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Use of temperature logs in coal seam gas reservoirs: Application to the Sydney Basin, Australia

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ABSTRACT

This study examines the relationship between borehole temperature logs and gas distribution in coal seams, both spatially and with depth. Temperature logs are often utilized in hydrogeology to monitor groundwater flow which can introduce methanogenic consortia into coal seams, resulting in the generation and accumulation of coal seam gases. Areas of hydraulic connectivity, characterized by open cleats and fractures, provide a pathway for the meteoric influx, whereas tight, mineralized sections of strata prohibit vertical flow and have the potential to trap coal seam gases, or to limit the influx of methanogens and the generation of secondary, biogenic methane. The combination of these concepts raises the possibility of utilizing temperature logs for mapping coal seam gas distributions and assisting exploration activities. Wireline temperature logs are inexpensive to obtain as part of any exploration, production or monitoring program, but provide information pertaining to flow regimes and *in situ* geological environments. A case study is presented from the Sydney Basin of Australia to demonstrate the types of analyses and interpretations relating to coal seam gas distribution that may be gleaned from temperature log datasets.

1. Introduction

1.1. Purpose

Mapping of coal seam gas content and composition distribution is a critical aspect of gas exploration and production planning. Gas distributions are controlled by a number of factors, but principally related to temperature and pressure conditions in addition to coal properties (Crosdale et al., 1998, 2008; Pashin, 2010; Pashin and McIntyre, 2003; Scott, 2002). Temperature, in turn, generally increases with depth but varies in response to in situ conditions such as proximity to volcanic activity, nature of lithological sequence and groundwater flow (Anderson, 2005). The latter is particularly pertinent in areas hosting biogenic gases because meteoric waters moderate conditions for gas generation as well as retention (Pashin, 2007; Scott, 2002). This study explores the relationship between temperature, water circulation and gas distribution; and investigates the potential for the use of temperature logs in predicting changes in gas content and composition in the subsurface using a case study from the Sydney Basin of Australia.

1.2. Background

Heat flow in the Earth's crust is generated below the lithosphere (Hill, 1990; Schoeppel and Gilarranz, 1966); temperature tends to cool towards the surface (Hill, 1990; Prensky, 1992; Schoeppel and Gilarranz, 1966; Serra, 1984). Heat is distributed through the crust by two main processes: conduction and convection (also referred to as advection) (Bjorlykke, 1993; Grant and Bixley, 2011; Jessop and Majorowicz, 1994). Conduction is heat transfer via 'direct' interaction of two bodies' particles, whereas convection occurs via a fluid medium such as water or gas. Near the surface (e.g. less than ~1–2 km depth), heat transport mainly occurs via fluid flow in rock pores and fractures (e.g. Bodri and Rybach, 1998; Anderson, 2005; Kohl et al., 2005; Nagihara, 2010). Fluids generate pressure in the pores and fractures, and hydrostatic conditions prevail in structurally unconfined (or hydraulically linked) strata. Elsewhere, for example, in compartmentalized sequences, over- or under-pressure can develop as a result of a number of mechanisms, such as increased tectonic influences, hydrocarbon cracking, or changes in salinity or fluid density via osmosis (Bjorlykke, 1993; Fertl, 1976; Gurevich and Chilingarian, 1997; Gurevich et al., 1994; Hunt, 1990; Kreitler, 1989).

Thermal conductivity of rocks generally increase with decreasing porosity (e.g. Birch and Clark, 1940; Hurter et al., 2007; Schoeppel and Gilarranz, 1966), but other parameters such as mineralogy and organic content also play a role (Beck, 1976; Kayal and Christoffel, 1982; Cercone et al., 1996; Hurter et al., 2007). Detailed thermal conductivity information on various rock types is available in the literature (e.g. Anderson, 2005; Cercone et al., 1996; Eppelbaum et al., 2014; Hurter et al., 2007).

High thermal conductors such as salt, sandstone and crystalline rocks are considered to have low thermal gradients (e.g. small

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temperature change over a thick strata interval), whereas low conductors (i.e. thermal resistors) such as coals and carbonaceous shales exhibit high thermal gradients on a temperature log (e.g. large temperature change over a thin strata interval) (Mwenifumbo, 1993; Mwenifumbo et al., 1989; Rider, 2002; Serra, 1984). Coal in particular has very low thermal conductivity (0.13–0.5 W/m°C (Cercone et al., 1996; Eppelbaum et al., 2014; Herrin and Deming, 1996; Hurter et al., 2007)) and is considered an insulator of heat originating from strata above or below. Cercone et al. (1996) found that coals can have a retardation effect on heat fluxes in a basin and contribute as much as 10 K increase in the temperature of surrounding strata. Further, they also noted that horizontal thermal conductivity in coals can be up to 2.5 times greater than their vertical conductivity. This thermal anisotropy means that coals transport more heat (and water) along bedding than across to over- or under-lying strata layers.

These observations highlight the importance evaluating log responses in the geological context. The geothermal gradient is a series of gradients pertaining to the heat profile of the strata at particular horizons. In this manner, the temperature gradient changes can be used for the estimation of water movement and overall hydraulic connectivity of strata. For example, Grant and Bixley (2011) reported on two reservoirs from Italy exhibiting similar thermal gradients that appeared to be isolated by a low permeability layer on the temperature log; however, pressure data showed that the units were in hydraulic communication (Fig. 1).

The extent of groundwater recharge is commonly monitored using wireline temperature logs (Prensky, 1992; Rider, 2002; Taniguchi, 2000; Taniguchi et al., 1999). This type of analysis is applied to intervals that are thicker than individual strata units. In general, concave (upward) trends on the temperature log are interpreted as meteoric water recharge, while convex patterns indicate influx of deeper groundwater (or formation water) into the borehole from elsewhere in the strata, including along bedding (e.g. Anderson, 2005; Hurter et al., 2007; Rider, 2002; Taniguchi et al., 1999). These principal patterns and their associated interpretations are illustrated in Fig. 2.

Temperature data may also be mapped spatially, either as formation temperatures or geothermal gradients (e.g. Pashin and McIntyre, 2003; Saar, 2011). Maps of isotherms (i.e. lines of constant temperature) or absolute temperature of specific horizons such as bottom-hole temperature (BHT) can also be produced (e.g. Davis, 2012; Kohl et al., 2005; Rider, 2002).

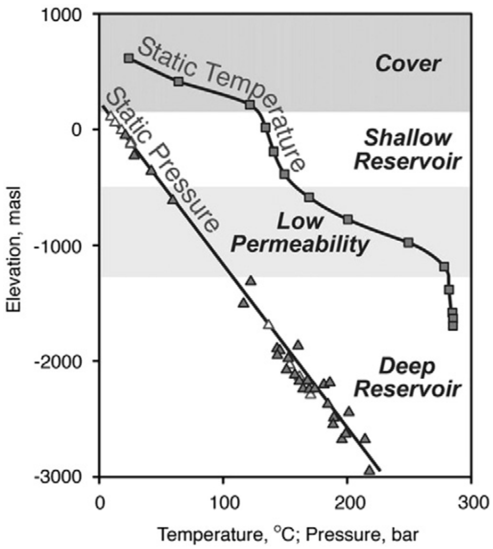

Fig. 1. Elevation–Temperature and pressure profiles depicting two apparently isolated reservoirs with corresponding temperature gradients that are in hydraulic communication, as shown by the pressure data (Grant and Bixley, 2011).

The significance of these observations is that the temperature logs do not only record the thermal properties of individual rock units but also provide an indication of the *in situ* heat (and water) flow conditions. With an understanding of the local geological setting, the tool has a potential to add value in the interpretation of hydrological regimes, which in turn can lead to better understanding of the *in situ* gas regime, particularly in regions where the gas distribution is related to hydrogeology as in parts of the Sydney Basin (Burra et al., 2014a). Previous work (Burra, 2011) showed that changes in temperature gradients coincided with changing gas characteristics with depth, but a mechanism for this was not investigated. This study aims to fill this gap in literature.

1.3. Geological setting

The Sydney Basin is a Permo-Triassic coal-bearing sedimentary basin on the east coast of Australia comprising fluvial-deltaic, coal-bearing deposits interspersed with marine strata (Herbert, 1980). Heat flow in the basin was thought to have originated from deep-seated igneous and metamorphic basement rocks (Sass et al., 1976 in Facer et al., 1980); however, these influences are considered too minor for regional effects (Facer et al., 1980; Middleton and Schmidt, 1982). The effect of overlying sediment thickness is considered a more likely early heat source in the basin (Facer et al., 1980); or more specifically, the length of time interval while the basin experienced maximum burial (Middleton and Schmidt, 1982). This is supported by the close correlation of coal rank distribution in the basin to thickness of strata and proximity to basement (Facer et al., 1980). The presence of significant thicknesses of coal in the total sediment sequence, similar to those reported from Pennsylvania, USA (Cercone et al., 1996) may also be pertinent (e.g. Danis, 2014).

In terms of more recent groundwater circulation, the elevated basin margins to the north, west and south act as recharge zones for the basin and pass surface and groundwater towards the center of the basin and then to the coast in the east (Scott and Hamilton, 2006; Webb et al., 2009). Many units of the basin experience dual porosity flow and are dominated by secondary or fracture flow (MacDonald et al., 2009; McLean et al., 2010b; Webb et al., 2009); although convection throughout the basin has not been studied in detail (Danis et al., 2012). It is also recognized that convection occurs in shallow aquifers in the basin, with heat flow in deeper strata occurring principally via conduction (Danis, 2014).

Hydrodynamics and hydrochemical changes with depth and along groundwater flow path have been shown to be a strong influence on coal seam gas distribution in the basin (Burra et al., 2014a,b). Coal seam gas distribution in the Sydney Basin is complex but is well-mapped (Burra et al., 2014a; Faiz et al., 2003; Pinetown, 2010; Thomson et al., 2008). In general, gas content increases with depth to around 450–850 m depth, below they decrease, forming a parabolic trend with depth (Burra et al., 2014a; Faiz et al., 2007).

In general, meteoric recharge along basin margins provide groundwater with dissolved carbonates that are precipitated along a graduated flow path with increasing salinity. Methanogenesis is associated with the meteoric influx and results in increasing gas contents with depth to a peak gas horizon around (Burra et al, 2014a). Bicarbonate-rich groundwaters mixing with saline waters more abruptly in structurally complex terrains may also lead to the liberation of excess CO_2 which adsorb in the coals, resulting in the accumulation of extensive CO_2-rich gas reservoirs that are present in the inland regions. The deep CO_2-rich coal seam gas zone is located between the shallow biogenic and deep thermogenic CH_4 accumulations. Gas composition along the less compartmentalized coastal region in the east is predominantly $CH_4$with minor wet gases in the thermogenic methane zone below approximately 800–1000 m depth.

Based on coal seam gas carbon isotopic evidence, the origins of the hydrocarbons are well-understood (Faiz et al., 2003; Smith et al.,