Gas and groundwater migration through faults: the role of faulting in unconventional gas resources. The Galilee Basin (Australia) as an analogue for the Magallanes Basin (Chile).

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Abstract. When it comes to Energy, Chile is not a self-sufficient country as it imports more than 72% of its total energy required for internal consumption. Consequently, finding new energy resources within Chilean territory is a must. In the last three decades the global energy market has been experiencing a gas revolution, and nowadays gas reserves worldwide have increased drastically due to the exploitation of unconventional gas resources, which include shale gas, coal seam gas and tight gas. Unconventional gas resources are hosted in relatively impermeable rocks (e.g. shale, coal) in comparison to conventional sources which are hosted in permeable rocks (e.g. sandstones). Nowadays, the development of new technologies has enabled the recovery of unconventional gas.
Faults play a key role in gas and/or groundwater migration. When the host rock is impermeable, faults may form areas of naturally increased permeability which can enhance gas flow during the exploitation process. This abstract presents a comprehensive study of the Galilee Basin (Australia), which has been under coal seam gas exploration since 2010, and it compares this basin to the Magallanes Basin in Chile, in order to assess this basin's gas extraction potential which could eventually solve Chile's energy problems.

Keywords: faults, methane, groundwater, coal seam gas, coalbed methane, shale gas.

1 Introduction

The most common types of unconventional gas resources are coal seam gas (CSG; also referred as coalbed methane), shale gas and tight gas. The United States of America is the largest producer of unconventional gas in the world. In 2007, the US unconventional gas production exceeded conventional gas production mainly due to shale gas extraction (Rogers, 2011). World reserves of unconventional gas have also rapidly increased, and are expected to exceed reserves of other fossil fuel sources by 2020 (IAE, 2012). In Australia, CSG is the most exploited unconventional gas type and its exploration has increased quite rapidly in the last 15 years. For example, estimated reserves for CSG exceeded the ones for conventional gas in Queensland in 2011 (Queensland Government, 2011).

In unconventional gas resources, methane gas is generated by either the biogenic or thermogenic degradation of organic matter associated to the source rock material. In the case of Shale Gas, the methane gas is trapped within the shales — fine grained sedimentary rocks which act both as gas source (e.g. organic matter inside the rock) and storage. On the other hand, in the case of CSG, methane gas is adsorbed to the coal matrix with hydrodynamic pressure acting on coal cleats, as coal seams are saturated. Permeability is usually lower in shale gas reservoirs than in CSG reservoirs (Jenkins & Boyer, 2008). Tight Gas is found in relatively impermeable rock formations having lower permeabilities than in the two previous cases. Because of these differences, gas extraction methods are also different. Two methods are required in order to extract Shale Gas and Tight Gas: hydraulic fracturing and horizontal drilling. Hydraulic fracturing (also known as "fracking") requires the use of a mixture of water, chemicals, and sand injected at high rates in order to fracture the host rock to artificially enhance rock permeability (Sakmar, 2010). Horizontal drilling requires drilling horizontally at a desired depth in order to increase the contact area in the reservoir; once this is done, hydraulic fracturing is required. In the case of CSG high volumes of water need to be extracted in order to release the hydrodynamic pressure keeping the gas adsorbed within the coal, and hydraulic fracturing or horizontal drilling are generally not required.

2 The Galilee Basin

One example of a coal seam gas basin in Australia is the Galilee Basin in Queensland. Due to the success in exploration and development of CSG in the Bowen and Surat basins in Queensland, the Galilee Basin became a new target by the Energy industry in Australia. This basin consists of Carboniferous to Triassic sedimentary clastic sequences composed mostly of interbedded sandstones, siltstones and mudstones. It also contains Permian coal seams that are an exploration target for CSG since 2010. It is overlaid by the Eromanga Basin, which is a Jurassic to Cretaceous sedimentary sequence, lithologically similar to the Galilee Basin but with the absence of coal seams. The hydrostratigraphy of these basins is summarised in Figure 1. Both basins dip south-west and consequently, formations depths increase in that direction. Currently CSG pilot wells are operating in the basin where the coal seams present an approximate depth of 1000 m.

In CSG extraction, groundwater plays a key role as methane is adsorbed to the coal matrix by the action of the hydrodynamic pressure exerted on the coal pores by groundwater. Consequently, in order to extract methane gas, large volumes of groundwater needs to be pumped to the surface to reduce the hydrodynamic pressure in order to release this gas, which then flows to the surface along with the extracted groundwater. The study area is located within the Great Artesian Basin (GAB), which comprises the entire Eromanga Basin sequence and the Upper Galilee Basin (particularly the Triassic formations; Figure 1). The GAB is the most important groundwater resource in Australia and one of the largest artesian basins in the world (Ransley and Smerdon, 2012). Consequently, studying the relationship between GAB aquifers and underlying coal seams is essential before any gas extraction takes place.

Inter-aquifer studies within GAB aquifers in the Galilee Basin and their relationship with coal seams were carried out recently (Moya et al. 2014; 2015; under review). The purpose of these studies was to understand whether GAB aquifers could be affected by gas extraction. The studies also included an assessment of regional faults through the development of a 3D geological model, which highlighted significant aquifer compartmentalisation through faults in the Study Area. A complete hydrochemical characterisation was carried out in order to understand groundwater processes occurring within the basin and, in addition, an isotopic study, which included dissolved methane samples, was carried out to constrain inter-aquifer mixing (Moya et al. 2014; 2015; under review). All faults were mapped in the subsurface by analysing seismic surfaces created as a combination of thousands of 2D seismic lines. Aquifer and coal seam displacements were observed along faults, reaching values of up to 650 m of vertical displacement (e.g. Thomson River Fault; Moya et al. 2014). In most of these cases the coal seams and aquifers are abutted either against the basement or against aquitards (both impermeable), thus creating an impermeable barrier for groundwater movement (Moya et al. 2014). The hydrochemical characterisation identified carbonate dissolution and silicate weathering as the main processes controlling groundwater chemistry but also recognised the presence of dissolved carbon dioxide (Moya et al. 2015). The presence of CO_2 is very important because this highlights the occurrence of methanogenesis. With this process, methanogenic bacteria anaerobically consume CO_2 and produce methane gas in coaly environments, which suggests the presence of methane in the coal seam formations of the Galilee Basin. The isotopic characterisation (δ^2H, δ^{18}O, δ^{13}C, ^{87}Sr/^{86}Sr, and ^{36}Cl) showed that mixing between groundwaters from the coal seam bearing formations is unlikely in a regional scale. In addition, the 3D geological model showed that the coal seam formations are well separated from the aquifers by impermeable units. Although these units isolate individual aquifers, the vertical influence of faults could be an important aspect to consider. Faults have already been demonstrated to be horizontal flow barriers, but their vertical influence has not been demonstrated. Dissolved methane in groundwater samples collected from wells completed in the Hutton Sandstone aquifer (Figures 1 and 2), in the proximity of two regional faults, indicated the presence of important amounts of methane. However, methanogenesis within this aquifer is not expected to have occurred directly in this unit because the Hutton aquifer does not contain any coal material. In addition, electrical conductivity values for these samples are higher than mean values for samples collected away from the faults in this aquifer, and closer to the ones for the coal seam bearing formations. Methane gas can migrate either during formation or after natural depressurisation events (e.g. with uplifting) (Scott, 2002). Consequently, it is possible that the methane gas present in the Hutton Sandstone migrated upwards from the coal bearing units through these faults, which would act as vertical conduits for gas and groundwater movement. Even though regional inter-aquifer mixing is unlikely, it is possible this occurred locally through faults in this case (Figure 2; Moya et al. under review).

3 The Magallanes Basin

According to the IEA (2012), Chile possesses the third largest shale gas resource in South America after Argentina and Brazil, and it is placed on the 13th place in the world. In Chile, these resources are contained within the Magallanes Basin, which is located in the southernmost part of Chile and Argentina (where it is known as the "Austral Basin"), covering an area of 168350 km^2. The main source rock (for shale gas) in the basin is the Lower Cretaceous Lower Inoceramus Formation (Tithonian-Aptian), which contains black organic-rich shales. Another important source rock in the Austral-Magallanes Basin is the Margas Verdes Formation (Aptian-Albian), which comprises marine mudstones and marl with moderate total organic content (TOC). The combined thickness of the Lower Inoceramus and Margas Verdes shales ranges from 240 m in the north to 1220 m in the south. TOC of these two main source rocks generally ranges from 1.0% to 2.0%,

with a hydrogen index of 150 to 550 mg/g (USEIA, 2011). The recoverable gas resource at this location is estimated at about 1680 million tonnes (84 TCF) in the Lower Inoceramus Formation and 1760 million tonnes (88 TCF) in the Margas Verdes Formation. Although the total recoverable resource in the basin is 3440 million tonnes (172 TCF), only 1280 million tonnes (64 TCF) would be located in Chilean territory (about 37%), and these reserves are not yet proven.
In 2014, ENAP signed a technical agreement with ConocoPhillips to jointly study and determine the unconventional hydrocarbon resources potential in the Magallanes region, in Southern Chile. On that year, ENAP also signed a memorandum of understanding with Galilee Energy Limited to jointly explore for unconventional hydrocarbons in the north-west portion of the Magallanes Basin. According to this memorandum, the exploration will cover an approximate area of 7200 km^2, targeting the CSG potential of the Loreto Formation (Eocene-Oligocene), which contains 10-20 m thickness coal at depths ranging from the surface to 1200 m. In addition, ENAP is also exploring for tight gas (Enrique Zurita, personal communication). These ongoing and future exploration activities highlight the importance and gas potential of the Magallanes Basin.
The Magallanes Basin is located in part of the Patagonian fold and thrust belt (Suarez et al. 2000). Hence understanding how tectonism and particularly faulting has affected the basin, is essential to identifying areas where permeability could be naturally increased by the faulting, which would help identify gas accumulations and sweet spots.

4 Conclusions

The study of the Galilee Basin in Australia highlights the importance of faults as possible vertical conduits for groundwater and gas migration. Although this study was developed in a CSG basin, it may be reproduced in other types of unconventional gas basins, particularly in basins presenting source rocks with lower permeabilities than the permeabilities of coals seams in the case of CSG. It is especially useful to identify possible gas conduits in basins with low permeability as this may facilitate the extraction process.
An important exploration phase is about to commence at the Magallanes Basin, and large reserves of unconventional gas resources are expected to be found.
Most of this gas will be found in very impermeable rocks, hence, studying the effect of faults on gas migration is very important to identify areas with higher permeability, in order to promote gas recovery.
In a country like Chile, where most of the Energy is imported, finding this type of gas resource would not only signify a dramatic change in the local Energy matrix, but would also help this country attain an important level of Energy self-sufficiency.

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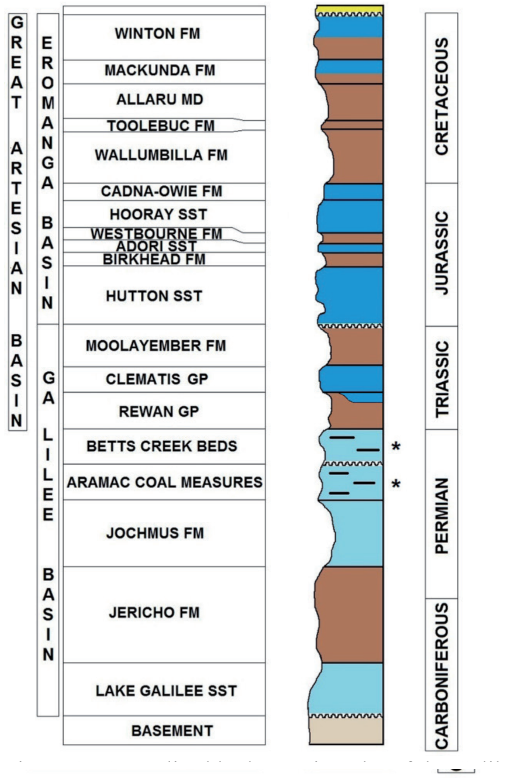

Figure 1: Generalised hydrostratigraphy of the Galilee and Eromanga basins. Note: the marker (*) highlights the position of the coal seam bearing formations.

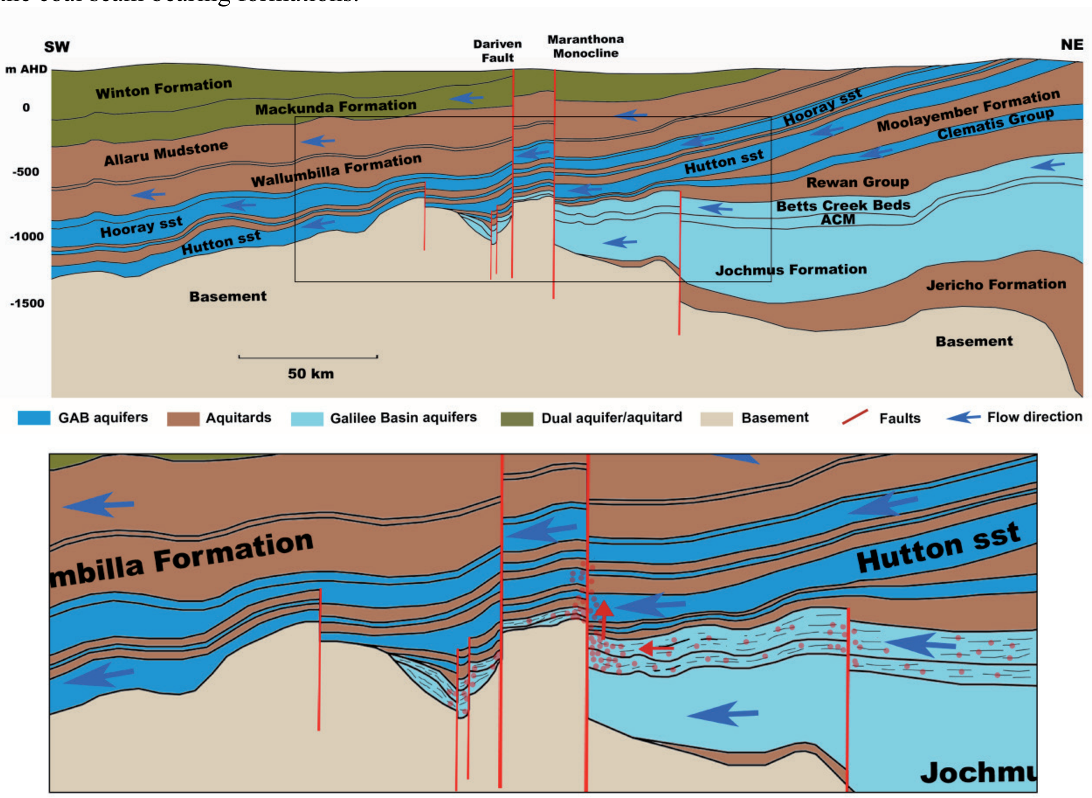

Figure 2: Cross section highlighting the area where gas (red circles) and water migrates upwards along the Maranthona Monocline. Abbreviations: ACM, Aramac Coal Measures; sst, Sandstone. Vertical exaggeration 40x. (after Moya, under review).