Play resource evaluation and geological risk assessment using model-based stochastic simulation as applied to unconventional oil plays in WCSB

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Abstract Unconventional petroleum resources have changed the structure and nature of global petroleum supply dynamics in the oil and gas markets. Unconventional resource plays represent significant augmentation of the existing opportunities to expand petroleum productions across the North America. The newly recognized unconventional resources opportunities in Canada have attracted international investors. Finding petroleum resource opportunities and identifying economically viable "prospects" within the resource plays present new challenges and requires innovative technologies and concepts to maximize their production potential. A model-based resource assessment simulation and risk evaluation has been developed by the Geological Survey of Canada (GSC). This method includes a geological model representing essential petroleum system elements for petroleum accumulations, a resource model describing distribution characteristics of petroleum accumulations, and a simulation procedure integrating available data, relevant information and geoscience constraints to generate scenarios of petroleum resource maps in a play. This approach has been applied to evaluating conventional petroleum potential and assessing geological risk in conventional plays, where subsequent exploration drillings are used to validate the model predictions. In this paper, examples from shale and tight sand light oil plays in the Western Canada Sedimentary Basin (WCSB) are used to illustrate the application of the GSC model-based simulation to unconventional play resource evaluation and risk assessment.

Introduction

The Lower and largely Upper Cretaceous Colorado Group of the Western Canadian Sedimentary Basin (WCSB) consists predominantly of mudstone

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deposited during major marine inundations interspersed with relatively thin sandstone and conglomerate beds deposited during lesser regressive intervals[1]. The Colorado Group petroleum system contains a large portion of the light-medium oil and significant natural gas reserves within the Middle Jurassic to Cretaceous foreland basin succession of the WCSB. It is a supercharged, high efficiency, high impedance petroleum system. Where mature, its source rocks of interspersed marine mudstone generate large volumes of crude oil [1]. Crude oil and natural gas reserves are found in discrete conventional pools of high porosity-permeable sandstone reservoirs as well as in continuous extremely low porosity-permeability "tight" or "shale" reservoirs. Petroleum plays in this foreland succession are typically crude oil and natural gas plays with a mixture of both conventional and unconventional resources. Estimating the resource potential in the unconventional reservoirs, particularly the recoverable portion, is a challenge for both governments and the petroleum industry. These challenges must be adequately addressed to ensure efficient conversion of the unconventional resource potential into recoverable reserves and petroleum supply.

In this paper, examples from tight sand crude oil plays in Cardium Formation in the WCSB are used to illustrate the application of the model-based simulation where both conventional and unconventional plays contribute to a mixed play resource evaluation and risk assessment. The results show that the predictions from the model-based simulation capture successfully the essentials both for geological controls on spatial distribution of petroleum accumulation and the magnitude of the remaining undiscovered unconventional resource which contributes valuable insights for exploration strategic planning and risk reduction for a major tight sand resource play.

Methods and data

The proposed resource evaluation and risk assessment approach has three major components, each of which has a distinct role. These components include:

1. a geological model that constrains the determination of likely undiscovered petroleum accumulation locations;
2. a resource model for characterizing the magnitude and internal correlation of the accumulations; and
3. a stochastic model for performing the spatial correlation and data integration.

The out put of this approach includes a petroleum resource map indicating the geographic location and magnitude of all petroleum accumulations, both discovered and undiscovered and a geological risk map showing the chance of success for all potential resources within the study area. This approach can also be used to analyze and determine the essential geological factors controlling the potential resource distributions.

A geological model provides a quantitative description of geological conditions for petroleum accumulation in the area studied. The geological model could be a map that describes the likelihood of petroleum occurrence, such as a geological favorability map or a probability map of petroleum occurrence, or it could be a set of tables of rules and data, depending on data availability and method applied. The geological model is derived from the combination of geoscience data and our understanding of the essential geological processes and controls on petroleum occurrences. Where data are insufficient, a conceptual model based on geological analogues can also be helpful. Chen and Osadetz [2] proposed a Bayesian multivariate statistical method to construct geological models based on the analysis of petroleum system elements.

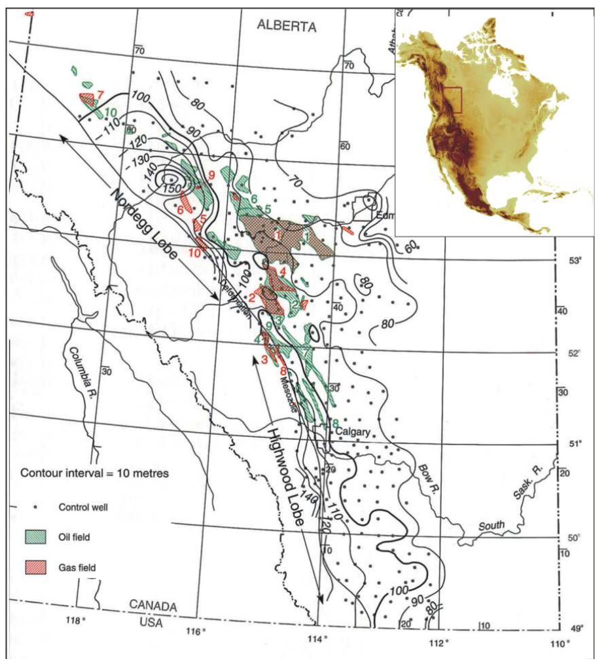

Figure 1 Map showing the location of the study area in the Alberta Basin and major petroleum discoveries in the Cardium Formation. The contours are Cardium Formation thickness in meters (modified from Geological Survey of Alberta, 2006). Index map in upper-right shows the location of Alberta Basin.

A resource model is a quantitative expression of the material (magnitude) and spatial (geometric) characteristics of a resource. The resource model is derived from exploration data, such as discovered petroleum accumulation size, their location and areal extent combined with, petroleum shows and dry in well located outside the identified discoveries. A fractal model is used to represent the size distribution and the geometry of petroleum accumulations [3]. The spatial correlation among the petroleum accumulation is also characterized by the fractal model.

The third part of the proposed approach is a stochastic simulation procedure, which is used to integrate key data with other geoscience information and constraints to produce equally probable total resource scenarios that honor the geological and resource models and other available constraints. A Fourier integral approach is employed to integrate data containing the magnitude and the spatial correlation of petroleum accumulations and other exploration history constraints that indicates the possible location of undiscovered resources [4].

Three types of data are available for this study including production history (date, incremental volume produced) from both conventional vertical wells and horizontal wells completed more recently using multi-stage hydraulic fracturing stimulations. More than 4000 vertical wells and about 600 horizontal wells were analyzed to estimate the ultimate resource (EURs). The second dataset consists of pyrolysis (RockEval/TOC) experiments of more than 4000 Colorado Group rock samples from wells. The organic geochemistry data are used to evaluate the generative potential and volume of petroleum expelled from the source rock intervals into secondary migration pathways, which can supply oil resources to the target reservoir rock bodies. The RockEval/TOC data also constrains both the residual oil volume and matrix porosity/permeability of the source rock stratigraphic intervals. The third dataset comprises of more than 3200 well logs that characterize the physical properties of the target stratigraphic intervals. Petrophysical evaluation of the well logs generates estimates of petroleum pore space. Other data such as regional structure maps, production well locations and reserves of individual petroleum pools from the Geological Atlas of Western Canada Sedimentary Basin [5], Alberta Energy Resource Conservation Board Report [5] and GSC in house database, are used to constrain and improve the model.

Results

The Cretaceous Cardium Formation, predominantly marine shoreline sandstones and conglomerates reservoirs, hosts the largest conventional oil field, the Pembina oil field in WCSB, which was discovered in 1953 and produces primarily from the Cardium Formation. The conventional oil reserves in Cardium reservoirs were primarily developed and exploited using vertical wells between the 1950s to the 1980s. Only about 20% of the original in-place reserve has been recovered using this predominantly vertical well development strategy [6]. Since 2006, many horizontal wells completed with multi-stage hydraulic fracturing programs have been drilled to develop and exploit the relatively low permeability reservoir components, especially along the margins of existing conventional

Cardium oil pools. These low porosity and low permeability reservoirs commonly consist of upward coarsening muddy sandstones and siltstones with porosity typically between 5-12% and with reservoir permeabilities (measured from cores with air) of 0.1-10 mD. Most of the oil pools are in stratigraphic traps. Both the conventional reservoirs and unconventional low permeability reservoirs are enveloped in the mudstone and shale of Colorado Group.

The total in place Cardium Formation oil resource from the simulation model is estimated to be 4.4 $x10^9$ m^3 of which the remaining crude oil is 2.7 $x10^9$ m^3, that is inferred to occur largely in unconventional tight reservoirs. Considering the cost of horizontal wells and current completion practices, a threshold of 40,000 barrels recoverable oil per well is set as a current lower economic limit. The simulated estimate of recoverable oil resources exceeding this cut-off ranges from 0.031 $x10^9$ m^3 (0.29 billion barrels) to 0.079 $x10^9$ m^3 (0.73 billion barrels) with a mean of 0.061 $x10^9$ m^3 (0.57 $x10^9$ barrels), where a correlation coefficient between the resource density and recovery factor of 0.6 is applied.

The remaining resource potential is also estimated from the well performance data set. All horizontal wells with production data records exceeding 10 months and less than 60 months, where we assume that multi-stage hydraulic fracturing stimulation is employed, are modeled using the Valko model [7] to estimate the ultimate recoverable reserves. Assuming four such horizontal wells are drilled in a section (1 mi^2 areas or 2.856 km^2), the well-based resource density can be converted to an area-based resource density. The distribution of areas containing the unconventional resource can then be derived from the conditional probability map of the geological model that characterizes the likelihood of Cardium Formation oil occurrence. The product of the reserve density distribution and the unconventional oil resource area distribution then gives a Cardium Formation oil resource potential distribution with a mean of 0.736 $x10^9$ and a median of $0.546x10^9$ barrels of recoverable oil. The result of the resource density distribution method is consistent with that estimated using geological model-based simulation resource potential analysis.

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