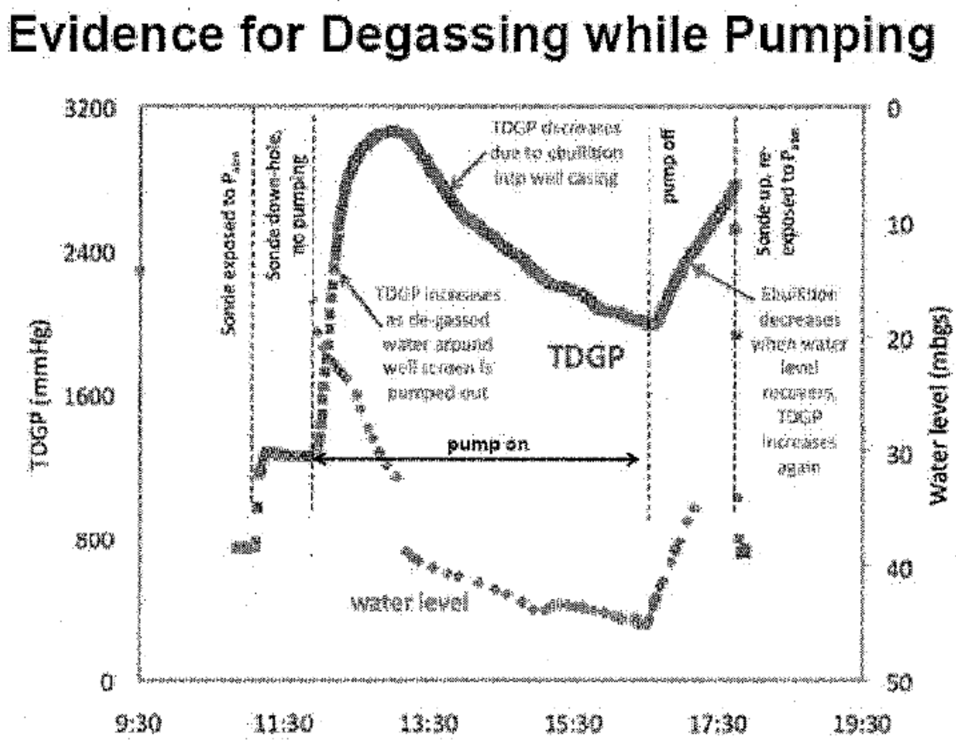

Figure 4 Response of the total dissolved gas pressure (TDGP) to pumping (Source: Roy and Ryan, 2011).

This degassing issue gives impetus to the application of down-hole methods. The US EPA (2010) encourages the use of low-flow sampling. The low flow pumps are placed close to the screens and are meant to pump at a rate comparable to the inflow to the bore. In this way, there is as little disturbance possible for the water in the bore.

Down-hole diffusion cells may also be used. Barber and Briegel (1987) developed a sampler that required relatively little time for gas in the sampler to equilibrate with that in the groundwater. There have been some recent developments to simplify the design and to improve the precision of measurements. There are also a range of non-diffusion samplers. These come in various degrees of complexity and work under a range of physical principles (Hirsche and Mayer, 2009). However, for broader surveying, such techniques can be labour- and time-intensive.

Taking the sample

Assuming the water is discharged from the bore in some form or another (i.e. not using the passive in situ approaches), one needs to capture the water sample itself. The most common approach is that of the inverted bottle method as this can be used where there is access at the surface. Geosciences Australia (Sundaram et al., 2009) provides a detailed description of a protocol, which is an adaptation of the USGS approach (Stolp et al., 2006). This allows quantitative concentrations of the dissolved gas per volume of water to be obtained. The method relies on discharging bore water into the bottom of a serum bottle until full. The bottle is then submerged into a bucket of water and the operator continues to discharge water until the bottle has been purged by two volumes. This needs to be done, without having bubbles adhering to the side of the bottle. A stopper is placed in the bottle and then crimp sealed with aluminium crimp caps.

The primary disadvantage of the method is the difficulty of avoiding bubbles and providing a good seal. Accurate measurement requires exemplary sampling. A poor seal will results in equilibration of the dissolved gases with the atmosphere during storage and transportation and a lower estimate of the true dissolved gas content. To obtain reproducible results, it is important to keep sampling procedures as consistent as possible.

An alternative to this method is the bubble strip method (Kampbell and Vandegrift, 1998). The method is based on the principle that gases will undergo a partitioning between a vapour phase and a liquid phase that are in contact with each other. The stripping procedure involves filling the gas sample bulb with the water solution being analysed and then introducing an inert gas (e.g. 20 mL) to the sampler. The water sample continues to be pumped through the sample bulb, which causes agitation in the aqueous phase. The agitation of the pumping helps the partitioning of the dissolved gases between the two phases until equilibrium is reached. When equilibrium is reached, a syringe is used to sample gas. The main difficulty is that the agitation may cause excessive degassing. It is also more difficult to use than the static headspace equilibrium method, described in a little while below.

Transportation and storage

Samples must also be kept at 4°C at all times to lower the rate of microbial degradation and minimise sample loss. Samples cannot be frozen and should be shipped for analysis within several days of collection.

Separating dissolved gases from water samples

As soon as groundwater samples containing dissolved gases are collected, the dissolved gas has to be separated from the water sample prior to chemical and isotopic analyses. Two commonly applied methods are the static head space equilibration technique and the vacuum ultrasonic method.

The static headspace method is used with samples taken either by the inverted bottle method or downhole methods. Preparation of the sample at the analytical laboratory or in the field requires creating a headspace in the sample bottle (typically with helium or other inert gas). A syringe is used to equilibrate with the atmosphere. The sample is then shaken for enough time for equilibration of gases. An aliquot of the headspace is withdrawn and analysed using gas chromatography. It is important that there is no contamination with atmospheric gases and sufficient time is allowed to equilibrate. There are a number of variations of the method in which sample bottles are not always full, different gases are used and different equilibration times.

An alternative method is the vacuum ultrasonic method in which water samples are subject to ultrasonic agitation while in a water bath. The released gases are carried under vacuum to another place of the apparatus and then sampled using a syringe. A reported difficulty is that ultrasonic agitation may break down short hydrocarbon chains (Hirsche and Mayer, 2009).

Analytical techniques

The chemical analysis of dissolved gases and free gases obtained from water bore samples is conducted by gas chromatography (GC) using various detectors. A discussion of the different types of gas chromatographs, detectors, carrier gas, columns, temperatures etc. is beyond the scope of this review. Further details are available from Hirsche and Mayer (2009).

2.2.2 FREE GAS SAMPLING AND ANALYSIS

Analysis of entrained/evolving gases is not a widely used monitoring practice in Australia, but has been used with some success for hydrocarbon prospectivity in Australia (Sundaram et al., 2009). The technique is particularly suitable for semi-quantitative field analysis of gases, particularly methane and carbon dioxide. While the degree of quantification is less than for dissolved gas analysis, the samples do not require refrigeration, and, if field analysis is conducted, there is less chance of contamination (i.e., gas loss) during transportation and storage. This technique can be used for sampling groundwaters at elevated temperatures, where collection of dissolved gas samples is either too hazardous or where a high proportion of the dissolved gases may have volatilised (Sundaram et al., 2009).

Sampling methods

The sampling techniques rely on depressurisation of water samples. The most simple of these is the inverted bottle method for free gas (Figure 5). As water is brought to atmospheric pressure, gas is released. A bottle with no gas is purged with at least two volumes of water. Once sufficient gas is exsolved, the bottle is capped. Pumping rate is used to estimate the volume of water producing the gas. The bottle is transported upside down to point of analysis. A variation of this method is to provide a throttle to encourage gas to exsolve from solution.

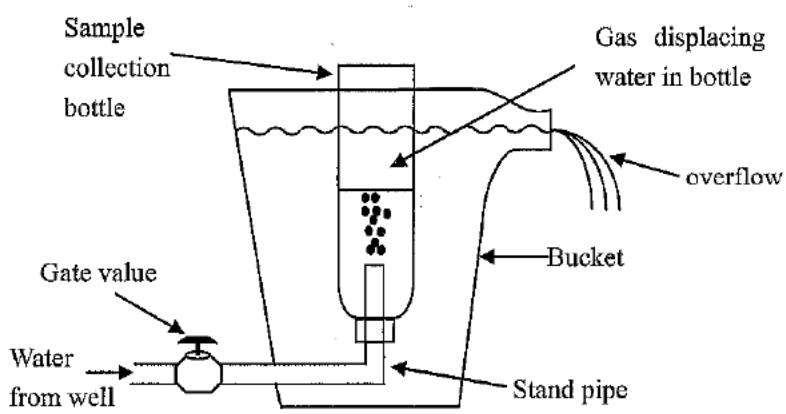

Figure 5 Inverted bottle method for free gas sampling (Modified from Keech and Gaber, 1982).

A reasonably common throttle is the use of flow through samplers (Figure 6). Most samplers consist of a plastic or glass sampler with a metal cone-shaped tube and three valves: 1) an inlet valve for water 2) an outlet valve for water and 3) extraction point for gas. The sampler is first filled with water, and then the water exit valve opens with some water exiting through the gas sampling point. The inlet valve is subsequently closed until no water leaves through the gas extraction point. When the gas valve is closed, water should be at even pressure. As water passes through the end of a metal tube, gas is released and floats to the top of the sampler. When there is sufficient gas, a gas sample is taken. Again, the volume of water is estimated.

While such samplers are practical to use, each type of sampler has a different shape and different protocols. This leads to inconsistencies in analyses between instruments. While some of the instruments have specified efficiency of degassing under given conditions, this is not always the case. In some cases, the samplers cannot handle the discharge from the bore and a T-junction may be required.

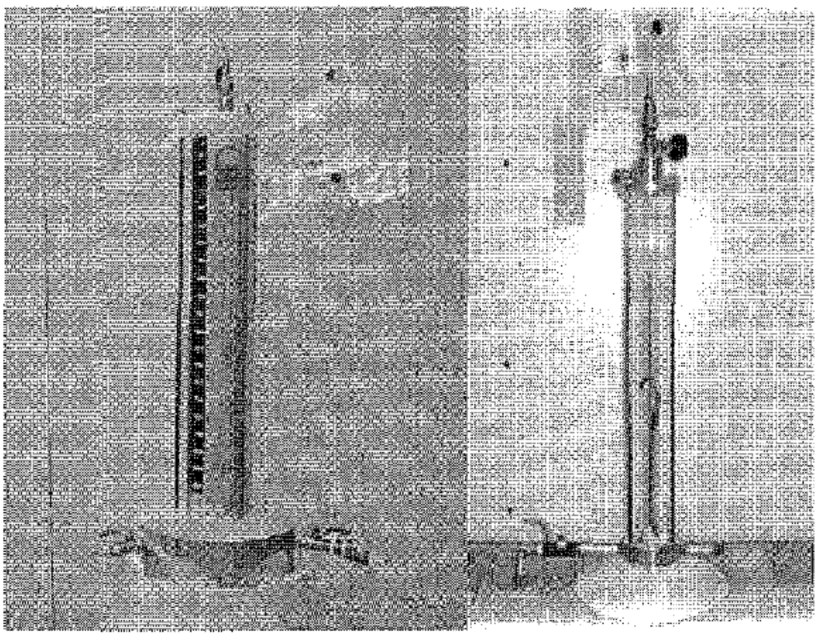

Figure 6 Flow-through sample cells (Source: Hirsche and Mayer, 2009)

Transportation and storage

The main criteria for adequate transporting and storing samples is to ensure leak-tight containers and prevent chemical or biological conversion of the gas components of interest. Commercially available electro-polished stainless steel containers are highly suited for this purpose. Typically, analyses should be done within a month from sampling and within a week if H_2S is present. A cheaper alternative is the Tedlar or Flexifoil Bags, which can store samples for a few days. Glass vials with grey butyl stoppers can be used for longer times.

Van Holst et al. (2010) tested various containers for long term storage of both CO_2 and methane. They recommended that only stainless steel cylinders, aluminium cylinders and aluminised five-layer bags be used for long term storage of gases.

2.2.3 REPEAT SAMPLING AND ANALYSIS

Methane concentrations are notoriously variable in time. Yet, very rarely is more than one sample collected.

Sampling and analytical error are part of the cause of this variability. A case study in which duplicate samples collected successively using careful methods, were shown to have about a 6% difference between minimum and maximum samples (Gorody, 2012). On the other hand, a study using split samples sent to different laboratories showed about a 40% variation, presumably due to calibration errors (Gorody, 2012). This suggests that a certain number of duplicate samples should be part of any larger survey, perhaps one in ten.

The same case studies showed that samples collected within a 95 day period and analysed by the same laboratory had about a 14% variability and a longer-term variability of about 25%.

As will be discussed in the next section, there are a range of physical reasons for this variability. For situations where we want to see how concentrations may change over time due to causes such as coal seam gas development or repressurisation of aquifers due to capping, we need to look at changes greater than the variability and hence we need to understand the variability. Also, if we want to look at causes for methane occurrence, we also need to understand the variability not only in the bores but also of the potential sources of methane.

2.2.4 SUMMARY AND DISCUSSION

This chapter highlighted the properties of methane and how this was linked to potential risks and also how we might monitor methane concentrations. The effort that goes into any monitoring program needs to be commensurate with the risks and tailored to highlight mitigation measures. For some of the risks, there is a well-established mitigation process established and some of this may not require an expensive monitoring program. However, for evaluation of the larger effects of the impacts of a coal seam gas development or for better delineating causes of poorer bore quality, one does require monitoring that is more comprehensive and consistent. Regular duplicates need to be part of that scheme. Where there is only above-ground access to bores, there will be issues of variability due to the effects of pumping samples to the surface and then analysing them. For a larger baseline program, this might be the only practical approach.

2.3 Monitoring strategies

Monitoring is done throughout the development of a new coal seam gas field, starting from before any development occurs (baseline monitoring) and finishing well after decommissioning. The purpose of the monitoring is to:

- identify any potential risks;
- measure changes in state of individual water bores and groundwater resource that might possibly have been caused by methane;
- identify causes for any changes; and
- target mitigation measures.

Monitoring can be related to an individual bore, but also to a sub-regional or regional groundwater resource. For the individual bore within a region, where methane is found in the ambient groundwater, the landholder often has lived with evidence of methane for some time. Typically, this includes evidence in drilling logs, signs of gas in water, gurgling sounds and problems with pumps (see section 3). Monitoring provides objective input to the owner on which to make decisions on measures that he or she may undertake with respect to ventilation, bore-works, pumps, bore maintenance etc. Such monitoring, if repeated regularly, may provide data about any sudden changes in methane concentration. The sampling of gas within the bore head using a commercial gas analyser can provide immediate and direct data on the specific risks of ignition. The accuracy of actual concentrations, however, are subject to a range of processes. To make this a reliable estimate, especially for its applicability to understanding trends and its reliability about emerging risks, measurement of methane concentration of both dissolved gas and of free gas, which has come out of solution, is required.

For a better understanding of the impact of coal seam gas extraction and depressurisation on methane in groundwater resources as a whole, a more systematic sub-regional and regional strategy is required. This supports the identification of sudden changes, irrespective of cause, that may potentially affect multiple landholders. It further promotes an understanding of the periodic changes of methane that may not be of concern.

To measure changes in state of individual water bores and the groundwater resource as a whole requires, in the first instance, a baseline survey across relevant bores and then sampling at time intervals afterward. For any detection of change or trend, the change needs to be larger than the noise in the baseline. This noise could be due to variability related to sampling and analysis but it also can be related to real processes that cause methane concentrations increase and decrease. Some of these processes will be described in the next section. To provide confidence about the extent of change, it is important to get some sense of the variability of the analyses. Conversely, the lower the analytical variability is, the more likelihood there is of detecting any trends.

For any area where coal seam gas occurs, there is always likely to be some natural levels of methane in groundwater and in the vapour phase of the unsaturated zone. These levels would have changed as a result of bores, respectively wells being installed for extraction of water and oil and also due to depressurisation caused by pumping for water. However, because of the lack of suitable monitoring, there is little evidence as to whether there has been an increasing level of methane. In addition, there are other biological sources of methane caused by man's activities. For example, lack of bore maintenance or presence of nearby landfills can be sources of methane production. For these reasons, it is more difficult to obtain a baseline level of methane than if all methane was due to coal seam gas development.

Some of the overseas experience points to the need for rigorous protocols and training around determining natural levels of methane if the variability is to be both known and sufficiently small to detect changes. In the San Juan Basin in the USA, such a rigorous approach has led to the situation where it could be shown that apart from a few bores, coal seam gas development has not had a measurable impact on methane levels regionally (Gorody et al., 2005). Because of the natural variability of measurements, it is not feasible to make such an assessment in Alberta, Canada (Alberta Environment, 2006). However, some individual bores had such increases in methane in their water over time that clearly suggested there was a problem. These were investigated and most changes were found to be due to reasons other than coal seam gas. In the Marcellus Basin, the monitoring was able to show regional trends, as well as identifying some individual bores that needed addressing. But, after some debate about the interpretation, the weight of evidence is suggesting that the gas industry is affecting the groundwater (Jackson et al., 2013).

Many of these overseas case studies adopt a common database. The Alberta Science Review Panel (Ryan, 2008) made several recommendations to improve the database, so that it could form a basis for making decisions. It was only through this exercise that the magnitude of the inconsistency between different consultants measuring methane became apparent. It was also the debate in Colorado about the initial measurements of methane that led to more emphasis on understanding the variability and improvement of the sampling protocols. Similarly, the initial debate in the Marcellus Basin had led to much more focussed measurements.

As will be shown, methane will not be the only constituent measured as part of any survey. Apart from there being other risks, there is a need for other constituents to be measured to interpret the causes of any change. Many of these analyses are expensive. This raises the issue of the cost of monitoring being commensurate with the risks involved. If there is a need for rigorous measurements, taken over long enough time to detect trends, and for a range of analytes, there is a need for a process that maximises information while minimising cost (NSW Chief Scientist & Engineer, 2014a). It may not make sense to spend much more on monitoring than it would take to implement measures such as venting, pumps and water treatments everywhere.

However, it has been found that leaks through disused bores or through production bores can cause some serious risks for several landholders locally and may also have impact on a regional water source for a lengthy time. A more problematic situation exists if a local industry is dependent on that source of water, or requires infrastructure that becomes at risk. A further risk is that to people that may be within confined spaces within buildings. There are also reputational risks to industries, which could be affected by public perceptions of either industries being no longer viable or seeming to cause unreasonable damage to the environment.

Risks may need to be considered by government, industry and individual landholders. For each of these, the risks are different and the roles in managing risk are different. Hence, the type of monitoring each may be engaged in is different. Under the 2010 amendments to the Queensland's Water Act 2000, each coal seam gas proponent is required to undertake baseline surveys in their tenements. This does not prevent landholders from undertaking their own surveys. The Cotton Research and Development Fund is supporting a project led by Associate Professor Bryce Kelly from the University of New South Wales in conducting a baseline survey and other analyses to support a forensic evaluation. The University of Southern Cross is providing a service for landholders in the northern NSW region (part of the Clarence-Moreton Basin) to have their water samples tested. The Queensland Government is the custodian for a database containing data submitted by Industry proponents. They also maintain a data base of drilling logs that should report gas shows in a well.

Once the issues are identified, there is a need to move to retrospective or forensic studies. These aim to identify causes for any changes, target mitigation measures and ensure these measures are working. In some cases, the identification may need to be unambiguous, the data defensible and there may be the need to prove that any defined threat is removed. Before going into these studies, the next section discusses the sources, transport and consumption of methane.

2.4 Processes

This section discusses the sources of methane, transport processes from those sources to the bore, pathways through which this transport occurs and transformations that might occur along the way. This forms a basis for understanding how chemical and isotopic data might inform us about the causes of gas occurrences and possible mitigation measures.

2.4.1 METHANE SOURCES

Most methane in water bores can be attributed to two types of processes: Biogenic or thermogenic methane production (Moore, 2012). Abiogenic methane is produced under strongly reducing conditions found deep within the earth's crust and is not significant to the current discussion.

Biogenic methane production is the most common of the processes in shallow groundwater systems. Biogenic methane is produced by bacterial decomposition of organic matter in the absence of oxygen through either fermentation or reduction. These processes can occur under conditions found in both the near ground surface, as well as at depths to several hundred metres below ground surface. Shallow sources include organic-rich soils, landfills and manure/sewage storage systems. Gas derived from such shallow sources have likely only had a short time to develop, and may have limited resources (e.g. carbon pools). Thus, although the accumulation rate might have been rapid, the accumulated volume in potential reservoirs might be relatively small and localised, especially in the absence of an upper low permeability cap. Furthermore, the slow transport mechanisms and the short time for migration after such recent gas production mean that the location of these gas deposits is usually coincident with the source, in the absence of pumping.

Thermogenic methane is formed by the thermal breakdown of complex hydrocarbons resulting from decomposition of organic material largely originating in ancient shales. This process generally occurred after organic matter was buried under a sufficient thickness of sediments to generate the high temperatures and pressures required for gas generation. Thermogenic gases typically originated at great depths (several 1000s of m); however, over geologic time these gases may have migrated far from the original source area and subsequently accumulated at shallower depths. Thermogenic methane may be associated with a wide range of heavier hydrocarbons such as ethane (C_2) and propane (C_3), as either gases or crude oil liquids, CO_2 and hydrogen sulfide (H_2S). The ratio of methane to ethane and propane ($C_1/(C_2 + C_3)$) is commonly used to distinguish between microbial and thermogenic gases (Figure 7).

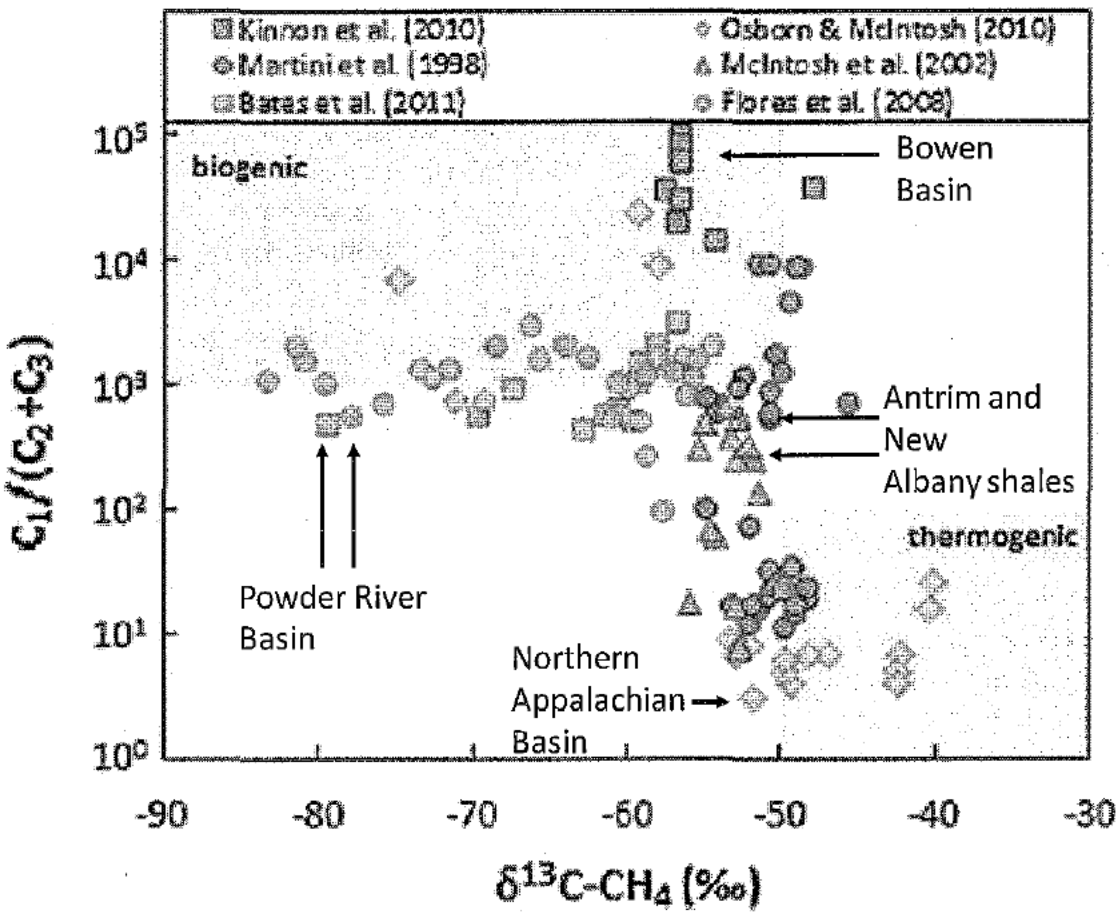

Figure 7 Gas dryness ($C_1/(C_2 + C_3)$) versus δ13C–CH_4 for northern Bowen Basin CSG wells and wells from US basins (Modified from Golding et al., 2013).

Methane will form to some degree if there is coal, but will represent an economically valuable resource only if a sufficient volume of gas is stored and can be produced. Therefore, the coal beds must have formed in an environment with sufficient overlying pressure to prevent gas loss during the coal-forming process. At the same time, in order for the coal layer to act as a gas reservoir, it must have a sufficiently high gas permeability (either natural or induced via hydraulic stimulation) to enable gas movement toward recovery bores. Permeability of coal seam gas reservoirs is due to cleats (natural fractures within the coal) and pore spacing (porosity). Cleats in coal almost always occur as two equally perpendicular sets of fractures. The "face cleat" is the dominant fracture system whereas the "butt cleat" is less laterally continuous and nearly always terminates where it intersects a face cleat (Figure 8).

Coal seam gas recovery is related to the three forms in which it is stored in coal: sorbed in micropores within the coal matrix, as free or dissolved gas (if the gas is saturated) in cleats, and in larger-scale macro-fractures. The pressure of the overlying water and rock keeps the gas in place.

In summary, natural gas sources in the subsurface are varied in nature and strength; the general relationship is that gas sources grade from biogenic to thermogenic with depth. Also, some sources could have associated H_2S, or may tend to have more free gas, rather than low concentrations of dissolved gas.

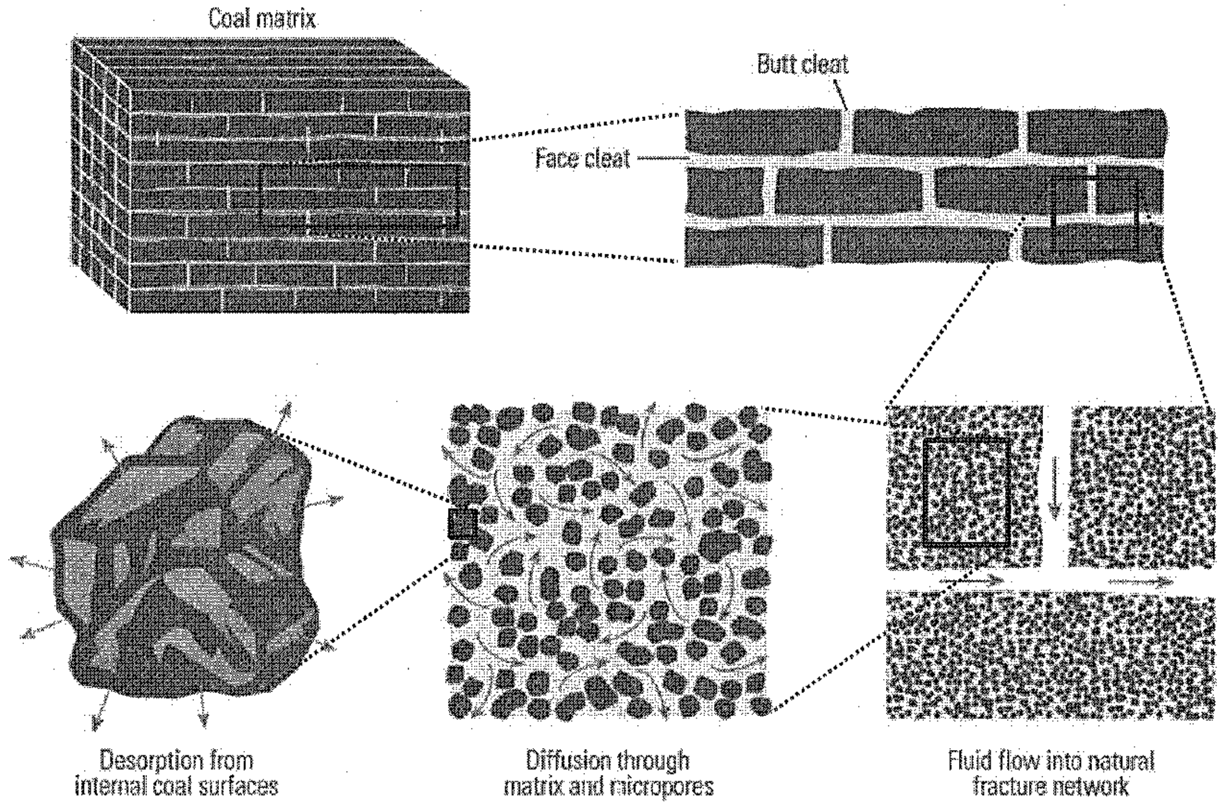

Figure 8 Flow paths through coal with indication of coal cleat orientation. During the initial stage of production, water is produced causing the formation water pressure to decrease allowing liberation of methane adsorbed on the surface of the coal matrix and stored in the micropores. The gas then diffuses through the matrix, migrates into cleats and fractures and eventually flows into the well (Modified from Al-Jubori et al., 2009).

2.4.2 DESORPTION AND DEGASSING

In the context of coal seam gas, an important state of methane is that which is absorbed to rocks and especially coal. The general rule is that as pressure is decreased, and/or temperature is increased, methane will transfer from the adsorbed phase (i.e. desorb), to the dissolved phase (if water is present) and/or to the free-gas phase (i.e. exsolve or de-gas). For the purpose of this report, only pressure changes will be considered, as generally temperature does not play a major role in the migration of methane.

In the case of water-saturated coals, the groundwater must be pumped from a well to decrease the water pressure in the surrounding coal. As the water pressure is decreased, methane desorbs (Figure 9). Desorption of the gas typically occurs at pressures close to atmospheric. This methane first dissolves in water. Because methane solubility in water is limited (about 25 mg/L under atmospheric pressure), the recovery efficiency of dissolved methane is not very high. Efficiency is increased when the water pressure in the well and the formation is decreased sufficiently for methane to exist largely as a free gas phase and to migrate to the production well. This migration involves the movement of both water and gas from the source of methane (i.e. the coal matrix and micro-pores) to the well. These phase transitions occur because the pressure decreases from the coal formation to the pumping well.

However, the pumping for production is not the only way to create the pressure reduction needed for gas to form. Dissolved methane can exist in the groundwater near a water bore. When the water bore is pumped, water pressures in both the bore and the adjacent formation are decreased. Such a decrease in pressure can lead to methane degassing (if the dissolved methane reaches its saturation level at the corresponding pressure) as water is drawn into the bore. Pressure declines due to pumping are exacerbated if the pumping rate is increased or if adjacent water bores start to overlap and interfere with each other or if pumping continues long-term. These declines in pressure could lead to enhanced methane degassing from increasingly larger areas around the bores.

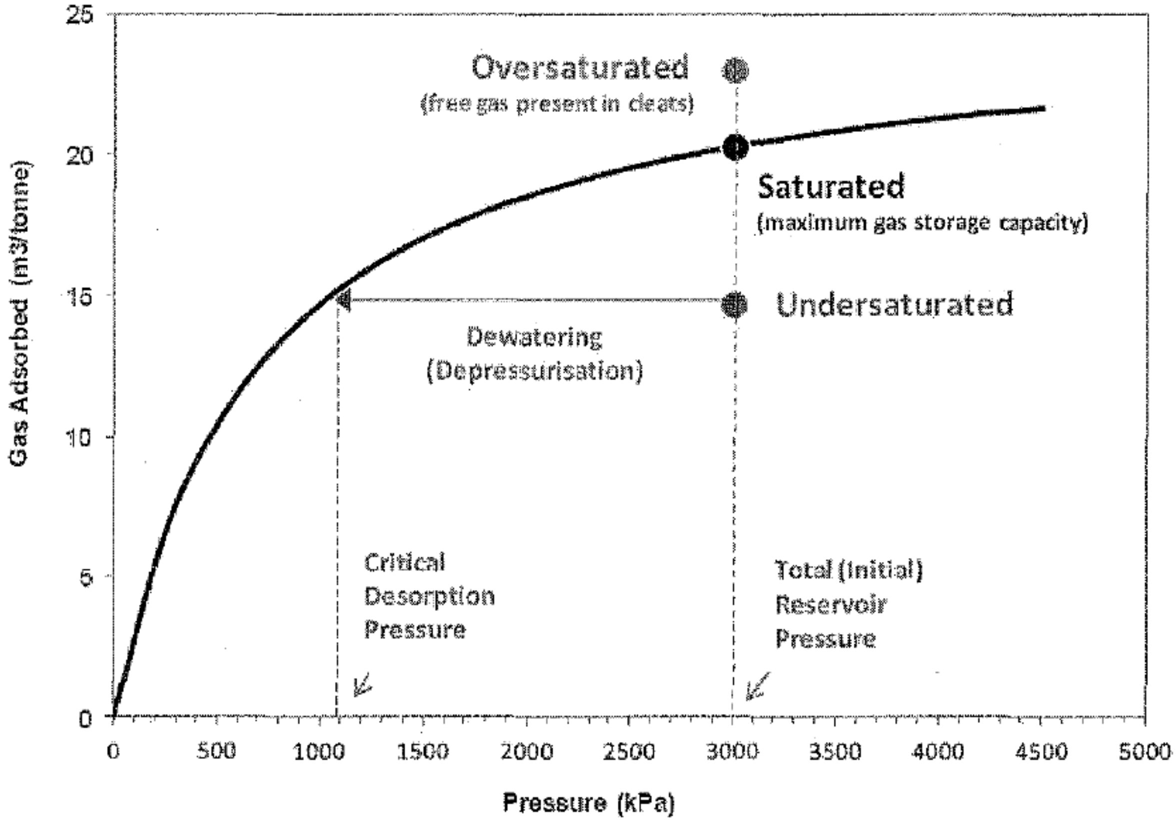

Figure 9 Gas desaturation curve in relation to coal gas saturation (Source: Sydney Catchment Authority, 2012).

Finally, water will undergo a pressure reduction as it moves through the CSG well towards the land surface, resulting in a reduced head of water. This can cause gas release under natural conditions.

2.4.3 TRANSPORT MECHANISMS FOR METHANE

The main transport mechanism for methane in groundwater is by advection. Advection is the movement of the compound (methane in this case) with the bulk fluid phase. Where methane is present in its dissolved form, it will be carried by the water it is dissolved in. The water will move in response to a change in hydraulic gradient (combination of pressure and gravity); the amount of fluid carried is a product of the gradient and the hydraulic conductivity. The hydraulic conductivity represents the ability of the material to transmit water. Larger gaps or fractures within material can conduct larger volumes of water. In general terms, aquitards and cap rocks (e.g. clays and shales) have low conductivities, while aquifers and reservoirs (e.g. sands and sandstones) have high conductivities. Under natural conditions, groundwater will move from recharge or outcropping areas (often higher land) to discharge areas (which could be in the form of springs, streams, ocean and low-lying land). Water will move laterally through aquifers and vertically across aquitards in response to pressure changes (Figure 10).

The main difference between the movement of dissolved gases and free gases is buoyancy. Gases tend to move from high pressure to low pressure but also tend to rise due to buoyancy in water. Advective free gas migration from a point source to the surface can only occur when a continuous free gas phase path is established through an otherwise water-saturated rock matrix. Gas will preferentially invade the largest pore spaces. These have the lowest threshold capillary entry pressures, which makes it easier for gas to enter. Permeable horizontal bedding planes can often have the large pore network necessary for stray gas to migrate both laterally and vertically toward the surface. Highly inclined fractures can also provide a vertical pathway.

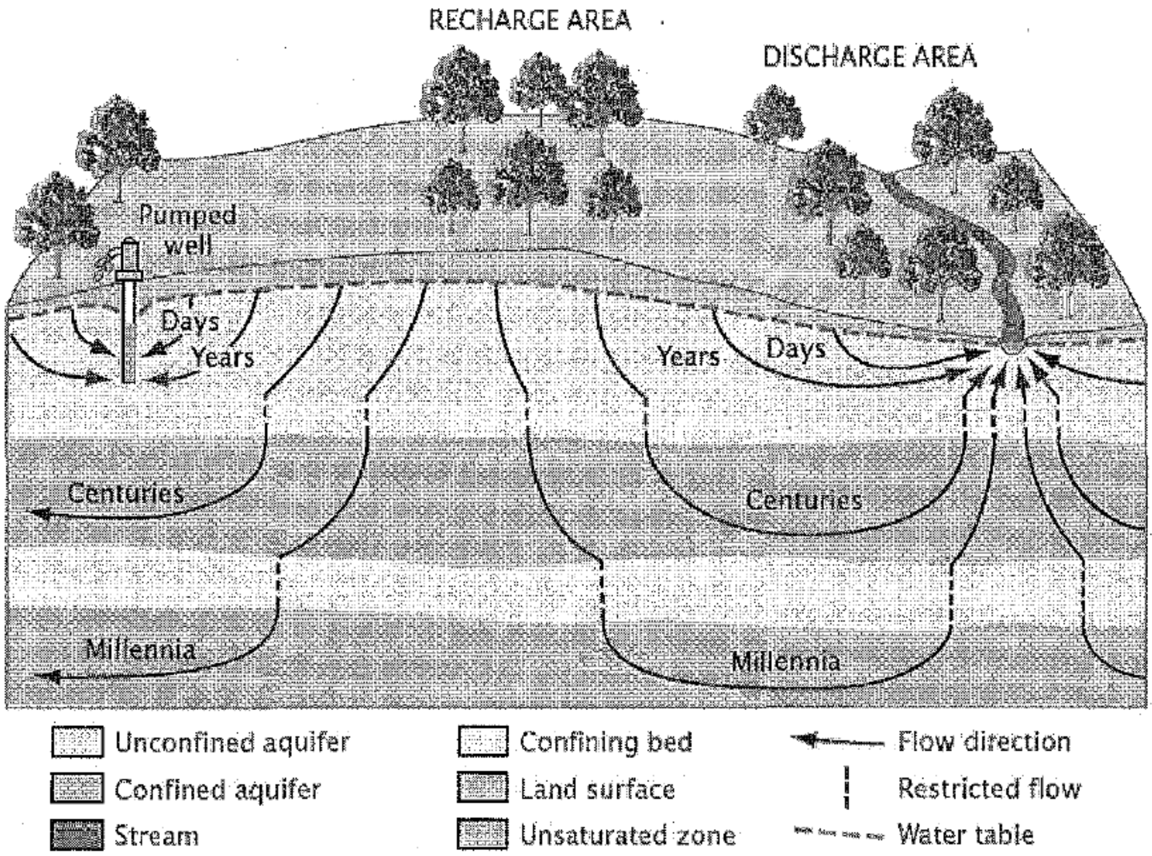

Figure 10 Idealised cross section showing groundwater flow paths from recharge to discharge areas. An unconfined aquifer below the water table flows into a stream. Below that, two confined aquifers are renewed over much longer time scales (Source: CSIRO, 2011).

Rather than gas migration via continuous air pathways, pulsed migration is a dynamic process of free gas movement in pulses through air pathways which intermittently open and close. In pulsed migration, there is a constant competition between capillary forces and gas migrating under pressure through the subsurface. Free gas discharges at the surface in both seeps and affect water bore headspace gas concentrations. The gas breakthrough temporarily releases pressure along the migration path. This allows water to imbibe along the migration path and shut off gas flow. Subsequent pressure build-up at the source then acts to drive water back out of the capillary spaces, re-establishing flow to the surface. Such dynamics can lead to highly variable headspace concentrations of methane. This can lead to pulses of gas in the bore headspace or at least highly variable concentrations. Once the source of gas pressure is mitigated, maximum headspace gas concentration also rapidly declines in a series of pulses.

Depressurisation can lead to gas bubbles migrating to larger pores. This will then block water flow through the larger pores, and reducing the hydraulic conductivity of the aquifer. Thus, an event of gas migration can lead to a reduction of water flow, possibly to water bores.

Advection and buoyancy will lead to the transport of methane from the source of gas to zones of groundwater discharge. In doing so, there can be mixing of water and methane, as pathways coincide. The mixing of water will lead to concentrations of any constituents being between the respective concentrations of the different sources.

2.4.4 METHANE CONSUMPTION

Methane concentrations in groundwater can vary considerably depending on the rate at which it is consumed by bacteria. The domestic bore environment is generally oxidizing, with a strong oxygen gradient between the air-water interface and the bottom of the bore. Due to poor water bore maintenance practices, high concentrations of bacteria can form. These compete for available dissolved or chemically bound oxygen. Many of these bacteria consume methane as a source of carbon to build proteins, and effectively do so at very high rates.

Similarly, when fugitive methane migrates upward along boreholes of oil and gas wells, it may migrate into shallow aquifers or pass through overlying soil to the atmosphere. In a field study near Lloydminster, Alberta, Canada, Van Stempvoort et al. (2005) found hydrogeochemical evidence that such fugitive methane from an oil well had been attenuated by bacterial sulphate reduction under anaerobic conditions. The results supported an interpretation that in situ bacterial oxidation of methane has occurred, linked to bacterial sulphate reduction.

Similar conclusions were made by Gorody et al. (2005) for the San Juan Basin. Available data indicate that anaerobic methane oxidation in the presence of dissolved sulfate ions is the dominant metabolic mechanism in water bore environments. It was also shown that dynamic water bore environmental conditions significantly affect dissolved methane concentrations. Therefore, the amount of residual, oxidized methane present at any given time can be expected to vary significantly, depending on the rate of methane oxidation compared to the rate of fresh methane influx.

2.5 Impact of water, oil and gas development

There are two main ways in which hydrocarbon extraction development has affected the movement of methane. The first is depressurisation that leads to increased gas production and desorption of methane into water. This has been discussed previously.

The second way is by making conduits through the stratigraphic units by water bores or gas production wells. Such borehole breaches present a number of opportunities for leakage of fluids in the vertical direction. Higher heads at depth could transport dissolved gas vertically, while buoyancy effects, and perhaps excess gas pressure, could cause bubbles or stringers of free gas to migrate upwards. Leakage of CO_2 to surface via existing boreholes is the greatest risk to loss of containment in carbon capture and storage monitoring risk registers.

The ability of the fluids to move vertically depends upon the integrity of the borehole. Leakage could occur, for example, through cracking of the cement, cracking or corrosion of the metal casing, poor seals due to poor completion or degradation of materials. The impact of commercial gas operations on natural gas migration from coal seams to the surface can be nearly instantaneous. Buoyancy rapidly drives gas upward through the nearest and largest permeable paths. The free gas phase may migrate up-dip towards the surface along possible pathways including shallow bedding plane boundaries, permeable shallow aquifers, and shallow fractures as well as manmade structures. The USA experience has shown that methane escaping from a problematic commercial oil and gas well is most likely to surface within a 1 km radius of such a point source (Alberta Environment, 2009).

The USA experience has tended to indicate that older bores producing oil and gas from deep conventional reservoirs are more likely to provide gas migration pathways to the surface than shallower and newer coal seam gas wells. For example, in the La Plata County part of the San Juan Basin, approximately 20% of the conventional wells required remedial cement or were plugged and abandoned, while during the same period, approximately 3% of the coalbed gas wells were found to require remedial cementation or were plugged and abandoned (USEPA, 2004). In the Animas River valley groundwater aquifers were contaminated with methane migrating from historic bores that had an uncemented annulus in contact with the Fruitland Formation (Chafin et al., 1993; Chafin, 1994). After leaky point gas sources are remediated, the effect on near-surface gas seepage is also nearly instantaneous. Gas bubbling tends to cease quickly, and areas affected by seeps are rapidly reduced to below detection levels. Declining dissolved gas concentrations in contaminated groundwater plumes, however, may not necessarily be as immediate.

Hydraulic fracturing could also provide preferential conduits for fluid flow. Stimulation of shallow and highly cleated coal seam gas reservoirs often results in horizontal to sub-horizontal fractures that are largely confined to the particular geologic unit (US EPA, 2004). Under some circumstances it might be possible for an induced fracture to propagate as far as an adjacent bore. This is particularly possible where there is a high density of bores. The fracture could then provide a conduit to transmit gases, either as dissolved gas or free-phase gas, between the coal seam gas well and the nearby water bore. There are possible circumstances in which coal seam gas is drawn, through a fracture, to a pumping water bore. This would be limited to situations where water bore and coal seam gas wells are only separated by no more than 200 m.

In a recent review of abandoned wells by the NSW Chief Scientist and Engineer (2014b), reference is made to preliminary results of a collaborative study measuring and comparing methane emissions from various sources including CSG projects and open cut coal mines in NSW and Queensland. At least one abandoned well linked to coal exploration, was found to be emitting methane at concentrations higher than the maximum range of the detection system, at ignitable levels (UNSW, 2014).

2.6 Forensic analyses

The purpose of forensic analyses is to identify causes for any changes to the baseline information target mitigation measures and ensure these measures are working. In some cases, the identification may need to be unambiguous, data defensible and there may be the need to prove that any threat is removed.

An important part of any interpretation is the identification of distinguishing features of the different possible sources of methane. Different types of analytical methods can be used to help determine if a methane gas is of biogenic or thermogenic origin, or a mixture of the two. The analytical methods used to differentiate between the two types of methane are well-known, scientifically accepted, and summarized in Kaplan et al. (1997). Some publications refer to this as 'fingerprinting' (Coleman, 1989; Tilley and Muelenbachs, 2012). Generally, sources cannot be characterised in a unique fashion as the name 'fingerprinting' suggests. However, isotopic composition of methane is very different dependent on the form of methane formation.

Biogenic gases produced in situ in shallow aquifers are predominantly composed of CH_4 with low $\delta^{13}C$ (−50 to −110‰ VPDB) (Figure 7) and δ^2H values (as low as −350‰ VSMOW). In contrast, thermogenic gases generated at elevated pressures and temperatures are usually composed of methane (CH_4, abbreviated as C_1) and higher alkanes, especially ethane (C_2H_6, abbreviated as C_2) with $\delta^{13}C$ values often ranging between −55 and −25‰. "dryness" (often estimated as the ratio $C_1/(C_2+C_3+..)$) is used to characterise natural gas (Golding et al., 2013). For biogenic gas, the dryness is typically more than 1000 and for thermogenic gas is less than 1000 (Figure 7). These are usually visualised using a Schoell diagram (a plot of ^2H in methane against ^{13}C in methane) and a Bernard diagram (a plot of wetness against ^{13}C in methane). Stable isotope analyses and dryness parameters when used together and visualised through the use of Schoell and Bernard diagrams can be an effective tool to assess the sources of natural gas in shallow aquifers.

The characteristics of the various methane sources can be variable. Large differences between point source gas compositions can occur if source gases invading the shallow groundwater environment are derived from mixtures. It is important to characterise all sources. Also, produced gas samples can have variable isotopic compositions when the completion interval is long. A particularly important source required for the isotopic fingerprinting of gas-bearing formations is the characterisation of $\delta^{13}C$ values of gases in drilling muds recovered from the vertical portion of energy wells (Jackson et al., 2013).

Methane can migrate from thermogenic sources over long periods of time and pervade various formations. Hence, the methane in each formation may be a mixture from different sources. As part of the baseline survey, it would be important to characterise locally the chemical and isotopic compositions of natural gas in all gas-bearing formations. It may also be possible to identify the formation from which gases in water bores have been derived.

The approach in any forensic analysis is to sample potential gas sources within a certain radius of influence and to compare them with monitoring data of free and dissolved gases from affected water bores in baseline and subsequent surveys. If there is good contact between a source of natural gas and a gas seep, then the stable isotopic composition of the free gas phase at the seep tends to correspond precisely to that of the source.

When methane occurs in the dissolved phase, the composition is likely to be affected by the processes occurring during transport such as dilution, mixing and consumption. There are long-established methods for investigating mixing and dilution using hydrochemical methods. Direct mixing between two sources shows up as a straight line when two constituents are plotted against each other with the ends of the straight line representing end-members. It is important to note that direct mixing between two end members is not very common and where it is assumed it is probably often an oversimplification. Emphasis is placed on finding constituents which distinguish different sources. Dilution is also distinguished by ratios of constituents being constant, generally a conservative tracer such as chloride as the denominator.

Consumption requires measurements directly relevant to this process. The chemical effects of bacterially-mediated aerobic and anaerobic methane oxidation can be readily observed on the basis of stable isotope ratios for carbon in methane and dissolved carbon dioxide, and deuterium in methane. Bacteria preferentially consume methane with the more depleted (lighter) isotopes. Accordingly, bacterially-mediated methane consumption leaves a residual pool of dissolved methane enriched in heavy isotopes. Bacterial respiration, on the other hand, generates a dissolved carbon dioxide pool which becomes correspondingly depleted in heavier isotopes. If bacterial methane consumption rates are higher than the rate at which dissolved methane is introduced into a water bore, then methane concentration will decrease, the stable isotopes of residual methane will become enriched in the heavier isotopes, and the stable carbon isotopes in dissolved inorganic carbon will become increasingly depleted. The opposite becomes true if the rate at which methane is introduced into a bore outpaces the ability of bacteria to consume it. Temporal analyses of stable isotopes in methane and dissolved inorganic carbon from water in a bore are necessary to document either variable source methane mixing dynamics or increasing methane concentrations resulting from a contaminant plume (Gorody et al., 2005).

To reduce costs and focus effort on problems, a monitoring strategy needs to be tiered. This could be initially on the basis of whether methane is biogenic or whether there is a threshold value of methane. Initially monitoring should test isotopic composition of methane, other hydrochemical indicators as well as methane and should characterise methane sources and water in bores near production wells. This characterisation should include spatial and temporal variability. Subsequent testing may then focus on bores with thermogenic or mixed methane and where methane concentrations are above a threshold. Where the methane concentration is increasing or if the methane concentration is sufficiently high, a forensic analysis should be considered.

2.6.1 THE SAN JUAN EXAMPLE

Perhaps the best illustration of the power of a well-constructed and tiered baseline survey is that of the San Juan valley, Colorado (COGCC, 2003; Gorody et al., 2005). In 2000, the Colorado Oil and Gas Conservation Commission (COGCC) mandated testing of groundwater bores prior to and following drilling additional wells in the Fruitland Formation. As a condition for obtaining a drilling permit, operators are required to sample the two closest domestic groundwater bores within a 900 m radius of each planned well in the Fruitland Formation. If dissolved methane is detected in a concentration exceeding 2 mg/L, chromatographic analysis of the gas and carbon isotopic analysis of methane carbon is required to determine gas type (thermogenic, biogenic, or a mix of both). If test results reveal biogenic gas, no further isotopic testing is necessary. If the carbon isotope tests result in a thermogenic or mixed signature, annual testing is required. If the methane concentration level increases by more than 5 mg/L between sampling periods, or if the concentration increases to more than 10 mg/L, the operator responsible for testing must submit an action plan to determine the gas source.

As of 2004, over 2000 data records containing measurements of dissolved methane concentrations in groundwater were available in the COGCC database. Groundwater samples had been collected from over 1000 different water bores. Of those, there were 589 sites with multiple water quality analyses. Dissolved methane was measurable at 65% of all bores sampled (Gorody et al., 2005).

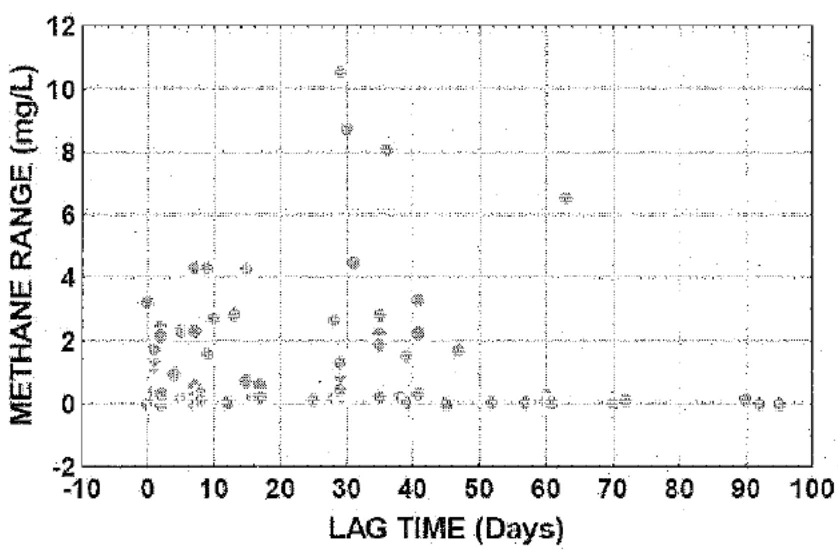

Figure 11 Difference between minimum and maximum methane concentrations in water bores sampled multiple times within a period of 95 days (Source: Gorody et al., 2005).

Multiple data sets from individual water bores also allowed the COGCC to evaluate in detail the factors that influence dissolved methane concentrations in groundwater (Gorody et al., 2005). The COGCC's study showed that methane concentrations in selected bores with multiple sampling results collected within a sampling period of 95 days was variable (Figure 11). It showed that maximum values (MaxC1) differed from minimum (MinC1) values by a factor of 1.14×MinC1 + 0.55 mg/L (Gorody et al., 2005). The long term variability between the minimum and maximum dissolved methane concentration among multiple samples collected at 397 water bore sites in the San Juan Basin exhibited an average variability of +/- 54%. Of 292 sample pairs of water bore samples collected prior to and after drilling, 113 sample pairs had detectable levels of dissolved methane at least once; of those, 52 (46%) had post-drilling methane concentrations that were not lower than pre-drilling values; of those, 14 had post-drilling methane concentrations that were both greater than pre-drilling values and that exceeded the expected variability over the short term; of those, only 10 of the 14 water bores sampled in consecutive years contained more than 2 mg/L dissolved methane; of those, 8 contained biogenic methane. The remaining 2 sites contained methane with stable carbon isotope measurements of thermogenic origin. Detailed analysis of the data from both remaining sites with dissolved thermogenic methane demonstrated that the observed increase in post-drilling methane concentration was not due to drilling new Fruitland wells (Figure 12). Among the several causes for increased methane concentration, a decrease in Na_2SO_4 type fluids available to dilute methane bearing NaCl type waters was reported.

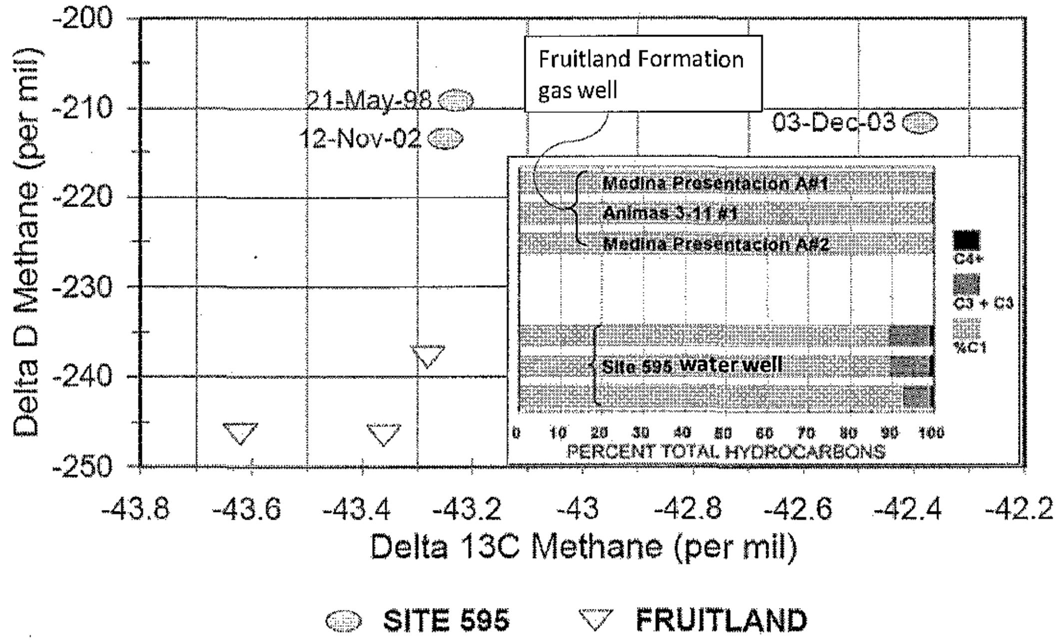

Figure 12 The dissolved gas composition (inset) and the stable isotope composition of methane at site 595 (water bore) methane does not correspond to that in the underlying Fruitland Formation gas. C1 = methane, C2 = ethane, C3 = propane, C4 = butane (Modified from Gorody et al., 2005).

In the San Juan valley the two principal environmental factors controlling methane concentrations in water bores are (Gorody et al., 2005):

- There are numerous, vertically stratified, confined and unconfined aquifers at all locations in the basin. There are four main water types in the basin, which can be described on the basis of major ion chemistry. Most water bores appear to tap more than one of these aquifers even though they may be screened across thin completion intervals. Depending on the relative contribution of water to a bore from any of these layered aquifers at any given time, dissolved methane originating in water from one aquifer can be variably diluted. Alternatively, dissolved methane of different origins can become variably mixed depending on the relative contribution and mixing rates of different aquifer fluids in a water bore; and

- Due to poor water bore maintenance practices, the overwhelming majority of water bores in the basin have been documented to contain in excess of 1 million colony-forming units of bacteria per mL of water. This has led to bacterially-mediated methane consumption of methane, further contributing to methane variability in addition to the variability owing to presence of multiple aquifers with different characteristics.

3 Occurrence of gas in Surat and Bowen basins

3.1 Introduction

The objective of this section is to collate readily available information in relation to gas in water bores prior to CSG developments in the Surat and Bowen basins in Queensland. A historical perspective is important to build up the baseline information, with which to measure subsequent impacts. As with all coal seam gas basins, methane gas has always been present in both shallow and deeper layers in the Surat and Bowen basins (DNRM, 2013). As can be seen through the press clippings (see Historical media reports section 3.2), presence of methane gas has become more apparent as exploration for water, oil and gas has occurred. Not only does the exploration expose the presence of methane during drilling, making its presence more obvious, but the construction of bores potentially provides conduits for methane migration. The subsequent development of these resources leads to potential depressurisation of the aquifers causing gas to desorb from coal surfaces and to exsolve from the water, potentially making methane occurrences more frequent.

Methane will move naturally to the surface through either advection with water or buoyancy. Pathways can be natural, especially through fractures and faults or through man-made conduits such as bores. Natural discharge of methane can then be found at the surface as micro-seeps, bubbles in streams and wetlands or emissions to the atmosphere. Surveys conducted on micro-seepage areas prior to CSG development will be briefly discussed in this section. Although not directly linked to groundwater, such measurement is evidence of gas migrating to the surface and provides clues as to the spatial and temporal pattern of gas in the unsaturated layer. Increased presence of such areas can be a sign of emerging problems with water bores.

The records of drillers are an important first clue to the expression of free gas in water. Not only should drillers be recording presence of gas, but some of the more significant events are likely to have been recorded in the press. While this report also covers evaluations of drilling logs, the section below reports on press clippings and some analyses based around drilling logs.

As groundwater enters the bore under pressure, it can degas. Harris et al. (2012) reports on "Anecdotal evidence from landowners includes references to 'gassy' bores, 'burping' bores, flaring bores and rumours of lighting farmhouses from the gas produced from the water bore. Further evidence is provided from the need to replace bore pumps due to the motors burning out as a result of cavitation when the dissolved gas comes out of solution."

This section will then describe:

1. Historical media or reports related to the topic;
2. Any collated data on gas in bores or during drilling; and
3. Studies on land surface seepage areas.

3.2 Historical media reports

Within this section, we extract some key quotes from media related to the topic. The use of quotes is deliberate as any conversion of the words will inevitably invoke a bias, in this case, to what we understand is the science and what we understand in hindsight.

3.2.1 ROMA 1900 - 1908:

Courier Mail (Brisbane) May 26, 2001[4]:" Since Roma had been gazetted in 1862 as a centre to serve the rich pastoral runs around it, they had been desperately searching for water, the more so since the railway, with its thirsty steam locomotives, had arrived in 1880".

"At Roma in 1900, natural gas blew into a water bore at 1123 metres."

Courier Mail (Brisbane) May 26, 2001: "AT FIRST there was just a rumble -- more of a burp, really -- from deep beneath a little rise somewhat extravagantly known as Hospital Hill. Then, at 1.15pm on October 16, 1900, the wellhead exploded, sending water and mud about 15m into the air above the small collection of stores and shacks known as Roma. Cheering around the drilling derrick soon subsided. Townspeople's noses wrinkled as much in disappointment as distaste. ...Now the air was filled with the stink of natural gas, the water subsiding to little more than a trickle. The government hydraulic engineer pronounced it "swamp gas", good for nothing. It did not occur to anyone that this could be the first indication of vast fossil fuel reserves beneath Australia's wide brown crust."

The Brisbane Courier (Brisbane), Saturday 8 December 1900, page 11: "The Water Supply Department intended to take measures to separate the gas from the water, and convert the flow from the two bores into one flow, which will be available for the use of the townspeople. If the efforts to be made to secure the gas be successful, it will be possible, it is hoped, to use it for illuminating purposes, which will be incalculable advantage to Roma. The idea, so far as it can be surmised, is to put a pipe down inside the casing to a spot below the stratum, which now furnishes the water, so as to intercept the gas, and thereby conduct it to the surface through the pipe in the water. Once this is successfully accomplished, it will be easy to connect the pipe with a gasometer, and from that storage, the gas can be conveyed to any part of the town."

Courier Mail (Brisbane) May 26, 2001: "After that first strike, for instance, Roma and the state government squabbled for six years before deciding to light up the town with natural gas lamps and fittings. Came the big day and Roma dazzled its citizens and wildlife alike with brilliant light until, 15 days later, the gas ran out. It had been allowed to gush freely into the atmosphere for those six years".

Figure 13 shows a picture of an apparatus for separating natural gas from artesian water.

3.2.2 ROME BORE 1908

Western Star and Roma Advertiser (Toowoomba), Wednesday 28 October 1908, page 2: "When the man in charge of the shift noticed that the water was gradually rising over the casing. Then he noticed that the water had become less in volume and was impregnated with air or gas...when suddenly the beam bearing the weight shot up , and an immense volume of gas rushed from the mouth of the casing with a terrific roar...Perhaps for a quarter of an hour it continued thus, when suddenly , with an explosion similar to the discharge of a canon, the gas was converted to flames... the flame shot up to a height of 40 feet or more and none could nearer to it than 50 yards, so intense was the heat...The flames consumed everything , and including the engines...It was remarkable that the immense flames were for a long time unaccompanied by smoke, but in a few hours, the flames were discoloured by black smoke, and the fierceness with which they

[4] http://www.energyandresources.vic.gov.au/earth-resources/geology-of-victoria/exhibitions/history

roared was greatly intensified. The change was attributed to the presence of petroleum in large quantities...The first and only thing to be done now is to find a method of extinguishing the fire."

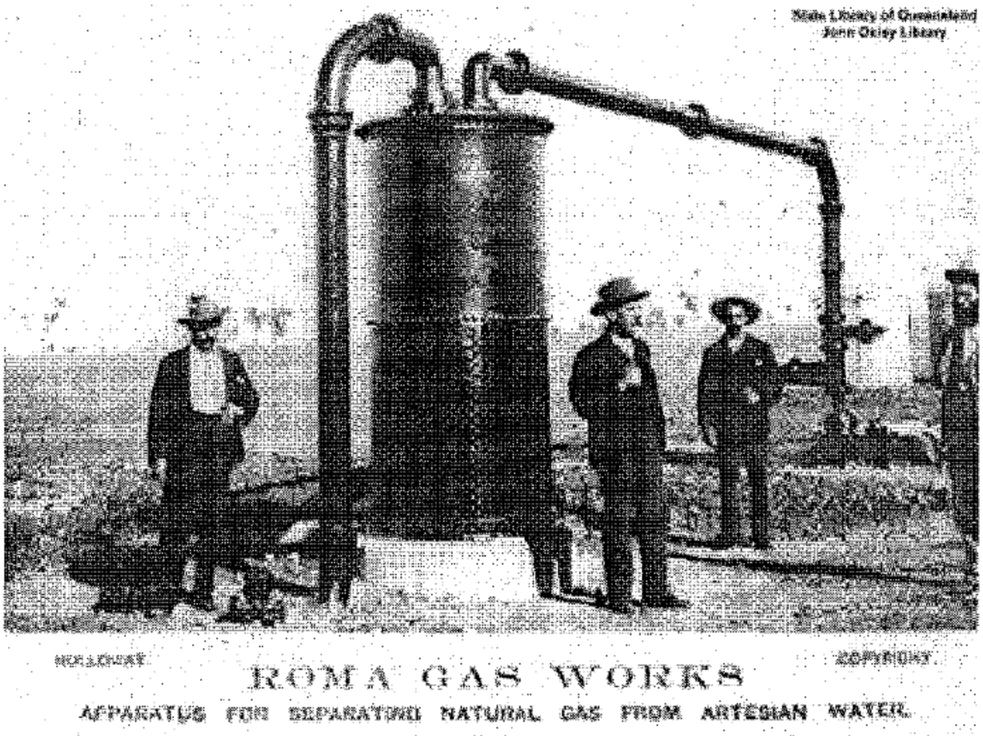

Figure 13 Apparatus for separating natural gas from artesian water at the Roma Gas Works, Queensland, ca. 1906 (Source: State Library of Queensland, John Oxley Library, -26.573429, 148.787323)

Cairns Morning Post (Cairns), Friday 30 October 1908, page 5: "He attributed the outbreak to the wind driving the gas out of the fire under the boiler....Mr Taylor said that kerosene in abundance was coming from the bore".

Courier Mail (Brisbane) May 26, 2001, Saturday: "The year 1908 saw the beginning of Roma's tourist industry. People from hundreds of kilometres around arrived by train, car, horseback or buggy to see a huge gas fire caused when a drilling operation, financed in part by the Queensland government, allowed escaping gas to be ignited by a steam boiler. The blaze lasted 46 days. Three years later the operating company went broke although the well remains a source of water for the town."

3.2.3 SEARCH FOR OIL IN QUEENSLAND FROM 1908 TO 1960'S (1908-1960)

Sydney Morning Herald (Sydney) March 8, 1988 Tuesday: "During the early 1900s, several eminent geologists believed Australia too old, geologically speaking, to have formed substantial oil or gas deposits. Others preferred to believe their eyes and mounted extensive drilling campaigns based on the occurrence of true seeps and inflows of oil and gas into water bores, particularly around Roma,"

Courier Mail (Brisbane) May 26, 2001;" With the motor car beginning to dominate private transportation, the 1920s saw an "oil boom" – something like 46 companies and fortune-seeking American drillers sinking holes all over the countryside. One of them brought in large quantities of light oil which, refined locally, was sold during the Great Depression as Roma petrol ".

The Northern Miner (Charters Towers), Saturday 13 November 1920, page 3: "The recent blow of gas at Roma has once more awakened interest in the possibilities of obtaining petroleum in Australia. The gas was induced to flow by lowering the head of water in the bore. The bore had been drilled 'wet', that is it was kept full of water, and when the American driller who was in charge struck the gas rock he reported it as a "small gas show". ..The pressure in pounds per square inch due to the water column in a bore is found by measuring the depth in feet and multiplying by 0.434 which is the weight in pounds of a column of pure water one square inch in section and one foot high, as that, taking the Roma bore, with a depth of 3700 feet we get a result of 3700 x0.434 per sq inch on the bottom of the bore. In order to overcome this pressure, and force the water up out of the bore, the gas pressure would need to be higher. The water level was lowered a few hundred feet at Roma, and the back pressure on the gas was thereby reduced to such an extent that the gas blew out"

The Western Champion (Barcaldine), Saturday 11 March 1922, page 17: "Dr H. I. Jensen, a geologist in the Mines department,... provided an interim report on leases ..20 miles west of Tambo... that no appreciable amount of oil has been found in boring for artesian water strongly discounted the chances of getting oil in payable quantities in the marine cretaceous".

The Western Champion (Barcaldine), Saturday 2 August 1924, page 16: "Turning to the evidence of petroleum. These are generally displayed in the form an evolution of inflammable gas, or the presence of an oily film on the surface of the water. This direct contains many evidences of this nature in the form of discharges of gas from artesian and sub-artesian wells... gas issuing with water ..certain proportion of liquid petrol in suspension..paraffin wax has been coming up.. appreciable discharge of inflammable gas. .. it must be remembered that ...a bore 3000 feet deep would have a pressure of roughly 1500 pounds to the square inch on the bottom.. if the water was excluded, and the bore bailed dry, the gas would come out in enormous quantities, at a pressure over 1000 pounds per square inch. .. this writer hopes to see at no distant date, some use made of this cheapest and best of nature's fuels, .."

Western Star and Roma Advertiser (Toowoomba), Wednesday 21 October 1925, page 1. "the evidence to date suggests there is still quite a possibility of tapping low-pressure oilbeds in either Roma or the Longreach-Windorah area, but the methods at present used in boring for water would tend to drown out any low-pressure reservoirs of gas or oil".

The Longreach Leader (Longreach), Friday 29 July 1927, page 30: "Mr J.W.Booker who was working on the Westland artesian bore... submitted to the Department of Mines several samples of oil indications for analysis ..Two samples were taken by submerges and displacement but the Government analyst's report dispelled any hope of its being petroliferous- the results were .. methane 89.1 percent and 87.4 percent.."

The Brisbane Courier (Brisbane), Thursday 13 September 1928, page 16: "The head driller ..has fixed a contrivance on the town bore which supplies the town with water, giving greater freedom for the gas to escape. When ignited, there is a continuous flame 5ft. or 6 ft. high".

The Queenslander (Brisbane), Thursday 19 September 1929, page 62:" In an interview with Dr H. I.. Jensen.. That the Walloons are the source of the oil manifestations at Roma is more than likely, because of the presence of traces of oil in many horizons of the upper, middle and lower Walloons, the wide gas development in pockets, .."

The Longreach Leader (Longreach), Friday 17 October 1930, page 10;" Water bore at Mitchell: A rush of gas, which immediately caught fire, was encountered during well-boring"

The Charleville Times (Brisbane), Friday 9 January 1931, page 10: "When the owners of Ruthven were notified of the oil in the bore sunk for water, they order the contractor to case it out and go on for water...

Sheep won't drink oil; it's water we want ...about ten miles east of St George. The natural gas met with at Eromanga is a pure methane gas."

The Charleville Times (Brisbane), Friday 23 January 1931, page 10: "The natural gas from Eromanga is 96.4 percent methane... Natural gas migrates more easily than liquid hydrocarbons. Where there are no water troubles, a well drilled to the upper surface of the oil sands, the release of pressure is so great, and causes readjustment of equilibrium between the various hydrocarbons that the simpler and lighter compounds, chiefly, gaseous, enter the well in great and increasing quantity before any oil, except perhaps for the merest light filtrate, can reach the bore. This may take place, before the oil-bearing sands are actually tapped, as was the case in the Roma bore"

Townsville Daily Bulletin (Townsville), Friday 15 June 1934, page 12;" The men employed by the Collinsville Colliery Company resumed work on the mine at Scottsville on Tuesday last week. Operations are to be confined to those parts of the property accounted free from any suspicion of deleterious gas emanations until adequate means are adopted to guard against any possible harmful results in exploiting other sections of the coal seam."

The Courier-Mail (Brisbane), Friday 16 June 1944, page 4: "Analysis of gas from a sub-artesian bore in the Chinchilla district shows that it is of a much higher value than ordinary domestic coal gas".

The Courier-Mail (Brisbane), Wednesday 15 November 1944, page 6;"Mr Gair said inflammable gas given off by the shallow coal seams in the Chinchilla district was rather irregular and there was no evidence that the volume reached normal commercial requirements, although it was understood to have been used to drive a small internal combustion engine."

The Central Queensland Herald (Rockhampton), Thursday 20 March 1952, page 4: "An old oil bore eight miles from Roma broke a nine-ton concrete seal this morning and hurled a column of gas and water 120 feet into the air".

The Courier Mail (Brisbane) March 8, 2008 Saturday: A little over 55 years ago four men drilling for water near Chinchilla sparked an explosion that reverberated around the world. They didn't know it at the time but they had spiked a massive methane gas chamber trapped inside an underground coal seam. When one of the men lit a cigarette, the blast sent them flying through the air. The Brisbane Telegraph reported that a 15m flame burned for weeks before a crack team of mining engineers from the US was able to cap it.

Morning Bulletin (Rockhampton), Saturday 9 January 1954, page 4: "drillers and boring inspectors had found gas and oil or wax with a flow water in numerous bores in the Surat Basin near Tambo and along the northern and western margin of the Eromanga Basin".

3.2.4 POST 1960'S

The Associated group discovered gas in 1960 at Timbury Hills-1 near Roma in the Surat Basin. It took until 1969 before that gas flowed by pipeline to Brisbane. However, in 1961, a joint venture of AOG, union Oil and kern County Land, drilled Cabawin-1 in the same area and flowed oil at 80 bopd. Although not commercial, this discovery provided encouragement for the JV to drill Moonie-1. Moonie-1 flowed oil and water at 500 bopd and was to be Australia's first commercial field."[5]

Sydney Morning Herald (Sydney) March 8, 1988 Tuesday: "Nevertheless, the doubters were finally disarmed by the fabulous run of discoveries in the 1960s, beginning with gas at Roma and oil at Moonie and

[5] http://www.energyandresources.vic.gov.au/earth-resources/geology-of-victoria/exhibitions/history

ending with both oil and gas in Bass Strait. Suddenly, Australia had earned a place among the international oil producers and the term "self-sufficiency" was heard for the first time. Nevertheless, the search is continuing and discoveries are still being recorded in regions such as the Eromanga Basin of Queensland and the Timor Sea. .."

Courier Mail (Brisbane) May 26, 2001, Saturday : "The post-World War II era saw a revival of the search for gas but it was not until 1969 that sufficient reserves were found in the Cooper Basin to warrant a pipeline to Brisbane and Gladstone."

3.3 State reports

In this section, we describe state reports relevant to the topic.

Gray (1967) reported on an investigation of an incident in which gas blew out from a water bore drilled near Brigalow on the eastern flank of the Surat Basin. The blowout reached a maximum height of 30 feet and lasted for approximately 40 hours before dying out.

DNRM (2011) reported on a number of occurrences of gas in water bores within 5 km of the Davis property, 15 km south of Chinchilla, prior to coal seam gas development. "Anecdotal records of gas in bores in this particular area date back to 1916. In the GSQ Publication Number 299, Occurrence of Petroleum and Natural Gas in Queensland, 1960, Brown's Scout Bores numbers 1 and 2 (now referred to as RN 22020) were drilled in 1929 to "investigate the possibility of petroleum in the area", as "gas under pressure had been reported from a water bore on the same portion in 1916" (page 18). A copy of this page of the publication is included on water licence file TMB/515/004(2353). Number 1 struck a small quantity of gas ... and number 2 struck a better gas show ... Further evidence of gas in water bores is summarised in Table 1.

Figure 14 shows a map of the occurrences of Petroleum and Natural Gas in QLD as of 1960 (Geological Survey of QLD, 1960). This map was compiled by the Geological Survey of QLD and the QLD Department of Mines. This map extends beyond the Surat and Bowen basins, but does show many sites within this area.

Table 1 Evidence of gas in water bores (DNRM, 2011).

Bore #	Date drilled	Evidence of gas
RN 8642	1938	Gas was evident in the bore by 1966, but it is not known how early gas was blowing from the bore
RN 10790	1946	In a letter to the department, the licensee noted that the bore started blowing gas in 1960
RN 24465	1946	Gas was evident in the bore by 1966, but only in very humid weather
RN 13600	1958	Gas was evident in the bore at the time of drilling
RN 14042	1958	Gas was evident in the bore at the time of drilling
RN 48528	1966	On a renewal dated 1996, the licensee noted that the renewal was not required as the bore produced too much gas
RN 24485	1966	Gas was evident in the bore later that same year, but it is not known if it was evident at the time of drilling
RN 33553	1969	Gas was evident in the bore at the time of drilling
RN38191	1971	Gas was evident in the bore at the time of drilling
RN 107762	2001	Gas was evident in the bore at the time of drilling

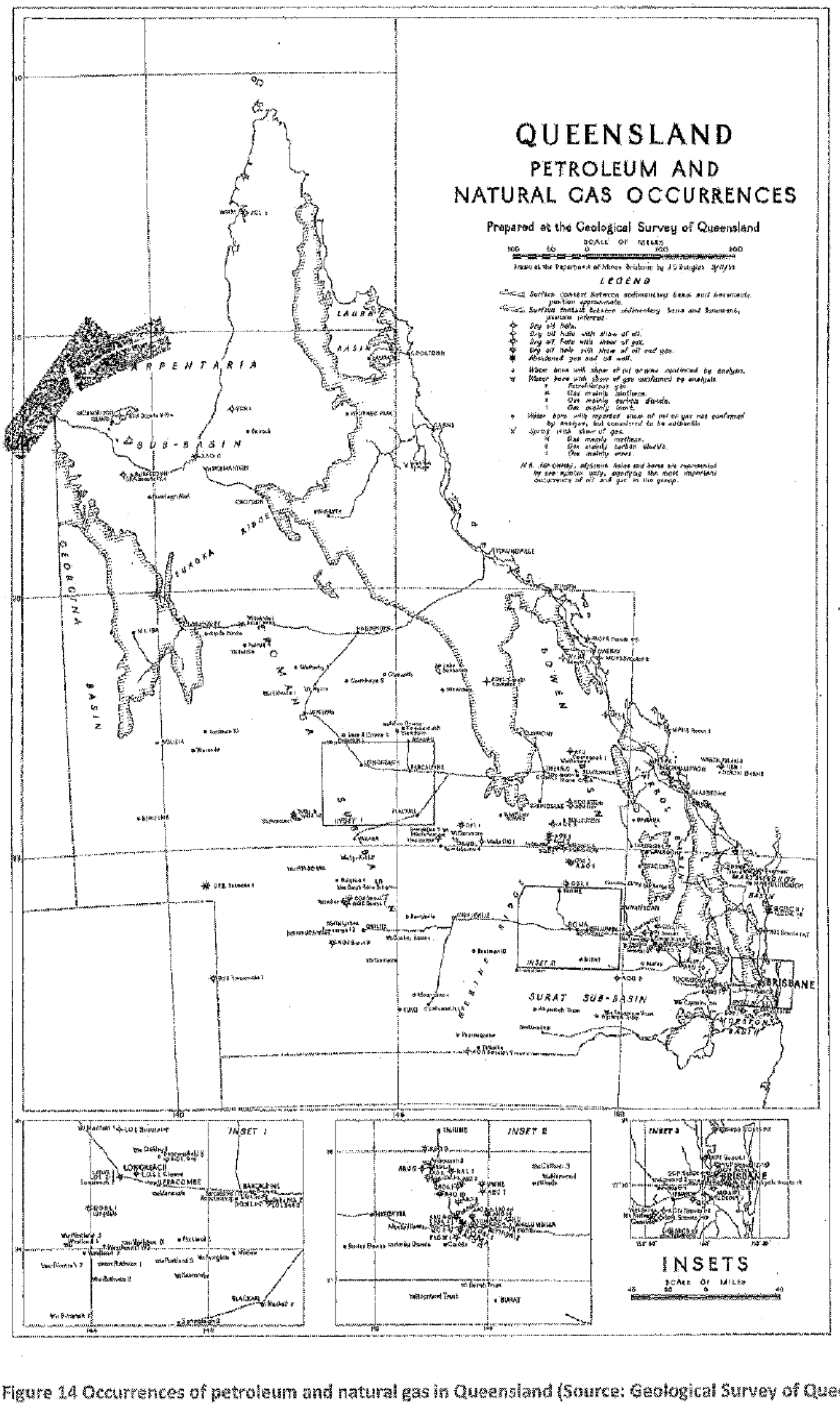

Figure 14 Occurrences of petroleum and natural gas in Queensland (Source: Geological Survey of Queensland, 1960)

3.4 Micro-seeps

Methane gas seepage refers to the diffusive flux of methane to the atmosphere through the land surface and water bodies, the localised flux of methane via connected pathways consisting of leads, faults and outcrops and the flux from agricultural bores. Seepage does not consider the fugitive emissions of methane occurring as part of open cut and underground coal mines or emissions occurring from infrastructure (wells, compressors, associated water reticulation, or gas pipelines) associated with coal seam gas production. A comprehensive review and analysis of literature on methane detection and flux determination is provided in Day et al. (2013). The review is part of a Gas Industry Social and Environmental Research Alliance (GISERA) project addressing the location and quantity of background methane emissions in the Surat Basin, Queensland, Australia.

Micro-seepage areas are often naturally occurring parts of the land surface, where methane escapes to the atmosphere. Generally, methane reserves would diminish over geological time, if much methane escaped to the surface through low permeability layers. Nonetheless, some gas is always likely to escape. This is likely to occur through fractures, faults or through up-trending or outcropping geological zones.

As new pathways are created or as depressurisation leads to increased fluxes, it might be expected that new seepage areas are created and that old ones may move or increase. Where there is a change, it is possible that this may become a risk to infrastructure including water bores, as seen in San Juan valley in the US, including water bores. Soil surveys can prove to be informative about the fluxes of methane through such seeps.

Historically, gas surveys have been conducted to provide information about possible production sites. The underlying principle for this method goes back nearly eighty years. It assumes that there is a migration pathway from a source of gas most likely by micro-bubbles going through micro-fractures driven by buoyancy forces. The method also relies on anomalous measurements against the broader background on the belief these were associated with reservoirs and migration pathways.

DNRM (2013) reports on 13 soil gas surveys within the Surat Basin. These soil gas surveys have been sampled below surface at depths down to 2 m. In many investigations hundreds of samples were collected. Many of these studies tested for other light alkanes – ethane, propane and butane. A few investigations measured above ground gas concentrations, using a helicopter flying at 5 to 10 m above ground surface, providing qualitative measurements. In some cases, they were able to correlate anomalies with faults and low measurements with wet weather (saturated soil).

Methane seeps may be distributed over very large areas of covering thousands of square kilometres and consequently some method of surveying a region is required for detecting the presence of individual seeps. One method is to use a vehicle fitted with a methane analyser (an Apogee leak detection system based on an infrared spectrometer) to detect elevated ambient concentrations of methane. When higher levels of methane are found, the source can be traced and other methods such as soil gas analyses and flux chambers can be used to characterise the seep. Figure 15 shows an application in Queensland where a vehicle is driven through the plume to measure ground level methane concentrations (Day et al., 2013).

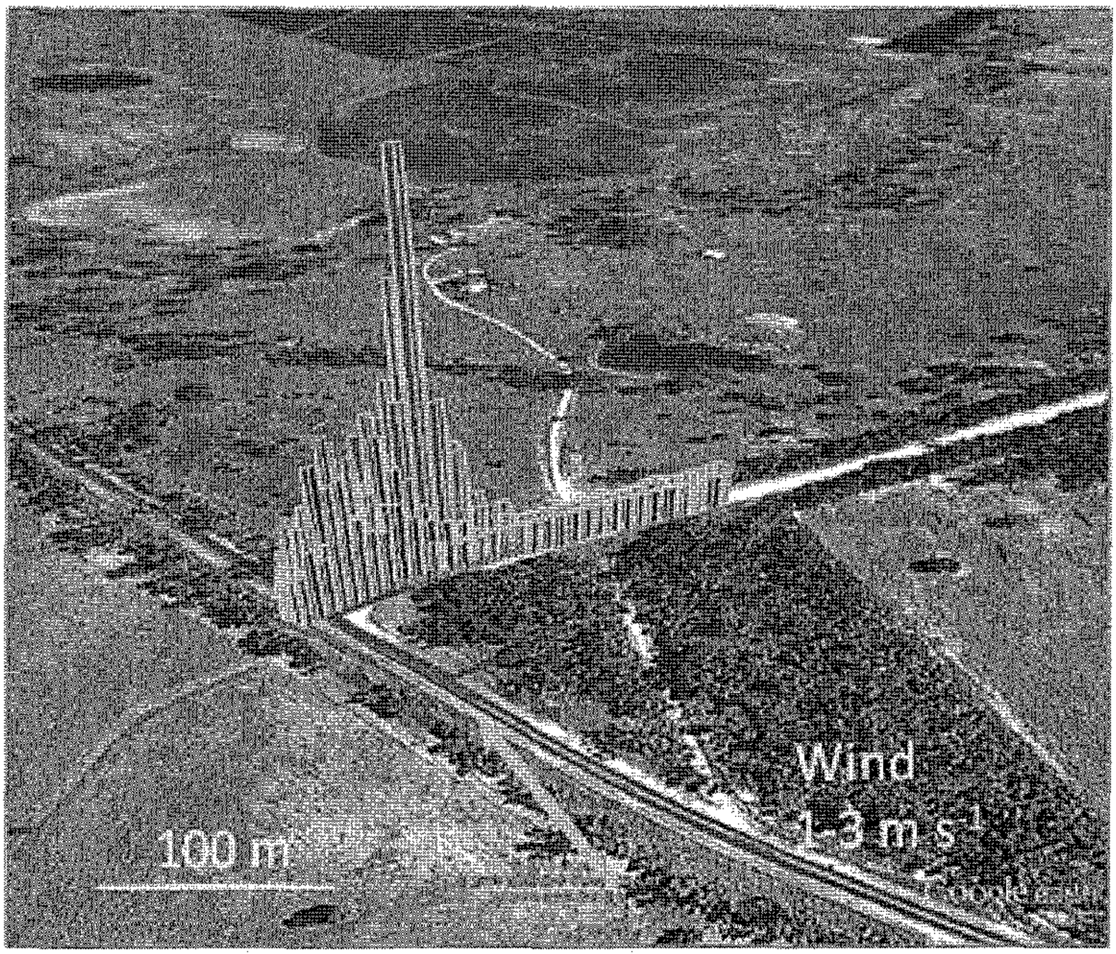

Figure 15 Methane concentration profile within a plume derived from a methane seep in Queensland (Source: Day et al., 2013).

3.5 Baseline surveys

An amendment to the Queensland *Water Act* requires proponents to undertake baseline assessments of water bores prior to the commencement of petroleum activities. These data are collated by the Office of Groundwater Impact Assessment within the Queensland government. This section reports on these data as it relates to methane. Figure 16 shows a map of the Surat Cumulative Impact Area with the dissolved methane measurements in groundwater from the baseline surveys. Harris et al. (2012) report on a subset of these surveys, but also include bore-head concentrations, which show a similar spatial distribution. They also show that methane exists in most formations at high concentrations. The collated baseline data shows a similar picture for the formations but the absence of formation information supplied by some of the proponents means that there is not much more information than in Harris et al. (2012). Harris et al. (2012) also reported on gas shows as found in drilling records within the Queensland government.

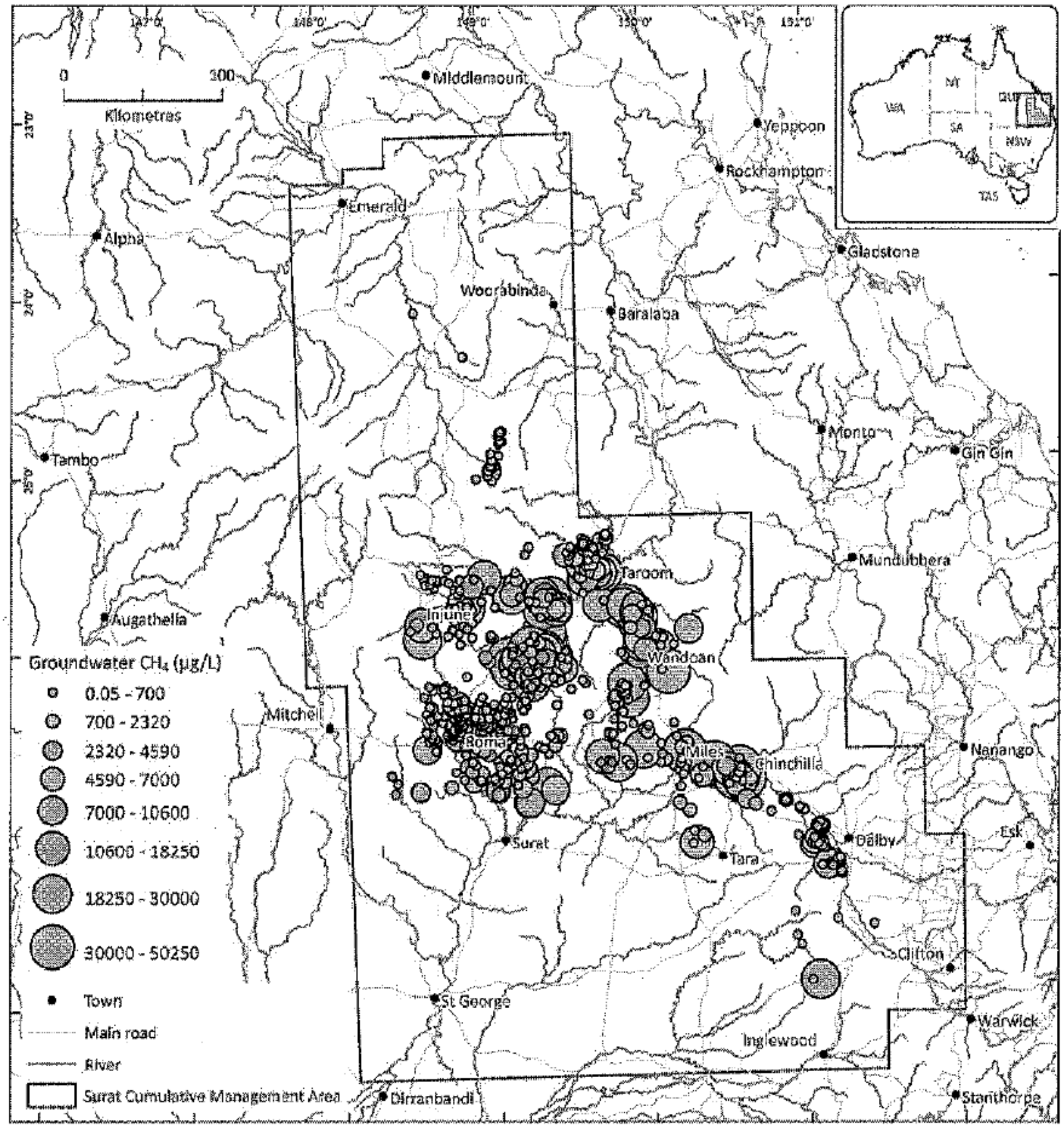

Figure 16 Map of the Surat Cumulative Impact Area with the dissolved methane measurements in groundwater from the baseline surveys (Data source: Queensland Water Commission, 2012).

Feitz et al. (2014) released a regional baseline set of hydrochemistry for the Denison trough and Surat Basin as a basis for developing future site-specific and semi-regional monitoring and verification programmes conducted by geological carbon capture and storage proponents. A map of methane concentrations as free gas is shown in Figure 17. This shows the presence of gas across the southern part of the region.

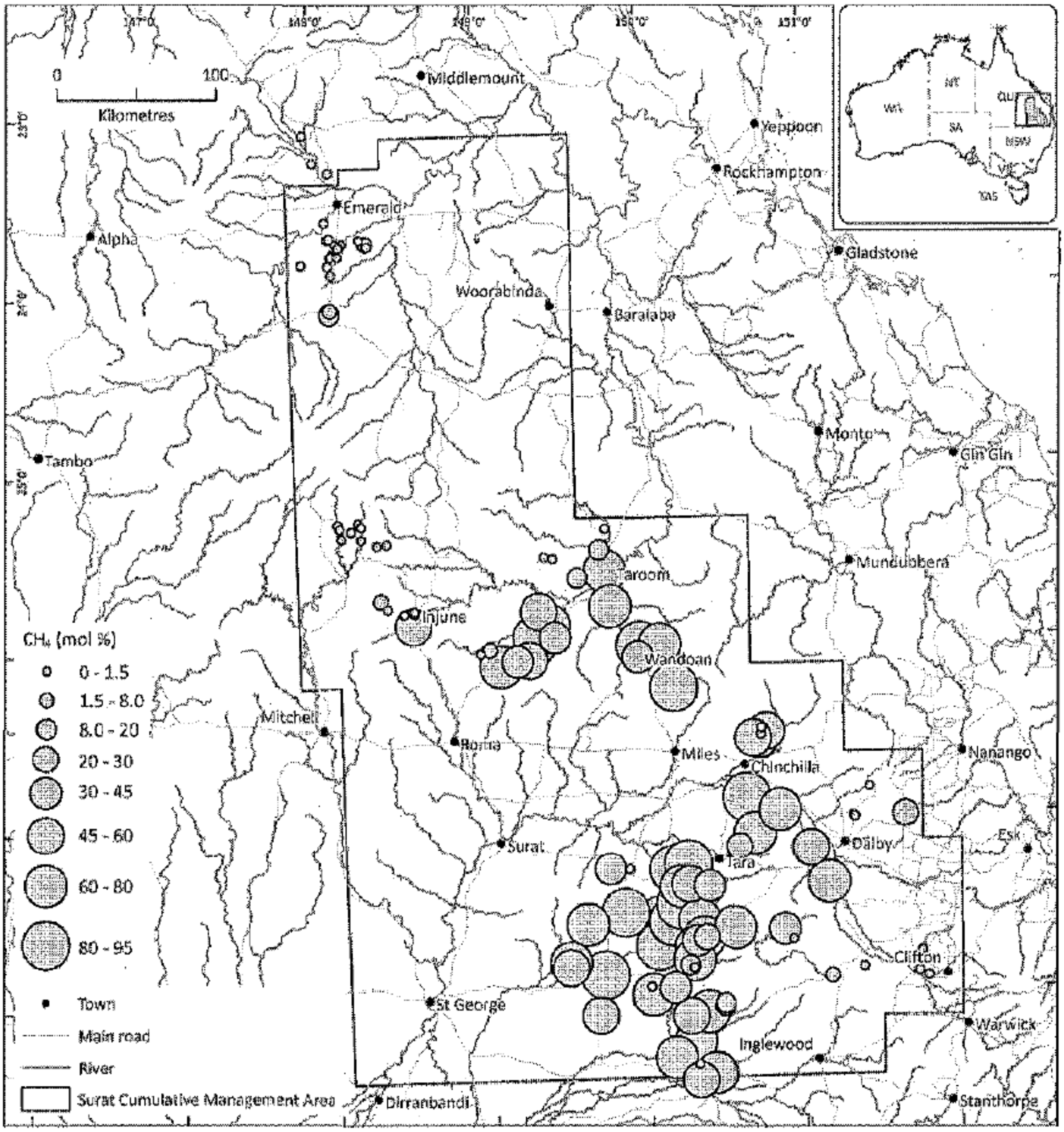

Figure 17 Map of the Surat Cumulative Impact Area with methane measurements in groundwater (methane concentrations as free gas) from a regional baseline set of hydrochemistry (Data source: Feitz et al., 2014).

3.6 Summary and Conclusions

This section has tried to look at various forms of information, as they exist without overlaying these with scientific interpretation. Generally, the information is consistent with the scientific picture that has been painted in other sections. More specifically:

1. Gas has been found historically when drilling for water and in water bores both in dissolved form and as free gas;
2. Gas is found in all geological formations;
3. The concentrations of gas vary in time according to atmospheric and other factors; and
4. Gas is broadly found across the region but is found at higher concentrations above features such as faults and above known gas reservoirs.

4 Relevant studies in Surat and Bowen basins, and elsewhere in Australia

The purpose of this section is to provide a brief description of activities being done or have been done recently that are relevant to this topic in Australia, especially in the Surat and Bowen Basins. The studies collated here do not include Queensland Government studies. Queensland Government has undertaken studies into any concerns over methane in water supplies and many of these have been referred to in previous section. The projects in this section are divided into 3 groups:

1. Methane in water bores;
2. Measurements of atmospheric methane; and
3. Hydrochemistry studies of groundwater.

4.1 Methane in water bores

There are three projects directly relevant to the topic of methane in water bores. These are:

- the Condamine seep study by Norwest/APLNG;
- the CRDC (Cotton Research and Development Corporation) methane baseline study in the Condamine by UNSW;
- the Southern Cross University baseline surveys in northern NSW.

4.1.1 CONDAMINE SEEP STUDY (NORWEST/APLNG)

In early 2012, seeps were reported in four Condamine River locations following a period of heavy flooding in the region. A subsequent Queensland Government investigation into the seeps found no evidence of safety risk or environmental harm. Anecdotal evidence suggests that at least one of the seeps may have been occurring for decades.

Norwest Corporation undertook a preliminary forensic study on behalf of Origin Energy into the causes of these seeps (Baldwin and Thoms, 2014). The region is at the early stages of development and no baseline survey had been previously done. Norwest found that gas originates from deeper aquifers such as the Springbok Sandstone and Walloon Coal Measures. They identified several possible mechanisms which could contribute alone or in combination to the seeps:

- Depressurisation – either from natural causes such as drought, or human activity such as water bores tapping the coal seams, CSG wells, or numerous open coal exploration bores;
- Repressurisation - impact of floods and aquifer recharge;
- Fractures, faults and springs - natural pathways for water and gas; and
- Capping and trapping - geological structures which “cap and trap” natural gas movement.

The Condamine River Gas Seep Investigation: Technical Report (Baldwin and Thoms, 2014) was subject to an independent scientific review coordinated by the Queensland Government’s Chief Scientist Dr Geoff Garrett.

Australia Pacific LNG is currently carrying out seismic survey analysis and constructing eight monitoring bores at four locations near the seeps. These monitoring bores feature real time telemetry data systems and will provide ongoing data on ground water levels and pressures.

4.1.2 CRDC METHANE BASELINE STUDY IN THE CONDAMINE (UNSW)

A project is being led by Associate Professor Bryce Kelly from the University of New South Wales to assess the extent of hydraulic connectivity between the Walloon Coal Measures and aquifers used by farmers in the Condamine Catchment in South-East Queensland. Apart from Associate Professor Bryce Kelly, project members include Professor Euan Nisbet and Dr Dave Lowry, Dr Dioni Cendón based at Australian Nuclear Science and Technology Organisation (ANSTO), and hydrogeologist Mark Hocking. A large focus of this study will be on methane. A baseline survey of both groundwater and the atmosphere (see next section) will be conducted. Professor Euan Nisbet and Dr Dave Lowry, from Royal Holloway, University of London, in association with colleagues from Royal Holloway, will conduct an air quality survey to map the concentration of methane in and around the irrigation districts and CSG production areas. In addition, UNSW researchers will measure the concentration of methane in the groundwater used for irrigation. They will 'fingerprint' the potential origin of the methane, by measuring the isotopes of carbon. As methane can be an indicator of connectivity between aquifers, this is part of a broader study of the connectivity involving examining the chemistry of the groundwater and mapping the geology of the region in 3D, analysing the historical groundwater level and chemical data sets, and examining pumping-impact scenarios. Groundwater from 30 irrigation and observation bores in proximity to new CSG production and exploration wells in the Condamine Catchment have been sampled. Dr Dioni Cendón will lead a team from ANSTO who have for example analysed the major and minor ion chemistry and the isotopes of carbon, hydrogen and strontium in the groundwater.

4.1.3 SOUTHERN CROSS UNIVERSITY BASELINE SURVEYS IN NORTHERN NEW SOUTH WALES

Associate Professor Isaac Santos and his group in the Centre for Coastal Biogeochemistry research have been conducting hydrochemical studies in surface water bodies and groundwater in the Clarence-Moreton Basin in northern New South Wales to better understand how they may be impacted by coal seam gas development in the region (Tait et al., 2013). Much of the work at this stage is to develop a baseline database on the chemical composition of groundwater and streams potentially impacted by CSG exploration. The concentration of methane and associated isotopes are considered a priority. They are also providing a service for landholders to test water samples for methane.

4.2 Measuring Atmospheric Methane

The migration of methane from underground sources often does not end up in the water bores, but escapes to the atmosphere itself. With international concerns of climate change and requirements for greenhouse gas accounting, emissions that occur as a result of coal seam gas and other developments may be a significant contributor to greenhouse gases. These studies usually have this endpoint in mind, but provide information of the variability of methane emissions in space and time and hence on potential conduits of methane from underground.

4.2.1 FIELD MEASUREMENTS OF FUGITIVE EMISSIONS FROM EQUIPMENT AND WELL CASINGS (CSIRO)

Methane emissions were measured at 43 CSG wells – six in NSW and 37 in Queensland (Day et al., 2014). Measurements were made by downwind traverses of well pads using a vehicle fitted with a methane analyser to determine total emissions from each pad. In addition, a series of measurements were made on each pad to locate sources and quantify emission rates. Of the 43 wells examined, only three showed no emissions. The remainder had some level of emission but generally the emission rates were very low, especially when compared to the volume of gas produced from the wells. The principal methane emission sources were found to be venting and operation of gas-powered pneumatic devices, equipment leaks and exhaust from gas-fuelled engines used to power water pumps. Although the well pad emissions were low, a separate, larger source of methane was found on a gas relief vent on a water gathering installation close to one of the wells examined during this study.

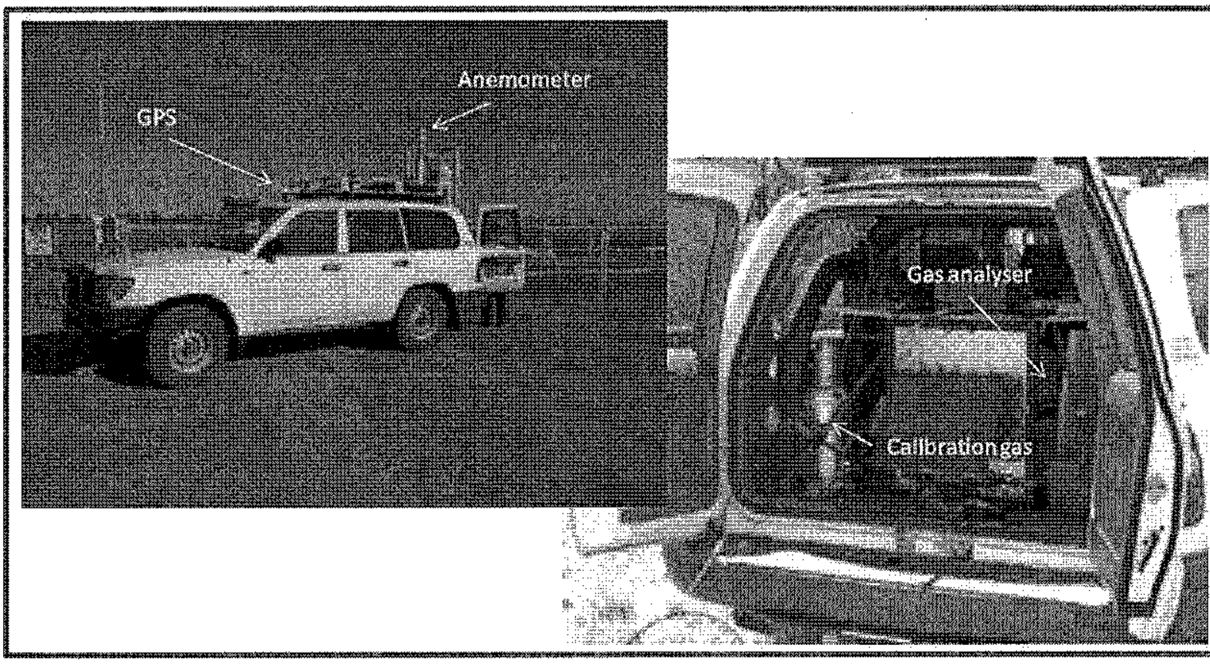

Figure 18 Photographs of the field vehicle with the GPS antenna and sonic anemometer are visible on the top of the vehicle (left hand photograph). The methane analyser and a calibration gas cylinder are shown in the rear of the vehicle (right hand photograph). (Source: Day et al., 2014).

4.2.2 ATMOSPHERIC METHANE CONCENTRATION MEASUREMENTS (SOUTHERN CROSS UNIVERSITY)

Atmospheric radon (^{222}Rn) and carbon dioxide (CO_2) concentrations were used (Tait et al., 2014) to gain insight into fugitive emissions in an Australian coal seam gas (CSG) field (Surat Basin, Tara region, Queensland). Atmospheric radon and CO_2concentrations were observed for 24 h within and outside the gas field. Both ^{222}Rn and CO_2 concentrations followed a diurnal cycle with night time concentrations higher than day time concentrations. Average CO_2 concentrations over the 24h period ranged from ~390 ppm at the control site to ~467 ppm near the centre of the gas field. A ~3 fold increase in maximum ^{222}Rn concentration was observed inside the gas field compared to outside of it. There was a significant relationship between maximum and average ^{222}Rn concentrations and the number of gas wells within a 3 km radius of the sampling sites (n = 5 stations; $p < 0.05$). A positive trend was observed between CO_2

concentrations and the number of CSG wells, but the relationship was not statistically significant. They hypothesized that the radon relationship was a response to enhanced emissions within the gas field related to both point (well heads, pipelines, etc) and diffuse soil sources.

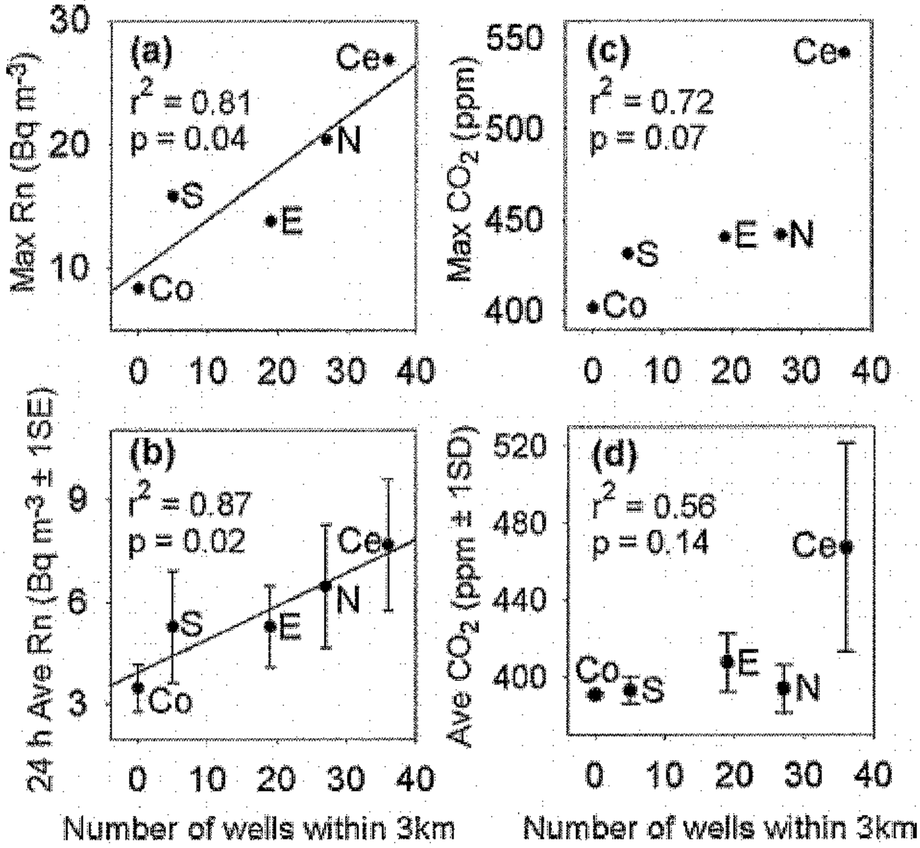

Figure 19 Results of atmospheric study conducted by Southern Cross University (Source: Tait et al., 2013)

4.2.3 CHARACTERISATION OF REGIONAL FLUXES OF METHANE IN THE SURAT BASIN, QUEENSLAND (GISERA PROJECT)

This GISERA project aims to address significant uncertainties associated with background seepage of methane and its detection and measurement in the Surat Basin, Queensland. Seepage is the diffusive flux of methane to the atmosphere through the land surface and water bodies, the localised flux of methane via connectivity pathways consisting of leads, faults and outcrops and the flux from agricultural bores. It does not consider the fugitive emissions of methane occurring as part of open cut and underground coal mines or emissions occurring from infrastructure (wells, compressors, associated water reticulation, or gas pipelines) associated with CSG production.

The research will provide:

(1) A desktop review and analysis of remote sensing imaging and direct detection (ground based flux) methods to quantify methane sources and fluxes. This activity is complete (Day et al., 2013);

(2) A field trial of methods at (i) a remote sensing pilot site, and (ii) a ground based direct detection and monitoring pilot site. The remote sensing pilot will test the acceptable method(s) developed in Task 1 for deployment within a defined test area and ability to detect methane seeps more broadly in the Upper

Condamine River catchment. The ground detection and monitoring pilot will test in situ measurement of on-ground methane fluxes at up to two pilot sites. Isotopic chemical tracers will assist in distinguishing coal methane seeps from biogenic methane sources. Each pilot is contingent on results from Task 1 and the client's input at decision points in the project; and,

(3) broad scale application of methods to a larger region in the Upper Condamine River catchment. This research will provide baseline monitoring data of methane seepage fluxes over different seasons. The final design is contingent on results from Tasks 1 and 2, their successful application and the client's input at decision points.

4.3 Studies of groundwater hydrochemistry

The hydrochemistry of groundwater can inform us about the sources of methane and other organics, processes in its formation, advective transport of constituents and reaction along the pathway and mixing processes. It is useful for understanding connectivity of aquifers and potential for leakage between them under stresses caused by water and gas development, connectivity with valued ecosystems and streams; and understanding potential for carbon capture and storage. The following are three recent or current studies. There are other more recent initiatives, such as that from the Centre for Coal Seam Gas at The University of Queensland, who are developing a publicly available web-based atlas of water chemistry data for CSG Fields. Other relevant research is that by Golding et al. (2013), Hamilton et al. (2012 and 2014), and Papendick et al. (2011) on fingerprinting the actual coal- bearing formations by using stable isotopes.

4.3.1 GEOSCIENCE AUSTRALIA AND GEOLOGICAL SURVEY OF QUEENSLAND SURAT AND BOWEN BASINS GROUNDWATER SURVEYS HYDROCHEMISTRY DATASET (2009-2011)

Geoscience Australia, the Geological Survey of Queensland and the Queensland Department of Mines and Energy (Feitz et al., 2014) are aiming to characterise the regional hydrochemistry of the Denison Trough and Surat Basin for the purposes of assessing their suitability for greenhouse gas storage and recovery. They have trialled different groundwater monitoring strategies to produce a regional baseline reference set for future site-specific and sub-regional monitoring and verification programmes conducted by geological storage proponents. The dataset provides a reference of hydrochemistry for future competing resource users, including coal seam gas proponents. Many of the analyses are needed for forensic studies for coal seam gas.

4.3.2 HYDROCHEMISTRY OF COAL SEAM GAS GROUNDWATERS IN THE SURAT AND CLARENCE-MORETON BASIN AND THEIR APPLICATION AS INDICATORS OF PROCESSES (QUEENSLAND UNIVERSITY OF TECHNOLOGY/CSIRO)

A group led by Professor Malcolm Cox in the School of Earth, Environmental and Biological Sciences, Queensland University of Technology has been studying the hydrochemistry of both the Surat and Clarence-Moreton basins in order to better understand how groundwater chemistry may influence the development of methane and vice-versa.

Two PhD projects assessing the hydrochemical and isotopic variability of groundwater in the Condamine River catchment (PhD students Des Owen and Jorge Martinez) are likely to improve the understanding of the process of methane formation, but will also provide useful information on the groundwater chemistry associated with methane formation. This enables better identification of methane sources within shallow groundwater and connectivity between aquifers, particularly between the Walloon Coal Measures and the Condamine River alluvium.

In an on-going PhD project in the Logan-Albert catchment within the Clarence-Moreton Basin, PhD student Clément Duvert has compared hydrochemistry, rare earth elements and isotopes of groundwater samples from the Walloon Coal Measures and overlying alluvial aquifers collected during dry and wet periods. The study demonstrates that there can be substantial temporal variability of hydrochemistry and isotopes within the Walloon Coal Measures and the alluvial aquifers at some bore sites, highlighting the importance of collecting time-series data where possible.

As part of a postdoctoral research project funded by the NCGRT, Dr. Matthias Raiber (now CSIRO) has in collaboration with Dr. Andrew Feitz (Geoscience Australia) analysed methane concentrations and the isotopic composition of δ^2H and $\delta^{13}C$ of methane on approximately 50 groundwater samples from the Walloon Coal Measures and other formations throughout the Clarence-Moreton and eastern Surat basins. The study indicates that methane concentrations within the Walloon Coal Measures are spatially highly variable, likely due to complicated hydrological processes (e.g. groundwater recharge). In addition, the study confirmed that methane is also present in other formations.

4.3.3 MONITORING OF HYDROCHEMICAL AND ISOTOPIC CHARACTERISTICS OF CSG FORMATION WATERS, ADJACENT AQUIFERS AND SPRINGS (GISERA).

This ongoing project is aimed[6] at: (i) a comprehensive hydrochemical and isotopic characterisation of groundwater and formation water within the proposed CSG extraction area prior to development; (ii) developing protocols for monitoring aquifers and formation water over the time period of extraction and post-development and (iii) establishing a set of criteria for ongoing assessment of the monitoring program and implications for aquifer interactions. A practical aim of the project is to provide a means of monitoring the progress and impact of large scale pumping and to inform potential modification of the pumping process to minimise potential impacts on spring-fed or baseflow ecosystems. More specifically, work is proceeding on 1) source of water in springs; 2) hydrochemical and isotopic sampling of the Hutton Formation (Figure 20) and 3) testing a technique for obtaining helium concentrations in quartz as proxy for helium in pore waters of low permeable formations such as aquitards (Smith et al., 2013).

4.3.4 REVIEW OF DISSOLVED HYDROCARBONS IN GROUNDWATER IN THE SURAT AND BOWEN BASINS (GISERA)

This project aims[7] to:

1. Collate and provide a summary of the available information on existing hydrocarbons in groundwater in the Surat and Bowen basins as a context and potential explanations for possible future detection and reporting of hydrocarbons during compliance monitoring programmes;
2. Outline strategies related to differentiation of naturally occurring hydrocarbons and those inadvertently introduced during drilling, completion and hydraulic stimulation; and

[6] http://www.gisera.org.au/research/research_progress.html
[7] http://www.gisera.org.au/research/research_progress.html

3. Interpretations on possible sources of the hydrocarbons encountered based on previous studies and new information gained through additional sampling/monitoring data acquired by the companies involved.

All hydrocarbon compounds of concern (TPHs, BTEX and PAHs) will be considered as well as phenols, for which concerns also exist, subject to data availability.

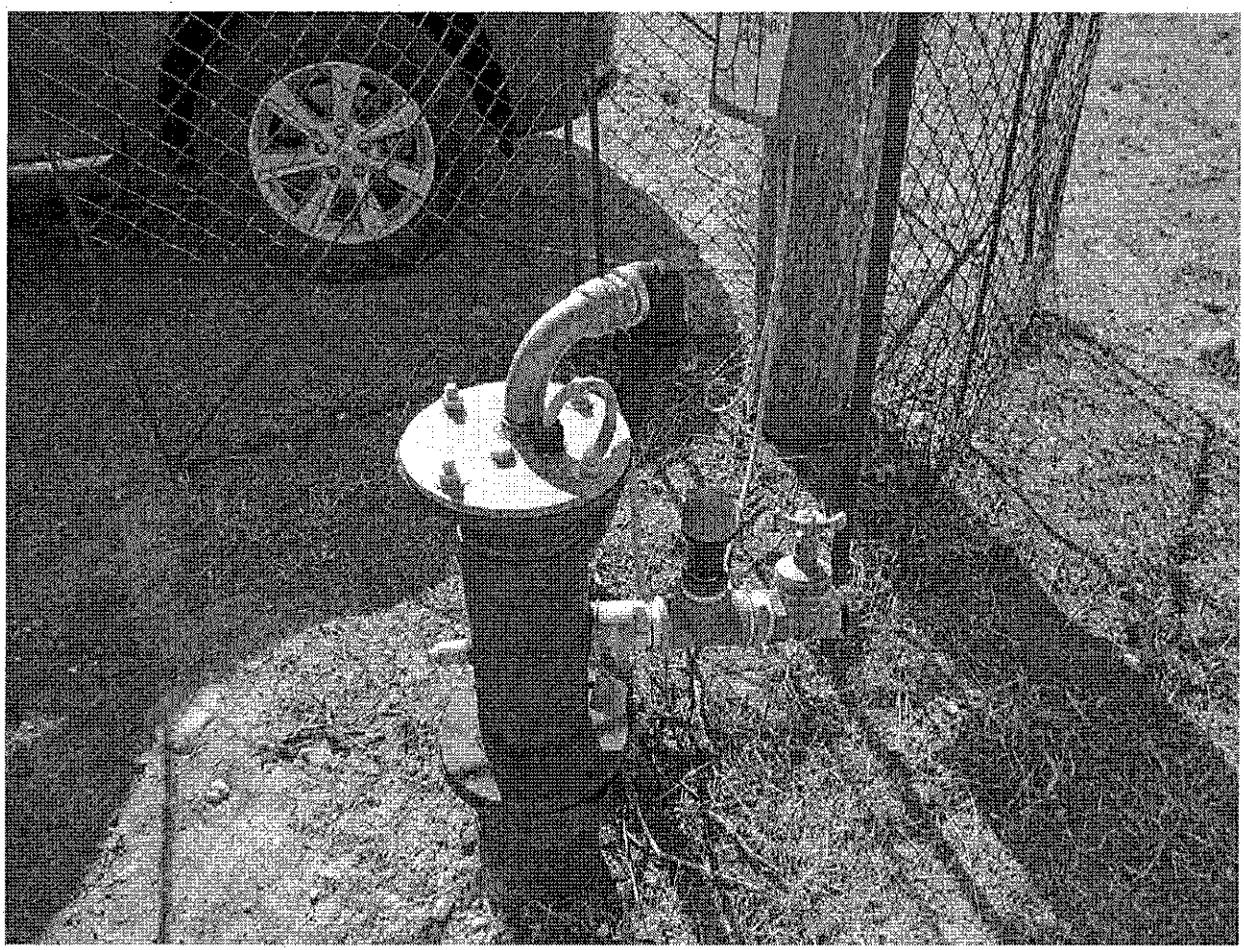

Figure 20 Sampling during the GISERA hydrochemistry project (Photograph courtesy: CSIRO).

4.4 Summary and Conclusions

The nature of research funding and research institutions means that there is a certain amount of coordination, but it is far from perfect. A number of organisations such as the Office of Groundwater Impact Assessment in Queensland Government, Office of Water Science in the Australian Government, Geoscience Australia, Gas Industry Social and Environmental Research Alliance (GISERA), production companies and Research and Development Corporations such as Cotton all try to ensure the best outcomes of their investments through coordination and communication. Technical meetings and scientific conferences facilitate exchange of ideas and results. However, there are reasons why coordination is far from perfect. The innovation sector is driven by competition: competition for funding, competition of ideas and competition between specialist skills and equipment. Also, this is a contentious topic with different sectors having different agendas and interests. Both of these issues can lead to a seeming lack of coordination. There is clearly a balance to be reached. A lack of coordination can lead to duplication, wastage of time of scientific specialists and specialist facilities and not achieving larger outcomes. Too much coordination leads to a lack of tension that drives thinking and discussion and too much focus on this topic or that. Each person will have a different view as to where this balance sits. However, it is possible to make some general comments on the relativity of the three topic areas.

There does appear to be good coordination in the hydrochemistry area. In discussions, most were aware of others working in the area and the type of studies being conducted. There appear to be different institutions coordinating work in this area; there are several papers in this area and there is a long history of collaboration in the groundwater area. On the other hand, the provision of baseline information and targeted studies of processing facilities is relatively new and there appears to be less coordination in this space. Atmospheric studies are often driven by greenhouse gas accounting, which is different in nature to assessing risks of methane in shallow groundwater. Nonetheless, it can provide useful information on the topic. The studies of methane in shallow groundwater appear to be a lower priority for both state and Australian governments, perhaps left for the other sectors. However, as has been shown in this report, the nature of the measurements and processes strongly means that coordination needs to occur; otherwise we may be in a situation of not being able to assess impacts or emerging issues. The work has been a higher priority in the USA and Canada, perhaps due the number of people living in shale gas and coal seam gas areas as well as the amount of infrastructure. However, the focus has led to a situation where there is a quick response to emerging trends and risks.

5 Conclusions

Methane in water bores is a major concern in areas of coal seam gas development. There are risks such as gas lock in pumps, colour and odour impacts from water quality changes, toxicity due to other gases and build up of gases affecting the integrity of the bores. A review was conducted of the state of the art of methods for investigating gas in water bores and analysis of resulting data. The historical presence of gas in water bores in the Surat and Bowen basins since the early 1900s was also reviewed. Information from this review is to be used to investigate and respond to reports of increased gas content in individual water bores across a large area in Queensland. For such work to be effective, it is critical to have a good understanding of (i) the different sources of methane gas in the subsurface, (ii) the processes responsible for gas migration and mixing and thus for variability in gas concentration, and (iii) methods for measuring gas in water bores.

Methane in water bores may be present as dissolved gas in solution and/or as free gas. Dissolved methane gas usually only exsolves from a still solution if the concentration of methane in the fluid exceeds its solubility. Gas solubility varies with temperature, salinity, and pressure: it decreases with increasing temperature and salinity and increases with increasing pressure. Coal seam gas-derived methane will often co-exist with other gases such as short chain hydrocarbon gases such as ethane, propane and butane, as well as carbon dioxide, nitrogen and hydrogen sulfide. The relative abundance of such hydrocarbon gases (and their isotopic signatures) may be used to determine the gas source.

When sampling for methane in groundwater, the sample should preferably be collected from deep within the bore close to the screen either by low flow pumping or an in situ device such as a diffusion sampler. Appropriate sampling techniques reviewed include the inverted bottle method as used for both free and dissolved gas and gas extraction samplers.

Methane concentrations have been shown to be highly variable in space and time. This variability can be related to processes that cause methane concentrations to increase and decrease. Some studies have shown that sampling error and analytical error also contribute to this variability.

When analysing methane data, careful consideration should be give to the following issues:

- methane occurs naturally in groundwater and in the vapour phase of the unsaturated zone, especially in areas where there is coal seam gas;
- methane concentrations will have been exacerbated by depressurisation caused by pumping for water and conventional gas development over time, as well as exploration for oil and gas before any coal seam gas development occurred;
- changes in methane may be due to a range of causes other than coal seam gas development. In many cases overseas, investigation of complaints have found that poor maintenance of water bores resulted in microbially-mediated methane production as a cause of changes in water quality;
- variability with time of measured methane concentrations due to sampling and analytical error and processes leading to presence of methane in the water bore; and
- variability of concentration of methane and related constituents within each of the different sources of methane.

For a better understanding of the impact of coal seam gas extraction and depressurisation on methane in the groundwater resource as a whole, a more systematic sub-regional and regional strategy is required.

This will allow the identification of gradual or sudden changes, irrespective of cause, and understanding of periodic changes of methane that may not be related to coal seam gas extraction. Such a strategy will need a sampling and analysis methodology that is robust enough to provide consistent measurements with sufficient sensitivity to detect trends in time and spatial patterns. However, the effort that goes into any monitoring program needs to be commensurate with the risks and customized to highlight mitigation measures. For some of the risks, there is a well-established mitigation process established and some of this may not require an expensive monitoring program. However, for evaluation of the larger effects of the impacts of a coal seam gas development or for better delineating causes of poorer bore quality, more comprehensive and consistent monitoring is required.

To measure changes in state of individual water bores and the groundwater resource as a whole requires first of all a baseline survey across relevant bores. For any detection of change or trend, the change needs to be larger than the noise in the baseline. This noise could be due to variability related to sampling and analysis but it also can be related to real processes that cause methane concentrations increase and decrease. To provide confidence about the extent of change, it is important to quantify the variability of the analyses.

Overseas experience has shown that consistent and reliable measurement of methane concentrations with sufficiently low variability requires focus on training, adherence to strict protocols, including split and duplicate samples, and consistency in the information recorded. Best overseas practice often has data stored on an audited transparent database.

Most methane in water bores is of biogenic or thermogenic origin; the gas sources grade from biogenic to thermogenic with depth. Biogenic methane production is the most common of the processes in shallow groundwater systems and involves bacterial decomposition of organic matter in the absence of oxygen through either fermentation of organic matter or reduction of carbon dioxide. Thermogenic methane is formed by the thermal breakdown of complex hydrocarbons resulting from decomposition of organic material largely originating in ancient shales. Thermogenic gases typically originated at great (1000s of meters) depths; however, over geologic time these gases may have migrated far from the original source area and subsequently accumulated at shallower depths.

Dissolved methane can exist in the groundwater near a water bore. When the water bore is pumped, water pressures in both the bore and the adjacent formation are decreased. Such a decrease in pressure can lead to methane degassing as water is drawn into the bore. These declines in pressure could lead to enhanced methane degassing and migration from increasingly larger areas around the bore.

Methane migration can also be affected by water, oil and gas developments, i.e. when water or gas production bores provide conduits through the different geological layers. Such borehole breaches present a number of opportunities for leakage of fluids in the vertical direction.

The ability to identify the sources of any high concentrations of methane in bores or changes requires measurements of other constituents using isotopes of hydrogen and carbon of methane and associated wet gas components. Other useful measurements are i) the stable carbon isotope ratio of dissolved inorganic carbon, which may be used to identify any bacterial consumption of methane that has occurred between the source and the bore and ii) the radioactive carbon isotope (^{14}C) which identifies a younger source of carbon originating from shallower groundwater unrelated to coal seams targeted for CSG extraction.

There has been a long history of methane detected in existing water bores or during drilling for water in the Surat and Bowen basins, dating back to the beginning of the twentieth century. The methane is found at higher concentrations above features such as faults and above known gas reservoirs.

There are a number of recent and current projects investigating issues related to methane in water bores in Queensland and NSW. For instance, the study of gas bubbling in the Condamine River showed that the source of the gas was from deeper aquifers. The study could not rule out any specific pathways or causes for any increase in gas bubbling.

Glossary

ANSTO: Australian Nuclear Science and Technology Organisation

Asphyxiation: A condition in which an extreme decrease of oxygen in the body accompanied by an increase in the concentration of carbon dioxide leads to loss of consciousness or death.

Artesian aquifer: A confined aquifer in which the pressure head of the groundwater rises above the upper confining layer of the aquifer. If the pressure is sufficient to cause the bore to flow at the surface, it is called a flowing artesian aquifer.

Bopd: barrels of oil per day

BTEX: Benzene, Toluene, Ethylbenzene, Xylene

Buoyancy: the tendency or capacity to remain afloat in a liquid or rise in air or gas

CSG: coal seam gas

CSGCU: Coal Seam Gas Compliance Unit

EC: electrical conductivity

GISERA: Gas Industry Social and Environmental Research Alliance

PAH: Polycyclic aromatic hydrocarbons

ppm: parts per million

TPH: Total petroleum hydrocarbon

VSMOW: Vienna Standard Mean Ocean Water

VPDB: Vienna Pee Dee Belemnite

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Document 12

Methane seeps in the Condamine River

This fact sheet presents the current state of scientific knowledge on methane seeps in the Condamine River including natural and human causes, and the human and environmental health and safety impacts of methane escaping from underground. This fact sheet has been developed by CSIRO researchers with expertise in the hydrogeology, geology, ecology and biogeochemistry and from multiple sources to summarise what we currently know about these methane seeps.

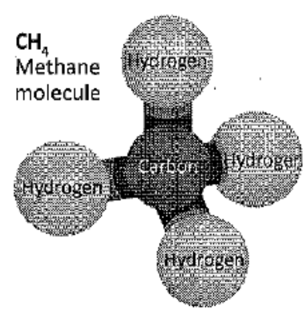
Key points

- Depressurisation of the Walloon Coal Measures during CSG production could generate horizontal migration of free methane gas. However, this flux of methane is likely to be small because of the shallow dip of the coal beds and the distance to gas production fields.
- Hydraulic fracturing is unlikely to be the cause of bubbling in the Condamine River because to date there has been no hydraulic fracturing by the CSG industry in these production fields.
- Variation in bubbling of the Condamine River may be caused by:
  - an increase in river water flow, moving sand and sediments that previously sat over the seeps and limited their seepage.
  - groundwater receding from the Condamine River alluvium since the 2011 floods has reduced pressure over the Walloon Coal Measures near Chinchilla, allowing trapped gas to expand and rise to the surface.
  - CSG industry activity in production fields 5 to 6 km away has reduced pressure in the coal seams leading to some possible up-dip flow of gas into the network of fractures and thereby into the Condamine River.
- CSIRO research has found no evidence that these seeps have any adverse environmental impact on the plant or animal life of the river and its surroundings. To date, there is no public health or safety risk caused by the methane concentrations measured in the area of these or any other seeps in the Surat Basin that CSIRO has measured.

Capturing methane

Methane is a colourless, odourless, non-toxic gas. It is the main component of coal-seam gas (CSG), a gas taken from underground coal seams. The gas is lighter than air, so rises into the air when released. Methane originates naturally from biological sources (lakes, rivers, wetlands), agricultural sources (cultivation, ruminants), and geological sources (coal seams). Methane may also be released by humans when digging for coal from mines, producing Liquefied Natural Gas (LNG) from CSG and from city waste (land fill).

CH_4 Methane molecule



Methane is a potent greenhouse gas with a warming potential about 28 times that of CO_2 when considered over a 100 year lifetime in the atmosphere[1].

Sedimentary basins around the world that contain coal or organic matter naturally leak methane to the atmosphere. About a third of the 200 million tonnes of methane released to the atmosphere annually comes from these geological sources, which are derived from ancient organic matter deposited over millions of years and turned to coal under high temperature and pressure conditions underground. The fossil fuel industry including natural gas, coal and oil contribute between 15 and 22% of total global methane emissions[2].

Where leaking methane can be captured, it can be used as fuel to generate electricity. On combustion, methane produces carbon dioxide and water vapour, which trap heat in the atmosphere less than the original methane.

1 Kirschke et al (2013), Three decades of global methane sources and sinks, Nature Geoscience, doi:10.1038/ngeo1955

2 Schwietzke et al (2016), Upward revision of global fossil fuel methane emission based on isotope database, Nature 538, pp 88- 91 doi: 10.1038

Geology of the Condamine River region

The Surat Basin is situated in southern-central Queensland and is part of Australia's Great Artesian Basin. The Surat Basin contains the Walloon Coal Measures with large quantities of methane gas that are being extracted for LNG production. The Condamine River, near Chinchilla in southeast Queensland, is situated on the eastern edge of the Surat Basin.

The Surat Basin formed tens to hundreds of millions of years ago[3]. It consists of multiple aquifers (typically consisting of sandstones) and aquitards (typically dominated by claystones, siltstones and mudstones)[4]. The Walloon Coal Measures rise at an angle of about 1 degree to the surface from the west and meet the alluvial sediments deposited by the Condamine River (the 'Condamine River alluvium'). The layers of porous and non-porous rock above the Walloon Coal Measures intersect the surface and can be seen as outcropping rock formations along the river channel. The Condamine River has eroded the landscape over aeons, and the Surat Basin formations are intersected with numerous faults that have dissected and fractured these underground formations[5].

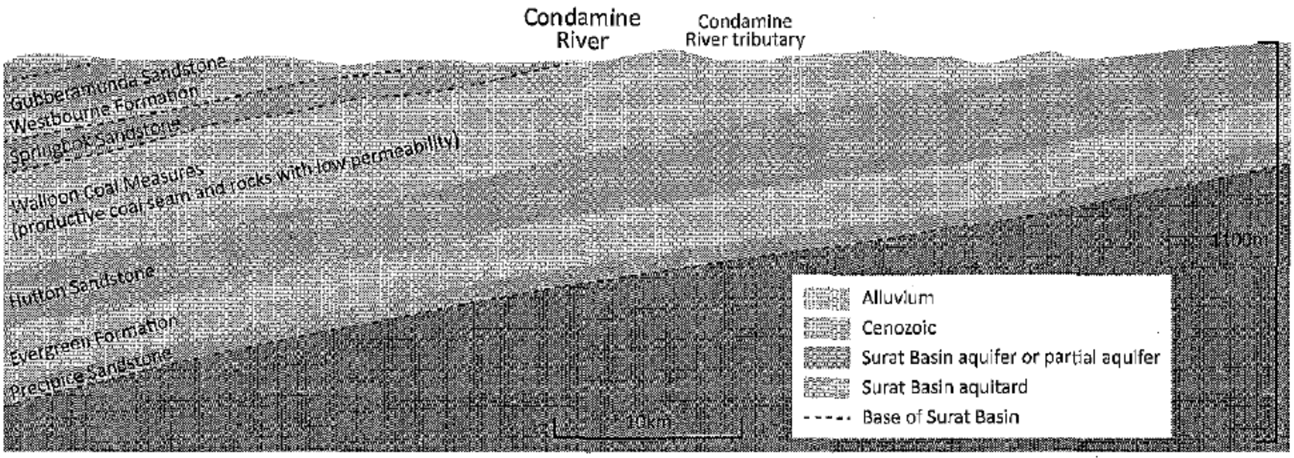
Geology of Walloon Coal Measures

Researchers have used seismic surveys, drill core data and other direct measurement techniques to create an image of the subsurface geometry and structure of the Walloon Coal Measures and other aquifers and aquitards beneath this region of the Condamine River.

This work has identified complex folding, faulting and deeply fractured rock layers beneath the surface[6]. These fractures can form natural links between coal seams and the surface via fissures and cracks that formed millions of years ago.

The Walloon Coal Measures in the vicinity of the Condamine River, near Chinchilla, Queensland, is a highly permeable underground environment which allows methane to flow easily[7]. In this part of the Condamine, the alluvium is very narrow and thin, and the Walloon Coal Measures are much shallower and closer to the base of the river than elsewhere within the catchment. The combination of fractured formations and permeability beneath the Condamine River allows migration of methane to the surface. The fractured geology also show structures underground at shallow depths where gas may accumulate in traps. These traps can collect methane under pressure (e.g. hydrostatic pressure from the alluvium above). As this pressure is eased the methane in these traps can expand and find its way to the surface. This could explain variation in methane fluxes we see at some places in the Condamine River.

In the vicinity of the Condamine River where bubbling occurs, it is possible that depressurisation of the Walloon Coal Measures during CSG production could generate some horizontal migration of free methane gas. However, with the shallow strike of these formations and the 6 to 10 km distance to gas production fields, this flux of methane is likely to be small.



Conceptual geological cross section of the Surat Basin and Condamine River alluvium near Chinchilla

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3 Jell, P.A. (2013), Geology of Queensland, Queensland Geological Survey, pp 928.

4 State of Queensland (2016) Underground Water Impact Report for the Surat Cumulative Management Area, The Office of Groundwater Impact Assessment, Department of Natural Resources and Mines.

5 Esterle, JS, Hamilton, SK, Ward, V, Tyson S, Silwa, R, (2013), Scales of Geological Heterogeneity within the Walloon Subgroup and its Coal Measures. February 2013. Final report of Activity 1.3 of the Healthy Head Waters Coal Seam Gas Water Feasibility Study. Department of Natural Resources and Mines.

6 Hamilton S.K., Esterle, J.S. & Sliwa, R. (2014) Stratigraphic and depositional framework of the Walloon Subgroup, eastern Surat Basin, Queensland, Australian Journal of Earth Sciences, 61:8, 1061-1080, DOI: 10.1080/08120099.2014.960000

7 S.K. Hamilton, J.S. Esterle, S.D. Golding (2012) Geological interpretation of gas content trends, Walloon Subgroup, eastern Surat Basin, Queensland, Australia, International Journal of Coal Geology 101, 21–35

Both CSIRO and the Gas Industry Social and Environmental Research Alliance (GISERA) are undertaking research to locate and measure these natural methane seeps, including the gas appearing as bubbling in the Condamine River. While the bubbling in the Condamine River is spectacular, it is only one location of many in this region where methane is being released at the surface. The other locations are cracks and fissures that are not visible and CSIRO researchers are using sensors to locate and measure the flow of methane at these locations[8,9]. CSIRO has also undertaken research on the potential impacts of the bubbling methane on the biogeochemistry and aquatic ecology of the Condamine River.

Natural and human causes of methane leakage

In addition to the natural underground formations and fissures which can form migration pathways for the methane to the surface, human activities such as drilling water bores, extracting gas, and exploring for gas and oil can allow methane to escape. Some of these activities (e.g. drilling of water bores or coal exploration holes) have created further pathways for gas to rise to the surface[10].

The presence of methane in water bores has been documented well before development of the region's CSG industry as far back as 1919[11]. Since the early 1900s, there has been natural gas in water bores in nearby Roma, which have led to well blowouts and occasionally caught fire. Methane in water bores in the Surat and Bowen basins has also been documented in drilling reports from the 1960s and 1970s.

CSIRO's isotopic analysis of methane gas collected from the main bubbling site in the Condamine River[12] shows that the origin of the methane is from bacterial metabolism of coal. Other research suggests that methane in groundwater of the Condamine River alluvium may originate from the Walloon Coal Measures or adjacent geological formations in the Surat Basin[13]. However, conflicting data also exists[14] suggesting virtually no migration of methane from the Walloon Coal Measures into the alluvium, at least at sites south-east of where bubbling occurs in the Condamine River. What is apparent, is that the methane seeps do not originate from biological sources in the river sediments.

The bubbling of methane from the Condamine River area has increased three-fold since ongoing measurement began in early 2015[15], but has declined again recently. There may be many reasons for this variation in methane flow to the surface through the Condamine River. CSIRO researchers provide three possibilities for this variation in methane flow:

1. that an increase in flow in river water has scoured the river bed moving sand and sediments that previously sat over the seeps and limited their flow
2. that groundwater receding from the Condamine River alluvium since the 2011 floods has reduced pressure over the Walloon Coal Measures near Chinchilla, allowing trapped gas to expand and rise to the surface
3. that CSG industry activity in production fields 5 to 6 km away has reduced pressure in the coal seams leading to possible up-dip flow of gas into the network of fractures and thereby into the Condamine River[16].

Scientists measuring methane gas using rising chambers from Condamine River (Source: Brad Sherman)

8 Day, S., Dell'Amico, M., Etheridge, D., Ong, C., Rodger, A., Sherman, B., Barrett, D.J. (2013) Characterisation of regional fluxes of methane in the Surat Basin, Queensland – Phase 1: A Review and Analysis of Literature on Methane Detection and Flux Determination. CSIRO, Australia

9 Day, S., Ong, C., Rodger, A., Etheridge, D., Hibberd, M., van Gorsel, E., Spencer, D., Krummel, P., Fry, R., Mark Dell'Amico, M., Sestak, S., Williams, D., Loh, Z., Barrett, D. (2015) Characterisation of regional fluxes of methane in the Surat Basin, Queensland: Phase 2: A pilot study of methodology to detect and quantify methane sources. CSIRO, Australia.

10 Walker, G.R., Mallants, D., Methodologies for investigating gas in water bores and links to coal seam gas development (2014). CSIRO. Australia

11 Gray, A.R.G. (1967) Natural Gas Occurrence in the Brigalow Area, March 1967. Queensland Government Mining Journal. 68, 394 - 396

12 Sherman B.S. and Ford, P.W. (2014) Condamine River Coal Seam Gas Emissions: Final Report. CSIRO, Water for a Healthy Country Flagship, Australia

13 Iverach, C.P., Dioni I. Cendón, Stuart I. Hankin, David Lowry, Rebecca E. Fisher, James L. France, Euan G. Nisbet, Andy Baker & Bryce F. J. Kelly (2015) Assessing Connectivity Between an Overlying Aquifer and a Coal Seam Gas Resource Using Methane Isotopes, Dissolved Organic Carbon and Tritium. Scientific Reports. DOI: 10.1038/srep15996

14 Owen, D.D.R., Shouakar-Stash, O., Morgenstern, U. & Aravena, R. (2016) Thermodynamic and hydrochemical controls on CH_4 in a coal seam gas and overlying alluvial aquifer: new insights into CH_4 origins. DOI: 10.1038/srep32407

15 CSIRO flux measurements https://www.aplng.com.au/topics/coal-seam-gas/condamine-river-seeps.html

16 Norwest report, Executive Summary, p.17-18

It is well known that water and gas extraction activities reduces pressure in underground coal seams and aquifers, thereby releasing methane. Experiments undertaken by the CSG industry that involve shutting down gas wells in these production fields have shown pressure changes due to gas industry activity in the vicinity of the Condamine River, but only a few per cent of the current methane flows in the Condamine River can be explained by these activities. Furthermore, the very low angle of dip (about 1 degree) of the Walloon Coal Measures would preclude large-scale transport of gaseous methane underground. Hydraulic fracturing is not the cause of this increase in bubbling in the Condamine River because there has been no hydraulic fracturing by the CSG industry in these production fields.

Impact on health and environment

CSIRO has found no evidence that the seepage of methane from the Condamine River area has any adverse environmental impact on the plant or animal life of the river and its surroundings[17]. While higher concentrations of methane are present in the river up to 8 km downstream the river seeps, temperature, electrical conductivity and turbidity are not affected. Nitrogen, ammonium, phosphorus and organic carbon concentrations in the vicinity of the seeps are not different to other parts of the river and are typical of Australian inland rivers. Phytoplankton, zooplankton and macroinvertebrates are unaffected by the presence of the seeps; although, bacterial and fungal populations were higher which is to be expected given that methane is the food source of methanogenic bacteria.

There is no public health or safety risk caused by the methane concentrations measured in the area of these or any other seeps in the Surat Basin CSIRO has measured[18,19]. Analysis shows the gas is very pure, composed almost entirely of non-toxic methane, with traces of carbon dioxide and nitrogen. There is no evidence of volatile organic compounds or dangerous hydrocarbons in the seeping gas. Metals, such as silver, cadmium, chromium, mercury, lead, aluminium, iron and manganese, were either at the threshold of detection or within the range expected for inland Australian rivers.

Methane is only dangerous if concentrated in enclosed spaces to levels where it is explosive, and there are safety risks if it is deliberately lit. In the Condamine River the seeps can only be lit when the river is not flowing and where flames are supported by additional combustible material.

Ongoing monitoring

CSIRO has been undertaking research on gas seeps in the region for more than three years. Scientists have used remote sensing, isotopic analyses, field surveys, computer modelling and other techniques to map methane sources and understand the processes that lead to methane emissions.

CSIRO will continue to independently measure and monitor methane from geological sources and from other origins including old coal exploration wells from the 1960s, fugitive emissions from the gas industry, and methane emissions from cattle and agriculture. In addition, the Queensland Government is monitoring water quality and gas levels to identify any environmental harm or safety concerns, and reviewing relevant research to ensure a high level of scientific rigour and independent research is maintained.

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17 Rees GN, Nielsen DL, Cook RA, Petrie R, Watson GO, Davey C, Oliver R, Lorenz Z (2016) Condamine River: Ecological study. Report to Origin Energy.

18 State of Queensland, Department of Natural Resources and Mines (2012) Summary Technical Report - Part 1 Condamine River Gas Seep Investigation.

19 State of Queensland, Queensland Health (2013) Coal seam gas in the Tara region: Summary risk assessment of health complaints and environmental monitoring data.

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Methane seeps in the Condamine River

Document 13

Pictures of methane ignition attract media headlines and public concern, but what does the latest science say are the natural and human causes, and the health and safety impacts, of methane escaping from underground?

Capturing methane

Methane is a colourless, odourless, non-toxic gas. It is the main component of coal-seam gas (CSG), a gas taken from underground coal seams. The gas is lighter than air, so rises into the air when released. Methane originates naturally from biological sources (lakes, rivers, wetlands), agricultural sources (cultivation, ruminants), and geological sources (faults and fractures in the ground associated with coal seams). Methane may also be released by humans in the acquisition of coal from mines, the production of Liquified Natural Gas (LNG) from CSG and from city waste (land fill).

Sedimentary basins around the world that contain coal or organic matter naturally leak methane to the atmosphere. About a third of the 200 million tonnes of methane released to the atmosphere annually comes from these geological sources, which are derived from ancient organic matter deposited over millions of years and turned to coal under high temperature and pressure conditions underground.

Where leaking methane can be captured, it can be used for fuel to generate electricity. On combustion, methane produces carbon dioxide and water vapour, which trap heat in the atmosphere less than the original methane.

Geology of the Condamine River region

The Surat Basin is situated in southern-central Queensland and is part of Australia's Great Artesian Basin. The Surat Basin contains the Walloon Coal Measures with large quantities of methane gas that are being extracted for LNG production. The Condamine River, near Chinchilla in southeast Queensland, is situated on the eastern edge of the Surat Basin. The Surat Basin features a unique geology formed tens of millions of years ago. The Walloon coal seams rise to the surface from the west and meet the eroded sediments of the Condamine River (the Condamine Alluvium) within about 70m of the surface at the Condamine River. The sandstone aquifers above the Walloon coal seams intersect the surface and can be seen along the river channel. The Condamine River has eroded the landscape over aeons, dissecting and fracturing these underground formations[1].

Researchers have used seismic surveys and other direct measurement techniques to create an image of the subterranean structure of the Walloon coal seams and associated sandstone aquifers adjacent to the Condamine River. This work has identified deeply fractured layers of rock beneath the surface. These fractures form a natural network of coal seams, fissures, cracks and other channels that formed millions of years ago to create a highly permeable underground environment for methane to flow from the Walloon coal seams beneath the Condamine River to the surface. The fractured geological structures also show structures underground at shallow depths where gas may accumulate in traps. These traps can naturally channel methane to the surface causing variation in the flow of gas.

[insert image – map of area including methane sources]

Image caption

CSIRO, through the Gas Industry Social and Environmental Research Alliance (GISERA), is undertaking a research program to locate and measure these natural methane seeps; including the gas appearing as bubbling in the Condamine River. CSIRO has also undertaken research on the potential impacts of the bubbling methane on the biogeochemistry and aquatic ecology of the Condamine River. While the bubbling in the Condamine River is spectacular, it is only one location of many where methane is being released at the surface. The other locations are not visible and CSIRO researchers use

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[1] Norwest report, Executive Summary, p.14

different types of sensors to locate and measure the flow of methane at these locations.

Natural and human causes of methane leakage

In addition to the natural underground formations and fissures which bring methane to the surface, human activities such as drilling water bores, extracting gas, and exploring for gas and oil can allow methane to escape. Some of these activities (e.g. drilling of water bores or coal exploration holes) have created further pathways for gas to rise to the surface.

The presence of methane in water bores has been documented well before development of the region's CSG industry[2]. There is evidence of methane seeps and gas having been present in water bores since the late 1800s. Since the early 1900s, there has been natural gas in water bores in nearby Roma, causing explosions and catching fire, and methane in water bores in the Surat and Bowen basins has been documented in drilling reports in the 1960s and 1970s.

CSIRO's isotopic analysis of methane gas collected from the main bubbling site in the Condamine River shows that the origin of the methane is from bacterial metabolism of coal, suggesting it came from the Walloon coal seams or adjacent geological formations in the Surat Basin. It has not come from biological sources in the river sediments.

The bubbling of methane from the Condamine River area has increased three-fold since ongoing measurement began in early 2015[3]. There may be many reasons for this increase in methane flow to the surface through the Condamine River. CSIRO researchers provide three possibilities for this increase in methane flow:

- that an increase in flow in river water has scoured the river bed moving sand and sediments that previously sat over the seeps and limited their flow
- that groundwater receding from the Condamine Alluvium since the 2011 floods has reduced pressure over the Walloon coal seams in this area, allowing trapped gas to expand and rise to the surface
- that CSG industry activity in production fields 5 to 6 km away has reduced pressure in the coal seams leading to up-dip flow of gas into the network of fractures and thereby into the Condamine River[4].

It is well known that water and gas extraction activities can reduce the pressure in underground coal seams and aquifers, potentially releasing methane. Experiments undertaken by the CSG industry that involve shutting down gas wells in these production fields have shown pressure changes due to gas industry activity, but only a few per cent of the current methane flows in the Condamine River can be explained by these activities. Furthermore, the very low angle (about 1 degree) of the Walloon coal seams would preclude large-scale transport of gaseous methane underground. Hydraulic fracturing is not the cause of this increase in bubbling in the Condamine River because there has been no hydraulic fracturing by the CSG industry in these production fields.

Impact on health and environment

CSIRO has found no evidence that the seepage of methane from the Condamine River area has any adverse environmental impact on the plant or animal life of the river and its surroundings[5].

There is no public health or safety risk caused by the methane concentrations measured in the area of these or any other seeps in the Surat Basin CSIRO has measured[6]. Analysis shows the gas is very pure, composed almost entirely of non-toxic methane, with traces of carbon dioxide and nitrogen. There is no evidence of volatile organic compounds in the seeping gas.

Methane is only dangerous if concentrated in enclosed spaces to levels where it is explosive, and there are safety risks if it is deliberately lit. In the Condamine River the seeps can only be lit when the river is not flowing and

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[2] Origin submission to the Senate Select Committee on unconventional gas mining, p.34

[3] Interview with Damian Barrett: "the flux has increased 3-fold over the past 14 months"

[4] Norwest report, Executive Summary, p.17-18

[5] Norwest report Exec summary p. 15 (and interview with Damien: 'There is no evidence of environmental impact of these seeps on the biota (plant or animal life) of the river, from CSIRO work.'); also Qld Govt report, p. 15 and p.21; and Origin submission to the Senate Select Committee on unconventional gas mining, p. 35.

[6] Qld Govt report, p. 14 and p.21

where flames are supported by additional combustible material.

Ongoing monitoring

CSIRO has been undertaking research on gas seeps in the region for more than three years. Scientists have used remote sensing, isotopic analyses, field surveys, computer modelling and other techniques to map methane sources and understand the processes that lead to methane emissions.

CSIRO will continue to independently measure and monitor methane from geological sources and from other origins including old coal exploration wells from the 1960s, fugitive emissions from the gas industry, and methane emissions from cattle and agriculture. In addition, the Queensland Government is monitoring water quality and gas levels to identify any environmental harm or safety concerns, and reviewing relevant research to ensure a high level of scientific rigour and independent research is maintained.

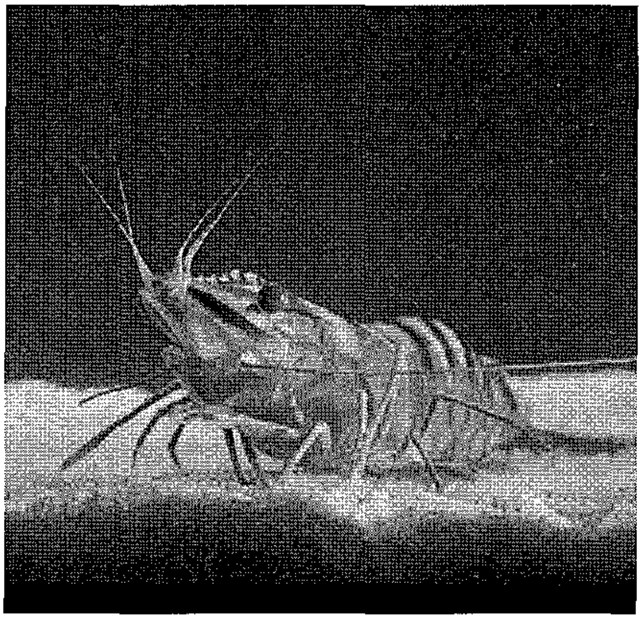

Image caption [style = caption]

Figures and photographs

Use style = Image placement, this will allow more space at the top of the image from text. The resolution of figures and photographs should be minimum 300 dpi.

The preferred file formats are jpg or png for photographs.

The preferred file format is Windows enhanced metafile for figures. This can be achieved by:

- copy the figure in the source file (e.g. Excel)
- in Word, choose 'paste special', then click 'Picture (Enhanced Metafile)' and OK
- right-click on the image and select Text wrapping and choose 'In Line with Text'.

Do not use any picture styles (rounded corners, drop shadows, frames) on photographs.

Column breaks

The text will automatically equally balance the height of the columns, to avoid this insert a column break (Page layout / Breaks / Column break).

Accessibility

Documents that are to be published on the web are required to be accessible to Web Content Accessibility Guidelines (WCAG) 2.0 Level AA. Documents should be provided in both Microsoft Word and Adobe PDF format.

To ensure documents are accessible, these requirements must be followed:

- Use short headings throughout the document, including the title. If necessary, a subtitle could be used.
- Use styles for all text.
  - Use only the recommended styles that are already contained within this template.
  - Table styles are also included.
  - Do not modify the current styles.
- Include alternative text (alt text) for all images, tables, equations and objects.
  - For images, use this statement for the alt text where it is not possible to describe the image: 'For a description of this image, please contact [email address].'
- All images and objects should be in line with text and not floating.
- Avoid the use of text boxes and columns.
- Tables:
  - Use the recommended table styles contained within the template.
  - Keep tables simple – try to avoid merging and splitting cells and only use simple, single row headers.
  - If complex tables (with merged cells) are needed, add this statement to the table alt text: 'For a description of this table, please contact [email address].'
  - Specify the table header row by selecting the first row, right-click the table, click 'Table Properties', 'Row tab' and then tick 'Repeat as header row at the top of each page'. You must do this for all tables that have a header row, even if they do not flow onto another page. You do not need to do this if you have a table that uses a header column instead.
- All web hyperlinks must include a ScreenTip.
- Do not use empty paragraph returns.
- Do not use double spacing or use multiple spaces for alignment.

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METHANE SOURCES AND EMISSIONS

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- CSIRO is looking at emissions near the Condamine River through GISERA and a commercial contract. CSIRO's isotopic analysis of methane gas collected from the main bubbling site in the Condamine River suggests that the origin of the methane is from bacterial metabolism of coal, and that the three-fold increase in bubbling methane since ongoing measurement began in early 2015 may have an industry component (likely to be small) and is highly unlikely related to hydraulic fracturing. Research to date also provides no evidence that the seepage of methane from the Condamine River area has any adverse environmental impact on the plant or animal life of the river and its surroundings.

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CSIRO-IN-CONFIDENCE

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CSIRO-IN-CONFIDENCE

Document 15

Unconventional Gas Fugitive Methane Emissions

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Meanwhile, the Condamine River gas bubbling (Refer previous fact sheet) is generating about 6,600 kg/day of methane. Current research indicates that the majority of this bubbling is from natural sources; although a component of these fluxes may be associated with coal seam depressurisation in CSG production fields 5 – 6 km away.

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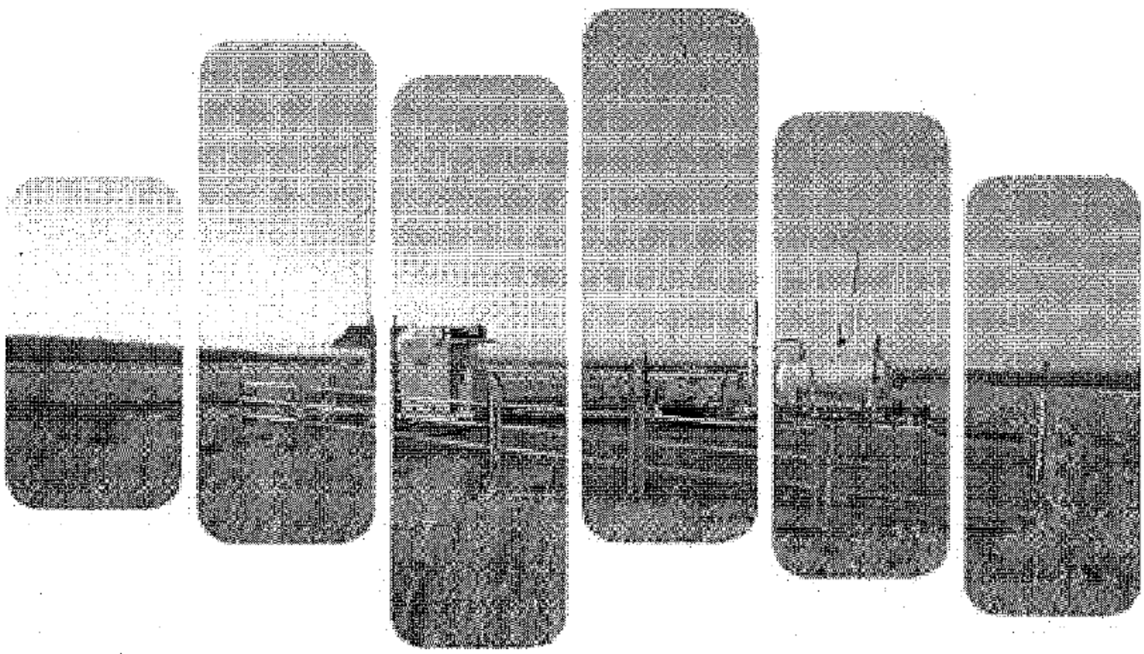
Document 16

GISERA Gas Industry Social & Environmental Research Alliance

Quarterly report

For period ending 31 March 2016



CSIRO | Australia Pacific LNG | QGC | AGL Energy in action | Origin | Santos We have the energy.

GISERA, GPO Box 2583, Brisbane QLD 4001, Australia

Contents

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Key communication activities during January-March 2016 include:

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- Damian Barrett participated in a pre-recorded interview with Mark Willacy (ABC) on a story they are doing on methane emissions from the Condamine River near Chinchilla. Broadcast on ABC news on Sunday, 21 February 2016.

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Contact us

Jizelle Khoury
Phone: [redacted] s47F
Email: [redacted]
www.gisera.org.au

Document 17

Gas Industry
Social & Environmental
Research Alliance

Appendix 1

Detailed Progress against project milestones
For period ending 31 March 2016

Contents

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List of Tables

Pages 1-99 Not Relevant - s22 - Removed

[redacted]

7 Greenhouse Gas Footprint

Portfolio Goal: Greenhouse gas (GHG) footprint research aims to improve characterisation and management of gas industry greenhouse gas impacts.

7.1 Methane seepage fluxes, Surat Basin, Queensland

Project scope: The aims of the current research project are to detect and measure methane seeping from underground in the Surat Basin, and identify sources of methane to provide methane emissions data on a regional scale. This data set can be used to compare changes in methane concentrations as coal seam gas production increases in the Surat Basin.

7.1.1 Traffic light report

Table 7.1 Greenhouse Gas Footprint project 1 – milestones

No	Description	Task Leader	Scheduled Start	Schedule Finish
Task 1.1	Review & analysis of literature	Stuart Day	July-13	Aug-13
Task 2.1	Remote sensing pilot study	Stuart Day	Oct-13	Sep-14
Task 2.2	Ground detection pilot study	Stuart Day	Oct-13	Nov-14
Task 3.1	• The continuous monitoring results – installation, commissioning and operation of the two field stations. • Preliminary data available.	Stuart Day	Jul-14	Nov-15
Task 3.2	• Modelled development and analysis of continuous data. • Periodic monitoring and field validation • Trial of remote sensing technologies.	Stuart Day	Dec-15	Nov-16
Task 3.3	• Delivery of final report for Remote sensing baseline study and Ground detection baseline study	Stuart Day	Dec-15	Nov-17
Task 4.1	New data prepared	David Etheridge	Nov-15	Nov-16
Task 4.2	Data screened, assessed	David Etheridge	Nov-15	Nov-16
Task 4.3	Models developed and applied to new data	Ashok Luhar	Jul-16	Aug-17
Task 4.4	Report prepared	David Etheridge	Dec-16	Nov-17

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Task 2.2

TASK NAME: Ground detection pilot study

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If the pilot site consists of methane fluxes from water bodies, the work will build on existing research undertaken in CSIRO in the Condamine River. Methane fluxes from aquatic systems with free water surfaces (e.g. river weir pools, farm dams) will be quantified using floating chambers used in one of two modes:

1) For low fluxes typical of natural waters the head-space gas is recirculated through a high precision gas analyser (Picarro CRDS) following the protocols used by CSIRO for similar research in water supply reservoirs;
2) For high fluxes (i.e. vigorous bubbling), a once-through system currently being developed and trialled by CSIRO will be employed in which gas captured by a chamber is diluted by ambient air drawn through the chamber and subsequently analysed using a high precision gas analyser.

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Gas Industry
Social & Environmental
Research Alliance

Contact us

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www.gisera.org.au

Document 18

Energy Technology Research Program Directors Report
May 2016
Dr Damian Barrett – Onshore Gas Program

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Engagement Highlights

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- Over the past month there has been a large number of media interviews given regarding GISERA research into the Condamine river. This was snowballed from a TV interview on The Project (channel 10) and 'went viral' including CNN, BBC, Washington Post, The Guardian and others!

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FOR CSIRO INTERNAL USE ONLY

National Assessment of Chemicals Associated with Coal Seam Gas Extraction in Australia (National Chemicals Assessment)

KEY SCIENCE MESSAGES

Pages 2-23 Removed - Exempt in Full - s22

[redacted]

Document 20

MINERAL RESOURCES, LAND AND WATER, ENERGY
www.csiro.au

Environmental Legacies of Australia's Resources and Industrial Sectors

Internal scoping report for consideration by the CSIRO Executive – not for distribution.

Lisa McKellar, Simon Apte, Justine Lacey, Paul Feron, Mike Trefry

July 2016

Citation

McKellar L, Apte SC, Lacey J, Feron P, Trefry MG (2016) Environmental Legacies of the Resources and Industrial Sectors. Internal scoping report for consideration by the CSIRO Executive – not for distribution. CSIRO, Australia.

Copyright

Important disclaimer

Contents

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Pages 5-44 Not Relevant - s22 - Removed

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Impacts on groundwater and surface water systems, including management of produced water and brine

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Groundwater level drawdown

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While the hydrogeological systems are being monitored closely and the environmental protection of Australia's water resources are a recognised high priority, there remains uncertainty in the behaviour of these sub-surface systems and there is still a lack of understanding about how the current scale of CSG development might create impacts over the longer term (Office of the Chief Scientist & Engineer, 2014b). For these reasons, monitoring activities are a high priority in all jurisdictions pursuing CSG development and relate to a number of impacts of water resources including changes to groundwater level, pollution of ground or surface water. Closely monitoring the hydrogeology of systems at the reservoir scale or wider also provides data to help identify any potential for long term cross contamination of aquifers from leaking bores.

Current groundwater monitoring networks in many regions do not provide an adequate baseline understanding on groundwater levels prior to CSG extraction. This is because traditionally, in areas such as the Condamine Catchment in the eastern part of the Surat Basin, groundwater extraction occurred primarily from the shallow (alluvial) aquifers. As a consequence, there are only very few nested groundwater monitoring sites where different aquifers are monitored simultaneously – and it is this monitoring which informs understanding of how different aquifers are connected.

There are a number of reviews currently examining the potential impact of depressurisation and associated drawdown of groundwater systems resulting from extraction of water for CSG development, including risk of subsidence. For example, when groundwater and gas are extracted from coal seams, the reduction in water pressure may result in compaction of the geological units in which depressurisation has occurred (IESC, 2014a).

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Pages 47-123 Not Relevant - s22 - Removed

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Gas Industry Social & Environmental Research Alliance

Project Order

Proforma 2016

1. Short Project Title (less than 15 words)

Regional Methane Emissions in NSW CSG Basins

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10. GISERA Objectives Addressed

Natural seeps of methane and other hydrocarbons are well known in gas fields but once major development has occurred it can be much more challenging to assess whether seeps are natural or caused by gas production activities (e.g. the Condamine River seep still remains a controversial issue despite considerable research into the phenomenon). Detection and quantification of landscape methane sources (either natural or anthropogenic such as legacy boreholes, abandoned oil and gas wells or water bores) ahead of development is essential for establishing a credible baseline. Understanding the contribution from other sources such as coal mining and agriculture is also important.

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Gas Industry Social & Environmental Research Alliance

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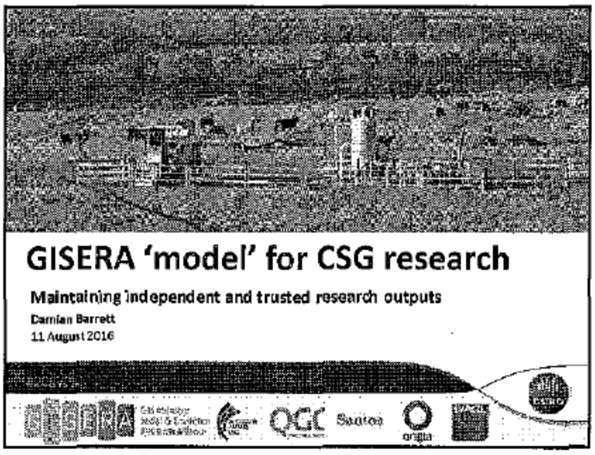
Document 22



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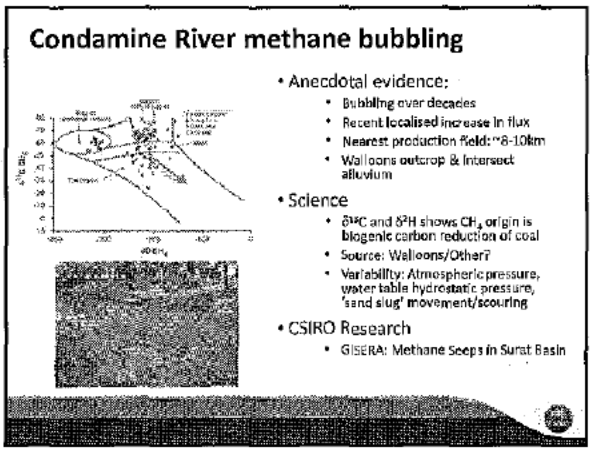

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Gas Industry
Social & Environmental
Research Alliance

GISERA National Research Management Committee Meeting No. 3

Thursday, 11 August 2016

2.00-4.00 pm

QGC offices, Kenya 2 Meeting Room, Level 30, 275 George Street, Brisbane

Telephone dial in details:

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Participants:

Damian Barrett: GISERA Director *(CSIRO)*
Rob Ully: Integrated Gas Environment Manager (*Origin*)
Joanne Pafumi: Vice President, External Affairs & Sustainability (*QGC*)
Rebecca Pickering: General Manager Production Operations - West (APLNG)
Douglas Jackson: Executive General Manager Group Operations (*AGL*)
Armon Hicks: Manager ENSW Public Affairs (Santos)
Nicole Hinton: Manager, Unconventional Gas, Onshore Gas and Governance, Energy Division (Department of Industry, Innovation and Science) – Alternate Independent Member
Peter Mayfield: Director, Energy Business Unit (*CSIRO*)
Paul Bertsch: Deputy Director-Science, Land and Water (*CSIRO*)
Dan O'Sullivan: Onshore Gas and Sustainability Advisor (*CSIRO*)
Jizelle Khoury: GISERA Executive Officer *(*CSIRO*)*

Apologies:

Mike Grundy: Research Director, Agriculture (*CSIRO*)

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Minutes
GISERA National Research Management Committee Meeting No. 2
Thursday, 19 May 2016
Santos offices, Boardroom level 22, Gateway Building, 1 Macquarie Place, Sydney

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4 **Activities in Queensland** *provided by Damian Barrett*

- There has been strong interest in methane emissions in the Condamine River which has resulted in a number of media activities.
- The GISERA mechanism for independence of CSIRO has been operating well up to this point. We have been able to deal with questions around our independence and perceptions of conflict of interest.
- The GISERA Director was asked to appear in an interview on Channel 10's The Project. The story was to provide an unbiased view on unconventional gas and the producer was keen on getting science into the story. During the story Jeremy Buckingham MLC questioned CSIRO's independence.
- The story received widespread interest and upon request, the GISERA Director provided interviews with BBC, CNN, The Washington Post, The Guardian and several other media outlets.
- CSIRO will issue a letter to Jeremy Buckingham MLC and have also scheduled a meeting with Mr Buckingham on 1 June 2016 to make clear the governance arrangements of GISERA and CSIRO's independence.
- This will impact how we work in this space. We will double our focus on how things will be perceived by wider community (the way we present our work, and the way we are seen operating with various groups including with government and with industry).
- The communication interactions between CSIRO and our industry partners will continue as normal.

- We are working to generate a fact-sheet on the Condamine River which will include the science and our best knowledge on the information available.

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10 NEXT MEETING

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Appendix 2 - - Summary of GISERA Representation and Engagement

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Pre-recorded interview for The Project (Channel 10)	22-Apr-16	Damian Barrett participated in a pre-recorded interview on Coal Seam Gas fire on Condamine River
Interview with Calla Wahlquist (The Guardian)	24-Apr-16	Damian Barrett did an interview for The Guardian – article title 'River on fire in Greens MP's video is natural, not fracking, says CSIRO'
Interview with Ben Guarino (The Washington Post)	25-Apr-16	Damian Barrett did an interview for The Washington Post - article title 'Australian politician blames fracking after he sets river ablaze with a lighter'

Briefing / Representation	Date	Purpose / Outcome / Lessons Learnt
Interview with CNN	25-Apr-16	Damian Barrett did an interview for CNN - article title 'River set ablaze nearly burns politician'

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Document 24

www.csiro.au

National Assessment of Chemicals associated with Coal Seam Gas Extraction in Australia

CSIRO Communication Brief for the release of Technical Reports

17 AUGUST 2016

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Will future research consider fugitive emissions from hydraulic fracturing operations, for example, methane?

- While fugitive emissions were outside the scope of this project, CSIRO and the Department of the Environment have worked together to measure fugitive emissions from the coal seam gas industry in Australia. Fugitive emissions include underground gases that escape to the air during gas production. They may occur through leaks, accidents or equipment failure, through venting or flaring (burning off), or exploratory drilling. The report is available on www.environment.gov.au.
- Recent media (early 2016) has focussed on the release of methane from the Condamine River and has attributed these emissions to coal seam gas extraction in the region. Emissions in the Condamine River have been the subject of ongoing scientific investigation since 2012 and the reports from these investigations and reviews by the Queensland Chief Scientist are available through the Department of Natural Resources and Mines and a technical report prepared by Norwest Pty Ltd can be viewed at http://www.aplng.com.au/pdf/1_Norwest_Report_Executive_Summary_-_Contents_-_Tables.pdf. The report provides details of potential sources for the Condamine methane seeps.
- Direct inquirers to these sources for any further comment.

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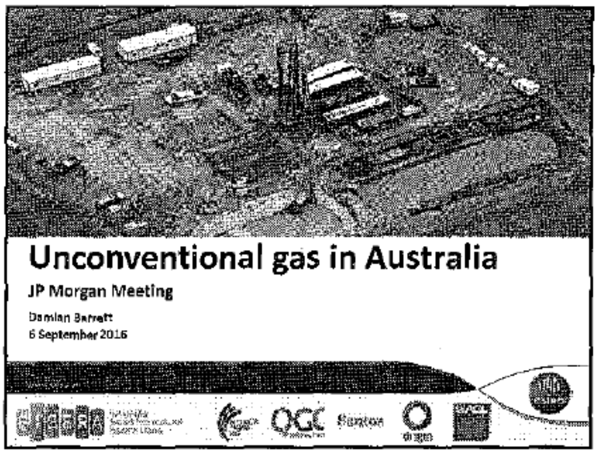
Document 25



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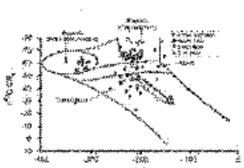
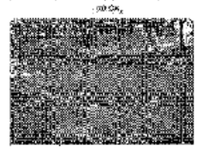
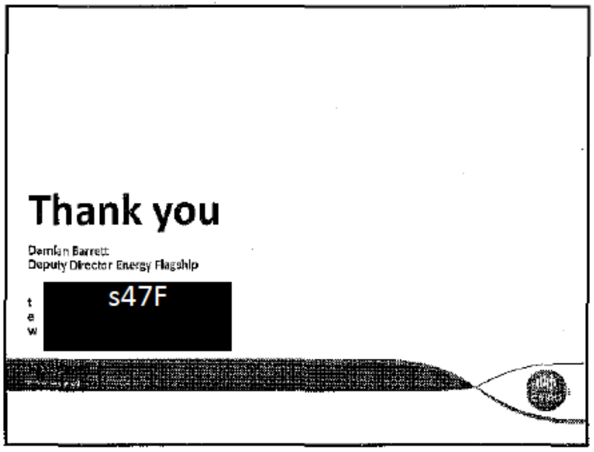
Condamine River methane bubbling





- Anecdotal evidence:
  - Bubbling over decades
  - Recent localised increase in flux
  - Nearest production field: ~8-10km
  - Walloons outcrop & intersect alluvium
- Science
  - $\delta^{13}C$ and $\delta^{2}H$ shows CH_4 origin is biogenic carbon reduction of coal
  - Source: Walloons/Other?
  - Variability: Atmospheric pressure, water table hydrostatic pressure, 'sand slug' movement/scouring
- CSIRO Research
  - GISERA: Methane Seeps in Surat Basin



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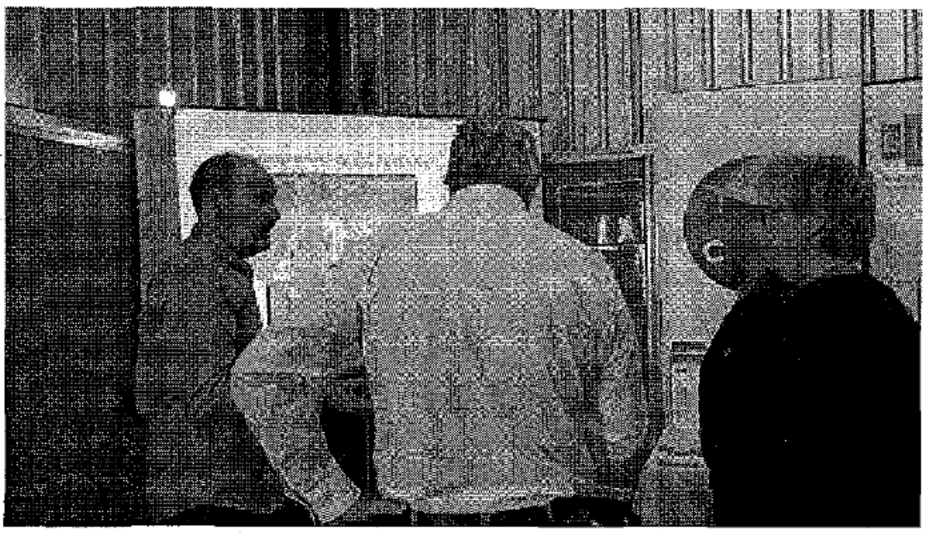
Document 26

Gas Industry Social & Environmental Research Alliance

National GISERA's communication strategy

Communication and engagement plan
12 October 2016



Source: CSIRO

GISERA, GPO Box 2583, Brisbane QLD 4001, Australia

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Table 2.3 Communication and engagement plan 2016-2017

Strategic goal	Activity/Event	Target Audience	Communication tool	Frequency/timing	Responsibility
Communicate in plain English information that helps to address knowledge gaps in environmental, social and economic impacts from onshore gas development, whether that is through original research or synthesis of existing knowledge	Fact sheet on the Condamine River and methane bubbles - fact sheet will draw on the latest scientific available data. Fact sheet to be peer-reviewed	Broader community, landholders, farmers, agricultural industry, industry associations, federal and state government departments, gas developers	Fact sheet, GISERA website	Nov/Dec 2016	Lead: GISERA Communication and Engagement Manager with support from GISERA Director

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Gas Industry Social & Environmental Research Alliance

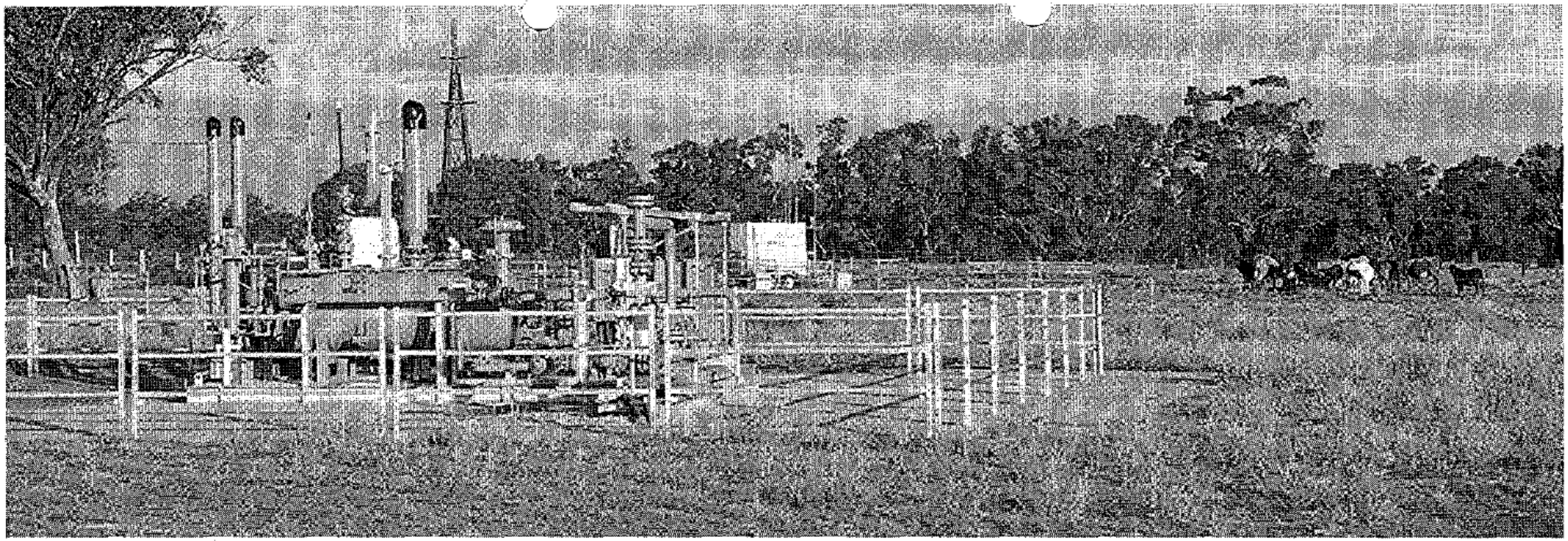
Contact us

Tsuey Cham

Phone: [redacted]

Email:

www.gisera.org.au



Document 27

CSG research in NSW

Narrabri Council

Damian Barrett

25 October 2016

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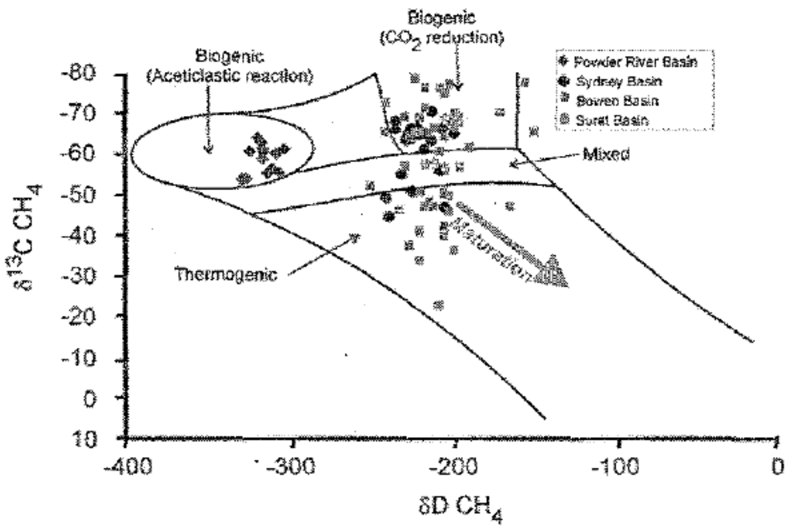
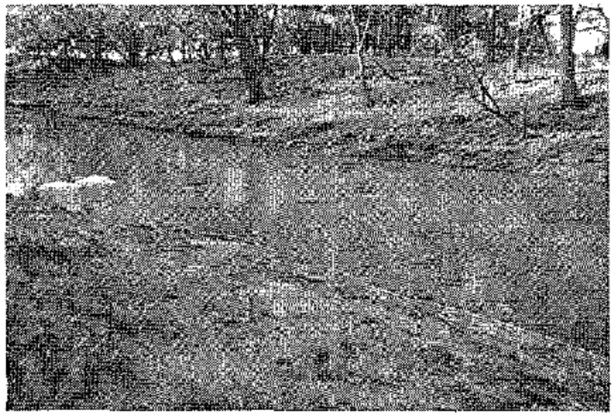
Condamine River methane bubbling





- Anecdotal evidence:
  - Bubbling over decades
  - Recent localised increase in flux
  - Nearest production field: ~8-10km
  - Walloons outcrop & intersect alluvium
- Science
  - $\delta^{13}C$ and $\delta^{2}H$ shows CH_4 origin is biogenic carbon reduction of coal
  - Source: Walloons/Other?
  - Variability: Atmospheric pressure, water table hydrostatic pressure, 'sand slug' movement/scouring
- CSIRO Research
  - GISERA: Methane Seeps in Surat Basin

Thank you

Damian Barrett
Deputy Director Energy Flagship

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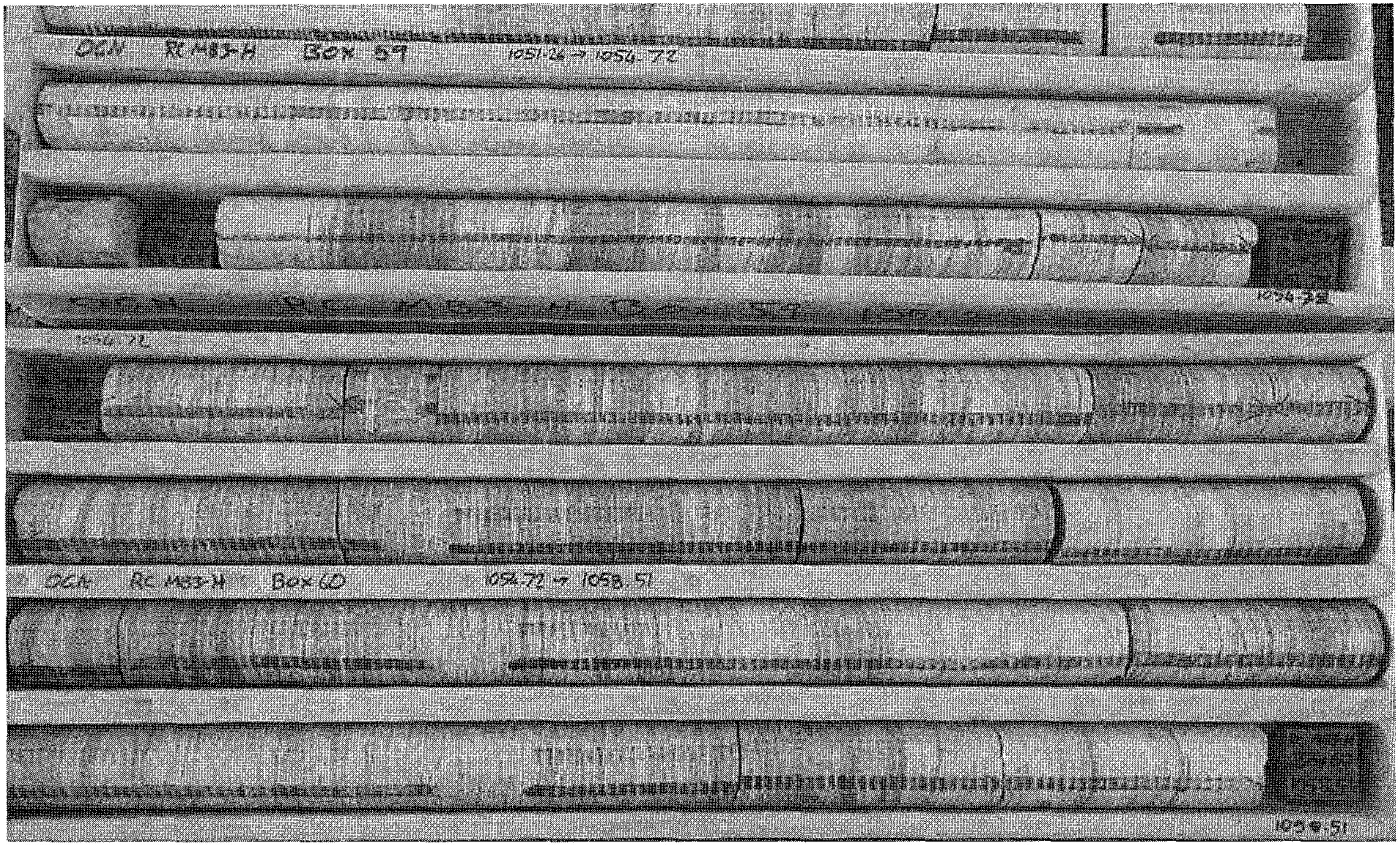

Evergreen formation

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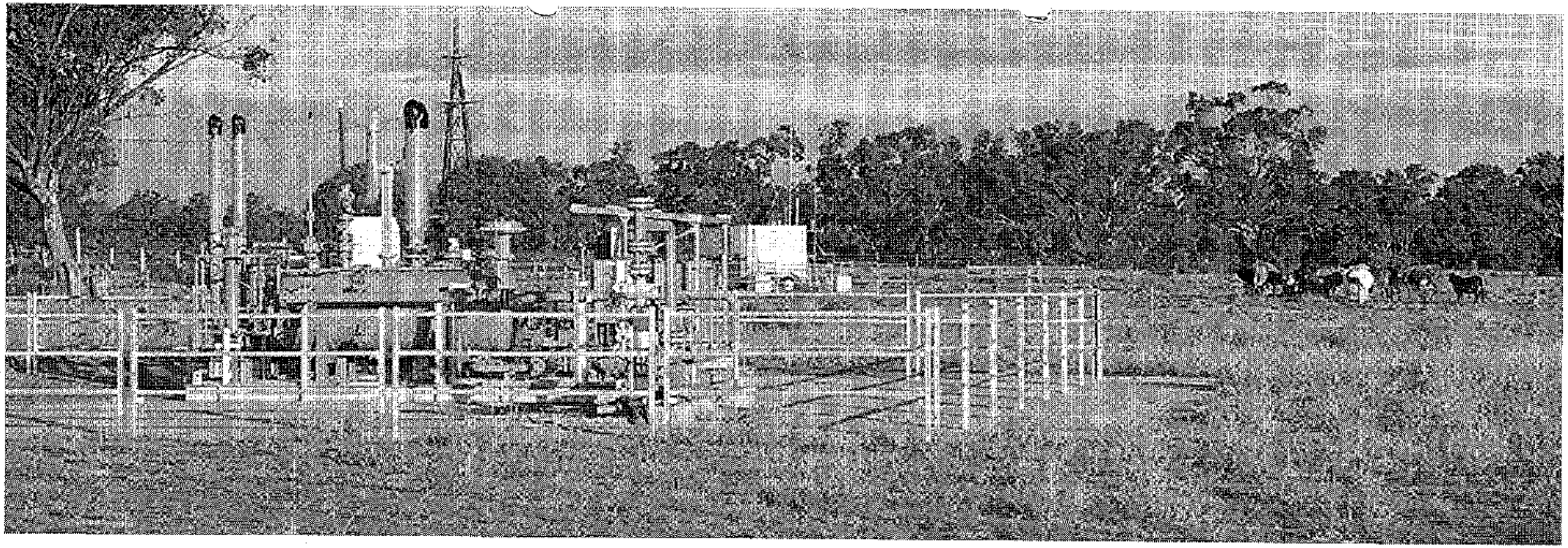

GISERA research in NSW

Document 28

NSW Government

Damian Barrett

28 October 2016

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Thank you

Damian Barrett
Deputy Director Energy Flagship

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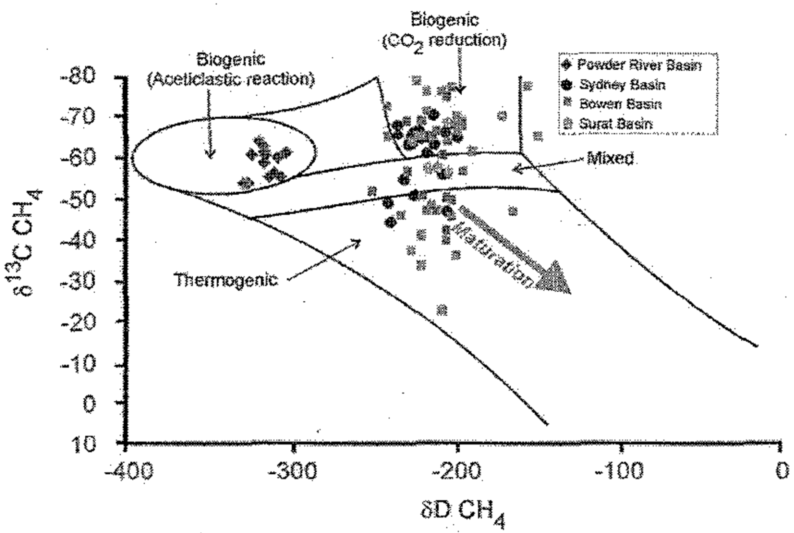
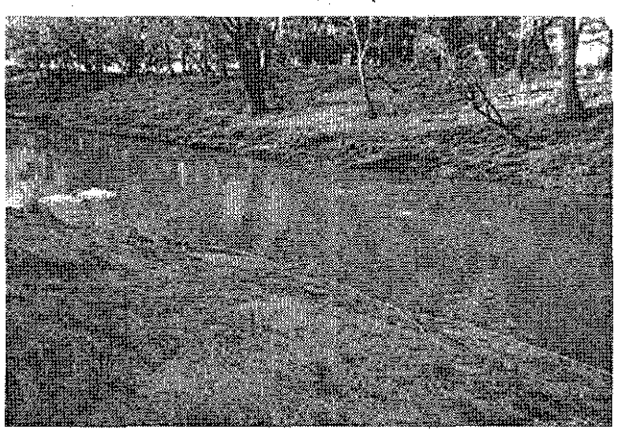
Condamine River methane bubbling





- Anecdotal evidence:
  - Bubbling over decades
  - Recent localised increase in flux
  - Nearest production field: ~8-10km
  - Walloons outcrop & intersect alluvium
- Science
  - $\delta^{13}C$ and $\delta^{2}H$ shows CH_4 origin is biogenic carbon reduction of coal
  - Source: Walloons/Other?
  - Variability: Atmospheric pressure, water table hydrostatic pressure, 'sand slug' movement/scouring
- CSIRO Research
  - GISERA: Methane Seeps in Surat Basin

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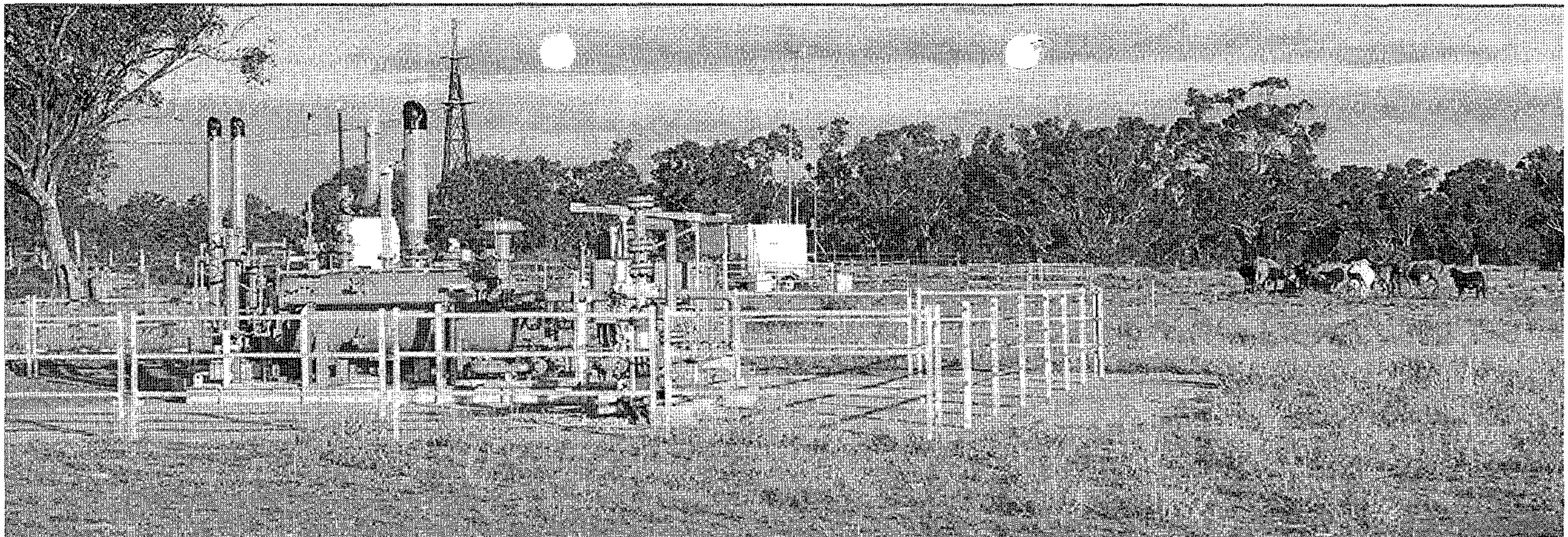

Unconventional gas in Australia

APA Group Meeting

Damian Barrett

14 November 2016

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[1] Wood Mackenzie (2015) 'Competitiveness of Australian LNG'

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Groundwater model of Walloon Coal Measures in Surat Basin, Qld

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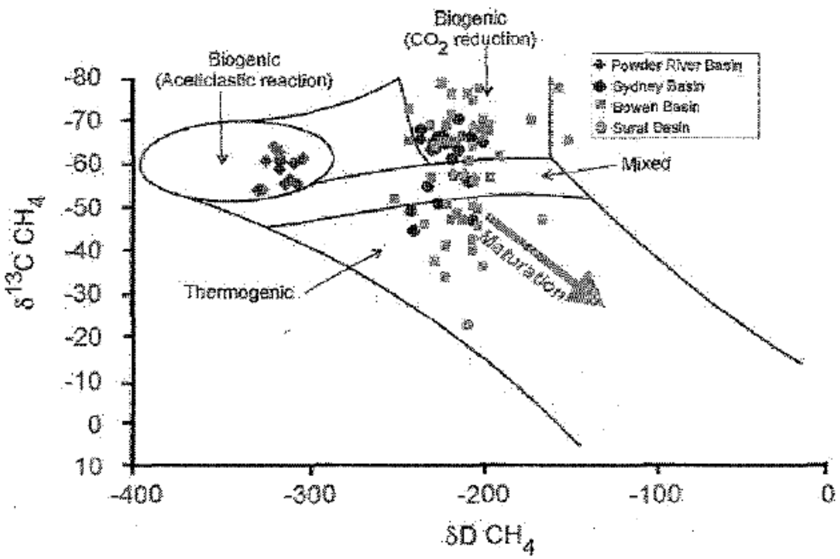
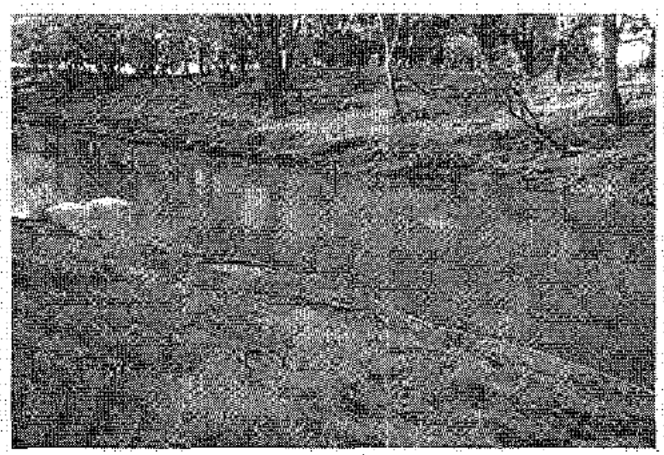
Condamine River methane bubbling





- Anecdotal evidence:
    - Bubbling over decades
    - Recent localised increase in flux
    - Nearest production field: ~8-10km
    - Walloons outcrop & intersect alluvium
- Science
    - $\delta^{13}C$ and $\delta^{2}H$ shows CH_4 origin is biogenic carbon reduction of coal
    - Source: Walloons/Other?
    - Variability: Atmospheric pressure, water table hydrostatic pressure, 'sand slug' movement/scouring
    - Some (minor) impact by CSG production
- CSIRO Research
    - GISERA: Methane Seeps in Surat Basin

Thank you

Damian Barrett
Deputy Director Energy Flagship

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CSIRO

Document 30

NATIONAL ASSESSMENT OF CHEMICALS ASSOCIATED WITH COAL SEAM GAS EXTRACTION IN AUSTRALIA (NCA)

CSIRO COMMUNICATION BRIEF FOR THE DEPARTMENT OF ENVIRONMENT AND ENERGY'S RELEASE OF THE TECHNICAL REPORTS

16 NOVEMBER 2016

INTERNAL USE ONLY

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Will future research consider fugitive emissions from hydraulic fracturing operations, for example, methane?

- While fugitive emissions were outside the scope of this project, CSIRO and the Department of the Environment have worked together to measure fugitive emissions from the coal seam gas industry in Australia. Fugitive emissions include underground gases that escape to the air during gas production. They may occur through leaks, accidents or equipment failure, through venting or flaring (burning off), or exploratory drilling. The report is available on www.environment.gov.au.
- Recent media (early 2016) has focussed on the release of methane from the Condamine River and has attributed these emissions to coal seam gas extraction in the region. Emissions in the Condamine River have been the subject of ongoing scientific investigation since 2012 and the reports from these investigations and reviews by the Queensland Chief Scientist are available through the Department of Natural Resources and Mines and a technical report prepared by Norwest Pty Ltd can be viewed at http://www.aplng.com.au/pdf/1_Norwest_Report_Executive_Summary_-_Contents_-_Tables.pdf. The report provides details of potential sources for the Condamine methane seeps.
- Direct inquirers to these sources for any further comment.

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Memorandum to the CSIRO Major Transactions Committee

Meeting No. 61	10 March 2017	Agenda Item: 2.5
Subject/OD no.	National GISERA (OD-205863)	
Author	Damian Barrett	
Sponsor	Peter Mayfield	
Business Unit	Energy	
Portfolio	Environment, Energy & Minerals	
Date	18 February 2017	
Action for MTC	For Decision	

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Table 2.3 Communication and engagement plan 2016-2017

STRATEGIC GOAL	ACTIVITY/EVENT	TARGET AUDIENCE	COMMUNICATION TOOL	FREQUENCY/TIMING	RESPONSIBILITY
Communicate in plain English information that helps to address knowledge gaps in environmental, social and economic impacts from onshore gas development, whether that is through original research or synthesis of existing independent and peer reviewed knowledge	Fact sheet on the Condamine River and methane bubbles - fact sheet will draw on the latest scientific available data. Fact sheet to be peer-reviewed	Broader community, landholders, farmers, agricultural industry, industry associations, federal and state government departments, gas developers	Fact sheet, GISERA website	Nov/Dec 2016	Lead: GISERA Communication and Engagement Manager with support from GISERA Director
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Pages 87-96 Not Relevant - s22 - Removed

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Document 32

GISERA
Gas Industry Social and Environmental Research Alliance

Quarterly report

For period ending 31 March 2017

Image: Stakeholder workshop - Biological traits and ecological aspects for plant population viability held 24 February 2017

GISERA, GPO Box 2583, Brisbane QLD 4001, Australia

Contents

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- A factsheet on methane seeps in Condamine River, Queensland was released on the CSIRO website in March 2017. It presents the current state of scientific knowledge on methane seeps in the Condamine River, including natural and human causes, and the human and environmental health and safety impacts of methane escaping from underground. This fact sheet has been coordinated through GISERA and developed by CSIRO researchers with expertise in the hydrogeology, geology, ecology and biogeochemistry and from multiple sources to summarise what we currently know about these methane seeps.

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Contact us

Jizelle Khoury
Phone: [redacted] s47F
Email: [redacted]
www.gisera.org.au

Document 33

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<u>GISERA Website upgrade and communications</u> GISERA website upgrade complete incorporating improvements identified in January 2017. Release of communiqué and short animation on economic forecasting complete. Release of fact sheets (Condamine River gas bubbling). Community Wellbeing Survey in Narrabri completed.	30 April 2017
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Document 34

ENERGY
www.csiro.au

CSIRO

Assessment of scientific knowledge of shale gas and shale oil impacts

Prepared for the Queensland Department of Natural Resources and Mines

Cameron Huddlestone-Holmes, Nerida Horner, Simon Apte, Stuart Day, Neil Huth, James Kear, Jason Kirby, Dirk Mallants, Tom Measham, Chris Pavey and Richard Schinteie

EP165346
April 2017

Pages 1-102 Not Relevant - s22 - Removed

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Figure 24 Development of an erosion rill alongside a coal seam gas access track near Chinchilla, Queensland (A), and (B) simulated water flows across an access track network from a 3D reconstruction of the ground surface within a forested section of coal seam gas development near Condamine, Queensland

Pages 104-191 Not Relevant - s22 - Removed

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GISERA
Gas Industry Social and Environmental Research Alliance

Document 35

GISERA National Research Management Committee Meeting No. 5

Wednesday 12 April 2017

9.30am - 11.30 am (AEST)

Location: Santos, Level 22, Gateway Building, Room 22.03, 1 Macquarie Place, Sydney ***and*** via Teleconference

Telephone dial in details:

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Participants:

Damian Barrett	GISERA Director *(CSIRO)*
Paul Bertsch	A/Director, Land and Water (*CSIRO*)
Mike Grundy	Research Director, Agriculture (*CSIRO*)
Armon Hicks	Manager ENSW Public Affairs (*Santos*)
Andi Horsbugh	Social Investment Advisor (delegate for Simon Nish) (*Shell QGC*)
Rebecca Pickering	General Manager Production Operations - West (*APLNG*)
Michael Sheldrick	General Manager, Onshore Energy Branch, Resources Division, Department of Industry, Innovation & Science (*Government*)
Rob Ully	Integrated Gas Environment Manager (*Origin*)
Jizelle Khoury	GISERA Executive Officer *(CSIRO)*
Dan O'Sullivan	Onshore Gas and Sustainability Advisor (*CSIRO*)
Emma Scott	GISERA Administration Officer (*CSIRO*)

Apologies:

Douglas Jackson	Executive General Manager Group Operations (*AGL*)
Simon Nish	Manager Social Performance and Community Engagement (*Shell QGC*)
Peter Mayfield	Acting Executive Director, Environment, Energy and Resources (*CSIRO*)

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Gas Industry Social and Environmental Research Alliance

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Interview with Leon Byner (Adelaide Radio station 5AA)	24-Mar-17	Damian Barrett participate in a live-to-air radio interview - What is fracking, methane emissions in the Condamine River, and what is the difference between coal seam gas and Shale gas extraction.

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