Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Reservoir Quality for Geothermal Energy in the Hutton Sandstone: from Analysis to Prediction

Antoine Dillinger, Cameron R. Huddlestone-Holmes, Horst Zwingmann, Ludovic Ricard, Lionel Esteban

CSIRO Earth Science and Resource Engineering, I Technology Court, Pullenvale QLD 4069

cameron.hh@csiro.au

Keywords: reservoir quality, diagenesis, Hutton Sandstone, Cooper Basin, Eromanga Basin, sedimentary

ABSTRACT

Geothermal resources hosted within sedimentary basins, also described as Hot Sedimentary Aquifers, have been explored as a geothermal play type in Australia. These resources have been targeted as they are thought to have high natural matrix permeability and are not expected to require significant permeability enhancement. However, at the resource temperatures (and depths) required to generate electricity, diagenetic processes may have destroyed permeability. This paper reports on the effects of diagenesis on geothermal reservoir quality in the Hutton Sandstone of the Eromanga Basin, Australia. This formation is a prolific oil and gas producer and is known to have good reservoir quality in oil fields, typically associated with structural highs. The geothermal potential was recently tested by the Celsius-1 well in the Nappamerri Trough. Well tests indicated good temperatures (160 degrees centigrade at 2,400m TVD) but extremely low permeability. Petrographic studies show that diagenetic effects, including compaction and neoformation of quartz (syntaxial overgrowths), kaolinite, and illite have destroyed the porosity and permeability in the formation. This study integrates a range of analytical techniques including petrography, SEM, and QEMSCAN. It results in a robust evaluation of the diagenetic history in a deep burial environment, its effects on flow properties, and implications for the geothermal potential of siliclastic formations.

1. INTRODUCTION

Geothermal resources hosted within sedimentary basins, also known as Hot Sedimentary Aquifers (HSA), have been successfully explored and developed for geothermal energy extraction worldwide (Lund et al., 1998, 2011). The best known examples in Australia are in Birdsville (Collins, 1987), and several projects in the Perth metropolitan area (Pujol, 2011). These areas have been targeted because of their potential high natural permeability, the presence of water, suitable temperatures and the extent of the resources. However these resources are all shallow, low enthalpy resources with temperatures less than 100 °C. More recently, deeper aquifers have been targeted with the aim of generating electricity at megawatt scale. Recent work by Augustine (2013) showed that very high flow rates (over 100 kg/s) would be required from production wells in sedimentary resources to be economically viable. Such flow rates will require permeability thicknesses in order of 10's of Darcy metres.

In 2010, a sedimentary geothermal resource in the Hutton Sandstone in the Cooper-Eromanga Basin (South Australia) was tested with an exploration well, Celsius-1. This resource was targeted as it was thought to have high natural matrix permeability similar to the prolific adjacent oil and gas fields, and was not expected to require significant permeability enhancement. Moreover, the region around Celsius 1 is known to be underlain by radiogenic granites, providing heat to the overlying formations including the Hutton Sandstone. Celsius 1 was drilled to intersect the full thickness of the Hutton Sandstone section and evaluate the flow capacity and exploitation potential of the formation. However, while temperatures were as expected (corrected bottom hole temperature of 160°C), well tests did not produce the anticipated flow rates at the resource temperatures required to generate electricity, raising the question of the impact of diagenesis on the reservoir quality of the sedimentary formation.

Transformations resulting from diagenetic processes have been proven to significantly affect and alter porosity and permeability and thus reservoir volume and flow rates. Yet, while conventional reservoirs have been intensively studied for oil and water production, the diagenetic influence in hot sedimentary reservoirs that occur at much greater temperatures and depths is not known and certainly different. The objectives of the study proposed herein are (i) to provide information on the diagenetic alterations and history affecting the flow properties of the Hutton Sandstone (iii) to acquire new data on the evolution of petrophysical properties, especially the permeability, of the target formation.

2. GEOLOGICAL BACKGROUND

The Cooper Basin consists of a broad downwarp with two main depocentres – the Poolowanna Trough and the Cooper Region – separated by the north-east-trending Birdsville Track Ridge, a complex of related domes and ridges. Three major troughs in the Cooper Region (Patchawarra, Nappamerri and Tenappera) are separated by structurally high ridges (GMI and Murteree Ridges) associated with the reactivation of northwest-directed thrust faults in the underlying Warburton Basin (Fig. 1). The Nappamerri Trough contains the deepest and thickest Cooper Basin sediments. The region forms part of a broad area of anomalously high heat flow, which is attributed to Proterozoic basement enriched in radiogenic elements. High heat producing granites, including granodiorite of the Big Lake Suite (BLS) at the base of the Copper/Eromanga sequences, form a significant geothermal play that was targeted to be Australia's first Hot Rock development at Habanero. The relationship between high heat flow, high temperature gradient and anomalous heat production in the BLS is well established. The thick sedimentary sequences of the overlying Cooper/Eromanga Basins provide a thermal blanketing effect resulting in temperatures as high as 270 °C at depths < 5 km.

The Lower to Middle Jurassic Hutton Sandstone consists of mineralogically mature, fine to coarse grained quartzoses with minor siltstone interbeds. The formation contains sands sourced from a cratonic provenance and clasts reworked from Triassic, Permian and older sediments. The Hutton Sandstone was deposited in braided stream to high energy, low sinuosity fluvial environments with influence from aoelian and lacustrine processes (Watts 1987). The wells drilled to date in the Eromanga Basin have been on structural plays and approximately 70 % of the oil discovered is contained in the Hutton Sandstone and sealed by the Birkhead Formation.

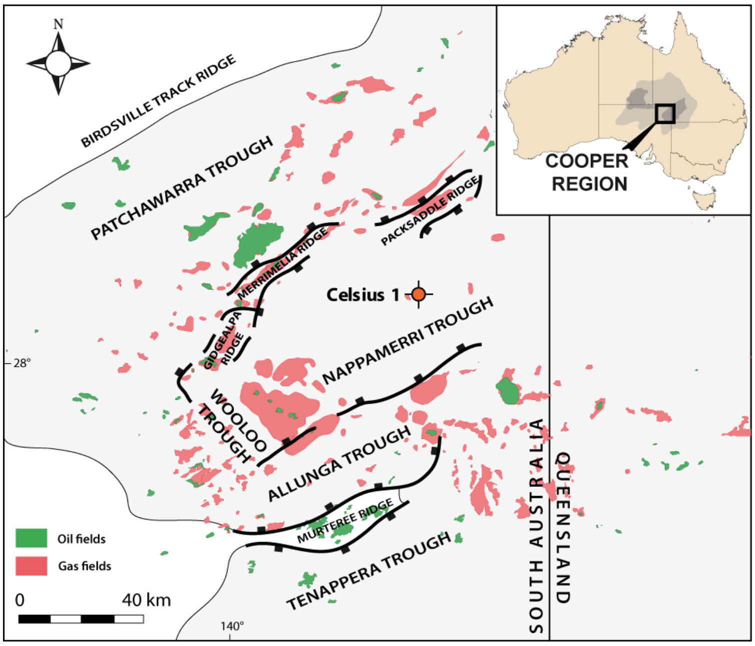

Figure 1: Structural map of the Cooper region and Oil & Gas fields

3. PETROLOGY OF THE HUTTON SANDSTONE

3.1 Celsius 1

The mineral framework is mainly constituted of sub-angular detrital quartz grains, with sizes from medium silts to very coarse sands (10 to 1000 µm). The grain contacts essentially consist of line or suture contacts due to moderate to high mechanical compaction. Grains are cemented and tightly interlocked by a fine-grained clayey matrix or a secondary cement, implying variable pore geometries and distributions. The dispersed argillaceous matrix exhibits characteristics of detrital clays with tiny, ragged abraded platelets (10 to 200 µm) naturally filling pores, coating the framework grains and creating pore-lining and pore-bridging fabrics. Diagenetic cements occur as sharp edged quartz overgrowths precipitated in optical continuity around the detrital quartz grains or pore-filling aggregates in interstitial or vugular pores with no apparent alignment to the framework grains. The most ubiquitous and widespread authigenic phases are quartz overgrowths and kaolinite. Neoformation of illite derived from the detrital matrix is the third most common authigenic process observed, with a frequency increasing with depth as the facies become increasingly clay-rich. This seems to be the main mode of formation of illite while kaolinite recrystallisation into illite is less widespread, perhaps due to the relative stability of kaolinite. Based on mineral area percentage obtained by QEMSCAN analysis, four lithofacies (A, B1, B2, and C) have been identified in the Hutton Sandstone at Celsius-1 (Fig. 2).

Correlating observations on diagenetic processes enables the reconstruction of the diagenetic history of the studied interval. Sandstones of the Hutton Sandstone are affected by burial diagenesis with processes associated to the eogenetic and mesogenetic phases. Nevertheless, the diagenesis affects the sediment in various fashions according to its initial composition. The facies classification scheme helps highlight three different diagenetic histories of the sandstone (Fig. 3).

Facies A shows processes of early diagenesis and hence has undergone a diagenetic evolution less pronounced than the other facies. Line grain contacts and brittle deformation of micas indicate moderate mechanical compaction and beginning of pressure solution. Its primary arenite composition depleted in clay matrix favors the development of silica cements while kaolinite and illite authigenesis are of less importance. No mesogenetic reaction has been recorded.

Facies B exhibits features of advanced eogenesis and early mesogenesis with both line and sutured grain contact and ductile deformation of micas pointing to moderate to high compaction of the sediment. Its medium to high content in clay matrix and ferromagnesians allows the formation of argillaceous cements such as kaolinite or illite and chlorite derived from micas. Sub-facies B1 differs from B2 by its abundance of illite replacing the clayey matrix or primary kaolinite. Sub-facies B2 is characterized by its kaolinite-rich composition originated from the clayey matrix or feldspars. Facies B also shows an example of authigenic muscovite as an evidence of early mesogenesis.

Transformations seen in **facies C** highlight advanced stages of diagenesis. Numerous sutured grain contacts and widespread authigenic quartz and clays confirm the late eogenetic stage undergone by the sandstone. Moreover, occurrences of kaolinite-derived chlorite, authigenic mica and titaniferous minerals are strong evidences for an advanced stage of mesogenesis.

Facies A tends to be more represented towards the top of the formation while micas/clay-bearing sandstones (facies B1, B2 and C) appears more frequent towards the base. This characteristic can be explained by the migration and evolution of the depositional systems over time generating variable sediment compositions.

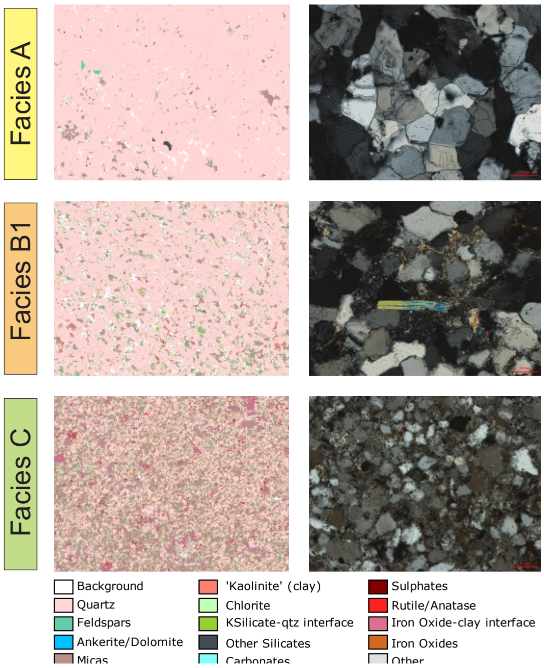

Figure 2: QEMSCAN and photomicrographs (with crossed polars) of the three main lithofacies found in the Hutton Sandstone in the Celsius-1 well. Bottom edge of QEMSCAN images approximately 3 mm. Note the line contacts, sutured contacts and undulose extinction in quartz grains (Facies A) and deformed micas (Facies B) indicating the high degree of mechanical compaction. There is very little pore space remaining in any of the samples, with quartz overgrowths (all facies) and clay fill (Facies B and C) occluding any primary porosity.

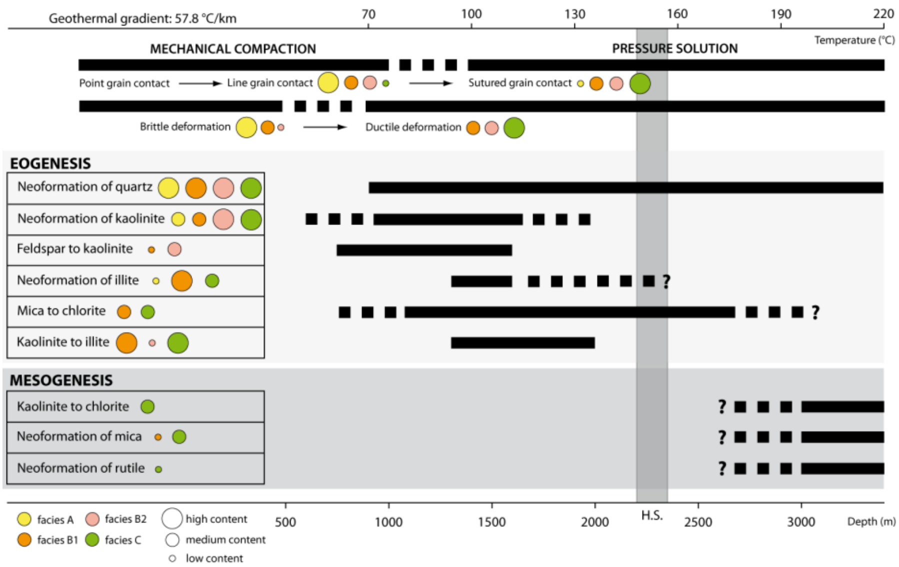

Figure 3: Timing of the burial diagenesis. Occurrence and relative frequency of the diagenetic processes in each facies are represented by colored circles. Grey bar labeled H.S. locates the Hutton Sandstone at Celsius-1.

3.2 Offset wells

The textural and diagenetic characteristics of the Hutton Sandstone at different locations of the basin are comparable. Textures of the grain frameworks highlight low to high mechanical compaction, brittle to ductile deformation and pressure solution. The diagenetic cements are mainly composed of quartz overgrowths or kaolinite booklets derived from the alteration of feldspars or recrystallisation of the detrital clayey matrix. Minor muscovite or chlorite neoformations also appear. The chief difference is that quart-rich sandstones in offset wells mostly belong to facies A, while facies B and C are trivial or absent, possibly due to the available cores predominantly sampled from oil bearing horizons at the top of the Hutton Sandstone.

4. PETROPHYSICAL PROPERTIES OF THE HUTTON SANDSTONE

Nuclear Magnetic Resonance (NMR) T_2 transversal relaxation time distribution provides significant information on the pore size and structure, the interactions between the pore fluids and pore surfaces, and the occurrence of pore-occluding clays in sandstone formations (Dillinger and Esteban, 2014). A T_2 distribution often displays a bi-modal behavior with (i) a short component (T_2s), proving the existence of micro-pores filled with irreducible capillary bound water or clay bound water; (ii) a long component (T_2l) corresponding to the inter-grain macro-porosity. The high variability of facies encountered tends to produce noticeable changes in terms of porosity distribution and contribution of T_2s and T_2l due to different texture and clay content, leading to variable positions of the peaks (i.e. the contribution of the specific pore size populations). Three distinct behaviors of the NMR signal can be distinguished: (i) a strong contribution of T_2s (< 6 ms) and a weak T_2l related to high clay content and cements filled with clay bound water, and sparse macro-porosity; (ii) a well-developed T_2l centered around 40 ms and negligible T_2s contribution associated to large pores where the water is free to flow in a clean grain framework; (iii) an uni-modal distribution with only one peak centered around 7 ms related to clay inter-layer filled with capillary bound water.

The middle part of the Hutton Sandstone (2232 – 2283 mMDRT) exhibits a well-expressed T_2l component where water sits in large pores and is free to flow. The weak T_2s component reflects the low amounts of clays and cements in this section. The effective porosity should be close to the total porosity. According to the facies characteristics, pore geometry, clay occurrence and distribution highlighted by the petrography analysis, this type of NMR spectrum defines clean sands typically associated to quartz-arenites from facies A. The NMR analysis also demonstrates the poor porosity and flow capacity of the top part of the formation (above 2230 mMDRT). Well-developed T_2s indicate that water resides in tiny pores sitting between clay layers (intergranular porosity). This feature reflects the advanced diagenesis affecting this section which led to the neoformation of siliceous and argillaceous cements acting as barrier to fluid flow. Uni-modal and short relaxation time distributions in these intervals should be related to clay-bearing quartz-wackes of facies B and C. Similarly, the lower part of the Hutton Sandstone clearly shows uni-modal distributions of T_2 associated to capillary bound water trapped in pore throats.

Average NMR porosity calculated in the section 2230 – 2303 mMDRT is 14.5 % from first amplitude and 15.1 % after inversion. Inferred values for permeability have been deduced from NMR porosities after inversion in this interval following the equation of Coates (Timur, 1968; Coeates et al., 1991; Coates et al., 1998). The average permeability within this restricted section of the Hutton Sandstone is 6.26 mD, with a minimum value of 0.0189 mD at 2301 mMDRT and a maximum value of 36.5 mD at 2232 mMDRT.

6. CONCLUSION

The results of this study indicate that the negligible flow rates obtained at Celsius-1 compared with the good reservoir quality of the adjacent fields are due to low permeabilities within the Hutton Sandstone. These low permeabilities are the results of diagenetic processes that have occluded porosity and pore throats through the preservation of a broad detrital clayey matrix and the formation of authigenic cements (quartz, kaolinite, and illite) at the top and base of the formation. These processes are not uncommon considering the pressure-temperature conditions that the Hutton Sandstone is expected to have experienced in the vicinity of Celsius-1 (e.g. Ajdukiewicz and Lander 2010). We are currently conducting analyses to constrain this burial history more precisely and applying predictive reservoir quality models to determine if there is a window of depth and temperature conditions (between the deeper, hotter Nappamerri Trough and shallower, cooler areas where oil and gas is produced from the same formation) that would be suitable for geothermal energy production from the Hutton Sandstone.

7. ACKNOWLEDGEMENTS

This research has been funded by an Australian Renewable Energy Agency Emerging Renewables Program Measure awarded to the University of Adelaide. CSIRO is a collaborator on this project.

REFERENCES

Ajdukiewicz, J. M., & Lander, R. H. 2010. Sandstone reservoir quality prediction: The state of the art. AAPG Bulletin, 94(8), 1083–1091.

Augustine, C. 2013. Parametric analysis of the factors controlling the costs of sedimentary geothermal systems - preliminary results. In Penrose Conference: Predicting and Detecting Natural and Induced Flow Paths for Geothermal Fluids in Deep Sedimentary Basins. Park City, Utah: Geological Society of America.

Coates, G.R., Miller, M., and Henderson, G., 1991. An investigation of a new magnetic resonance imaging log. Paper DD, in 32nd Annual Logging Symposium transactions: Society of Professional Well Log Analysts

Coates, G.R., Marschall, D., Mardon, D., and Galford, J., 1998. A new characterization of the bulk volume irreducible using magnetic resonance. The Log Analyst, Vol. 39, n°1 (January-February 1998), 51-63

Collins, R., 1987. Mulka Station 20 KW ORC Engine/hot Bore installation. Department of Resources and Energy, 41p.

Dillinger, A. and Esteban, L., 2014. Experimental evaluation of reservoir quality in Mesozoic formations of the Perth Basin (Western Australia) by using a laboratory low-field Nuclear Magnetic Resonance. Marine and Petroleum Geology, 57, 455-469.

Lund, J.W., Freeston, D.H., and Boyd, T.l., 2011. Direct utilization of geothermal energy 2010 worldwide review. Geothermics, 40, 159-180

Lund, J.W., Lienau, P.J., and Lunis, B.C., 1988. Geothermal direct-use engineering and design guidebook. Third edition: Geo-Heat Centre, Oregon Institute of Technology

Pujol, M., 2011. Examples of successful hot Sedimentary Aquifer direct-use projects in Perth, Western Australia. In: Middleton, M. & Gessner, K. (eds). Western Australian Geothermal Energy Symposium. Perth, Western Australia, 23

Timur, A., 1968. An investigation of permeability, porosity, and residual water saturation relationships for sandstone reservoirs. The Log Analyst, 9, 8-17

Watts, K.J., 1987. The Hutton Sandstone – Birkhead Formation transition, ATp 269P(1), Eromanga Basin. The APEA Journal, 27, 215-229