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

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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 McKenzies 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, full geochemical analyses (i.e. RockEval, organofacies, kinetics), calculated present day heat flow, and simulated paleo-heat flow, which was calibrated using published data 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 formations do not reach maturity until the Late Cretaceous to Paleogene time using standard kinetic parameters. Petroleum migration from source rock into the trap is a combination of lateral and vertical migration. 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.

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 aspects 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 harbours most of the known petroleum resources in the southern Saskatchewan subsurface. Vast marine systems govern the Paleozoic Era and according to Kent (1984), was characterised by the development of a distinct paleobathymetry zonation during the Silurian and Mississippian periods. Some of the widely accepted Paleozoic petroleum systems 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). However, the Ordovician, Devonian Brightholme, Devonian Bakken-Three Forks, and the Devonian/Mississipian Bakken-Madison petroleum systems (Figure 2) are generally defined for the Saskatchewan portion of the Williston Basin (Creany et al., 1994; Jiang and Li, 2001; Lillis, 2013).

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 Bakken (Upper and Lower Bakken Members) and the Mississipian Lodgepole Formation. The Model consists of eight 2D control 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 calculated using the McKenzie methodology and calibrated with 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 Phaerozoic 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 5) built within Schlumberger Petromod software using data from 38 control wells. Dominant lithological characteristics of the input stratigraphic units were interpreted from control wells augmented by published geological reports. Subsequently, the input structural cross sections, structural top maps, source rock geochemical data, thermal parameter, and calibrated boundary conditions were loaded into and forward simulated within Petromod using 2D and 3D petroleum systems simulation modules.

Results

Figure 4 and Figure 5 show an unrefined and a refined 1D burial history model of an example well 85A089 (06-09-007-13W2). 2D models of hydrocarbon generation mass and vitrinite reflectance derived source rock maturation status along transect A-A' and B-B' (Figure 1) are presented in Figure 6 and Figure 7. Figures 8, 9, 10, 11, 12, 13 and 14 are the maps of hydrocarbon generation mass and vitrinite reflectance derived source rock maturation status extracted from 3D models maturation models of the source rock units within the Ordovician Winnipeg, Ordovician Red River, Ordovician Stony Mountain, Devonian Winnipegosis, Devonian Bakken and the Mississippian Lodgepole Formation respectively. A simulated 2D model of hydrocarbon migration along transect A-A' is shown in Figure 15 while Figure 16 and Figure 17 present pools of hydrocarbon accumulation in various stratigraphic units along transect A-A'.

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, which 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, the models identifie 'micro-kitchens' of early generation that are identified in a series of 2D dynamic petroleum systems models. An example west-east trending 2D modeling transects (A-A' and B-B') are shown in Figure 6 and Figure 7. Simulated hydrocarbon generation mass along transect A-A' (Figure 6) overlaid with vitrinite reflectance based source rock maturation status 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 hydrocabon along transect B-B' (Figure 7) also shows early to main oil generation in the southeastern part of Saskatchewan for all source rock intervals.

Maps of hydrocarbon generation mass and simulated vitrinite reflectance based source rock maturation status (Figures 8, 9, 10, 11, 12, 13 and 14) were extracted from the 3D maturation models of the source rock units within the Ordovician Winnipeg, Ordovician Red River, Ordovician stony Mountain, Devonian Winnipegosis, Devonian Lower Bakken, Devonian Upper Bakken, and Mississippian Lodgepole respectively. Significant early to main oil generation are observed in the Devonian Lower Bakken and Upper Bakken members (Figure 12 and Figure 13). Of particular interest are the source rock 'micro-kitchens' in the southwestern, western and the central parts of the Devonian Lower Bakken Member, Upper Bakken Member and the Winnipegosis Brightholme Member (Figures 11, 12 and 13). The Ordovician Winnipeg Icebox, Red River Lake Alma, Stony Mountain Gunn and the Mississippian Lodgepole source rocks generally show hydrocarbon generation in the southern and southeastern parts of Saskatchewan (Figures 8, 9, 10 and 14). The hydrocarbon migration model generally shows a combination of lateral and vertical migration, as shown in Figure 15.

The Bakken Formation shows significant accumulation within the Middle member 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 16 and Figure 17).

Conclusions

Although this remains a '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. This study has demonstrated the immense potential of 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. The source rock maturation model revealed possible areas of 'micro-kitchens' that could lead to new discoveries or provide better understanding of existing petroleum systems. In addition, our model suitably replicates the present day distribution of the main oil and gas fields discovered within the study area, thereby facilitating the identification of some possible undiscovered hydrocarbon pools.

Acknowledgements

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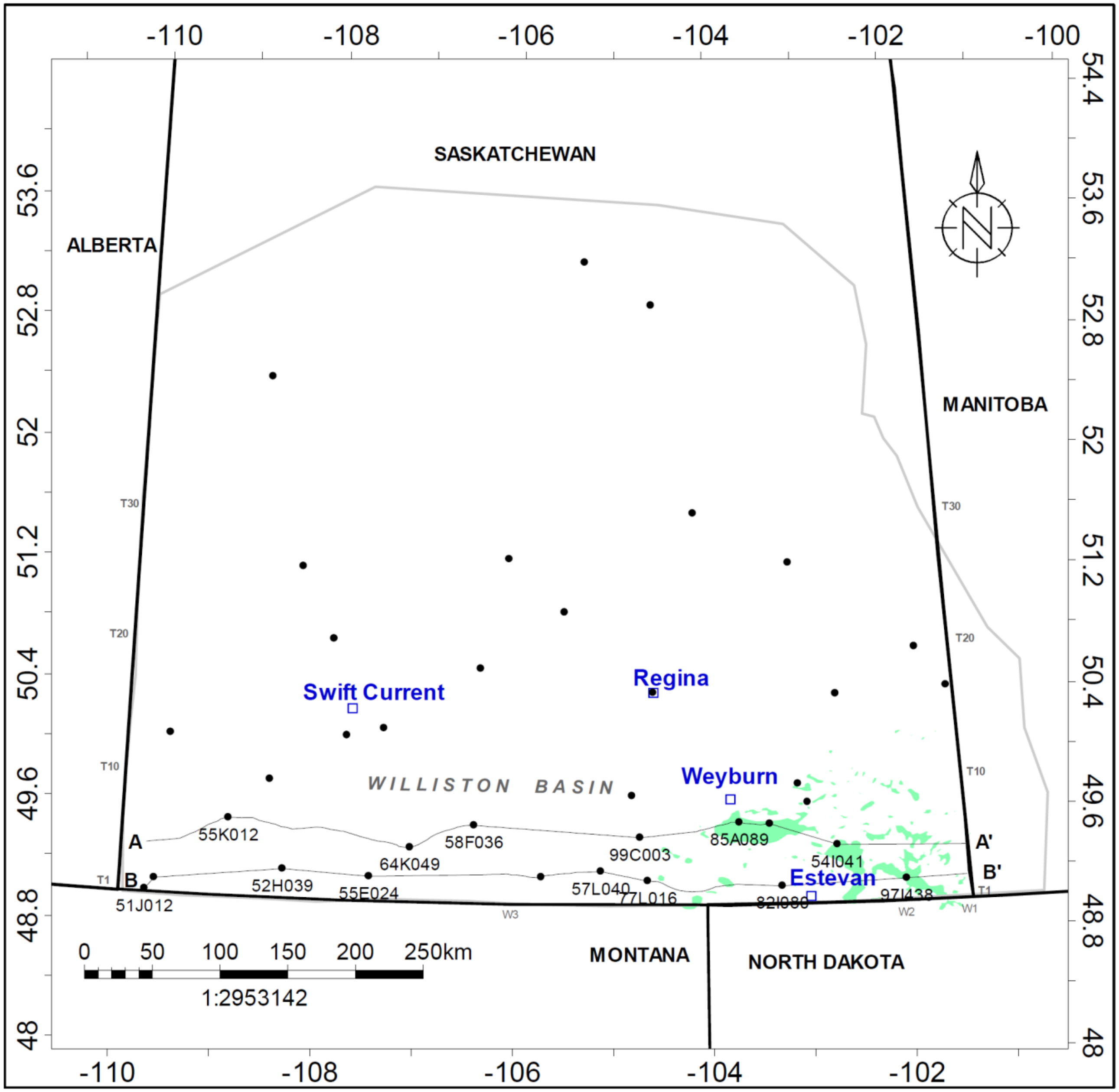

Figure 1. Location map showing 3D model boundary (light grey line), east-west 2D transects (A-A' and B-B'), 38 control wells (black dots), selected well for 1D burial history model example (black dot with square), and outline of present day oil pools (light green shades)

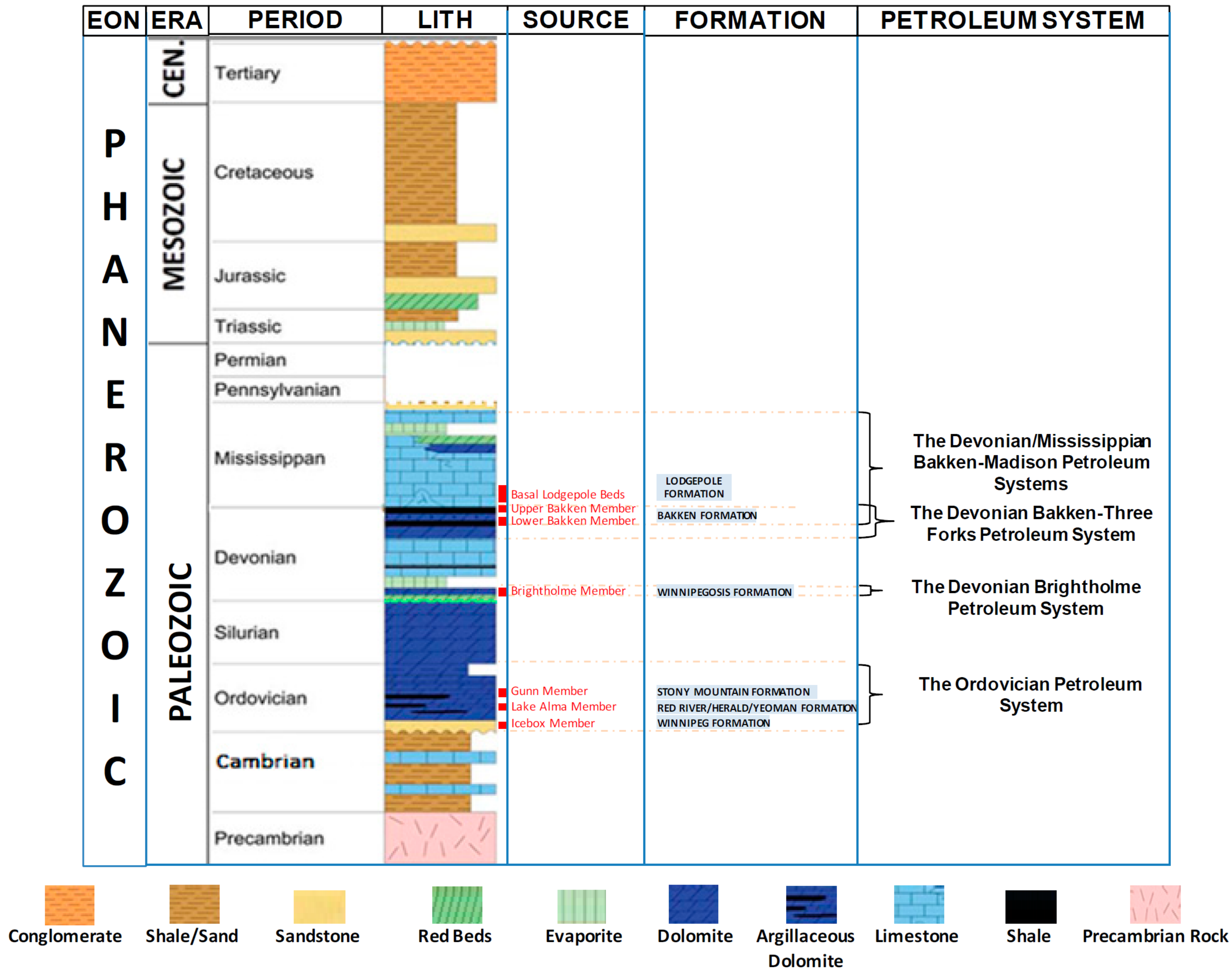

Figure 2. Generalised stratigraphic column showing the stratigraphic range of the Paleozoic petroleum systems within the Saskatchewan portion of the Williston Basin subsurface. Approximate stratigraphic position of source rock units are shown in red rectangular boxes, (modified from Creany et al., 1994; Nordeng, 2013; Osadetz and Snowdon, 1995).

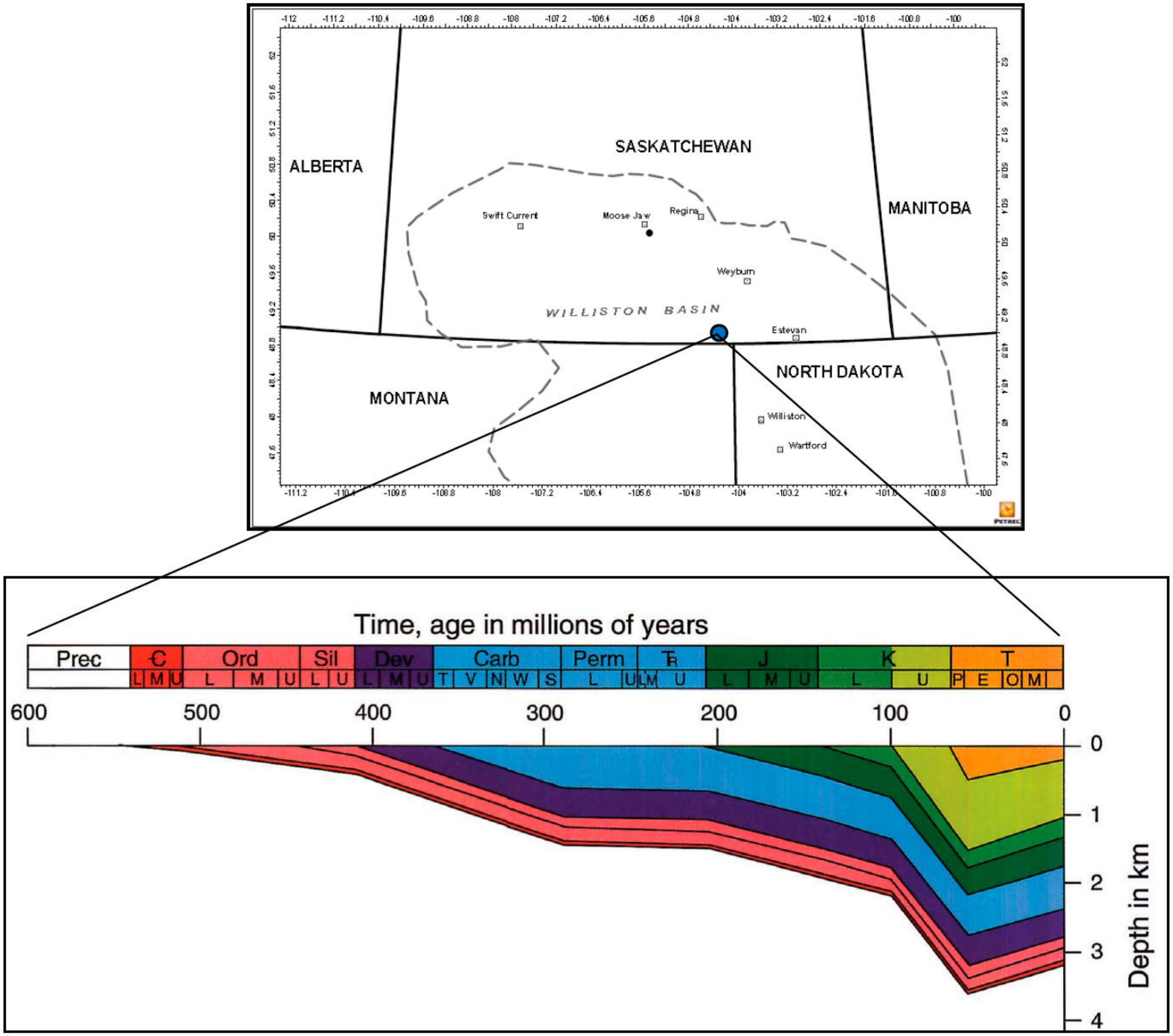

Figure 3. A previously published burial history plot (bottom) at well 08E125 (16-36-001-18W2). The well location is shown on the location map (top) within the simplified outline of the northern Williston Basin (modified from Alberta Geological Survey, 1994).

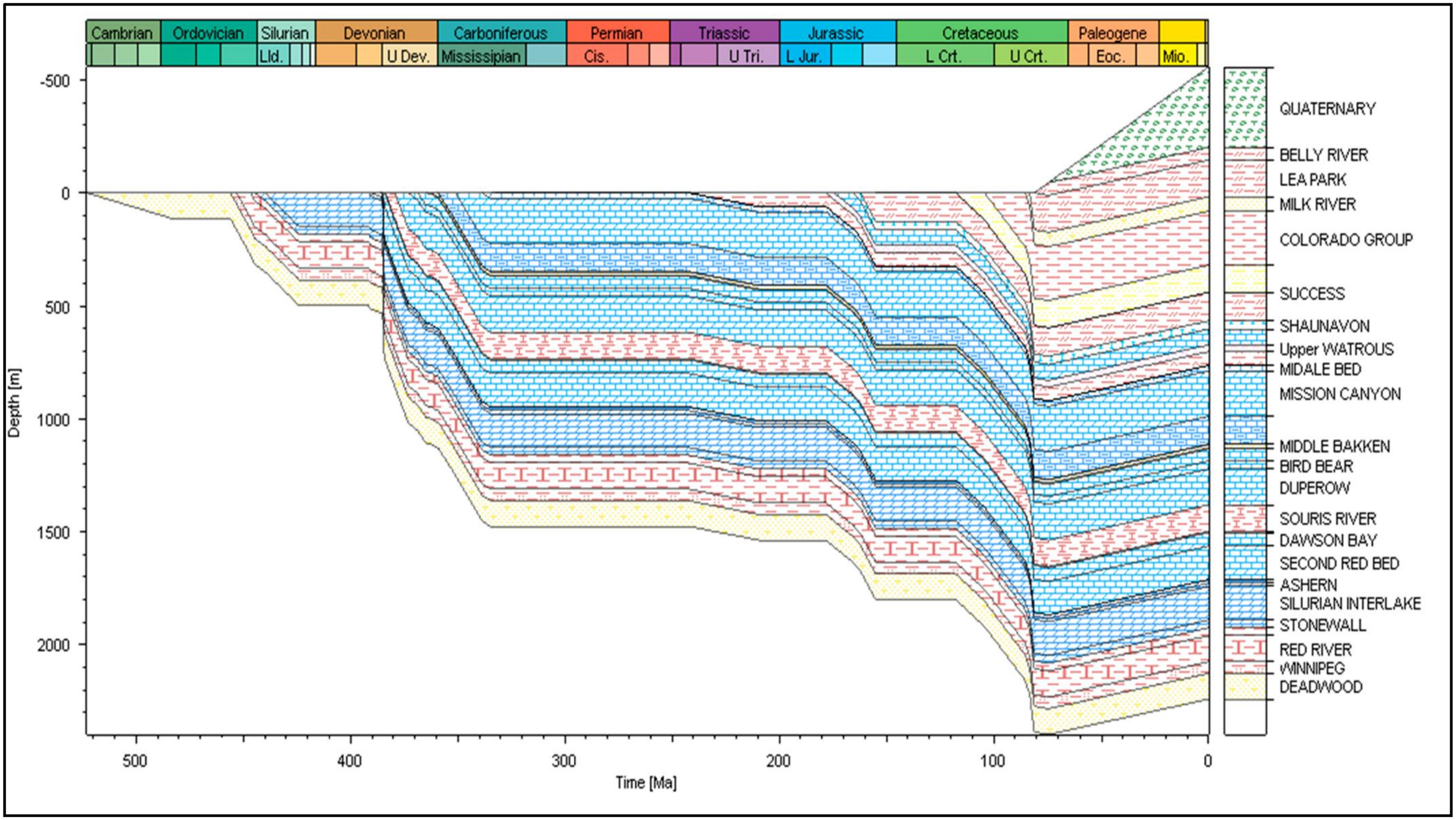

Figure 4. Unrefined burial history plot at well 85A089 (06-09-007-13W2) located along transect (A-A') shown in Figure 1.

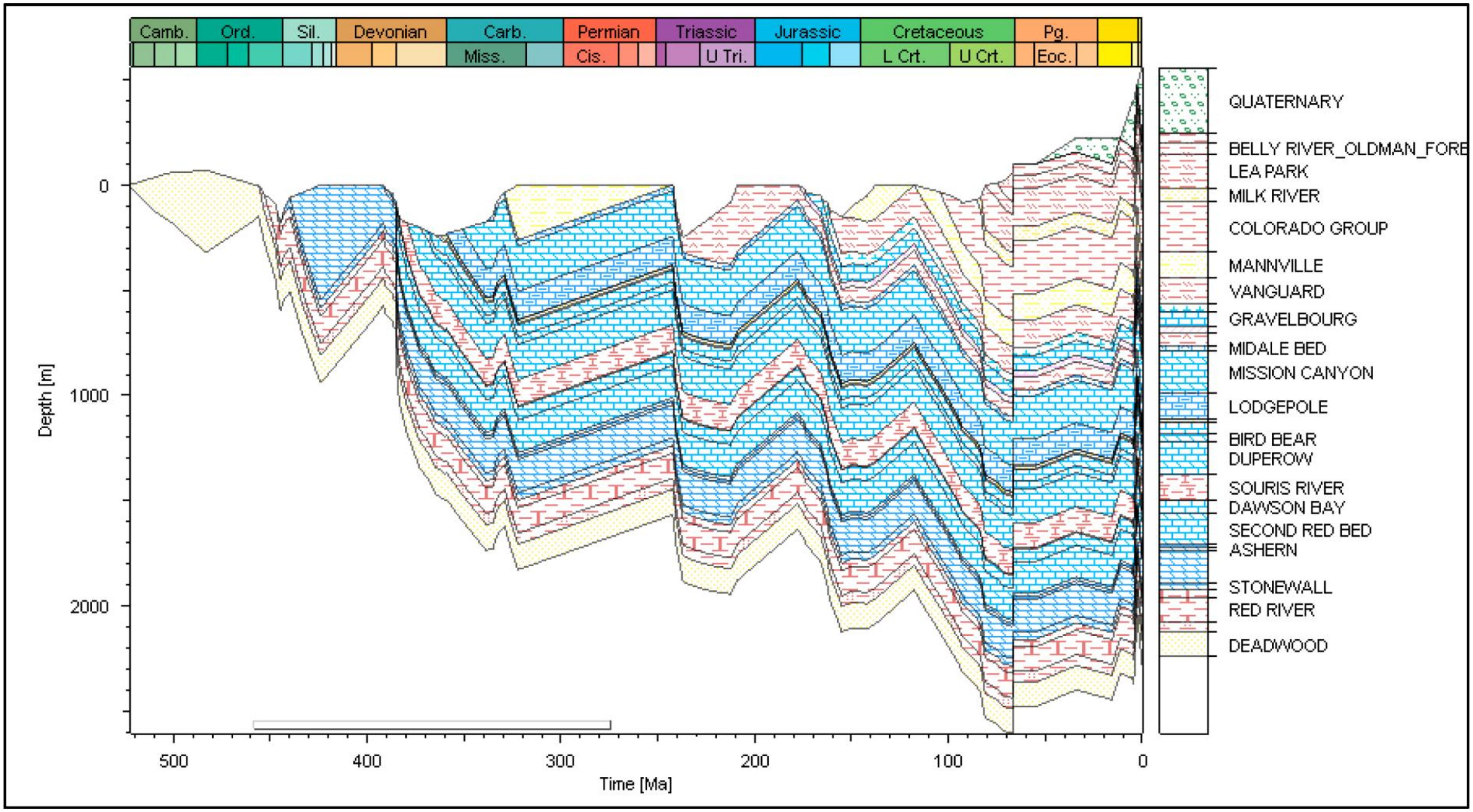

Figure 5. A refined burial history plot at well 85A089 (06-09-007-13W2) located along transect (A-A') shown in Figure 1. Refinement processes incorporate paleobathymetry and erosional episodes.

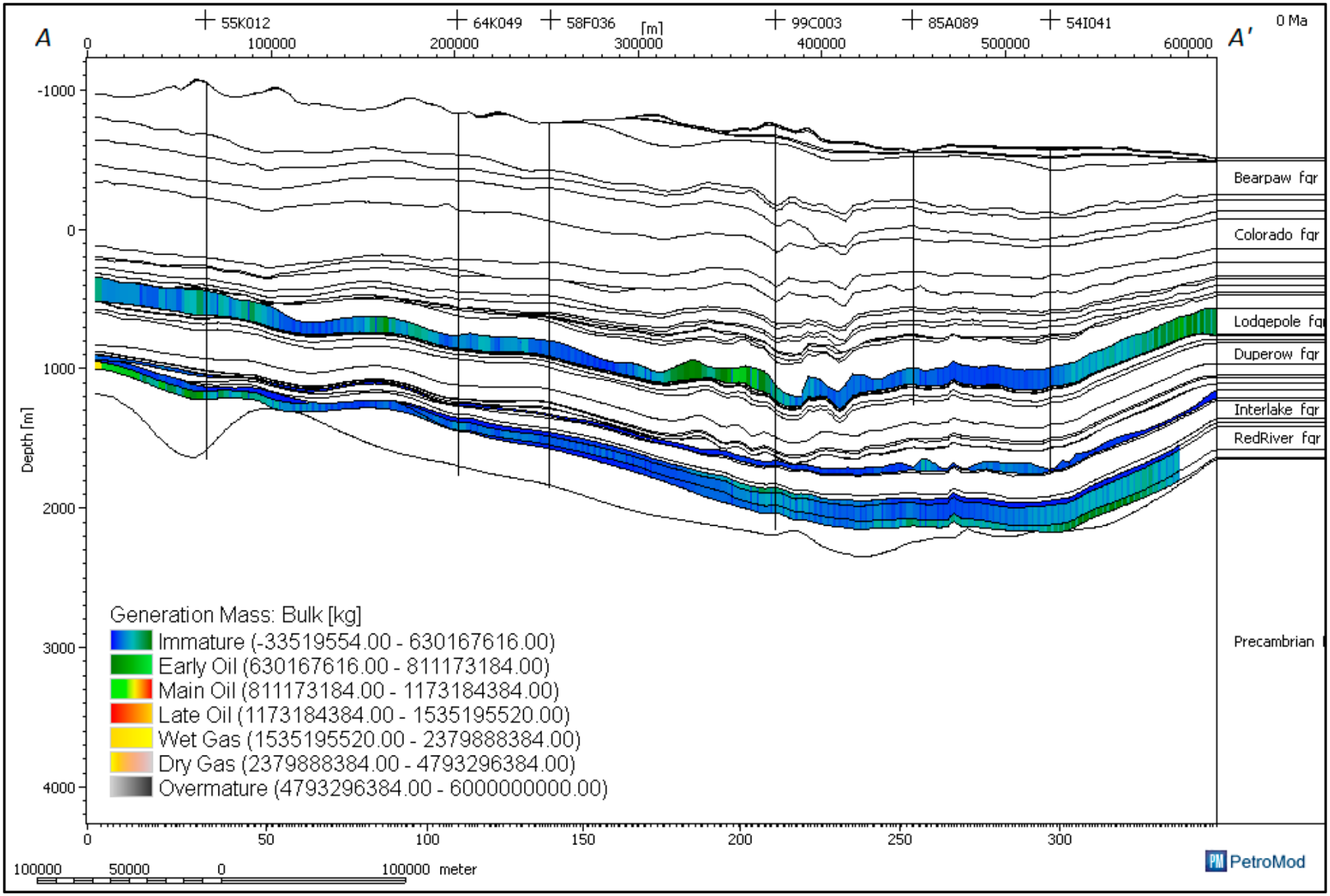

Figure 6. 2D model along transect A-A' showing hydrocarbon generation mass and source rock maturation status.

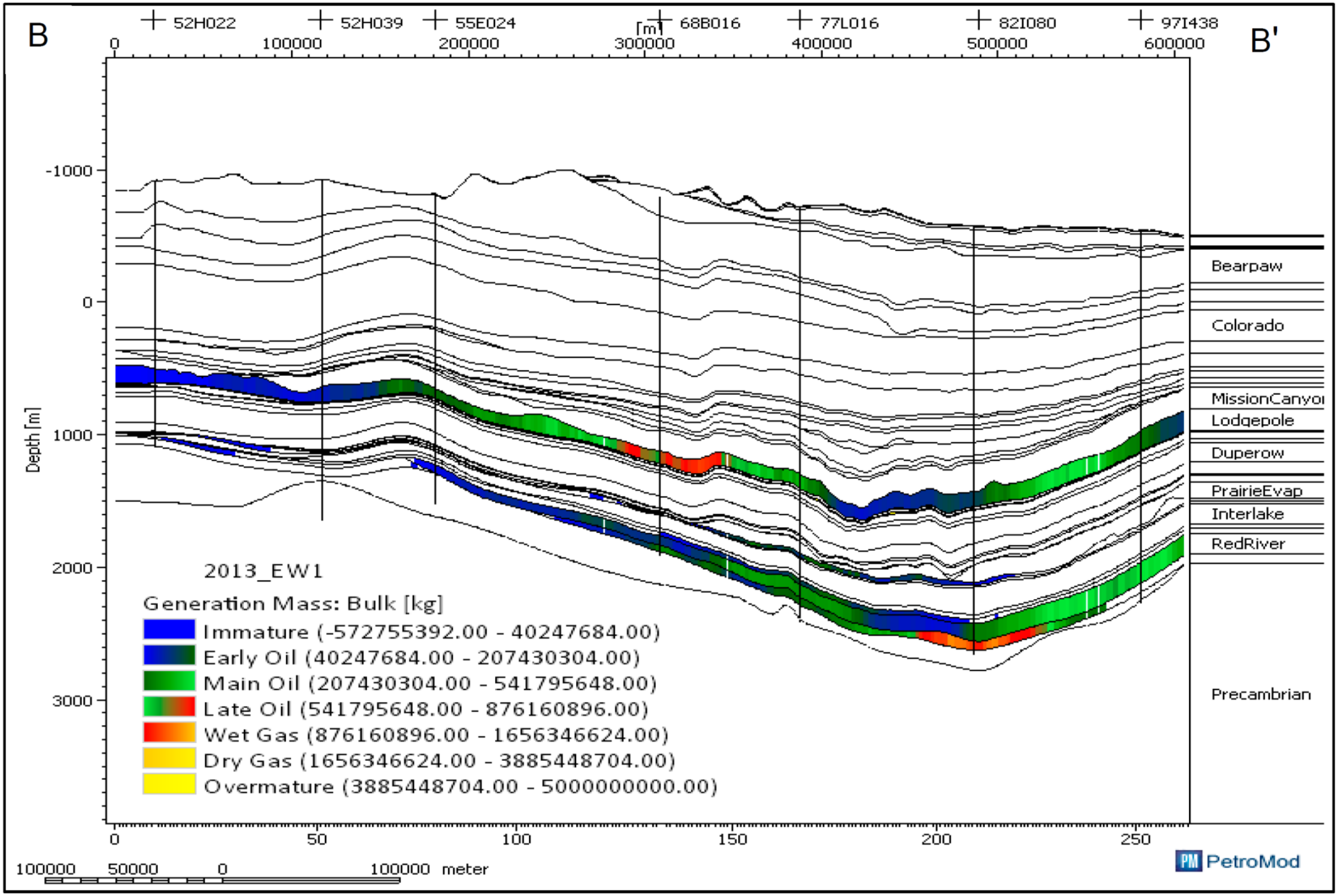

Figure 7. 2D model along transect B-B' showing hydrocarbon generation mass and source rock maturation status.

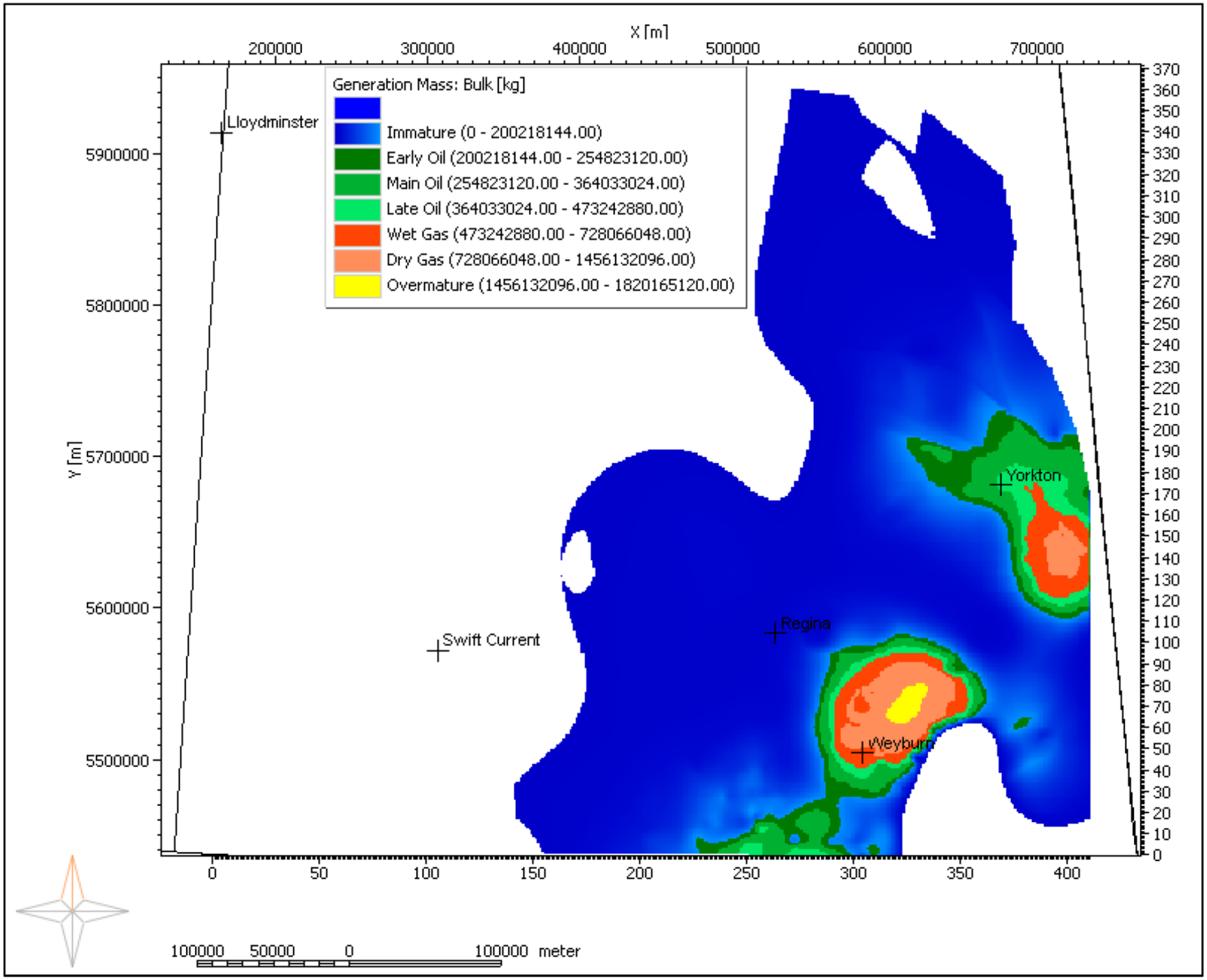

Figure 8. Map of hydrocarbon generation mass and source rock maturation status of the Icebox Member within the Upper Ordovician Winnipeg Formation.

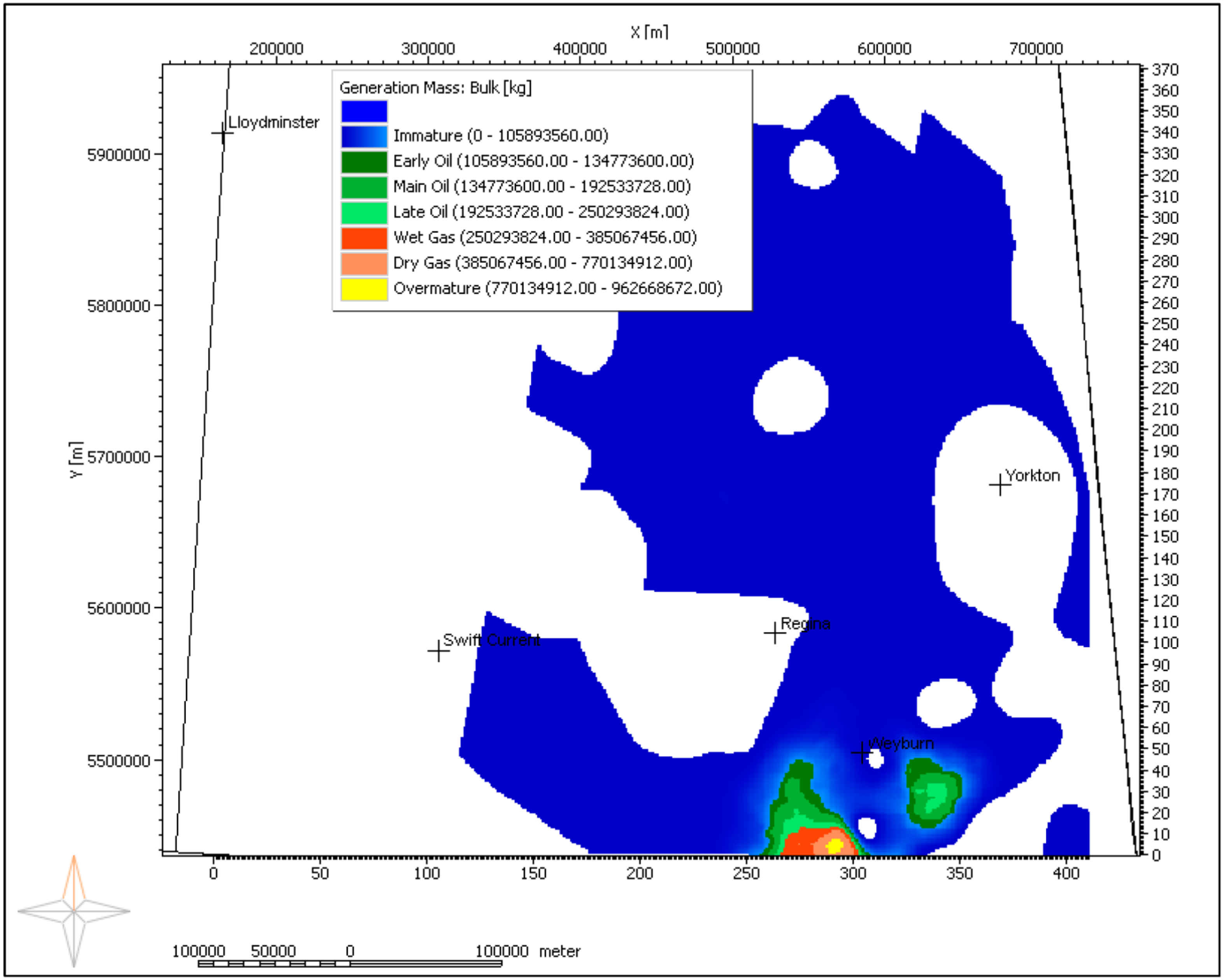

Figure 9. Map of hydrocarbon generation mass and source rock maturation status of the Lake Alma Member within the Upper Ordovician Big Horn Red River/Herald/Yeoman Formation.

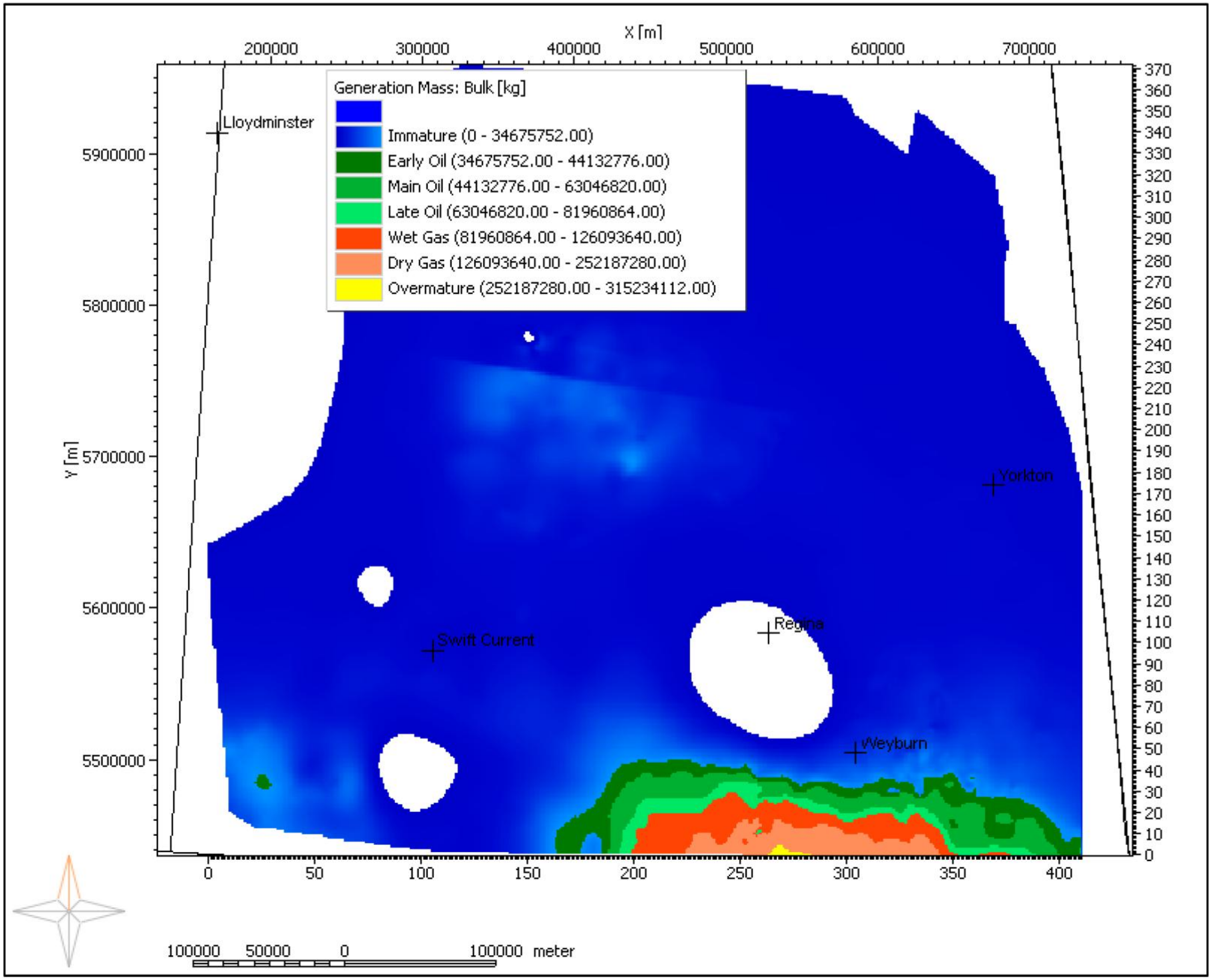

Figure 10. Map of hydrocarbon generation mass and source rock maturation status of the Gunn Member within the Upper Ordovician Big Horn Stony Mountain Formation.

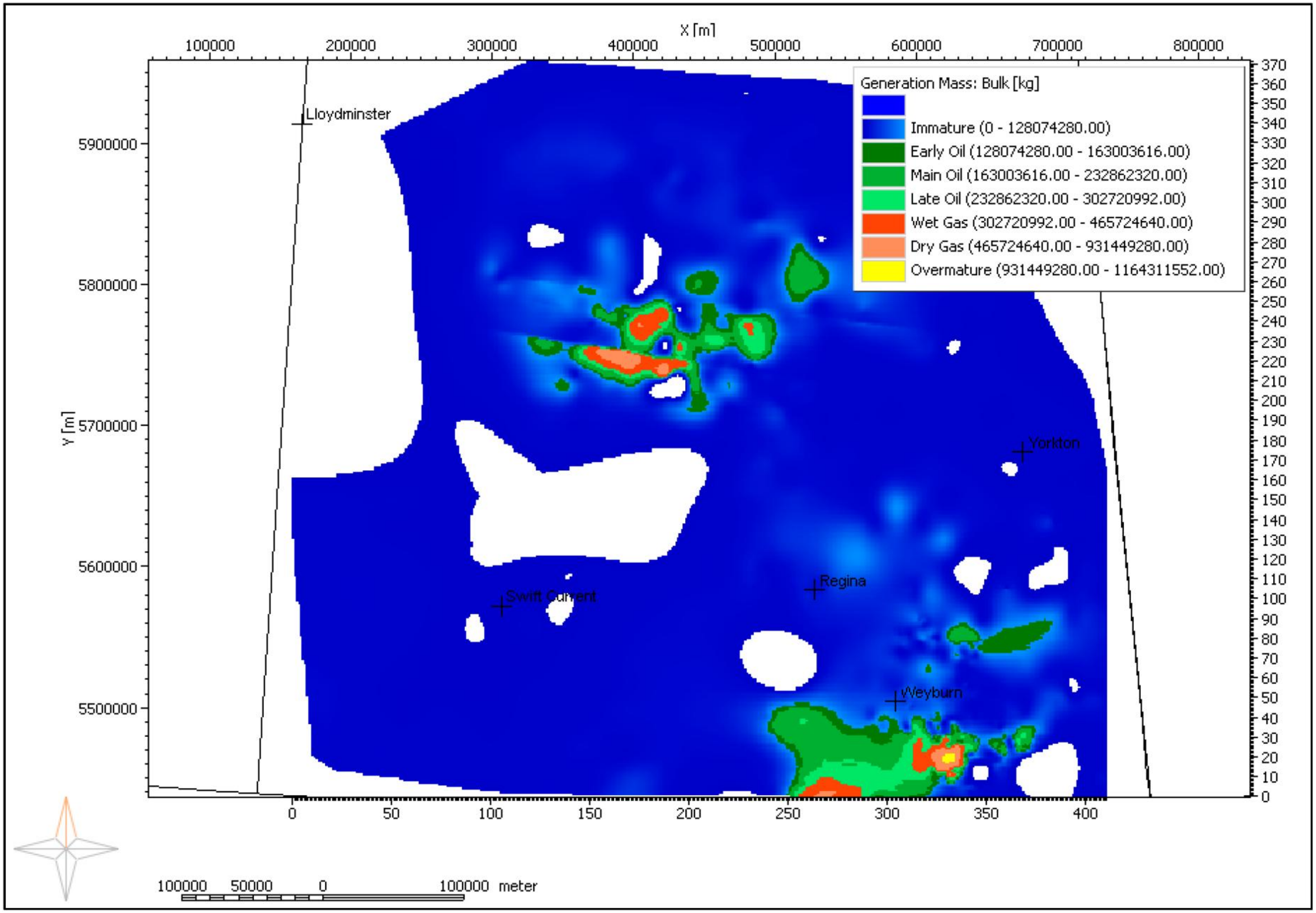

Figure 11. Map of hydrocarbon generation mass and source rock maturation status of the Brightholme Member within the Middle Devonian Elk Point Winnipegosis Formation.

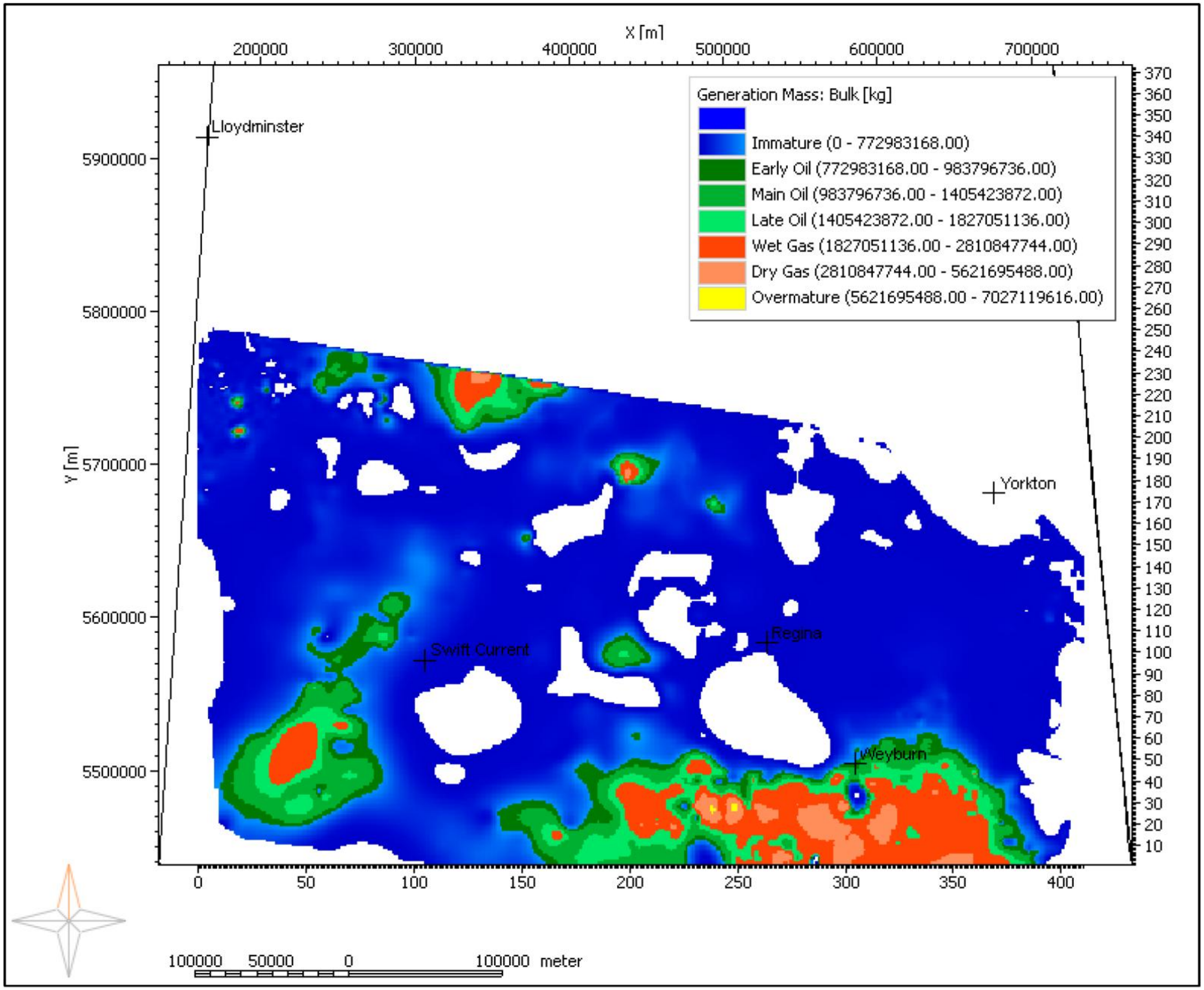

Figure 12. Map of hydrocarbon generation mass and source rock maturation status of the Lower Bakken Member within Upper Devonian Three Forks Bakken Formation.

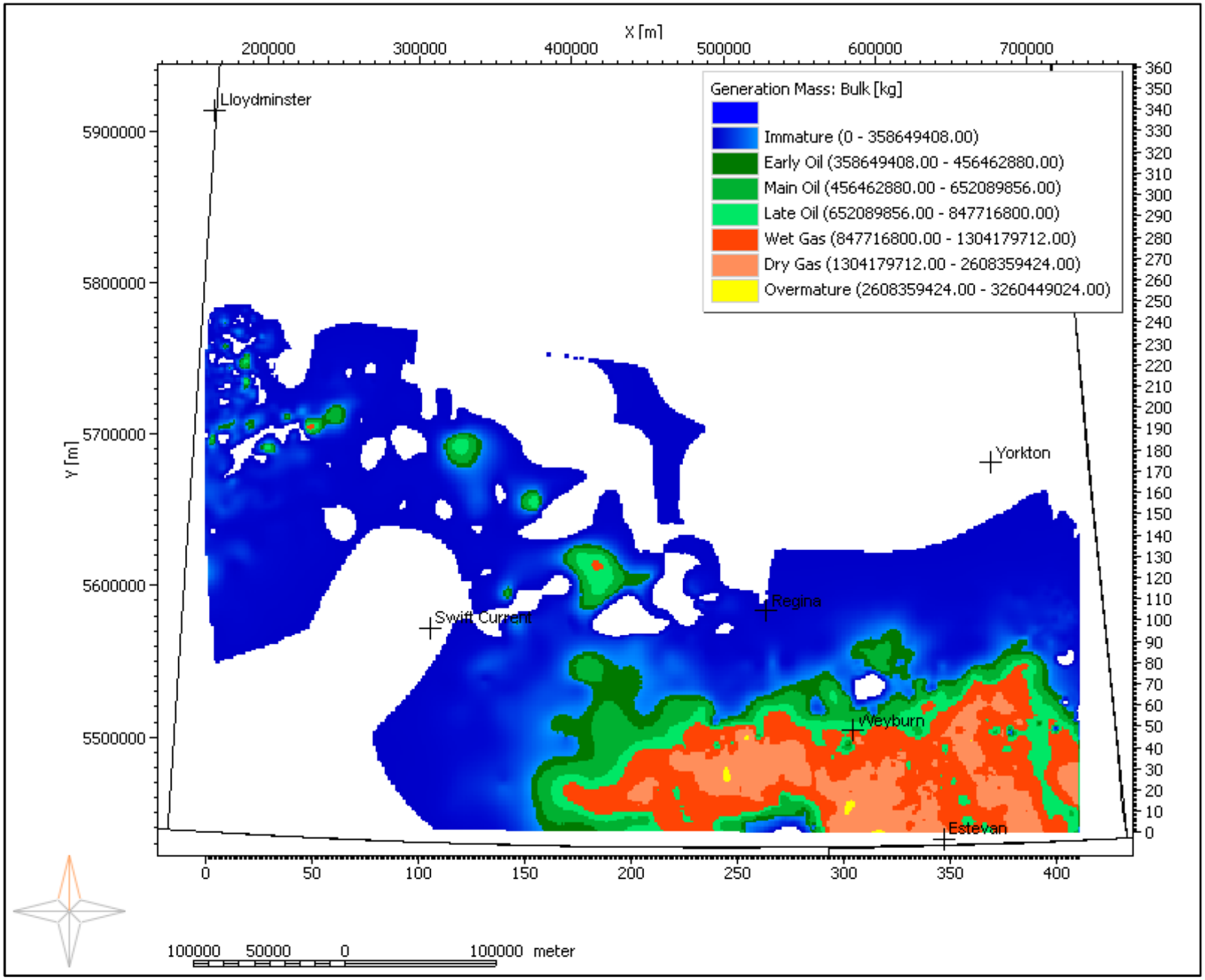

Figure 13. Map of hydrocarbon generation mass and source rock maturation status of the Upper Bakken Member within the Upper Devonian Three Forks Bakken Formation.

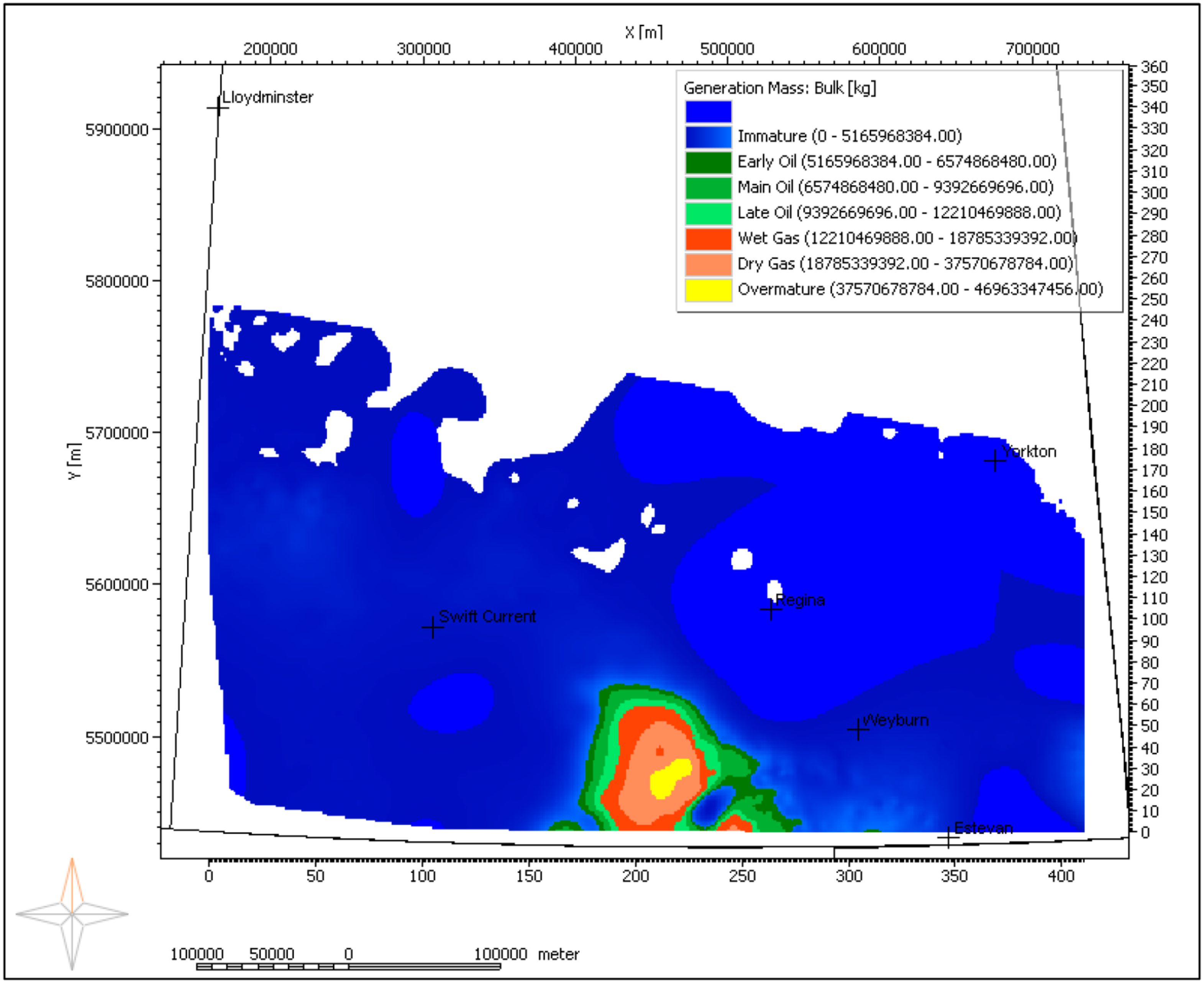

Figure 14. Map of hydrocarbon generation mass and source rock maturation status within the Lodgepole Formation.

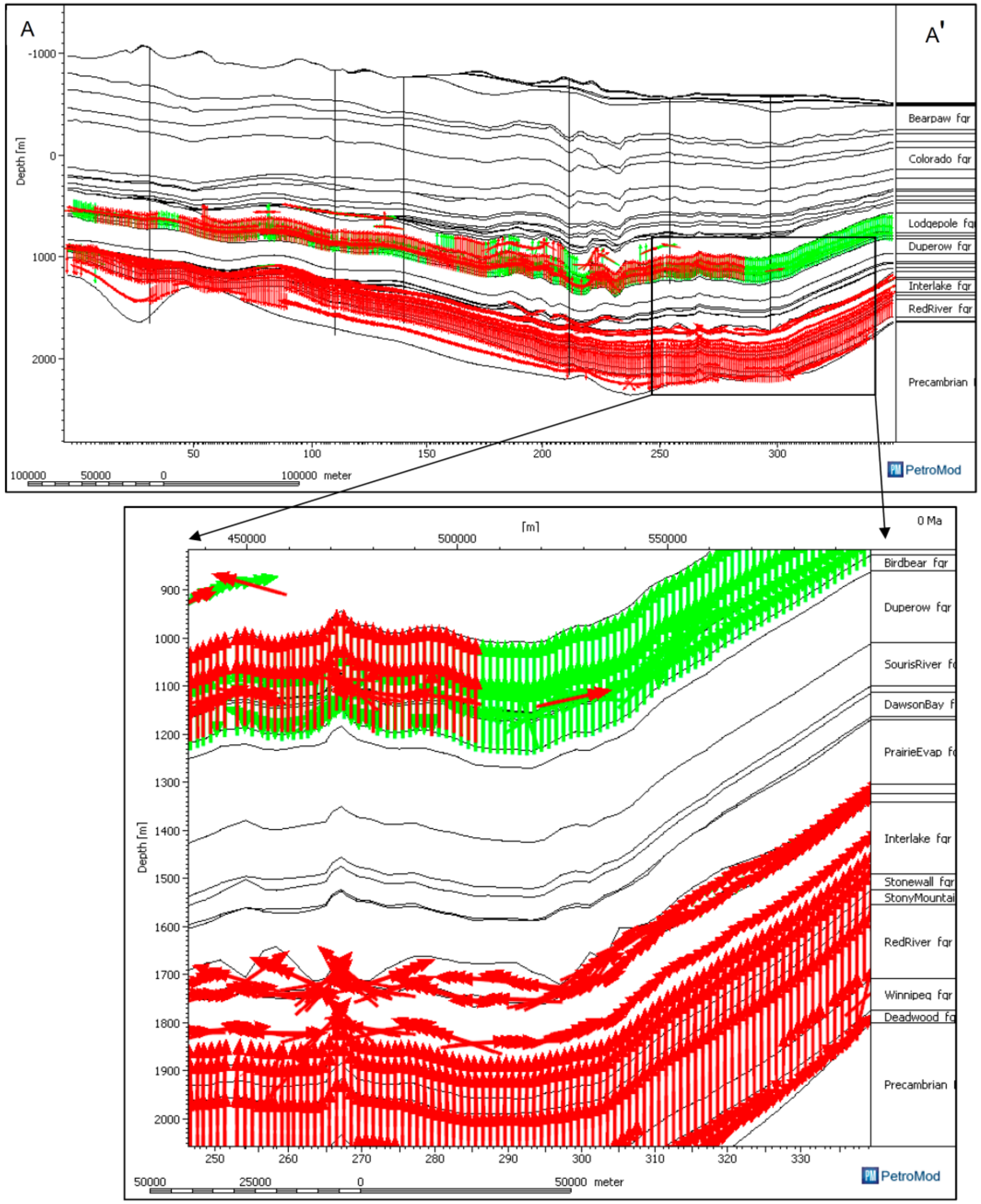

Figure 15. 2D model along transect A-A' showing a combination of lateral and vertical migration of the generated hydrocarbon. Green lines represent oil migration while red lines are condensate/light oil/liquid vapor migration.

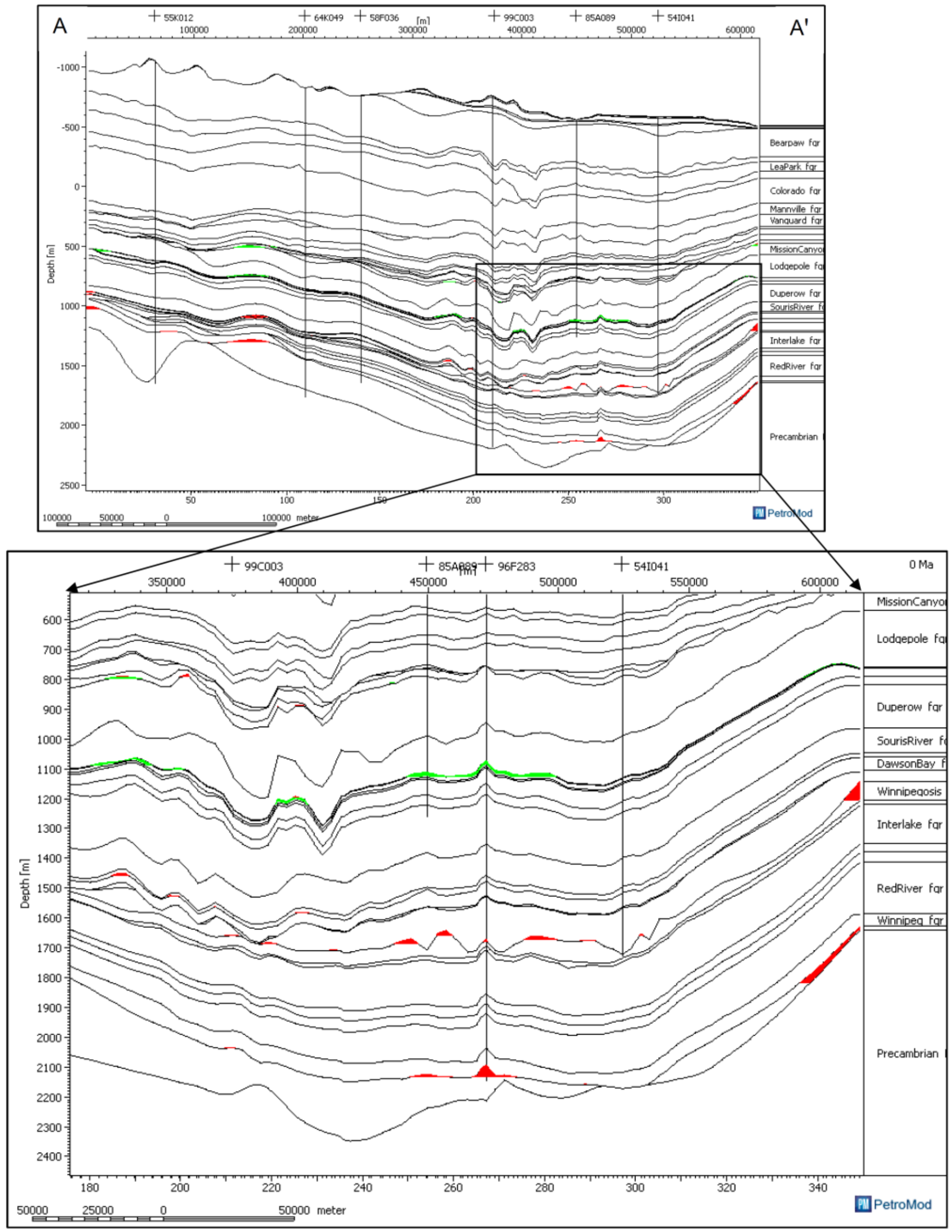

Figure 16. 2D model along transect A-A' showing oil (green) and condensate/light oil/liquid vapor migration (red) accumulation in mostly structural traps. The model replicates existing pools.

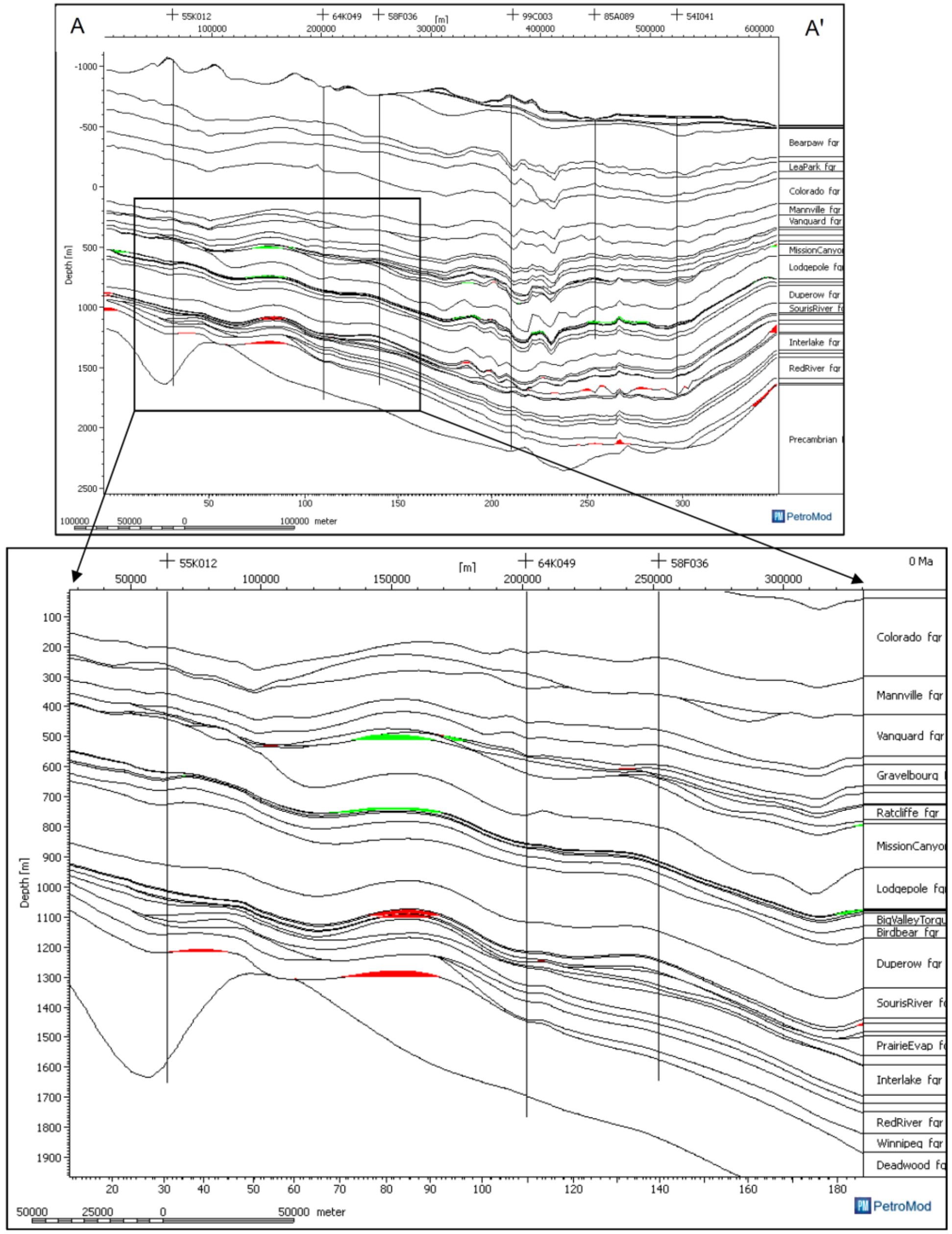

Figure 17. 2D model along transect A-A' showing oil (green) and condensate/light oil/liquid vapor migration (red) accumulation in mostly structural traps. The model shows potential hydrocarbon pools.