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Regional study of the thickness of exhumed sediments in the foredeep section of the Western Canada Foreland Basin using the sonic compaction based technique

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Summary

The study of the burial history of a basin is an important step in petroleum system analysis, because the subsidence and uplift may impact the petroleum system elements. For example, the integrity of the reservoir, seal and overburden may be compromised by uplift and erosion processes. In the case of the source rock, the potential to generate hydrocarbons, expressed by its maturity level, is strongly dependant of the maximum paleotemperature, which is determined by the burial depth and the geothermal gradient.

The Western Canada Foreland Basin (WCFB) is well known for hosting several prolific petroleum systems (Allan and Creaney, 1991). The amount of uplift and erosion that this basin has undergone is not well-constrained, therefore the burial models have high associated uncertainty. Preliminary results in this study show how different exhumation estimates for an area can affect the modelling of petroleum system elements and thereby, petroleum system analysis.

In this work, the estimation of exhumed thickness was done in different locations spanning the foredeep section of the basin in order to analyze the regional pattern of uplift and erosion. The results will be incorporated in burial models that may contribute to further understanding of the subsidence history of the basin.

Introduction

The Western Canada Foreland Basin was formed in the Middle Jurassic to Early Tertiary as a consequence of deformation along the western edge of the North American craton caused by the accretion of exotic terranes from the Pacific (Wright et al. 1994).The load imposed on the lithosphere by the tectonic thickening and overthrusting of the exotic terranes was responsible for the isostatic flexure and the subsidence process (Porter et al. 1982). After the end of the compressive deformation in the Middle Eocene, the basin was subject to uplift and subsequent erosion (Wright, 1994). The Cypress Hill peneplain in South Alberta, for example, provides important evidence of the Neogene erosion. This peneplain occurs at an elevation 700 m above the surrounding plain and, through projection, it is possible to infer erosion of at least 450 to 1500 m of strata in the Plains and up to 3 km of strata near the mountains (Bustin, 1991).

The amount of uplift and erosion has been the subject of several studies using either compaction-based methods (Magara, 1976; Connolly, 1989; Polcheau, 2001) or organic maturity-based methods (e.g. Hacquebard, 1977; Nurkowski, 1984; England and Bustin, 1986; Osadetz et al., 1990). These models have been scrutinized (e.g.: Bustin, 1991), since the differences between estimates for the same area are extremely large.

The Western Canada Basin is one of the most prolific hydrocarbon provinces on Earth (Creany and Allan, 1990). Burial below thick sequences of Upper Cretaceous and Tertiary sediments deposited in the foredeep played an important role in the maturation of source rocks (Bustin, 1991); reduced uncertainty in the burial and exhumation process that affected these stratigraphic sequences — particularly with respect to source rock maturation and hydrocarbon generation — will aid the characterization of petroleum systems.

In this work, the eroded thickness in areas spanning the foredeep section of the basin has been calculated with the purpose of evaluating the pattern of exhumation in the regional context of the WCFB history. Constraining uncertainty in the magnitude of erosion will contribute to more reliable burial models and these, in turn, will further understanding of the subsidence process in the basin.

Theory and method

Using the compaction-based technique, Magara (1976), Connolly (1989) and Polcheau (2001) calculated the eroded overburden thickness in the Alberta Deep Basin. The compaction technique is based on the reduction of interval transit time during burial. Since depth-controlled compaction of sediments is largely irreversible, formations that are shallower than their maximum burial-depth have an anomalously low interval transit time with respect to their present burial (Mempes and Hillis, 1995).

According to Magara (1976), the relationship between shale interval transit time (δt) and depth (z) in the shallow intervals of many sedimentary basins can be approximated by a normal compaction trend that can be described by equation [1], where δt is the transit time at depth z, δto is the surface transit time and b is the exponential decay constant. This normal compaction trend is extrapolated above the present surface to a sonic transit time value (200 µ/ft) that is considered to correspond to a non-exhumed succession. The vertical difference in depth between the transit time corresponding to a non-exhumed succession and the transit time corresponding to the present day surface would yield the eroded thickness.

$$\delta t = \delta to exp(-bz) \qquad [1]$$

By applying this method in Colorado shales from the Alberta Deep Basin, Magara (1976) estimated between 520-1220 m of eroded sediments. Connolly (1989) refined Magara's (1976) method by applying a regression technique to adjust the compaction trend to the sonic data from the Wilrich Member of Spirit River Formation; between 400 and 2000 m of removed material were estimated, increasing toward the Rocky Mountains. Polcheau (2001) modified Magara's method by establishing a single compaction trend from different wells using Colorado Group shales. The eroded thickness calculated varies between 700 and 2800 m increasing toward the Rocky Mountains. This estimate is different from Connolly (1989); Polcheau (2001) states that the difference is because the Spirit River Formation is deeper than Colorado Group.

One important limitation of this methodology is that equation [1] does not predict the sonic transit time in a totally compacted rock (Kumar, 1978). Heasler and Kharitonova (1995) solved this inconsistency by including in equation [1] a shift constant (C) approximately equal to the sonic transit time of the matrix which represents the transit time for a totally compacted rock (equation [2]).

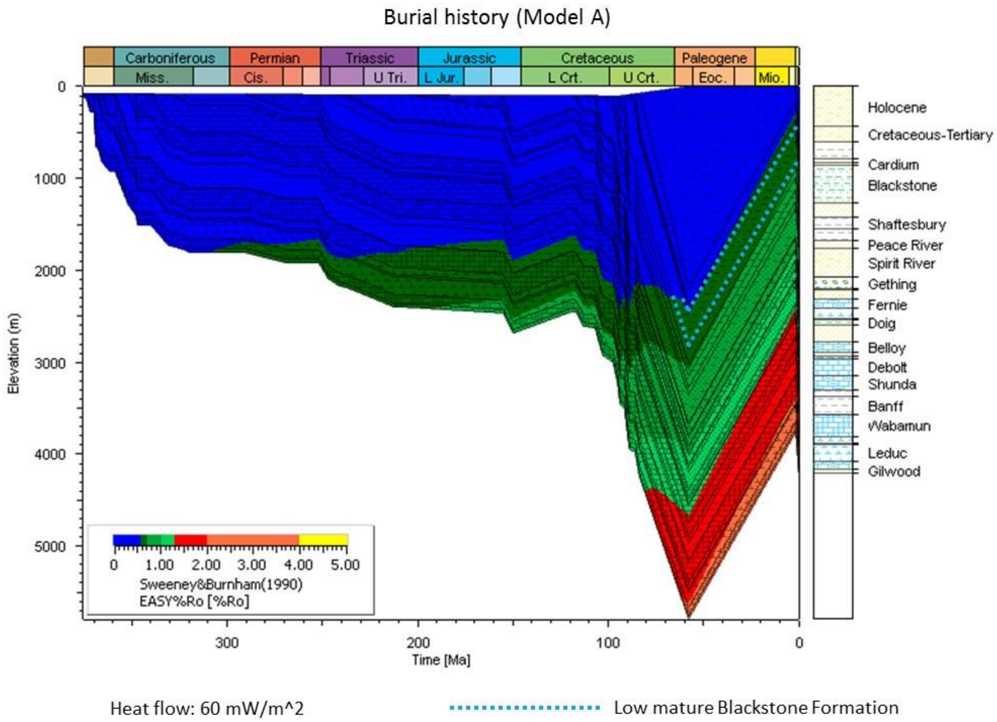
$$\delta t = \delta to exp(-bz)+C \qquad [2]$$

This improved version of the compaction based technique provided by Heasler and Kharitonova (1995) has been applied in this work by using a standard least squared technique to calculate the eroded thickness in Alberta. The generic procedure involves the comparison of a sonic transit time vs. depth curve for each well location that has undergone exhumation, with a reference normal compaction trend curve representing a non-exhumed succession in the basin. The displacement along the depth axis of the sonic transit time vs. depth curve of each well, from the reference normal compaction trend, will yield the value of exhumation (Corcoran and Dore, 2005).

Recent allostratigraphic evidence (Plint et al., 2012; Varban and Plint 2008) suggests that the Western Canada Foreland Basin experienced differential subsidence, where non-uniform loading produced localized depocenters that abruptly shifted up to hundreds of kilometres, in some cases on time scales represented by a single marine flooding surface (~ 10 kyr). Future work will involve the integration of the new allostratigraphic evidence with the refined exhumation estimates to produce burial models that reflect the complexity of the subsidence process in the basin.

Preliminary observations and discussion

The effect of burial depth in the maturation of source rocks and the impact of conflicting exhumation models in petroleum systems analysis are illustrated in Fig. 1. Two burial models were constructed from a well located in Northwest Alberta. In the model A the eroded thickness was taken from Connolly (1989) who estimated approximately 2000 m of sediments eroded in this region. In the model B, the eroded thickness is 1250 m according to Polcheau (2001).



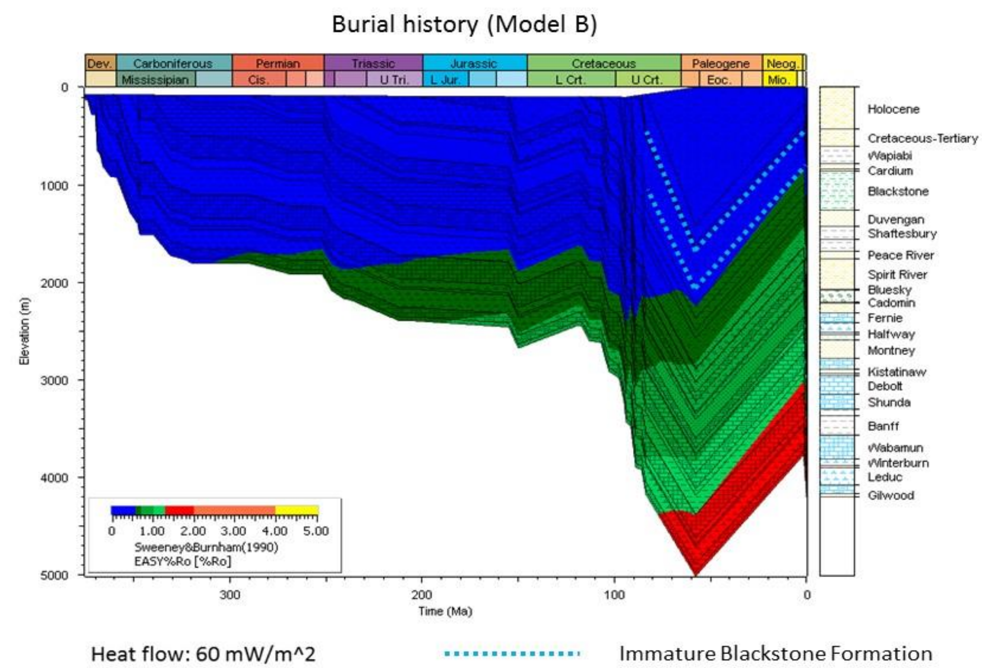


Figure 1: Burial histories for a well located in Northwest Alberta. In model A the exhumed thickness was taken from Connolly (1989) and is approximated to 2000 m. In model B the exhumed thickness was taken from Polcheau (2001) and is approximated to 1250 m.

In burial model A the Blackstone Formation, which is a prolific source rock, appears to be in an early mature stage according to the vitrinite reflectance data. In model B, in which the exhumed thickness and, hence, the maximum depth of burial is lower, the Blackstone Formation may be interpreted as immature, suggested by the vitrinite reflectance as well. When it comes to petroleum system analysis, these models may lead to erroneous interpretations and conclusions due to the high uncertainty associated with the low precision in exhumation estimates.

These results highlight the necessity to review the existing exumation models and to produce new estimations in order to constrain the amount of uplift and erosion and produce more reliable burial models.

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