Paleozoic Petroleum Systems of the Northern Williston Basin: a Quantitative Basin Modeling Assessment*

Oluseyi Olajide[1] and Stephen Bend[1]

Search and Discovery Article #20305 (2015)
Posted April 6, 2015

*Adapted from extended abstract prepared in conjunction with an oral presentation given at the 2014 GeoConvention, Calgary, Alberta, Canada, May 12-16, 2014, GeoConvention/Datapages © 2015

[1]University of Regina, Regina, SK, Canada (olajidol@uregina.ca)

Abstract

A series of 1D, 2D and 3D models of the Paleozoic petroleum systems within the northern portion of the Williston Basin were created by integrating geological, geophysical, geochemical subsurface data. The primary goal of this study is to quantitatively assess the response of source rock maturation, petroleum generation, expulsion, migration and accumulation within the Phanerozoic during the evolution of the Williston Basin. A suggested mechanism of subsidence of the basin by Klein and Hsui (1987) and Quinlan (1987) forms the basis of the modeling methodology employed in this study expressed as McKenzie's uniform lithospheric stretching methodology. This study also takes into account the Sub-Tertiary, Sub-Cretaceous, Sub-Jurassic, Sub-Triassic, Sub-Devonian and Mid-Ordovician erosional events using the McKenzie's lithospheric stretching methodology augmented by traditional methods. Paleobathymetry data was generated within the model and calibrated using reported biostratigraphic data. Measured bottom hole geothermal data, calculated present day heat flow, simulated paleo-heat flow solutions and full geochemical analyses (i.e. RockEval, organofacies, kinetics) were applied to the maturation solutions of each source rock unit.

The resulting source rock maturity history and hydrocarbon generation models suggest that Lower Paleozoic source rock units within the southern Saskatchewan, particularly the Upper Cambrian to Ordovician source rocks attain maturity by the late Paleozoic. In contrast, other Paleozoic source intervals such as the Bakken and Lodgepole Formation do not reach maturity until the Late Cretaceous to the Paleogene time using standard kinetic parameters. The 1D, 2D and 3D basin models also identify (and replicate) existing oil/gas pools as well as 'micro kitchens' of probable generation for stratigraphic units of the mid to late Paleozoic. Petroleum migration from source rock into the trap is a combination of lateral and vertical migration.

Introduction

Petroleum exploration is an expensive and increasingly difficult activity in today's oil-based economy. As petroleum becomes more difficult to find, basin and petroleum system modeling continues to grow in popularity because it provides an integrative exploration tool, which can be used to quantify many of the key aspect of an evolving basin and active petroleum systems within it. The abundant data resulting from extensive petroleum exploration and production activities in the Saskatchewan portion of the Williston Basin (Figure 1) created a unique opportunity to integrate the diverse geological, geochemical, geophysical and engineering data into a series of 1D, 2D and 3D models that dynamically simulate tectonic, sedimentologic, and the thermal evolution of the basin.

This study is a significant subtask of the main Phanerozoic Fluids project, which is focused toward performing an assessment of Saskatchewan's Phanerozoic fluids and petroleum systems. The work will address fundamental processes involved in the evolution of Saskatchewan's sedimentary basin that resulted in generation, migration, and entrapment of hydrocarbons in Phanerozoic strata. The goals and individual tasks of this multidisciplinary project have been previously documented (Whittaker et al., 2009).

The 1D, 2D and 3D modeling of petroleum systems within the northern Williston Basin was conducted to identify, analyze and characterize the fundamental geological processes that are involved in the generation, migration and entrapment of hydrocarbon within Phanerozoic strata. The Paleozoic stratigraphic succession of the Williston Basin is dominated by a succession of carbonate that harbors most of the known petroleum resources in the southern Saskatchewan subsurface. Vast marine systems dominated the Paleozoic era and according to Kent (1984), was characterized by the development of a distinct paleobathymetry zonation during the Silurian and Mississippian periods.

Some of the widely accepted Paleozoic petroleum systems (Figure 2) within the northern Williston Basin include: the Red River – Red River, Red River - Interlake, Red River – Winnipeg, Winnipegosis – Winnipegosis, Bakken – Birdbear, Bakken – Three Forks, Bakken – Bakken, Bakken – Lodgepole, Mission – Canyon Spear Fish, and Mission Canyon – Mission Canyon. Some debated or speculative petroleum systems according to include: Cambro – Ordovician – Deadwood, Winnipeg – Winnipeg, Winnipegosis – Interlake, Duperow – Dawson Bay, Duperow – Duperow, and Ratcliffe – Ratcliffe (Dow, 1974; Jarvie, 2001; Jarvie and Walker, 1997; Nordeng, 2013; Osadetz and Snowdon, 1995; Peterson, 1988; Williams, 1974; Zumberge, 1983).

Method

Seven Paleozoic source rock units are assessed in this study. These include the Upper Ordovician Winnipeg, Upper Ordovician Red River, Upper Ordovician Stony Mountain, Middle Devonian Winnipegosis, Upper Devonian/Mississippian Lower Bakken, Upper Devonian/Mississippian Upper Bakken, and the Mississippian Lodgepole Formation.

The Model consists of eight 2D transects with 38 control wells, each with a unique 1D model. Each 1D model contains a unique set of sedimentological, stratigraphic petrophysical and geochemical data that permits the construction of a burial history curve that forms the basis of the modeling process. The model also takes into account the magnitude of erosion associated with the Tertiary, Sub-cretaceous, Sub-Jurassic, Sub-Triassic, Sub-Devonian and Mid-Ordovician erosional events; in which the erosional data was derived using the McKenzie lithospheric stretching methodology augmented by traditional methods. Paleobathymetry data was also calculated using the McKenzie methodology and calibrated using reported biostratigraphic data. Measured bottom hole geothermal data, calculated present day heat flow, simulated paleo-heat flow solutions and full geochemical analyses (i.e. RockEval, organic facies and kinetics) were applied to the maturation solutions of each source rock unit.

Using Schlumberger Petrel software, stratigraphic data from approximately 12,000 wells were used to create stratigraphic top and thickness maps for 42 stratigraphic units representing the stratigraphic range of the entire Phanerozoic eon within the Saskatchewan portion of the Williston Basin (Figure 1). Structural cross sections were generated from the maps by extracting stratigraphic depth and thickness data along a series of control transects. Input heatflow, paleo-erosion and paleobathymetry data were extracted for each stratigraphic unit from a series of 1D maturity models (Figure 4 and Figure 5) built within Schlumberger Petromod software using data from 38 control wells (Figure 1). Dominant lithological characteristic of the input stratigraphic units were interpreted from control wells augmented by published geological report. Subsequently, the input structural cross sections, structural top maps, source rock geochemical data, thermal parameter, and calibrated boundary conditions were loaded into Petromod and forward simulated in 2D and 3D modules within Petromod.

Discussion of Results

The refined 1D burial history models (Figure 5) generally capture more episodes of uplift and subsidence when compared to other previously published burial history models (Figure 3). Source rock and hydrocarbon generation simulations also show that the Lower Paleozoic source rock units within the southern Saskatchewan (i.e., Upper Cambrian to Ordovician) reach maturity by the late Paleozoic. A comparative simulation of Bakken maturity, using differing activation energies, clearly supports the suggestion (Aderoju and Bend, in press) that the Upper and Lower Bakken generated hydrocarbon at relatively lower levels of thermal maturity, when using standard kinetic parameters, the Bakken essentially remains immature.

Also using formation specific kinetics where available (e.g. Ea, A, w-factor, Sorg), with organic facies, identifies ‘micro kitchens’ of early generation that are identified in a series of 2D dynamic petroleum systems models. An example 2D modeling transects (A – A and B – B) are shown in Figure 5 and Figure 6 that trend west to east within southern Saskatchewan. Simulated bulk hydrocarbon generation mass along transect A - A’ (Figure 6) shows a concentration of early to main oil generation in the extreme southwestern and towards the southeastern part of Saskatchewan. In a similar way, the simulated generation of hydrocarbon along transect B - B’ (Figure 7) also shows early to main oil generation in the southeastern part of Saskatchewan for all source rock intervals. The Bakken Formation in particular shows significant accumulation within the middle member. Accumulations within Middle Bakken are also in evidence while some additional pockets of accumulation are observed in the Ordovician Winnipeg, Ordovician Red River, Devonian Winnipegosis, Mississippian Mission Canyon Group and Mississippian Midale Formation (Figure 8, Figure 9, Figure 10, and Figure 11).

Although this remains work in progress, this evolving petroleum systems model of the northern portion of the Williston Basin has not only identified and replicated the generation of hydrocarbon within existing oil/gas pools, but has also identified ‘micro kitchens’ of probable generation for stratigraphic units of the mid to late Paleozoic within the Phanerozoic of southern Saskatchewan.

Conclusions

This study has demonstrated the immense potential in basin and petroleum systems modeling to address key questions that are related to source rock transformation, maturation, hydrocarbon migration and accumulation within the northern Williston Basin. Source rock maturation model revealed possible areas of ‘micro-kitchens’ (Figure 6 and Figure 7) that could lead to new discoveries or provide better understanding of existing petroleum systems. In addition, our model suitably replicate the present day distribution of the main oil and gas fields (Figure 9) discovered within the study area thereby facilitating the identification of some possible hydrocarbon pools (Figure 10).

Acknowledgements

We would like to thank the project sponsor, the Saskatchewan Ministry of the Economy and the PTRC as general Project Manager. Thank you also to Schlumberger for the provision of the Petrel™ and PetroMod™ academic license, the Geological Survey of Canada for sulphur, G.C. and G.C-M.S. analyses and the Western Diversification Fund, through IPAC-CO2, for the Vinci RockEval 6 analyzer.

Selected References

Kent, D.M., 1987, Paleotectonic controls on sedimentation in the northern Williston Basin, Saskatchewan: in J.A. Peterson, D.M. Kent, S.B. Anderson, R.H. Pilatzke, and M.W. Longman (eds.), Williston Basin: Anatomy of a Cratonic Oil Province, The Rocky Mountain Association of Geologists, Denver, Colorado, p. 45-56.

Klein, G., and A.T. Hsui, 1987, Origin of cratonic basins: Geology, v. 15, p. 1094-1098.

Nordeng, S.H., 2013, Petroleum systems in the Williston Basin: Geo News, p. 8-13, Web Accessed March 21, 2015, https://www.dmr.nd.gov/ndgs/documents/newsletter/2013Winter/PetroleumSystems.pdf.

Quinlan, G., 1987, Model of subsidence mechanisms in intracratonic basins, and their applicability to North American examples: in C. Beaumont and A.J. Tankard (eds.), Sedimentary Basin and Basin-Forming Mechanisms, Canadian Society of Petroleum Geologists Memoir 12, p. 463-481.

Whittaker, S., A. Marsh, S. Bend, and B. Rostron, 2009, Saskatchewan Phanerozoic Fluids and Petroleum Systems Assessment Project: in Summary of Investigations 2009, Volume 1, Saskatchewan Geological Survey, Sask. Ministry of Energy and Resources, Misc. Rep. 2009-4.1, Paper A-1, 3 p.

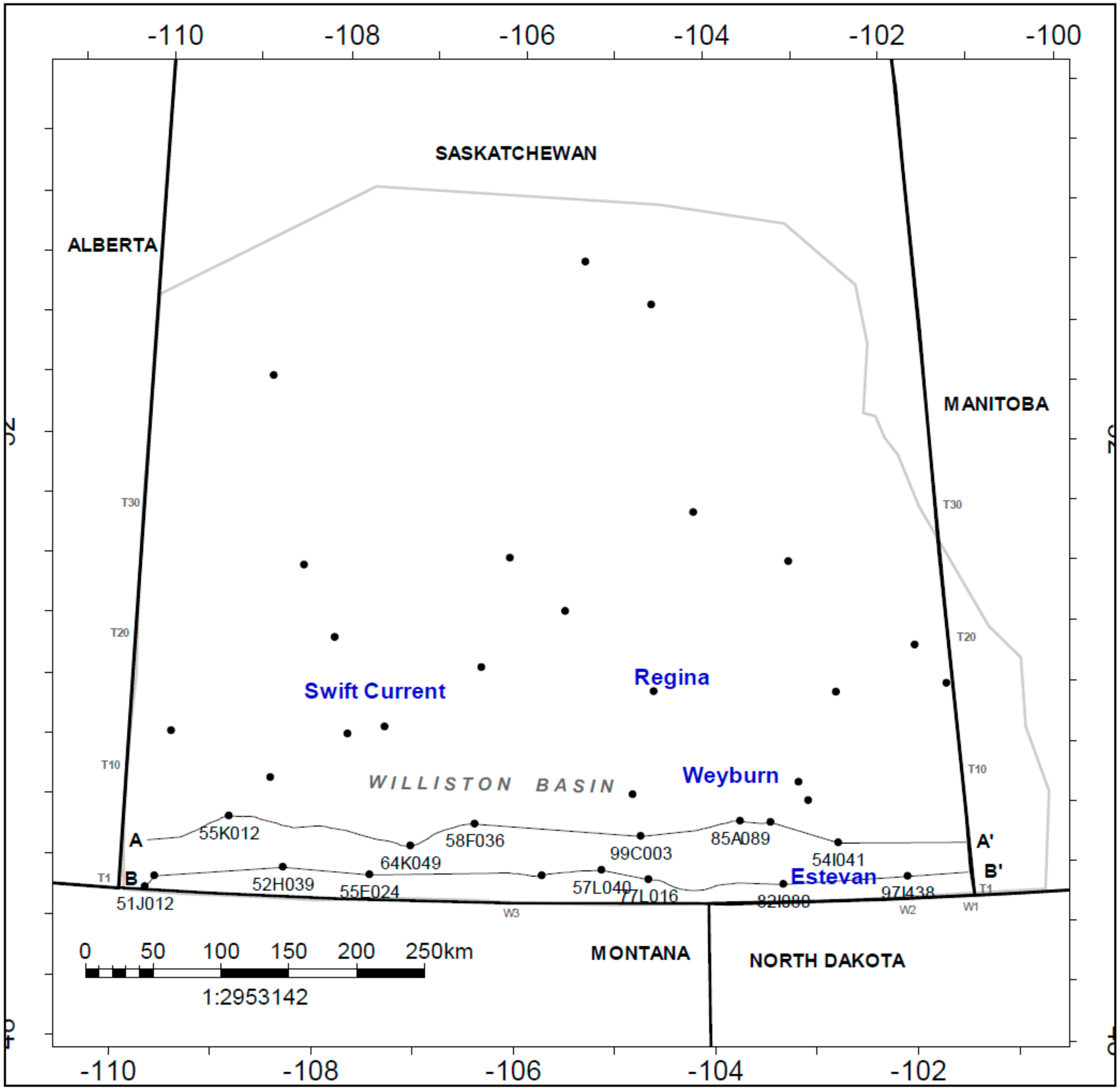

Figure 1. Location map showing 3D model boundary (light grey line), east – west 2D transects (A - A' and B - B'), 38 control wells (black dots), selected well for 1D burial history model example (black dot with square), and outline of present day oil pools (light green shades).

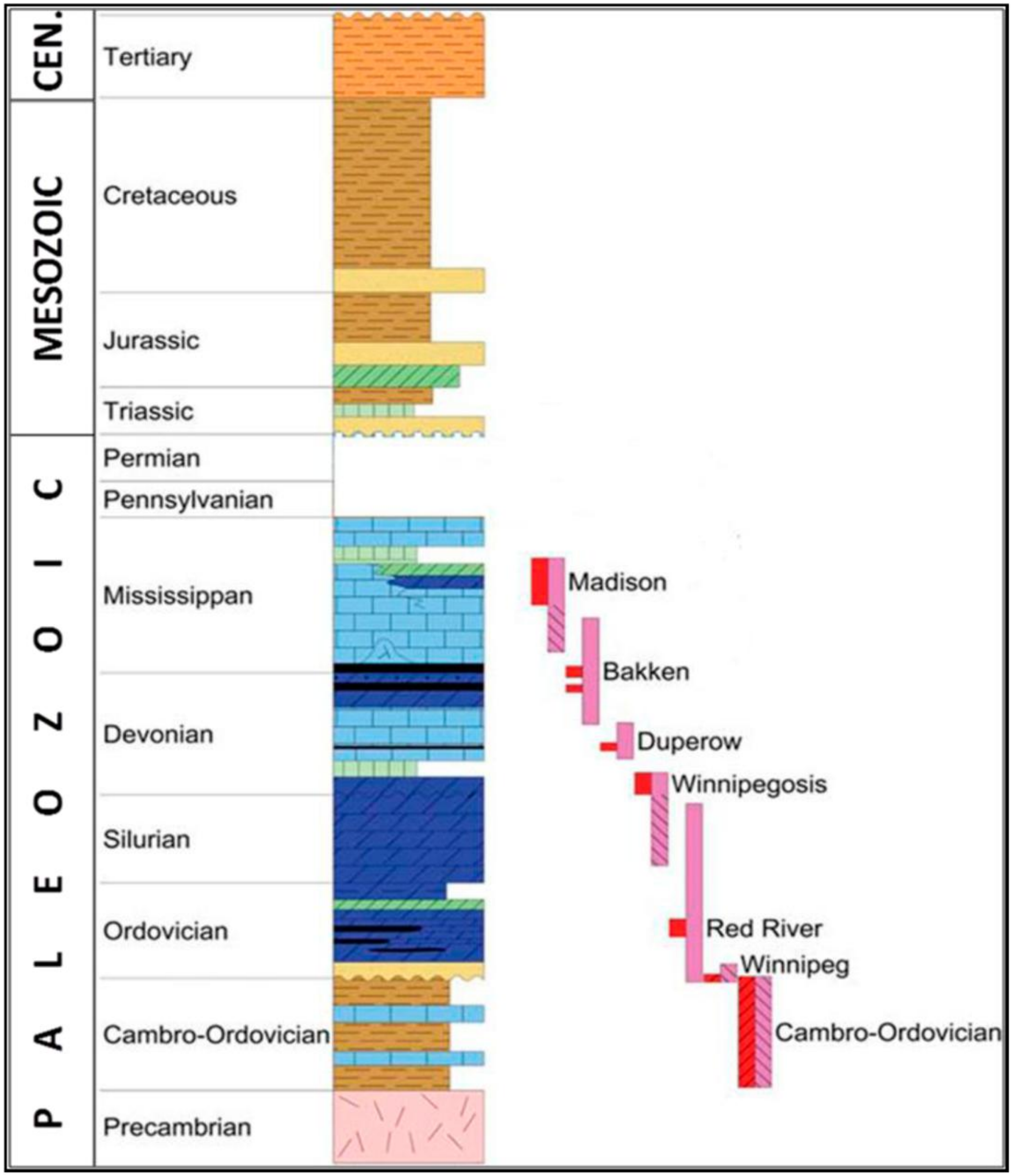

Figure 2. Generalized stratigraphic column showing the stratigraphic range of the Paleozoic petroleum systems in the Northern Williston Basin subsurface. Source rock range (red), reservoir rock range (pink), while hashed intervals represent questionable or speculative ranges (modified from Nordeng, 2013).

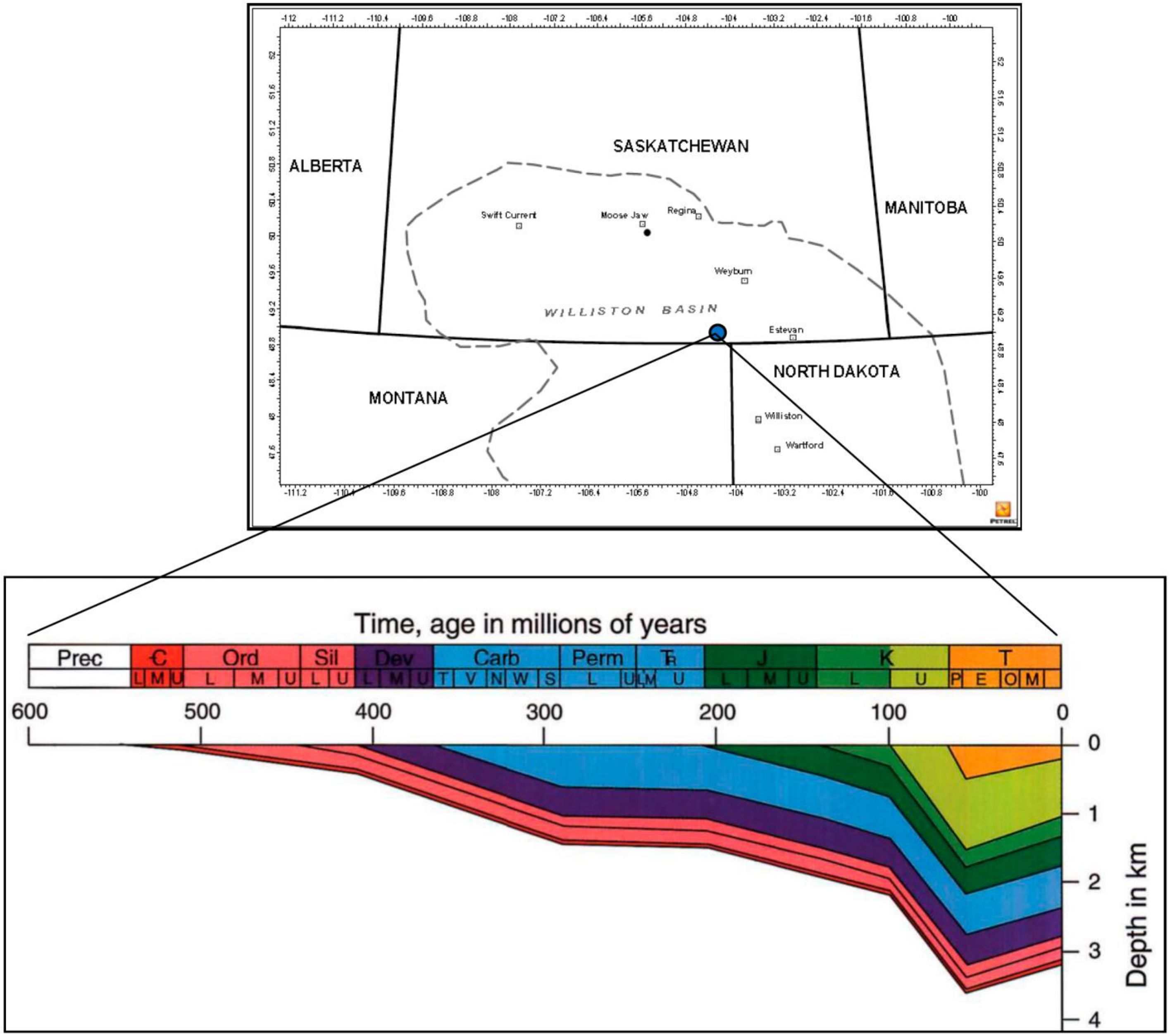

Figure 3. A previously published burial history plot (bottom) at well 08E125 (16-36-001-18W2). The well location is shown on the location map (top) within the simplified outline of the northern Williston Basin (modified from Alberta Geological Survey, 1994).

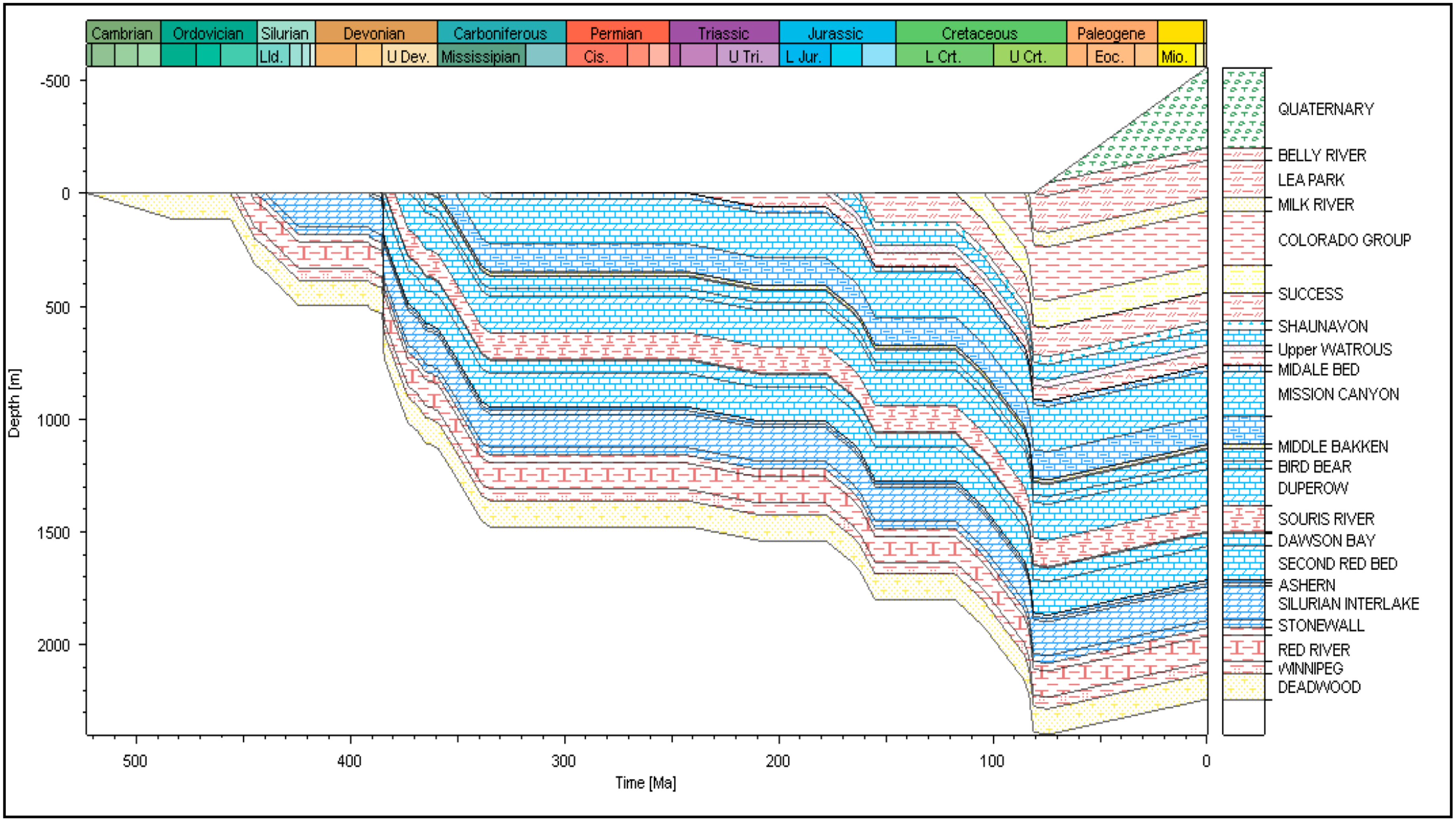

Figure 4. Unrefined burial history plot at well 85A089 (06-09-007-13W2) located along transect (A - A') shown in Figure 1.

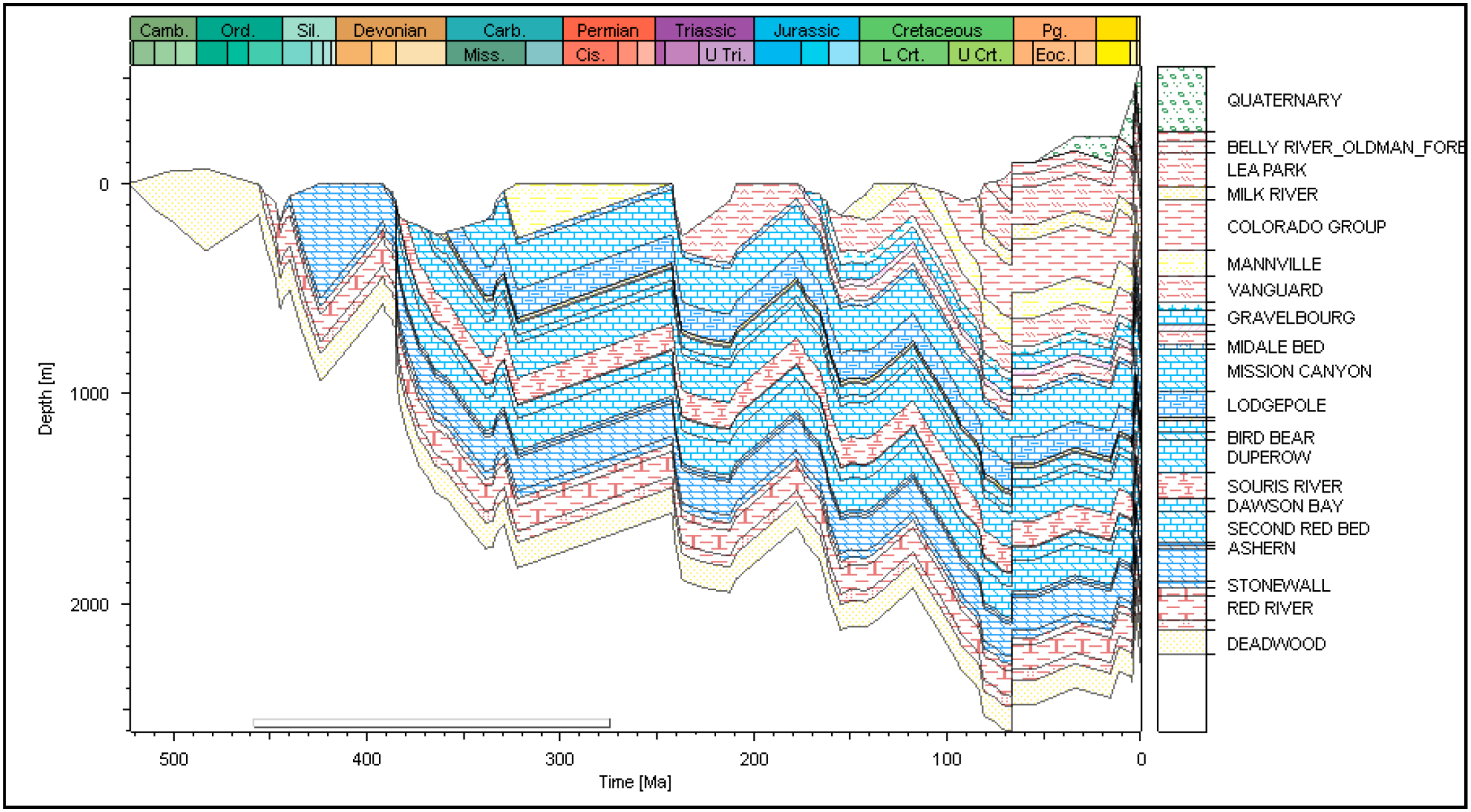

Figure 5. A refined burial history plot at well 85A089 (06-09-007-13W2) located along transect (A - A') shown in Figure 1. Refinement processes incorporate paleobathymetry and erosional episodes.

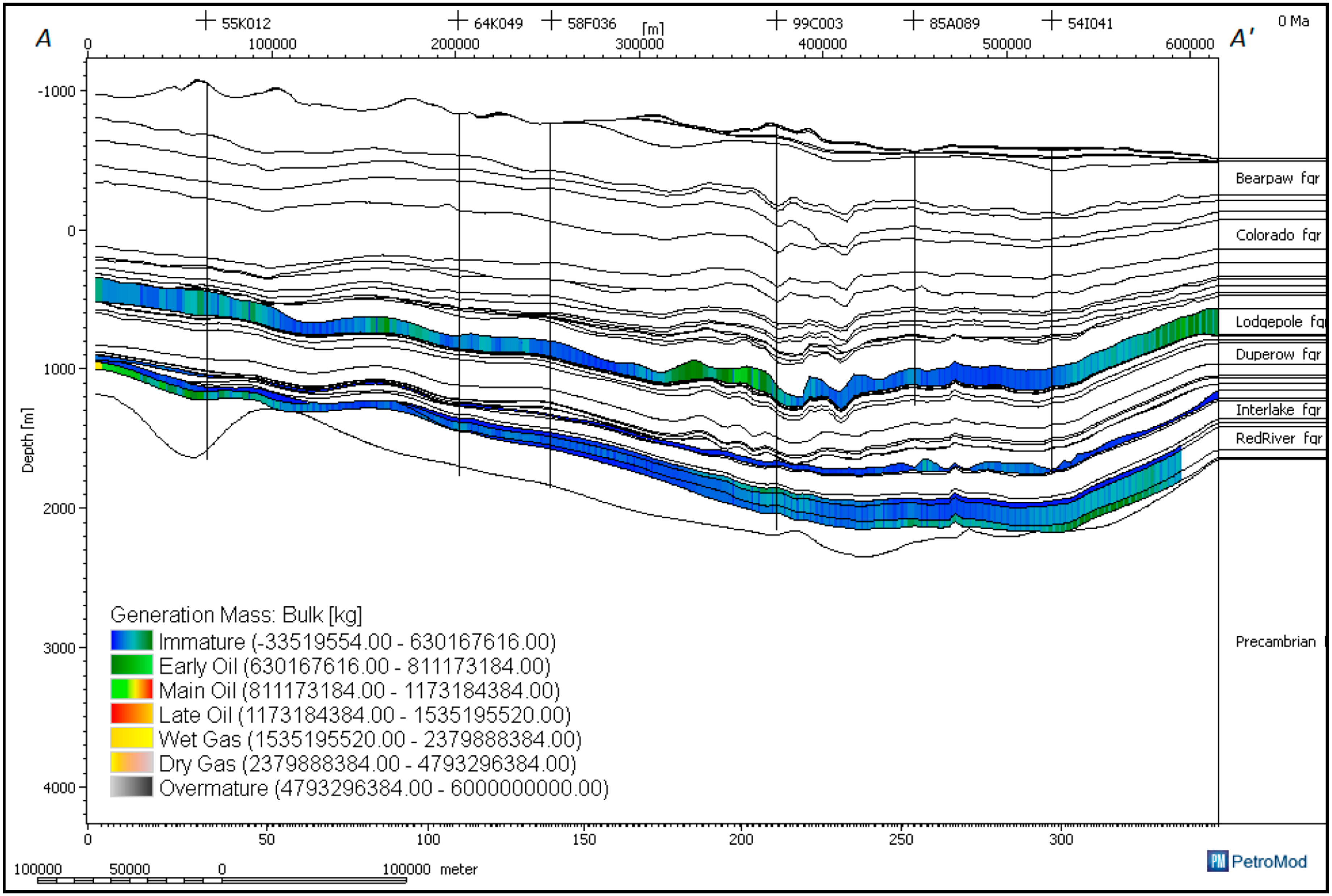

Figure 6. 2D model along transect A - A' showing hydrocarbon generation mass and source rock maturation status.

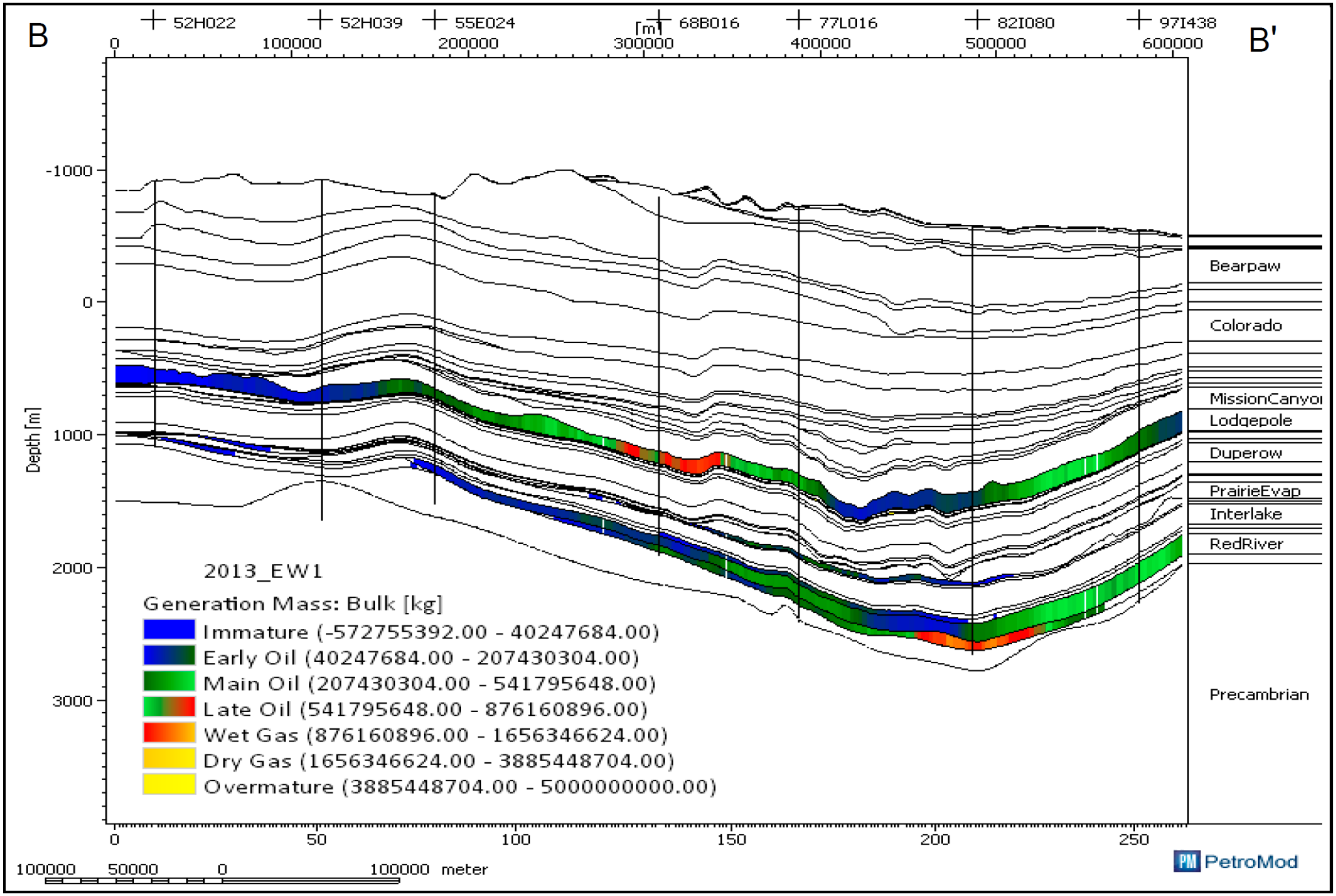

Figure 7. 2D model along transect B - B' showing hydrocarbon generation mass and source rock maturation status.

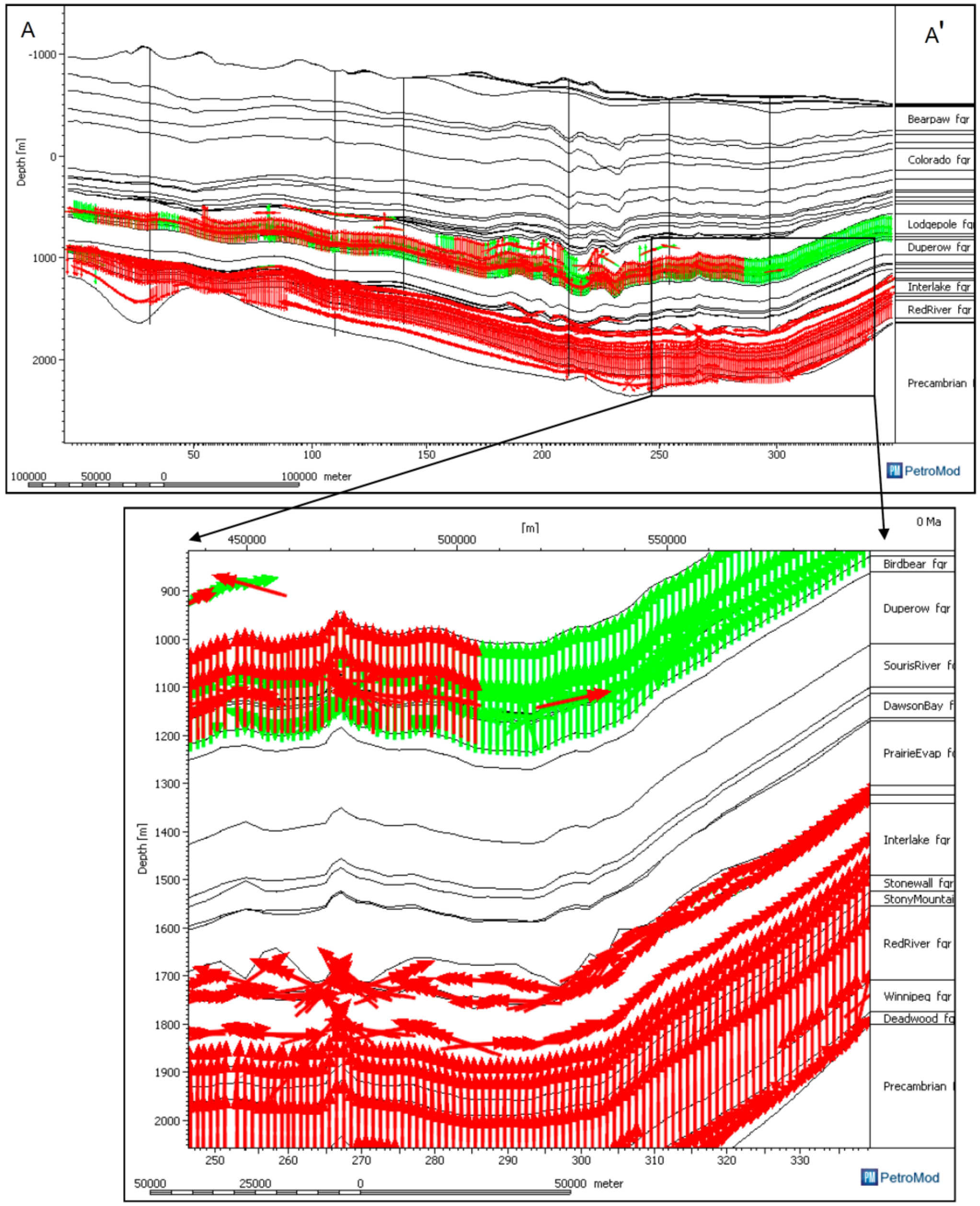

Figure 8. 2D model along transect A - A' showing a combination of lateral and vertical migration of the generated hydrocarbon. Green lines represent oil migration while red lines are condensate/light oil/liquid vapor migration.

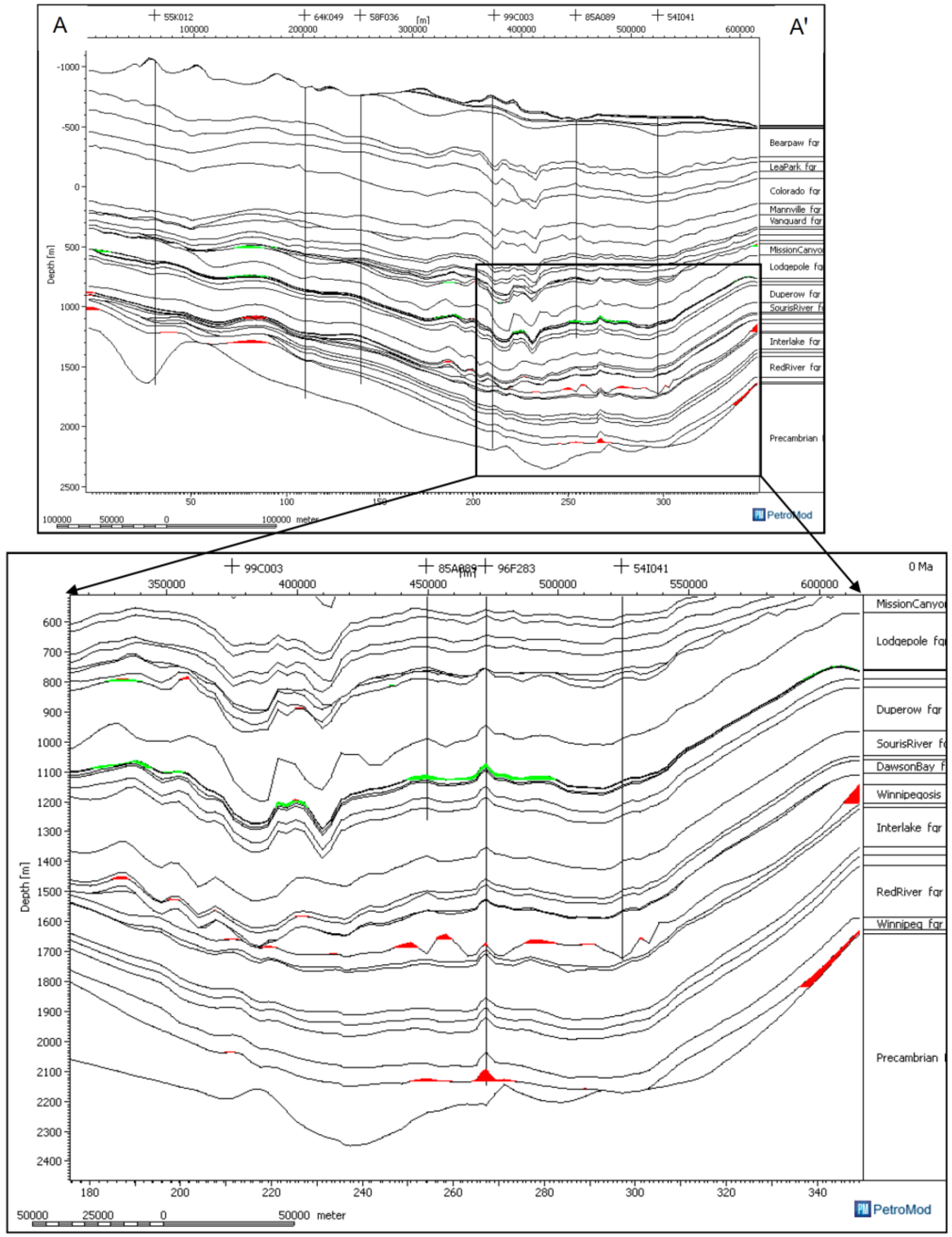

Figure 9. 2D model along transect A - A' showing oil (green) and condensate/light oil/liquid vapor migration (red) accumulation in mostly structural traps. The model replicates existing pools.

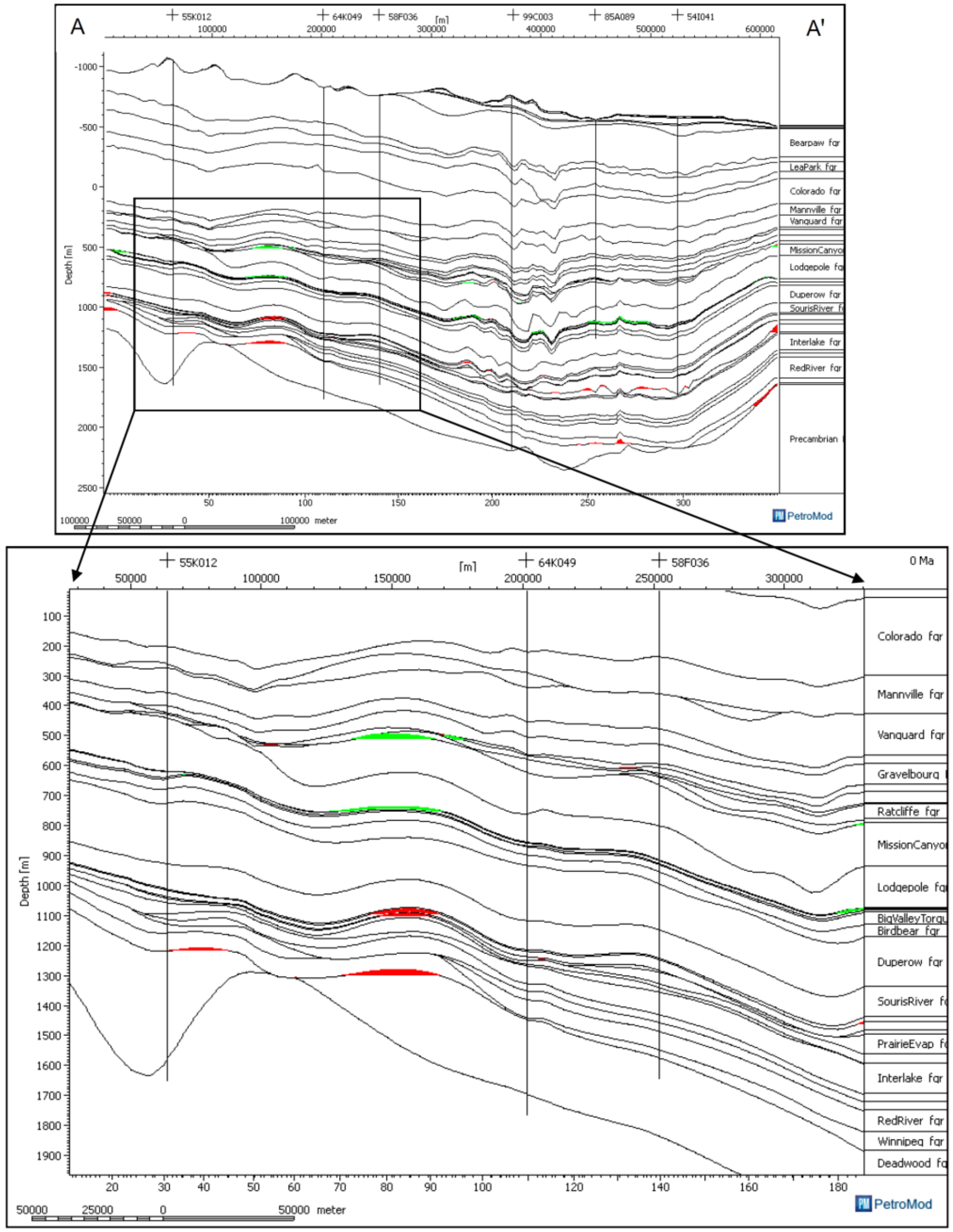

Figure 10. 2D model along transect A - A' showing oil (green) and condensate/light oil/liquid vapor migration (red) accumulation in mostly structural traps. The model shows potential hydrocarbon pools.

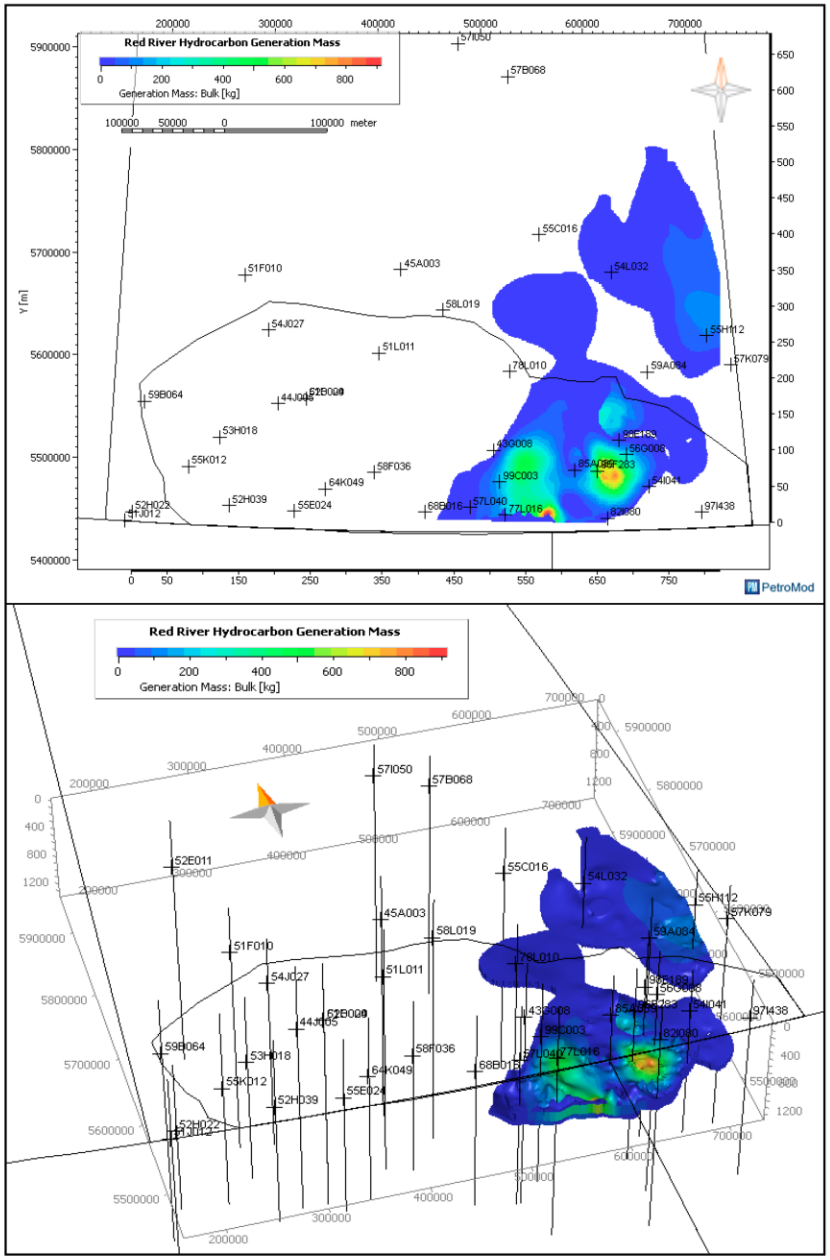

Figure 11. Map view of the 3D hydrocarbon generation mass of Red River Formation (top). The bottom capture shows the 3D view. Vertical lines are control wells.