Stress Regime in the Cretaceous Succession of the Alberta Basin: A Predictor for Coal Bed Methane Producibility

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ABSTRACT
Coal permeability is a critical factor in coalbed methane (CBM) producibility. In the absence of direct data, the stress regime is a good regional-scale indicator of areas with enhanced permeability, hence better CBM producibility potential, provided all other factors are equal. Estimates of vertical and minimum horizontal stress magnitudes and their directions in numerous wells in the southern and central parts of the Alberta basin where Cretaceous coal-bearing strata are found show that $S_V>S_{Hmin}$ and that S_{Hmin} orientations generally parallel the deformation front, indicating that coal face-cleat fractures will likely be vertical and aligned in a SW-NE direction. Consequently, the axisof maximum coal permeability is likely to be in this direction. This has significant implications for the local-scale design and siting of CBM production wells, and of CO_2 injection wells in case CO_2 is used for enhanced CBM recovery. Vertical stress magnitude gradients increase slightly with depth, but decrease significantly in a SW-NE direction. Gradients of S_{Hmin} magnitudes show a more complex pattern, with a few elongated lows parallel to the deformation front, varying in width between ~40 km and ~100 km, and in length from ~100 km to ~450 km. Stress gradients in southern Alberta, both vertical and horizontal, are generally high. The distribution of stress magnitude and gradients suggests that, on a regional scale, the most prospective areas for CBM production in Alberta would be in central-eastern Alberta, if all other factors, such as coal characteristics and gas content, are equal.

INTRODUCTION
Worldwide resources of methane trapped within the coal porous system are greater than the collective reserves of all known conventional gas fields. However, only in very few places, primarily in the United States, has this energy source been commercially tapped. Except for the Black Warrior basin, all major basins in the United States where coalbed methane (CBM) is produced or have producibility potential, such as the San Juan and Powder River basins, are foreland basins of the

Rocky Mountains. The coal beds in these basins are found in Cretaceous and Tertiary strata, similarly to the coal-bearing strata in the Alberta basin, whose CBM potential is estimated at 300 to 540 Tcf. However, exploration for coalbed methane in the Alberta basin is only in an incipient stage, driven mainly by the recent high price off natural gas.

Unlike conventional hydrocarbon plays, in CBM plays coal acts as both the source rock and the reservoir for the gas. This dual role of the coal bed leads to a paradox, namely, that in order for gas to be trapped, the coal has to be either sealed or have very low permeability, while, for exploitation, the gas must readily migrate to the production well (i.e., the coal should have high permeability). Recent studies (e.g., Tyler et al., 1997) have shown that coalbed methane producibility depends in an interdependent manner on:

- Geological factors such as tectonic, structural and depositional setting;
- Coal distribution and properties, such as rank and gas content;
- Hydrogeology of formation waters; and
- Coal permeability.

The tectonic and structural setting determines the subsidence regime, sedimentation patterns and the locus of peat accumulations, it dictates whether coalification proceeds to ranks sufficient for thermogenic gas generation through burial and thermal history, and it initiates stress-induced fractures in coal for enhanced permeability (Tyler et al., 1997). The depositional setting imposes a strong control on coalbed methane producibility because it determines the size, thickness, orientation and stratigraphy of the coalbed reservoirs.

Coal rank, ash content and maceral composition influence the volume of generated methane, coal gas content and gas composition, respectively. Coalbed gas composition directly relates to coal rank, maceral composition and basin hydrodynamics (Tyler et al., 1997). Hydrodynamics affects CBM producibility by maintaining (or not) the pressure needed for gas sorption on the coal surface. Vigorous flow of formation waters provides the means for long-distance migration to traps and introduces bacteria for generating secondary biogenic gases. On the other hand, basin hydrodynamics can be detrimental if too much water is produced.

Production rates of coalbed methane are extremely sensitive to reservoir properties, of which permeability is one of the critical parameters (Schraufnagel, 1993; Zuber et al., 1996). Regardless of the quantity of gas in place, there is a permeability value below which the resource cannot be produced economically, estimated to be 10^{-15} m^2 (1 md) (Zuber et al., 1996). Data from the Piceance, San Juan and Black Warrior basins in the US, and from the Sydney and Bowen basins in Australia, document a decrease in permeability with -burial depth. Thus, low permeability is likely to be a problem with deep coal seams in that coalbed reservoirs deeper than 1,500 m generally have permeabilities below what is required at present for economic production (Zuber et al., 1996). Characteristic permeability values for CBM plays in the San Juan and Black Warrior basins in the US are 2-35 x 10^{-15} m^2 (2-35 md) (Sawyer et al, 1990; Mavor et al., 1994).

The major coal-bearing units of the undeformed succession in the Alberta basin are the Lower Cretaceous Mannville Group, the Upper Cretaceous Belly River Group and Horseshoe Canyon Formation of the Edmonton Group, and the Upper Cretaceous-Paleocene Scollard and Paskapoo formations. The coal seams are gently dipping to the west and occur at depths ranging from the surface to more than 3000 m. Coals range from lignite to bituminous in rank, generally increasing in rank from east to west, which corresponds to increasing depth.

Very few data exist with regard to the permeability of coal beds in the Alberta basin, with available information generally indicating low permeability. Extensive studies of coal beds in the Sydney and Bowden basins in Australia show that coal permeability correlates strongly with stress magnitude (Enever et al., 1994; 1998; Sparks et al., 1995; Bustin, 1997). Thus, the stress regime in the Cretaceous coal-bearing strata of the Alberta basin may provide an indicator of enhanced coalbed permeability, and hence of coalbed methane producibility.

METHODOLOGY

The study of the stress regime in the Cretaceous coal-bearing strata of the Alberta basin is based on information from selected wells in the area from the US border in the south to Tp. 80 in the north, and from the Saskatchewan border in the east to the deformation front in the west. Because the Alberta plains are essentially flat on a regional scale and form a free surface, it is reasonable to assume that one of the principal stresses, S_v, is vertical, hence the other two principal stresses are horizontal and orthogonal to each other, S_{Hmin} and S_{Hmax}. Density logs from 39 wells were used to calculate S_v magnitudes and gradients for each major stratigraphic unit in the Cretaceous succession, down to the sub-Cretaceous unconformity. The magnitude and gradient of S_{Hmin} were determined on the basis of 10, 55 and some 600 micro-fracturing, mini-fracturing and leak-off tests, respectively, and of over 200 fracture-breakdown pressures in more than 800 different wells. Leak-off tests and fracture-breakdown pressures with gradients <12 kPa/m or >30 kPa/m were not used to estimate S_{Hmin}. The former were judged to be too low and the latter too high to reflect accurately the virgin stress magnitudes (Dahlberg and Bell, 1994). Because each type of test represents a different stage of hydraulic fracture propagation the S_{Hmin}-gradient values obtained from leak-off tests and fracture-breakdown pressures were normalized to the values obtained from micro- and minifrac tests which are the most reliable (Haimson and Fairhurst, 1970). Finally, horizontal-stress anisotropy and orientations were identified from wellbore breakouts based on dipmeter measurements in 58 wells. Stress trajectories were projected using the data on stress orientation.

STRESS REGIME

The magnitude of the vertical stress S_v decreases northeastward in each stratigraphic unit, from >45 kPa to ~5 kPa at the top of the Colorado Gp., and from >80 kPa to ~10 kPa at the sub-Cretaceous unconformity, consistent with the northeastward decrease in burial depth of Cretaceous strata in the Alberta basin due to both regional dip and topography. The corresponding S_v/depth gradients also decrease to the northeast, and increase slightly with depth, from >24 kPa/m to ~21 kPa/m at the top of the Colorado Gp., and from >24.5 kPa/m to ~22 kPa/m at the sub-Cretaceous unconformity. The slight increase in the S_v-gradient with depth is most probably due to increased compaction with depth as a result of greater burial depth. The southwestward increase in S_v-gradients is also caused by increased compaction caused by the former presence of a greater thickness of overburden in the basin foredeep than at its periphery. This result is consistent with studies of coal maturity and moisture content that suggest that >3 km of overburden have been removed from southwestern Alberta since the peak of the Laramide orogeny, but only <1.5 km in the east-central plains (Bustin, 1991). Regionally high S_v gradients are present in southern Alberta.

Gradients of the minimum horizontal stress S_{Hmin} vary between 12 and 24 kPa/m, but are everywhere less than S_v gradients. This indicates that fractures, including those in coal seams, will be sub-vertical rather than sub-horizontal. Since permeability tends to be greater in fractures in the plane perpendicular to the minimum stress (e.g., Heffer and Lean, 1991), the greatest fracture permeability is likely to occur in vertical fractures along the S_{Hmax} trajectory. Two elongated SE-NW trending lows in S_{Hmin} gradient, one ~300 km long and ~40 km wide and the other ~450 km long and ~100 km wide, are present in central Alberta at ~80 km and ~200 km distance, respectively, from and parallel to the Mesozoic deformation front. Two similar lows, smaller in size (~130 km long), are present in southern Alberta at ~70 km and ~160 km from the deformation front. In west-central Alberta, several narrow (~25 km) SW-NE trending lows lead away from the deformation front for distances up to ~100 km. Similarly to the S_v distribution, S_{Hmin} gradients are generally high in southern Alberta (>20 kPa/m).

The orientation (azimuth) of S_{Hmax}, hence its trajectory, varies from ~30^o in southern Alberta to ~70^o in west-central Alberta, maintaining a direction generally perpendicular to the deformation front. This orientation of S_{Hmax} corresponds to face cleat fracture trends in Cretaceous coals in Alberta (Campbell, 1979), indicating that they will most probably provide excellent connectivity in this general SW-NE direction. Thus, it is expected that the horizontal permeability of the coal beds will exhibit anisotropy related to the S_{Hmin} and S_{Hmax} directions.

CONCLUSIONS

Coal permeability is a critical factor in coalbed methane producibility, as demonstrated by CBM production from the Black Warrior, San Juan and Powder River basins in the US. Unfortunately, very little information exists with regard to the permeability of the Cretaceous coals in the Alberta basin. However, based on a generally demonstrated variability of coal permeability with stress, a regional-scale qualitative assessment can be made with regard to the most probable productive CBM plays in the Alberta basin on the basis of stress distribution and orientation.

Estimates of vertical and minimum horizontal stress magnitudes and directions in more than 800wells in the southern and central parts of the Alberta basin where Cretaceous coal-bearing strata are found show that S_V>S_{Hmin} and that S_{Hmin} trajectory parallels generally the deformation front, indicating that coal fractures will likely be vertical in a SW-NE direction. Consequently, the direction of maximum coal permeability is likely to be in this direction. This has significant implications for the local-scale design and siting of CBM production wells, and of CO_2 injection wells in case CO_2 is used for enhanced CBM recovery. The vertical stress in the coal-bearing strata increases with depth, reflecting greater burial depth. Gradients increase slightly with depth, but decrease significantly in a SW-NE direction. Gradients of S_{Hmin} show a more complex pattern, with a few elongated lows parallel to the deformation front, varying in width between ~40 km and ~100 km, and in length from ~100 km to ~450 km. Stress gradients in southern Alberta, both vertical and horizontal, are generally high. The distribution of stress magnitude and gradients suggests that, on a regional scale, the most prospective areas for CBM production in Alberta would be in central-eastern Alberta, provided that all other factors, such as coal characteristics and gas content, are equal.

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