Quantitative Assessment of Exhumation Magnitude and Paleobathymetry Using McKenzie's Lithospheric Stretching Technique*

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Abstract

This paper presents preliminary work and an exhumation and paleobathymetry solution as applied to basin modelling within the northern portion of the Williston Basin.

Exhumation and paleobathymetry corrections are paramount to the authenticity of the total petroleum systems models of partially exhumed basins as applicable constraints, risk and the tendency to overestimate undiscovered resource potentials pose significant challenges.

An attempt is made to quantify the magnitude of exhumation and estimate paleobathymetry within Williston Basin Phanerozoic successions as an application of the McKenzie lithospheric stretching technique. McKenzie lithospheric stretching technique has been said to be a valid framework for the evaluation of exhumation in intracratonic rift basins of which Williston Basin is a suitable example.

Theoretical subsidence curves are modelled for each selected well and fitted to their respective backstripped and decompacted subsidence curve by adjusting the stretch factors (β) for the crust and the mantle. Paleobathymetry is further estimated by adjusting the initial zero input to other numerical values where erosion is not reported. The resulting departure from the theoretical curve is a

measure of denudation as deterministic bathymetric values are extracted as paleobathymetry. Sub-Cretaceous, sub-Triassic, sub-Devonian and Mid Ordovician erosions are estimated.

While the Williston Basin Phanerozoic strata have undergone substantial erosions at the aforementioned periods, they are generally assumed to be deposited close to sea level. Most units with the exception of Bakken and possibly Lower Lodgepole formation are deposited in water depth less than 100 m hence, a notion that bathymetry effects could be considered negligible in Williston Basin burial history models.

The results show that paleobathymetry values vary with locations within the basin. An example is the estimated values from three selected wells (two located within Saskatchewan and the third close to the centre of the basin in North Dakota) that yield Bakken paleobathymetry of 150 m, 270 m and 385 m respectively. This is in agreement with suggested water depth as deep as 250 m for Three Forks Bakken and Lower Lodgepole in Saskatchewan portion of Williston Basin. The assessment is done under three scenarios: assumed negligible (zero) bathymetry, modelled Bakken bathymetry and modelled bathymetry for all non-erosion intervals.

Introduction

This project is part of a large, integrated assessment of the Phanerozoic fluids and petroleum systems of the Saskatchewan portion of Williston Basin conducted at the Universities of Alberta and Regina (Figure 1). The overall goal of this project is to examine, analyze and characterize the fundamental processes involved in the generation, migration and entrapment of hydrocarbons within Phanerozoic strata, specifically regarding how and where hydrocarbons in the Saskatchewan subsurface were generated and where and when they migrate over geologic time to help determine where they are most likely to have been trapped at the present time.

This particular study seeks to integrate various data sets, consisting of both existing and new data into a series of 1D, 2D and ultimately, 3D basin models that seek to describe the maturation, generation and migration of petroleum into, and within, southern Saskatchewan.

The creation of a burial history curve for a given well is typically the initial step in the process of creating any predictive geological model and one of the most fundamental steps, since the accuracy of the burial history curve will markedly influence the timing and onset of oil generation. However, one of the most challenging aspects facing modellers engaged in building burial history curves is the determination of erosional thickness and paleobathymetry. Uplift and the removal of overburden is referred to as exhumation (erosional thickness) while paleobathymetry refers to the depth of water depth within the depositional basin.

The determination, quantification and application of paleobathymetry and erosional thickness in the assessment of petroleum generation in a basin that has undergone periodic uplift helps minimize the overestimation or underestimation of hydrocarbon potential. It also facilitates the development of an approach that more accurately constrains resource assessment and the risk forecast.

This paper presents preliminary work and an exhumation and paleobathymetry solution as applied to basin modelling within the northern portion of the Williston Basin.

Concept and Method

Intracontinental sags, rifts, failed rifts, and passive continental margins fall within evolutionary suite of basins unified by the process of lithospheric stretching (Allen and Allen, 2005).

The quantitative relationship between crustal and subcrustal lithospheric extension and the subsidence histories of various continental basins and rifted margins was initially proposed by Falvey (1974). Developing the concept, McKenzie (1987) proposed a uniform lithospheric stretching model, as a means of proving a solution when seeking to predict synrift subsidence followed by an exponentially declining post-rift thermal subsidence.

McKenzie's uniform lithospheric stretching model facilitates the calculation of theoretical subsidence curves (for a given stretch factor β) which can then be compared to an observed tectonic subsidence profile derived from decompacted and backstripped water loaded sediment columns. Deviations of the observed from the predicted subsidence curves can be used, in most cases, to estimate the magnitude and timing of exhumation (Corcoran et al., 2005). Estimated exhumation data can be subsequently applied to burial history profiles, other forward simulation processes and general estimations of erosional thickness.

McKenzie (1978) defined uniform lithospheric stretching model as:

$$y_s = \frac{y_L \left\{ (\rho_m^* - \rho_c^*) \frac{y_c}{y_L} \left(1 - \alpha_v \frac{T_m}{2} \frac{y_c}{y_L}\right) - \frac{\alpha_v T_m \rho_m^*}{2} \right\} (1 - 1/\beta)}{\rho_m^*(1 - \alpha_v T_m) - \rho_s}$$

Where:

β = Stretch factor
y_L = Initial thickness of the lithosphere
y_c = Initial thickness of the crust
ρ_m* = Density of the mantle at 0°C
ρ_c* = Density of the crust at 0°C
ρ_s = Average bulk density of sediment or water filling the rift
α_v = Thermal expansion coefficient of both crust and mantle
T_m = Temperature of asthenosphere
y_s = Subsidence or uplift

To determine the magnitude of exhumation and estimate paleobathymetry using the McKenzie lithospheric stretching technique, theoretical subsidence curves are modelled for each selected well and fitted to their respective backstripped and decompacted subsidence curve (observed subsidence) by adjusting the stretch factors (β) for the crust and the mantle. Paleobathymetry is further estimated by adjusting the initial zero input to other numerical values, the observed water loaded basement subsidence and McKenzie's theoretical subsidence profiles converge at non-erosional intervals. The resulting vertical departure from the theoretical curve is a measure of denudation as deterministic bathymetric values.

For example, vertical differences *m*, *n*, *o*, and *p* in Figure 2 represent the estimated Mid-Ordovician, Sub-Devonian, Sub-Triassic and Sub-Cretaceous erosional events respectively. The resulting paleobathymetry and exhumation data were then applied to the 1D forward simulation processes of selected wells within the basin model.

Results and Discussion

Multiple paleobathymetry and exhumation solutions for three of wells shown in Figure 1 provide a number of significant results. Firstly, the derived McKenzie stretching solution data concur with the widely held belief that the water depth for the Bakken was approximately 250 m in the Saskatchewan portion of Williston Basin. Secondly, the results show that paleobathymetry values vary systematically across the basin, yielding Bakken paleobathymetry values of 150 m, 270 m and 385 m from the basin margin in the north to the paleodepocenter near Watford City, North Dakota (Figure 1).

Thirdly, attempts to generate burial history curves with and without applying the McKenzie stretching solution yield very different results, as shown in Figure 3a and 3b. The application of the McKenzie stretching method to better constraint 1D burial history curves was conducted following three scenarios: (1) assumed negligible (zero) bathymetry, (2) modelled Bakken bathymetry and (3) modelled bathymetry for all non erosion intervals. The resulting burial history profiles from three selected wells: A, B and C are shown in Figure 3a & 3b, Figure 4a & 4b, and Figure 5a & 5b. The paired plots present a striking contrast between uncorrected (Figure 3a, Figure 4a, and Figure 5a) and the corrected models (Figure 3b, Figure 4b, and Figure 5b) in which the full McKenzie stretching solution has been applied.

The corrected model generates a burial history curve that is not only more geologically realistic but generates data that actually better conforms to the evolution theory of the Williston Basin.

While the Williston Basin Phanerozoic strata have undergone substantial periods of erosion during the Sub-Cretaceous, sub-Triassic, sub-Devonian and Middle Ordovician, they were generally previously modelled as having been deposited close to sea level. In some cases, with the exception of Bakken and Lower Lodgepole in which formations are supposedly deposited in water depths less than 100 m, bathymetry effects could be considered as negligible in Williston Basin burial history models.

The application of the McKenzie stretching solution has other general applications outside basin modelling, providing a means of deriving estimations of erosional thickness.

Conclusion

Published 1D model are not typically decompacted or corrected for paleobathymetry and exhumation. These corrections are crucial and they have a profound impact on the outcome of any forward simulation model when seeking to determine the generative potential of a formation or basin through basin modelling. This study has provided a solution and workflow that allows the quantification and application of paleobathymetry and erosional thickness, thereby providing boundary conditions that are more accurate and improved forward simulation of basin evolution and petroleum systems assessment.

Acknowledgement

This project would not be possible without funding from the Saskatchewan Ministry of Energy and Resources and the Petroleum Technology Research Centre. We also wish to express profound gratitude to Schlumberger Canada for donating PETREL and PETROMOD software without which the development of various workflows being implemented on the project would be impossible.

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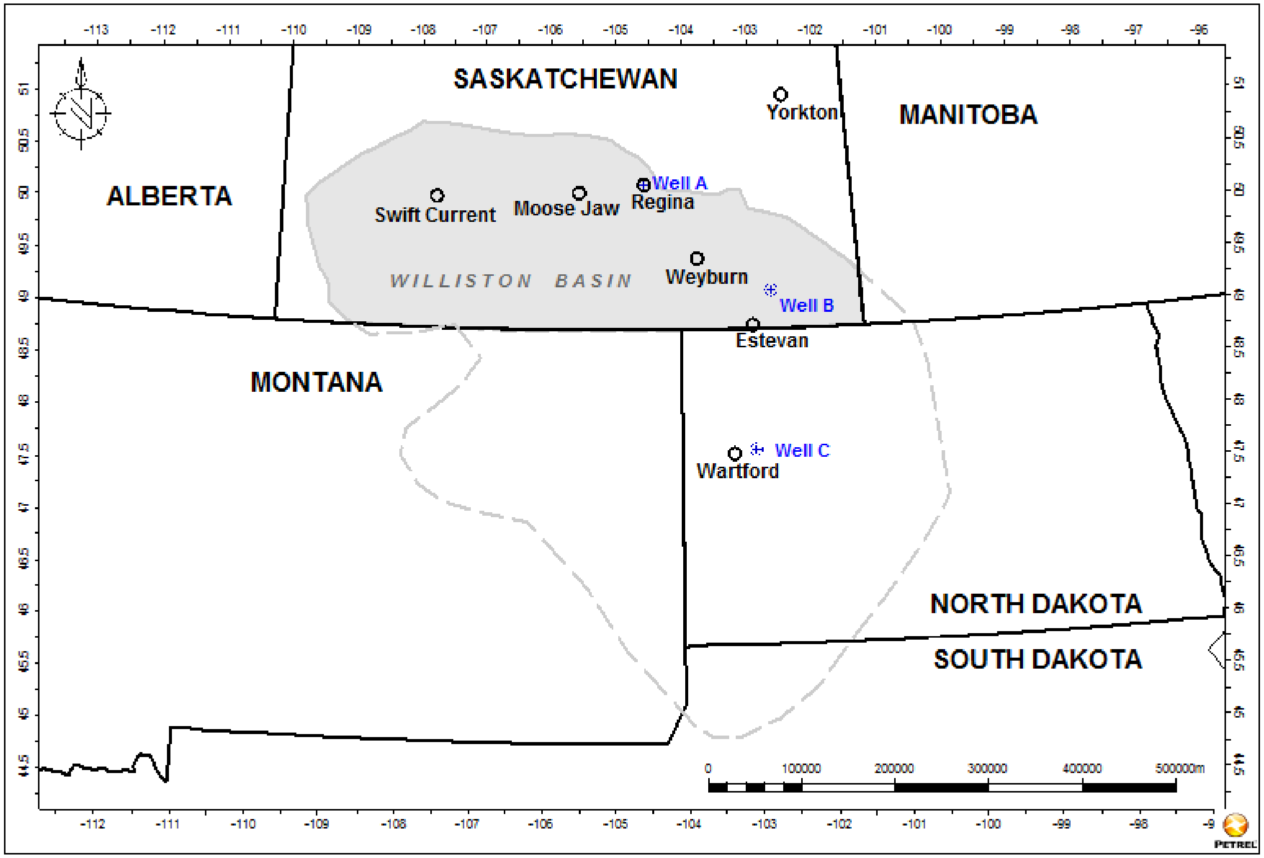

Figure 1. A general outline of Williston Basin showing location of the study area (shaded) and selected Well A, Well B and Well C.

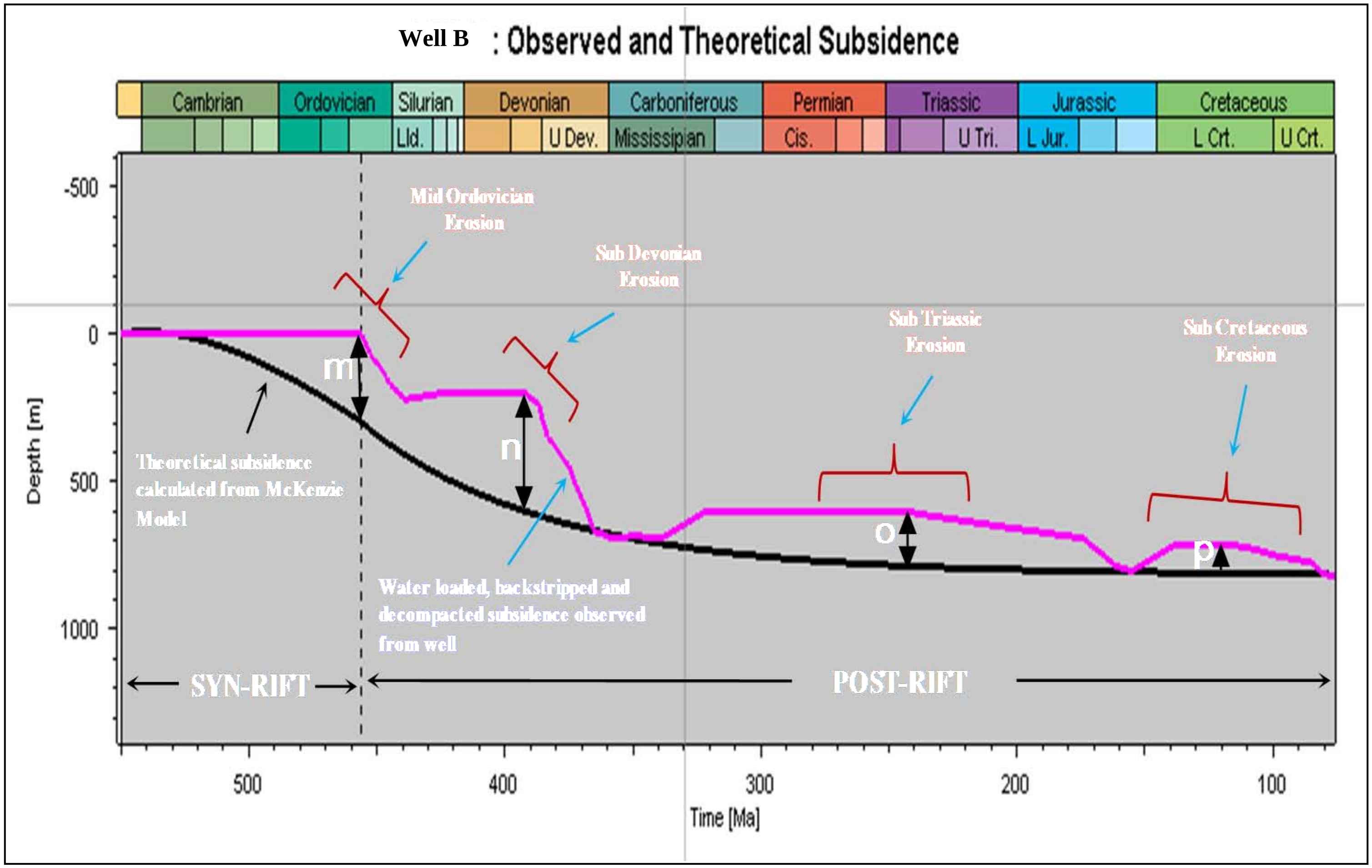

Figure 2. Observed basement subsidence curve (blue) compared to the McKenzie stretching solution curve (black), the vertical departures between curves represent uplift and erosional events.

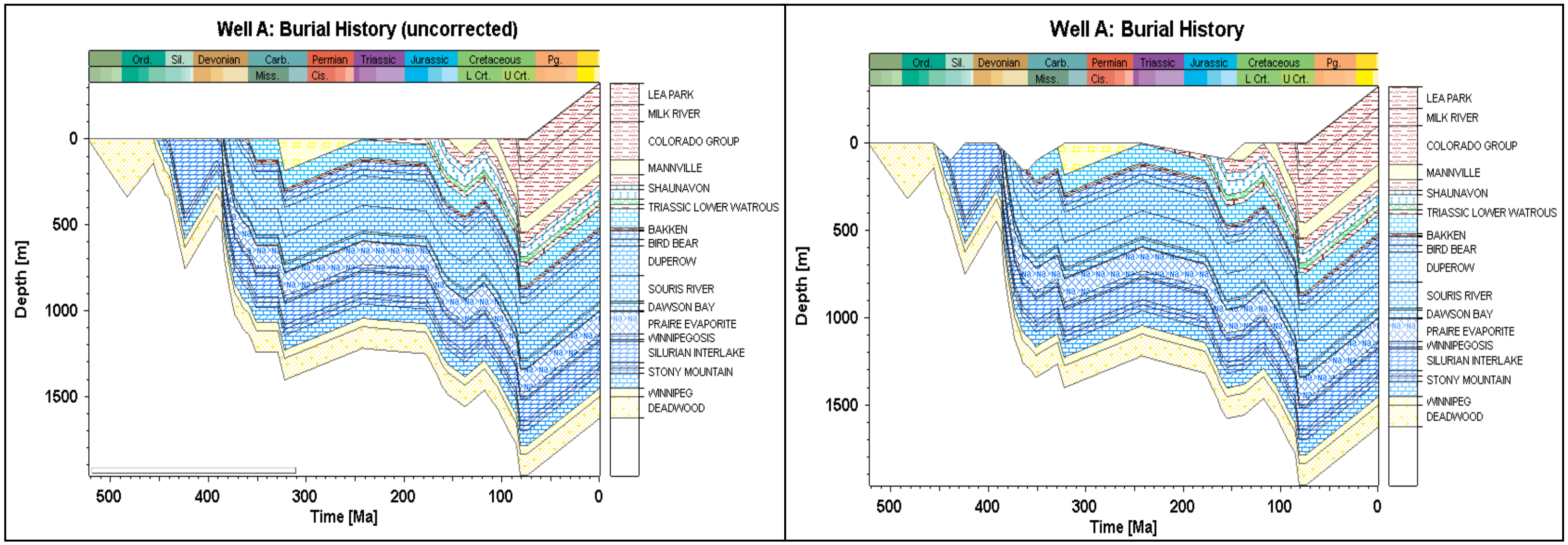

Figure 3. (A) Burial history profile from Well A with assumed zero paleobathymetry and no erosion correction. (B) Burial history profile from Well A with McKenzie's model derived exhumation and paleobathymetry corrections.

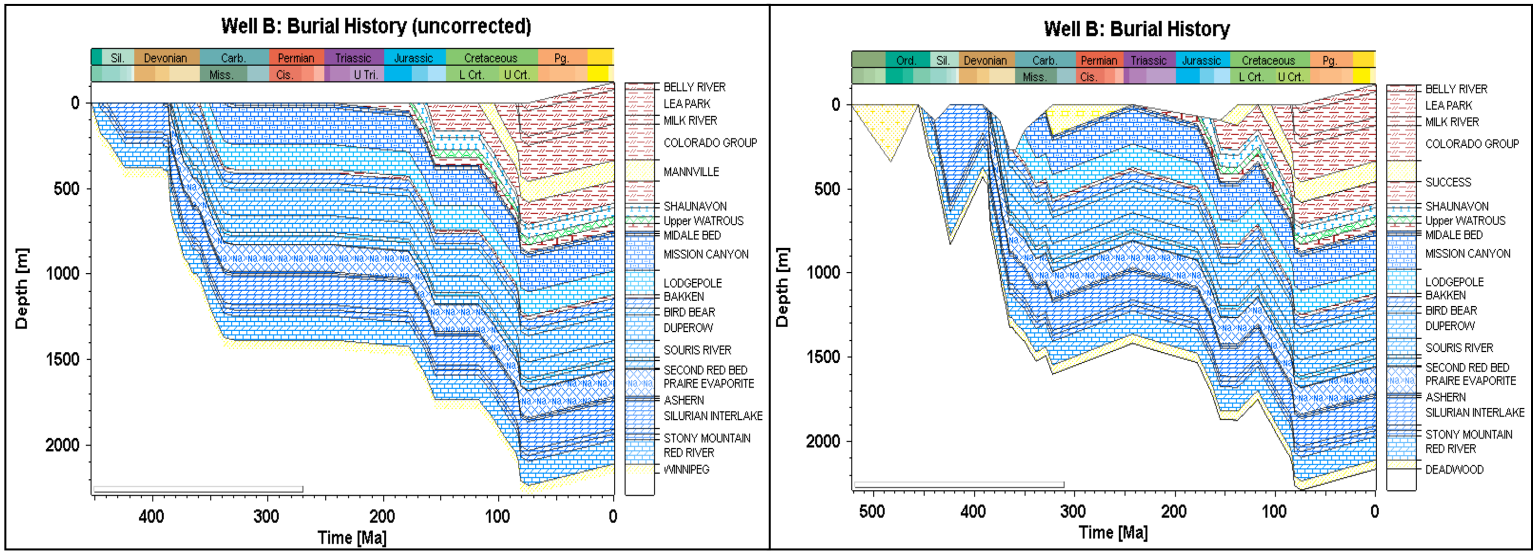

Figure 4. (A) Burial history profile from Well B with assumed zero paleobathymetry and no erosion correction. (B) Burial history profile from Well B with McKenzie's model derived exhumation and paleobathymetry corrections.

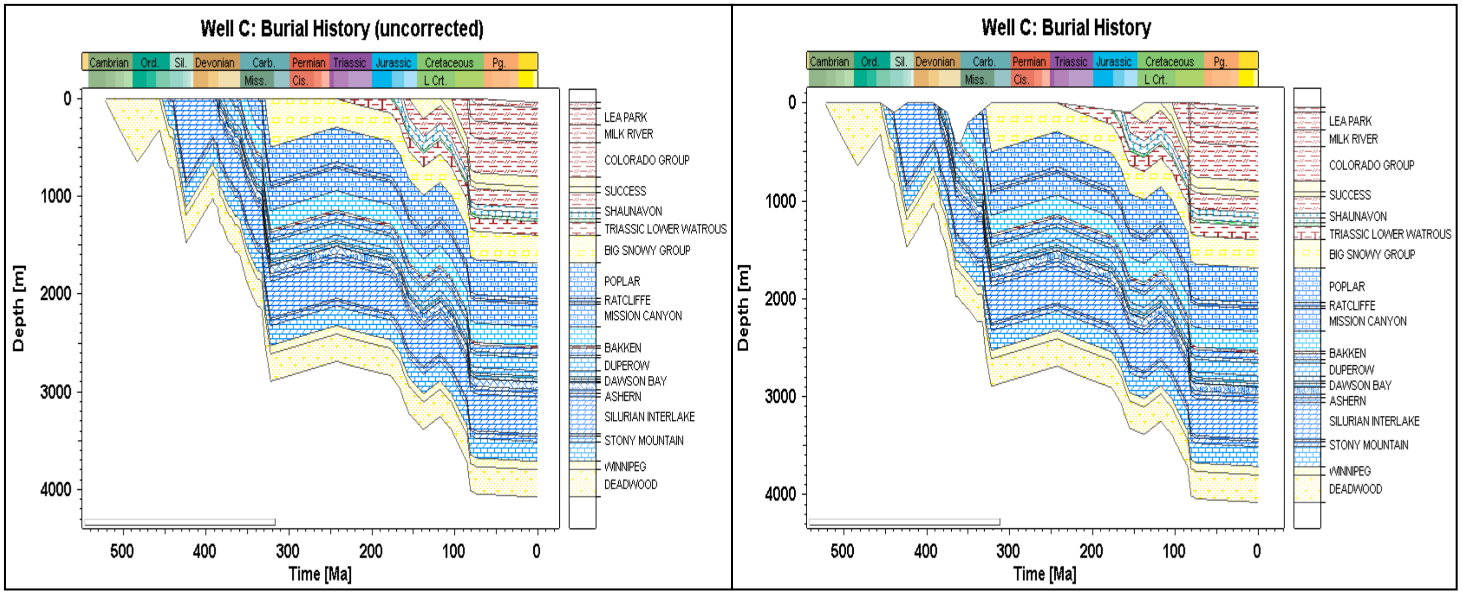

Figure 5. (A) Burial history profile from Well C with assumed zero paleobathymetry and no erosion correction. (B) Burial history profile from Well C with McKenzie's model derived exhumation and paleobathymetry corrections.