PS The Quantitative Modelling of the Northern Williston Basin: the McKenzie Lithospheric Stretching Model Approach*

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Abstract

The application of McKenzie lithospheric stretching theory as applied to the modelling of the evolution of the Williston Basin has been a subject of debate over the years. The key arguments for and against the McKenzie lithospheric stretching assessment and its application to the evolution of intracratonic basins are reviewed in this comparative and assessment study vis-à-vis some observed crustal and derived data within the Williston Basin. McKenzie's methodology was used to model the distribution of stretch factors thereby facilitating the calculation of the amount of crustal thinning. McKenzie's derived paleobathymetry and exhumation solutions were applied to a data matrix comprised of 38 wells within the northern part of the Williston Basin.

This study produced a number of significant results. Firstly, our modeled crustal stretch factors (βcrust) agree with the CONCRUST refraction seismic data that indicates between 3km to 4km crustal thinning within the northern Williston Basin. Secondly, McKenzie's derived paleobathymetry data concur with available and published biostratigraphic data, permitting the creation of a series of palobathymetry maps for selected stratigraphic units (Early Turonian Upper Colorado Second White Specks formation and the Upper Devonian/Lower Mississippian Lower and Upper Bakken Shale members). Results also show that paleobathymetry values vary systematically across the basin helping to refine the onset of deposition and basin initiation. Results also concur with widely held belief that the maximum water depth for the Bakken was approximately 250m while the Second White Specks had a maximum depositional water depth of 160m in the Saskatchewan portion of the Williston Basin. Thirdly, exhumation maps reveal trends in erosional magnitude within the northern part of the Williston Basin: Mid Ordovician and Sub Devonian erosion show a NW-SE trend, NE-SW trend characterizes Sub-Jurassic and Sub-Cretaceous erosion. The Sub

Triassic erosion shows a transition between NW-SE and NE-SW erosional trends.

The successful application of McKenzie's lithospheric stretching solutions within the Williston Basin indicates that subsidence was not linear and uplift prior to the initiation of the basin subsidence was not necessary. This assessment also demonstrates the successful application of the McKenzie methodology in an intracratonic basin without block rifting.

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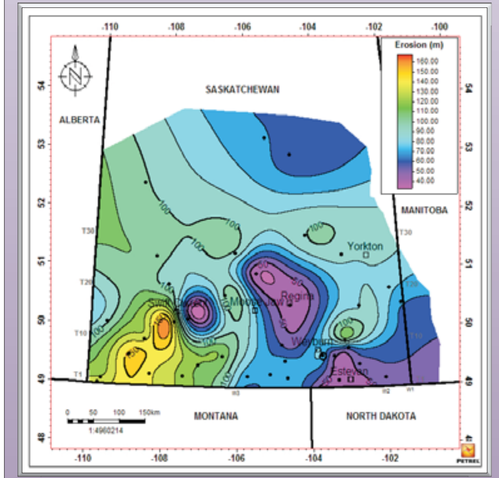
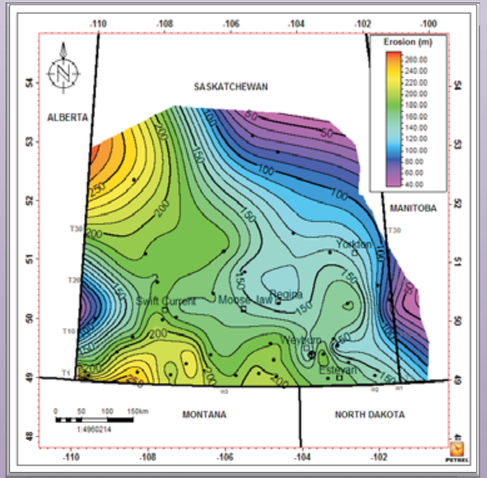
McKenzie's Model Based Paleobathymetry and Exhumation Solutions

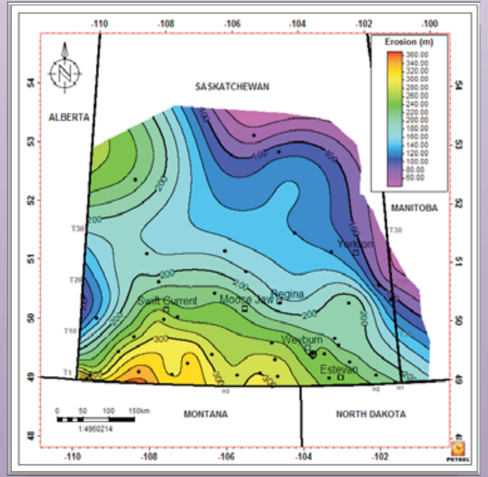
Sub-Tertiary Erosion Map



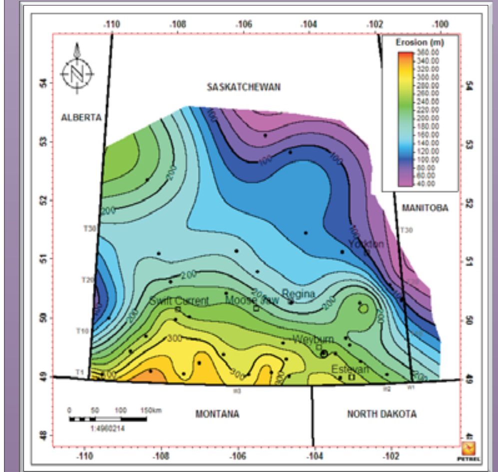
Sub-Cretaceous Erosion Map



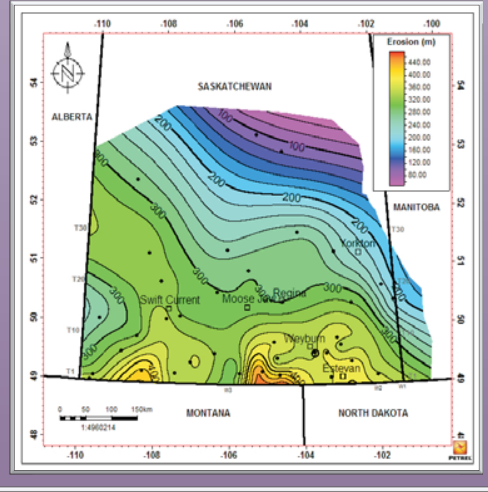
Sub-Jurassic Erosion Map



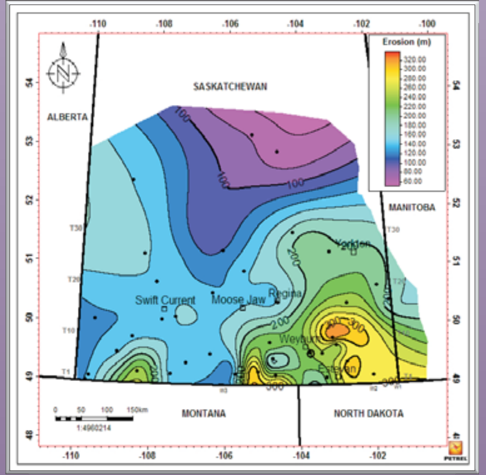
Sub-Triassic Erosion Map



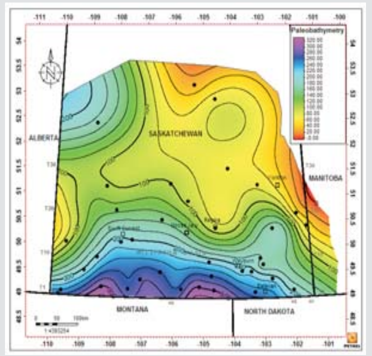
Sub-Devonian Erosion Map



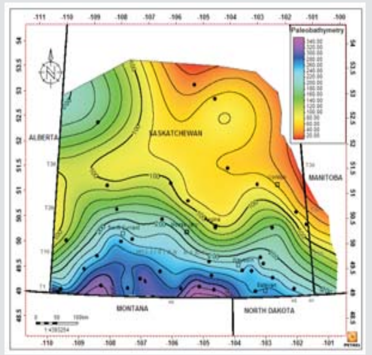
Mid-Ordovician Erosion Map



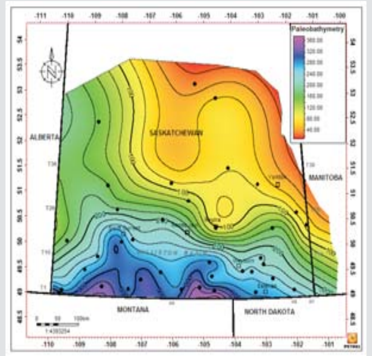
Selected Paleobathymetry Maps



Mississippian Lodgepole



Upper Devonian
Upper Bakken Member



Upper Devonian
Lower Bakken Member

PURPOSE OF STUDY

The overall goal of this study is to apply a modelling solution that provides a petroleum systems model with the highest resolution possible in the absence of seismic data. The purpose of this study is to investigate the application of the McKenzie's Lithospheric Stretching model as a viable basin modelling solution within the Williston Basin.

McKenzie's Uniform Lithospheric Stretching Model

Synrift subsidence due to isostatic adjustment

$$yi = \frac{yL\left\{(\rho m-\rho c)\frac{yc}{yL}\left(1-\alpha v\frac{Tm}{2}\frac{yc}{yL}\right)-\frac{\alpha v\,Tm\,\rho m}{2}\right\}\left(1-\frac{1}{\beta}\right)}{\rho m(1-\alpha v\,Tm)-\rho s}$$

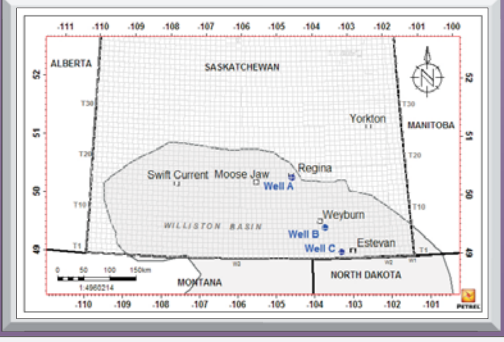
Post rift thermal subsidence

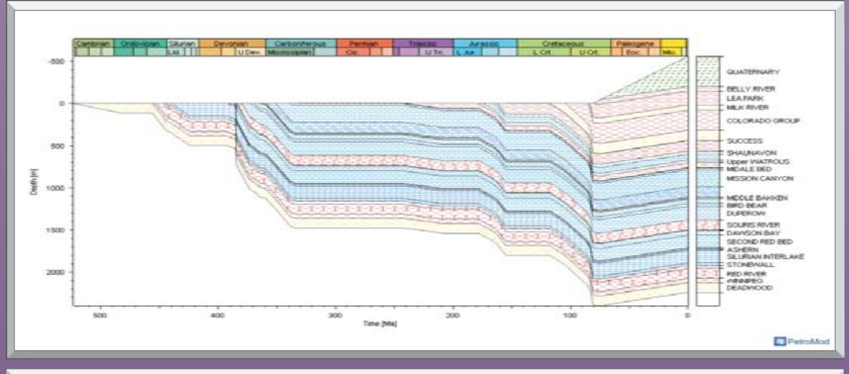
$$yt = \left\{\frac{4\,yL\,\alpha v\,\rho m(Tm-To)}{\pi^2(\rho m-\rho s)}\right\}\frac{\beta}{\pi}\sin\left(\frac{\pi}{\beta}\right)$$

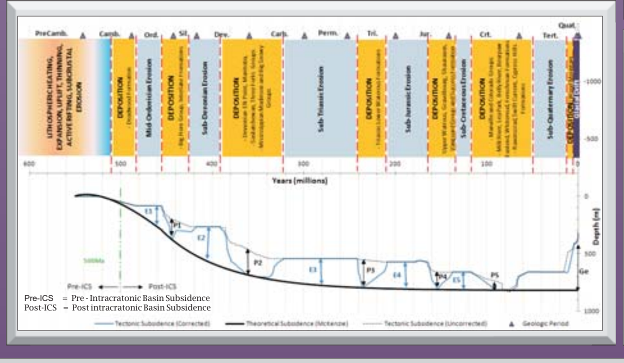
- β = Stretch factor (variable)
- yL = Initial thickness of the lithosphere
- yc = Initial thickness of the crust
- ρm = Density of the mantle at degC
- ρc = Density of the crust at degC
- ρs = Average bulk density of sediment or water filling the rift
- αv = Thermal expansion coefficient of both crust and mantle
- Tm = Temperature of asthenosphere
- yi = Initial subsidence due to isostatic adjustment
- yt = Thermal subsidence

In the case of intracratonic sag basins, major fault systems that typically form the boundaries of a depositional area or central rift zone may be absent. The subsidence in this class of basins is thought to occur predominantly in response to moderate crustal thinning or due to density differences between the underlying and neighbouring crust (Einsele, 2000). The intensities of the regional stress during the formation of non-rifted intracratonic sag basins are insufficient to overcome rock strength, hence resulting into moderate thinning and the absence of major extensional faulting (Allen and Allen, 2005).

Comparative Application of McKenzie's Methodology

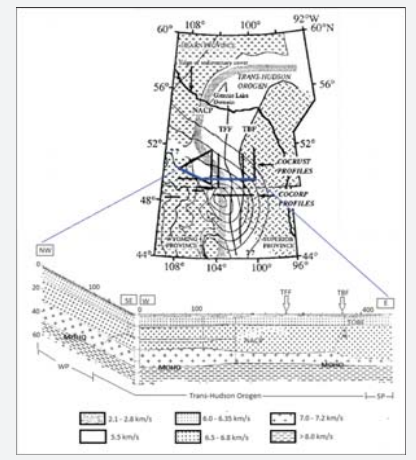


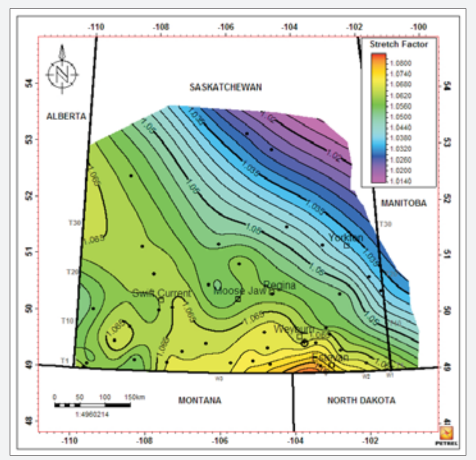




An illustration of McKenzie's solutions as applied to a Well B in the south-eastern Saskatchewan, showing exhumation estimates (E1, E2, E3, E4, E5, and Ge) and paleobathymetry estimates (P1, P2, P3, P4, and P5). Corrected profile (bottom right) captures more episodes of uplift and subsidence

Comparison of McKenzie's Model with some Published Data within the Williston Basin





$$\beta = \frac{\text{unextended thickness}}{\text{extended thickness}}$$

$1.065 = T_{unext}/50km$

$T_{unext} = 1.065 * 50km$

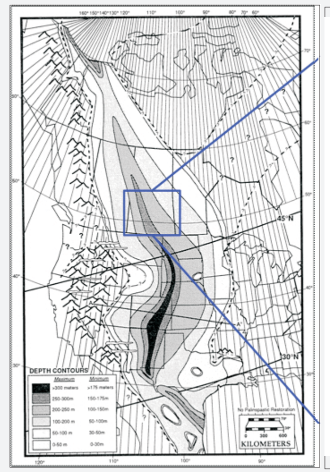
$T_{unext} = 53.25km$

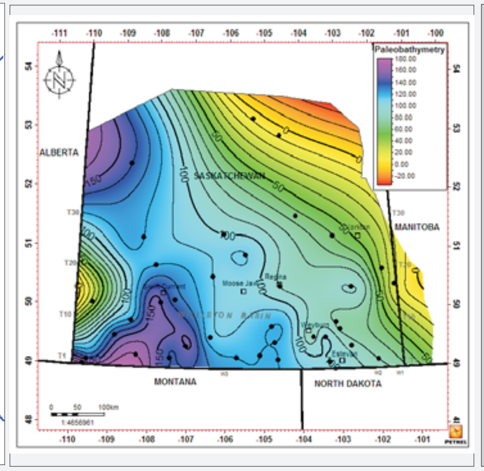
Thinning = 53.25 – 50km

McKenzie's model based crustal thinning **3.25km**

seismic interpretation based crustal thinning **3 - 4km**

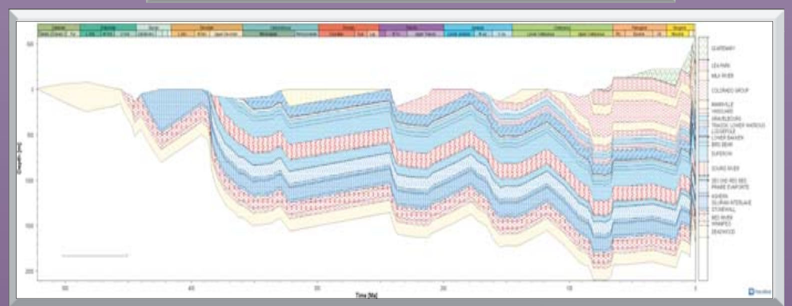
Comparing interpreted crustal thinning from COCRUST 2D Seismic line (left) by Morel-a-l'Huissier (1990) with the estimation from McKenzie's crustal stretch factor data (centre)



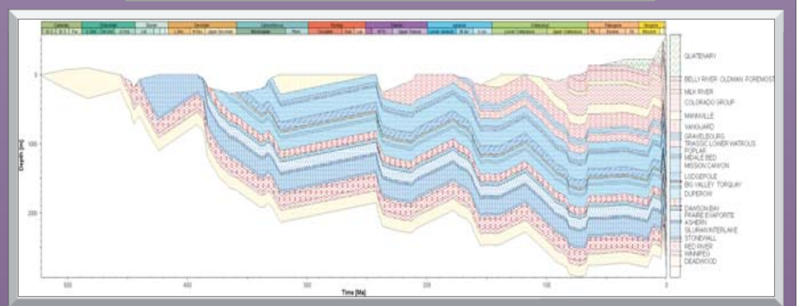


A comparison of the Early Turonian paleobathymetric map from biostratigraphic data (left) by Sageman et al. (1994) to the McKenzie's derived palobathymetric map (right). Locations of the control well are the black circular dots. The blue inset rectangle is the area covered by the McKenzie derived palobathymetric map. The comparison shows a striking correlation both in trend (NW-SE) and numerical values (minimum range).

Well A: Burial History Model



Well C: Burial History Model



CONCLUSION

The successful application of McKenzie's lithospheric stretching solution within the Williston Basin indicates that: (1) subsidence was not linear; (2) significant uplift prior to the initiation of the basin subsidence may not be necessary; (3) intracratonic basin block rifting is not necessary; (4) compares well with biostratigraphic data; (5) application of the methodology provides an estimation of paleobathymetry; (6) application of methodology provides a higher degree of refinement of exhumation; (7) provides solution that compares well to seismic data.

ACKNOWLEDGEMENT

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