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Horizontal stress anisotropy and effective stress as regulator of coal seam gas zonation in the Sydney Basin, Australia

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ABSTRACT

Coal seam gas zonation in the Sydney Basin, NSW, Australia is related to basin hydrodynamics and hydrochemical facies evolution along the flow path from the subcrop to the basin center. Biogenic methane corresponds with meteoric water under hydrostatic pressure and persists down to the top of the geopressured zone (~800 to 1000 m). Thermogenic gases, including wet hydrocarbons, can reach up to relatively shallow horizons of less than 500–600 m depth. In the transition zone between the top of the geopressured and base of the hydrostatic zone, a mixed water and gas regime prevails, comprising brackish waters, and gases of mixed biogenic, thermogenic and inorganic origins, including CO_2. Mechanisms for and the role of stress in the development of this layered hydrogeological and gas environment are investigated in this paper.

The inverse relationship between effective horizontal stress and permeability in coals through regulation of cleat volumes is well documented, and there is evidence of regionally compartmentalized stress regimes with depth within the Sydney and other eastern Australian coal basins. This regional stress regime can be overprinted by the effect of localized geological features. It is hypothesized that the *in situ* stress regime plays an important role in the regulation of groundwater flow regimes and extents, resulting in the development of the reported gas content and compositional zonation.

Analysis of regional gas and stress data obtained from public and private databases, as well as literature, supports this hypothesis. Changes in gas concentration and composition with depth correspond with discernable variations in horizontal stress anisotropy. Gas contents generally increase with depth down to a 'peak gas' horizon, below which concentrations decrease. This 'peak gas' zone is coincident with a horizontal stress anisotropy change from moderately high to low levels, associated with reverse to strike–slip faulting conditions, respectively. The stress release zone also marks the top of the thermogenic gas zone, identified by the first appearance of ethane in the vertical profile. This zone also hosts gases of mixed origins: biogenic, thermogenic and inorganic (CO_2) and represents a mixed (transitional) groundwater flow environment. The base of the mixed gas zone is the top of the 'geopressured-only' flow associated with thermogenic gases and is signaled by the return to high stress reverse faulting conditions below 850–900 m depth in the Sydney Basin.

1. Introduction

Gas distribution mapping is a key part of coal seam gas reservoir characterization. In particular, the controlling mechanisms for reservoir development assist with interpretation of exploration and gas production data. On a basin-wide scale coal seam gas distributions can be associated with geological (e.g. Burra and Esterle, 2012; Cao et al., 2001; Clark and Boyd, 1995; Creech, 1994; Draper and Boreham, 2006; Lamarre, 2003; Pashin, 1998), petrological (Bustin, 1997; Faiz et al., 2007a; Scott et al., 2007) and hydrodynamic parameters (Ayers and Kaiser, 1992; Groshong et al., 2009; Lamarre, 2003; Pashin, 2007; Pashin et al., 2014; Scott, 2002). Gas distribution in the Sydney Basin shows a distinct correlation to hydrodynamic and hydrochemical characteristics of groundwater (Burra et al., 2014). The hydrochemical facies evolve from basin margins to the basin center, and from inland to the coast. Mixed cation bicarbonate-rich fresh waters in recharge areas become increasingly sodium and chlorine-rich along flow paths, towards discharge areas. Meteoric groundwater under hydrostatic pressure penetrates basin sediments until further penetration is restricted by upwelling geopressured basinal fluids and/or reduced porosity and permeability. Gas contents are highest above the nexus between these flow regimes where salinity increases at the base of the hydrostatic-only flow region.

Permeability in coals is mainly related to natural fractures in extensive cleat systems (Gray, 1987; Groshong et al., 2009; Harpalani and Chen, 1992; Laubach et al., 1998). Cleats are thought to form by a number of processes, principally related to coal shrinkage during devolitization (Laubach et al., 1998; Li et al., 2004; Pashin et al., 1999), expansion during thermal gas generation (Pashin et al., 1999), or in

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response to tectonic forces post-coalification (e.g. Laubach et al., 1998; Solano-Acosta et al., 2007). Regionally, Kulander and Dean (1993) demonstrated that cleat domains can be related to underlying basement structure and sedimentological geometry, and that the domains can persist though different stratigraphic sequences regardless of lithotypes present. At more local scales, however, cleat intensity and spacing may also be altered in the vicinity of some sedimentary facies, for example, differential compaction effects around sandstone lenses (e.g. Laubach et al., 2000).

In addition to cleats, jointing and fracturing from tectonic processes also have the potential to enhance gas and fluid flow in coals (and other rocks), provided no extensive mineralization is present (e.g. Laubach et al., 1998). Fracture spacing in rock mass is proportional to the bedding thickness (Ladeira and Price, 1981); and therefore, fracturing in thinly bedded strata is more frequent than in massive competent units such as sandstone lenses or sheets. This has also been observed in coal cleats, where the average cleat spacing was found to be linearly correlated to the thickness of the vitrain bands in the host formation of a given rank (Dawson and Esterle, 2010). In general, dull, high ash and low rank coals have much sparser cleat spacing than bright or high rank coals (Pashin, 2008 and references cited therein) and dull coals in the Sydney Basin were demonstrated to display much higher sensitivity to permeability changes (due to stress) than bright coals (which have higher overall permeability), and this has a significant effect on gas producibility (Bustin, 1997). Coal rank varies spatially across the basin and with depth, as does the present day geothermal gradient.

The effectiveness of these fractures for flow is strongly related to the state of effective horizontal stress (Enever and Henning, 1997; Enever et al., 1994a; Gray, 1987; Jeffrey et al., 1997). This in turn affects coal seam gas producibility (e.g. Ambrose and Ayers, 1991; Sparks et al., 1995). Horizontal stress magnitudes are mainly related to rock properties such as elastic moduli (Dolinar, 2003; Enever and Lee, 2000; Gray, 2011) and these also determine the stress that is borne by different rock types in an interbedded sedimentary sequence (Enever and Lee, 2000; Gray, 2011; Gray et al., 2013).

In situ stresses and coal seam producibility are also known to change around local geological structures, particularly folds and faults, and other features that can limit or enhance fluid and gas flow such as dykes (e.g. Ambrose and Ayers, 1991). Fold structures have been documented to have lower stresses (tension) in the axes, and higher stress magnitudes (compressions) in the flanks of the structures (Dawson, 1999; Strout and Tjelta, 2005; Teufel et al., 1991). Similarly, large faults can affect stress fields both in terms of magnitudes and orientation (Bell, 2006; Gray et al., 2013; Kang et al., 2010), and footwalls of thrust faults have been linked to incidents of gas outbursts in underground coal mines (Cao et al., 2001), which are strongly correlated with large pressure gradient changes (and subsequent alteration of coal properties) induced by mining activities (An et al., 2013; Cao et al., 2001; Kang et al., 2010). Nevertheless, the underlying regional tectonic conditions remain (e.g. Bell, 2006), and it is the basin-wide scale trends that are the interest in the current study.

In general, Eastern Australia, including the Sydney Basin, is under a compressional tectonic regime (Hillis and Reynolds, 2003; Muller et al., 2012; Veevers, 2000; Zhao and Muller, 2001), but stress zonations with depth have been observed in some areas (Brooke-Barnett et al., 2012; Enever and Clark, 1997). The layered characteristic of coal seam gas distributions in the Sydney Basin is hypothesized to be related to these compartmentalized stress regimes. The apparent depth boundaries of the various gas layers coincide with changes in the relative stress magnitudes. This paper maps the relationship between these parameters in the Sydney Basin.

2. Background

The Sydney Basin is a Permo-Triassic coal-bearing sedimentary basin located along the eastern seaboard of Australia (Fig. 1). It is a south-easterly trending, asymmetric trough that is narrow in the north and inland areas, and widens as it extends offshore in the east. Inland, the basin margins are defined by a series of monoclines that are present downdip of regional highlands (Fig. 1). This geometry results in the regional bedding dip following the outline of the basin towards central and eastern areas, with strata dipping towards the center of the basin and out to sea in the east (Fig. 1). Permian sedimentary strata were deposited during a foreland loading episode of an emerging orogeny, consisting of cycles of marine and terrestrial sedimentation, including coal bearing fluvial to subtidal sequences. Regional syn-depositional and post-depositional folding of strata resulted in coal-bearing sequences lining the basin margin at or near surface, with the same coal seam located down to 1000 m depth in the central basin areas. Uplift and subsequent erosion of the youngest coal measures in the more active north–east area in the vicinity of the Hunter-Mookai Thrust Belt (Fig. 1) resulted in the outcropping of older sediments in the fault region. As a result, no coal seam is continuously present across the Sydney basin, precluding gas or stress distribution maps on individual horizons. Nevertheless, this setting provided the geometry for the subsequent meteoric influx from inland basin margin locations towards the coastal areas that is associated with the secondary (biogenic and inorganic) generation of coal seam gas distributions in the basin (Burra et al., 2014).

Coal seam gas distribution in the basin is well-documented, with accumulations dominated by methane, both of biogenic and thermogenic origins, and accessory carbon dioxide, which can form significant volumes in some regions (e.g. Faiz and Hendry, 2006; Pinetown et al., 2008; Thomson et al., 2008). Gas contents range from 0 to over 25 m^3/t (raw basis), with shallow horizons under 200–300 m depth typically less than 5 m^3/t; and middle horizons of 300–600 m ranging from 8 to 15 m^3/t. Gas contents in deeper reservoirs show high variance, from single digits to over 25 m^3/t (Burra et al., 2014). This zone of higher gas contents typically persists to approximately 600–1000 m depth, below which gas concentrations decline or stay constant to the base of the coal measures.

Regionally, the central, eastern and southern areas are dominated by methane-rich reservoirs, whereas the northern inland areas also contain significant CO_2 at depth. CO_2 accumulations mapped in underground coal mines in the southern (Illawarra) region (e.g. Faiz et al., 2003, 2007b) are considered to be local features, principally limited to the uppermost coal seams (Faiz et al., 2007b) and in gentle anticlinal structures (Faiz et al., 2003). In contrast, CO_2-rich reservoirs in the northern and central regions encompass over 20 major coal seams (comprising over 50 correlatable coal plies and a total coal-bearing strata thickness of up to 300 m) and tens of square kilometers in spatial extent (Burra et al., 2014). The source of the CO_2 in these regions have long been considered to be of magmatic origins (Faiz and Hendry, 2006; Smith et al., 1982); however, based on isotopic evidence, other sources such as coal oxidation, biogenic methanogenesis, thermal decarboxylation and dissolution of carbonates cannot be discounted (Burra et al., 2014; Smith et al., 1982). Other gases found in smaller amounts in the basin include wet hydrocarbons and nitrogen. The nitrogen is chiefly associated with near-surface zones around inland recharge areas, indicative of acetate fermentation process; but it also occurs at depth, below the deep CO_2 and ethane accumulations (Burra et al., 2014).

Thermal maturity (i.e. rank) of coals increases with increasing temperature and pressure during coalification (Hunt, 1979; Levine, 1993). Thermogenic gas generation as part of this process was described by Hunt (1979) and is summarized in Fig. 2 (Pashin, 2008). The pattern of gas compositional zonation in the Sydney Basin is very similar to this sequence; however, the rank ranges differ substantially. Additionally, the gas zone boundaries are diffuse, cross-cut specific coal sequences and structure (Burra et al., 2014; Thomson et al., 2008), and the gas, particularly in shallow areas, have been shown to be isotopically of biogenic origin (Faiz et al., 2003; Smith et al., 1992).