Insights into Migration Efficiency Based on Stochastic Mass Balance Calculations and Full-physics Forward Basin Modeling

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ABSTRACT

The quantification of losses associated with petroleum migration is a crucial parameter required to accurately predict trapped hydrocarbon volumes. However, the accurate assessment of the efficiency of migration and evaluation of its controls remains a challenge. This makes migration efficiency one of the least understood components of hydrocarbon charge, and consequently increases the uncertainty in pre-drill predictions of exploration risk.

Direct evidence of migrating hydrocarbons in the subsurface (velocities and rates) as well as the petrophysical properties and spatial extent (length and height) of secondary migration pathways are very rare and do not represent the evolution of the migrating fluids and flow paths during the complete history of migration. Numerical simulation concepts derived from producing fields have been adopted to quantify secondary migration on geologic time scales and regional spatial distances. However, the high levels of hydrocarbon saturation and large hydrocarbon columns encountered in producing fields are unlikely to be representative of the pathways used by secondary migration (Dembicki & Anderson, 1989). Furthermore, full-physics forward modeling tools require a detailed and complete petrophysical description of the geologic system that participates in secondary migration.

Stochastic mass balance approaches using analog data (Katz & Kahle, 1988) offer methods to quantify migration losses by effectively bypassing the intrinsic uncertainties associated with describing migration pathways and simulating the process of migration through geologic time. Lewan et al. (2002) have applied a material-balance approach on a basin scale but have also acknowledged the difficulties this approach faces regarding unequivocally attributing hydrocarbon losses to different processes and geologic factors, such as leakage and erosion. As such, the mass balance approach can be regarded as being applicable to petroleum systems with simple migration routes and filling histories (Muscio et al., 2013). This approach, however, appears to be inadequate when applied to field-scale migration systems with more complex migration routes and histories, warranting a full-physics, forward modeling approach (Yurchenko & Muscio, 2015).

The objective of the present study is to quantify migration losses based on two different approaches (stochastic mass balance and full-physics forward modeling) and improve our understanding of the key geologic factors that control the loss of hydrocarbons during migration. Migration losses were assessed for multiple field-scale petroleum systems from a variety of tectonic and structural regimes, depositional environments, source rock character and geologic ages. Selected petroleum systems include examples with the following characteristics,

according to the classification by Demaison & Huizinga (1991): Supercharged, laterally- versus vertically-drained petroleum systems, and low to high impedance. Source rock quality, maturity and effective thickness are well-documented through direct evidence enabling an improved definition of initial (prior to generation) source rock properties. Furthermore, the subsurface stratigraphy and geological framework is well-established in order to allow for representative fetch area calculations, a well-constrained geologic input model, and calibration of simulation results.

The stochastic mass balance approach used here (Muscio et al., 2013) employed a Monte Carlo engine to calculate distributions of hydrocarbon volumes available for trapping based on source rock character, maturity, fetch area size, and subsurface conditions. Migration losses using this method were defined as the difference between expelled volumes and in-place discovered volumes. Geologically-constrained sensitivity experiments were conducted based on key input parameters such as fetch area, source rock effective thickness and generation kinetics, in order to evaluate which parameter has the greatest impact on migration loss variation.

For the second method, a multi-step workflow was developed in order to define the boundaries of a self-contained, local petroleum system that was then submitted to a full-physics forward modeling simulation (Yurchenko & Muscio, 2015). The simulation results yielded a complete inventory of hydrocarbons generated, expelled, accumulated and lost, both spatially and through geologic time.

Preliminary results derived from the mass balance approach indicate that migration losses can vary from $P_{50}<10\%$ to $P_{50}>80\%$. The results suggest that migration efficiencies can be highly variable even within the same basin, implying that there is a strong local control on migration losses. Petroleum systems dominated by lateral migration and longer migration distances, hence implying more potential for migration loss, show efficiencies ranging from low to high. Therefore, the proximity to an active hydrocarbon kitchen and implied shorter migration pathways does not seem to favor lower migration losses. When applied to individual traps in a petroleum system with a fill-spill chain, this method can also overestimate losses and the derived values more closely represent trapped volumes at that location.

Based on preliminary results from full-physics basin modeling, both geologic time and the evolution of the migration pathway have a strong control on the volumes of hydrocarbons that either remain in the carrier system or are lost due to leakage through the sedimentary section over- and underlying the carrier system. While the evolution of volumes of generated and expelled petroleum is mostly driven by burial and thermal history, the history of migration losses due to seepage (outflow at the top of the sedimentary column) appears to follow a different pattern. Moreover, the balance between outflow and inflow of hydrocarbons for non-carrier components of the petroleum system varies through time and appears to be dependent on the stratigraphic proximity to the source rock.

Migration losses for local, field scale petroleum systems can be greater or smaller than basin-wide assessments of migration efficiencies. Field-scale losses that are significantly lower than basin-scale losses could indicate upside exploration potential for remaining, yet-to-find hydrocarbon volumes.