Oil Migration and Dynamic Traps in Chalk, Danish North Sea*

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Abstract

The pace of lateral oil migration in chalk is less than that of continental drift and. like plate tectonics. Oil migration is still happening, making the present day situation only a snapshot in time. However, over geological time, the oil can move significant distances and the fact that the majority of discoveries in the Danish Sector of the North Sea has been made in four-way closures, indicate that a substantial part of the oil has managed to migrate to these structural highs. The discovery of the Halfdan Field/Dan West Flank in 1998 proved that at least some oil is in non-structurally or dynamically trapped accumulations. The question is whether there may be more of these accumulations and to go even a step further, accumulations where there is no or only little oil in the structure up-dip, i.e. a fully “on-the-move” oil system. In combination with recent charge, the chances of encountering such a dynamically trapped oil accumulation may increase significantly

Introduction

Several papers have addressed the various aspects of oil migration and tilting oil-water contacts in chalk. The current analysis focuses on quantifying “on-the-move” oil accumulations and in particular those that may have originated from recent local charge. Recent charge from a local origin is supported by under-filled structures in the Southern part of the Danish Sector and geochemistry indicating that the oil in these fields is less biodegraded than the oil from more Northern fields. The Jurassic source rock in the area has only reached maturity in the last couple of million years and may generate up to 1000 rb/year based on basin modelling. Such high charge rates are considered feasible if compared to the filling history of the Northern fields in the Danish sector. If these fields were to be filled within a reasonable time frame, the charge rates must have been in the range of 100-1,000 rb/y. With little known about the vertical migration from the source rock to the chalk layers, the oil is assumed to enter the base chalk at certain leak points at a specified rate. The leak points can either be faults or fractures, but also areas where the Lower Cretaceous is thin or absent. Depending on the actual location of the leak point and timing of the charge, some of the charge may still be located in synclines or just started to migrate laterally towards structural highs (Figure 1). The lateral migration occurs in the Tor formation as the overlying Ekofisk has much lower permeabilities and the height of the oil column in the Tor is usually not sufficient to overcome the capillary entry pressure of the Ekofisk formation. In circumstances where a sufficient column in the Tor can accumulate, the Ekofisk starts to fill from below in the crest, which in itself can take several million years to complete.

Discussion

The challenge is then to predict the whereabouts and quantify the size of the moving oil accumulation because of lateral migration. The transport direction and migration speed of the oil are governed by the regional aquifer flow and top chalk topography, which can both change over geological time. Numerical simulation has been used to assess the oil saturation, lateral extent and location of the accumulation as apart from geometry and rock properties, capillary entry pressures and relative permeability need to be taken into account. A simulation example is shown in Figure 2, where the migrating oil accumulation is depicted on a flank after 1 million years. The accumulation contains some 0.5 billion barrels and the oil has still not yet reached the top of the structure which is known to be wet. The time window in this case is relatively short because of the buoyancy force associated with the 2-degree dip angle of the flank and can be longer in flatter areas. Without physical barriers or closures, oil saturations and columns in a dynamic trap for this geometry are expected to reach some 60% and 20 oil feet respectively (Figure 3) depending on the charge rate, which has a significant impact. The lateral extent is in line with the dimensions of migration corridors, which must have been kilometers wide and up to some 100 ft thick. Given that the oil saturation is known, e.g. from simulation, the migration speed can be adequately captured with an analytical expression that is in excellent agreement with the simulation results. Figure 4 shows the migration speed as a function of either formation dip or aquifer gradient for increasing oil saturations for a typical oil and chalk permeability in the Danish Sector. The figure shows that the buoyancy force associated with 1-degree dip is of similar magnitude as the viscous force corresponding to an aquifer gradient of 8 psi/km. With the top chalk dipping on average by 0.5 to 1 degrees towards the southeast and an aquifer gradient of approximately 8 psi/km in the same direction, the two forces enhance each other on a regional scale, but could cancel each other out on a local scale and as such the aquifer gradient can even bring closure to a structure that would otherwise be open to the North West.

Numerical simulation of oil migration has proved to be straightforward albeit with much larger time steps than used in ‘normal’ simulations. Some care needs to be exercised when choosing the simulation layering to minimize the effects from numerical dispersion. Without capillary pressures (segregated flow), maximum layer thickness would only be 1 ft, but with capillary pressures this can be relaxed to 5 ft for charge rates as low as 100 rb/y. Oil migration is a drainage process and the shape of the relative permeability curve for primary drainage in chalk is apparently still subject for debate. Based on experimental data, a curve with a Corey exponent of two seems appropriate and has been used. However, alternative curves equivalent to much lower Corey exponents have been suggested on theoretical grounds in literature and these would have far-reaching impact on the migration speed and corridor geometry, with the lower Corey exponents all but eliminating the chances of encountering an ‘on-the-move’ oil accumulation.

Conclusion

The work described above led to the maturation of at least one opportunity that is planned to be drilled during 2013 and a number of leads, which are still being evaluated. The forward plan is to improve the understanding of oil expulsion, vertical migration, aquifer flow, residual oil saturations in migration pathways and drainage relative permeabilities to construct a regional oil migration atlas. This atlas will also form the basis for a better understanding of the filling history and hydrocarbon fluid distribution in the existing fields.

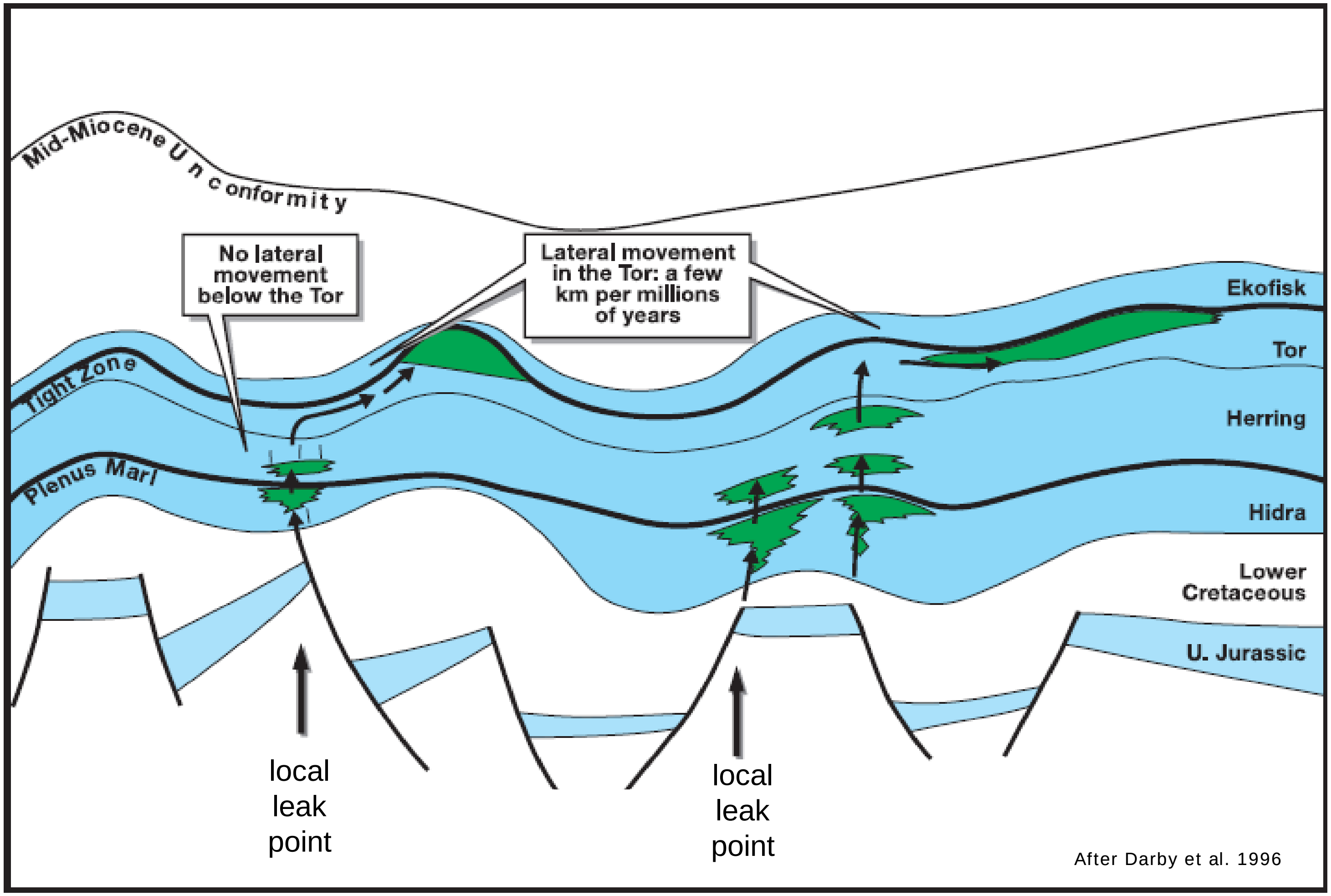

Figure 1. Oil migration from local leak point to (dynamic) trap. Lateral migration occurs in the Tor formation.

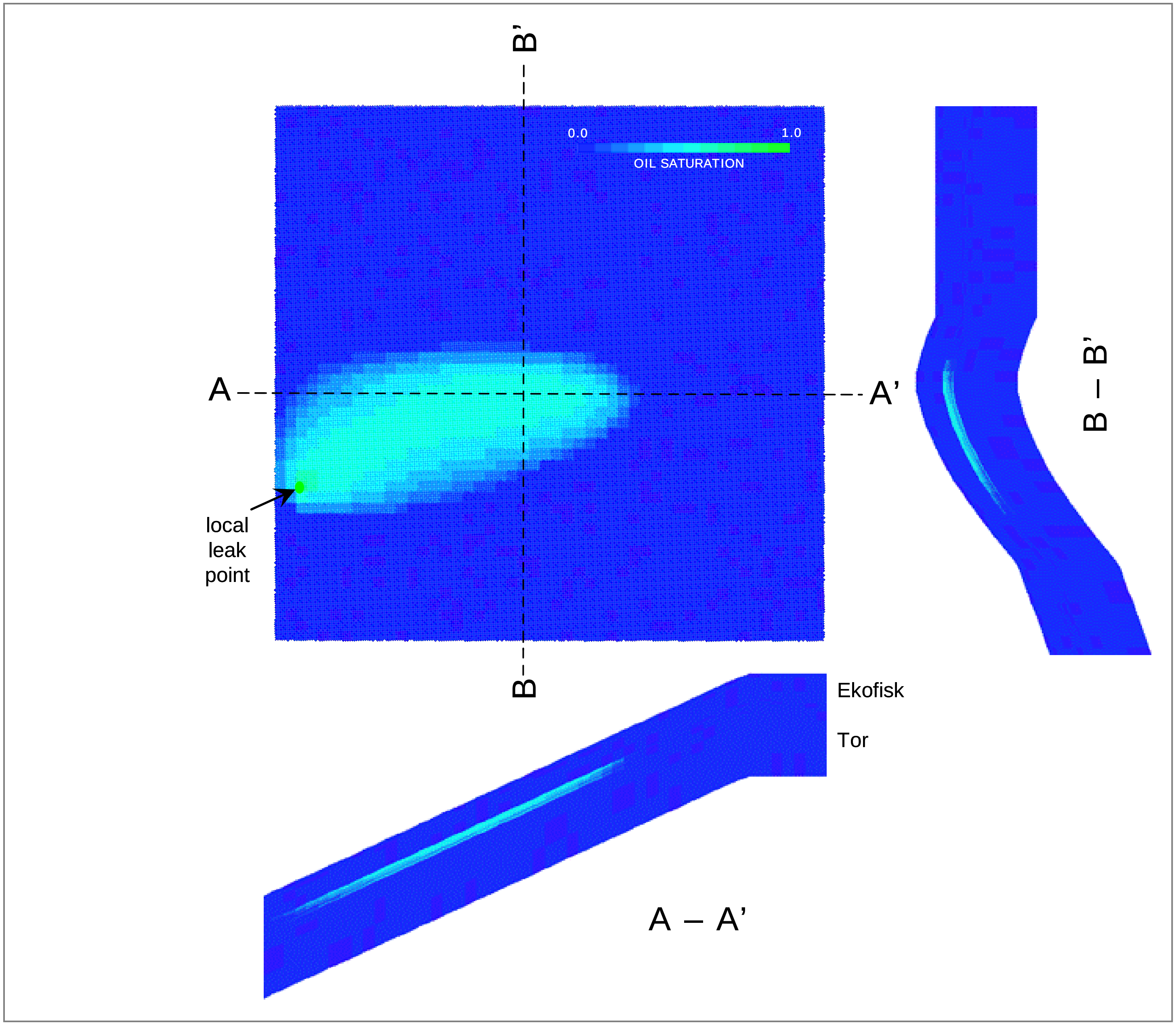

Figure 2. Simulated 'on-the-move' oil accumulation in the Tor formation resulting from local charge after 1 million years.

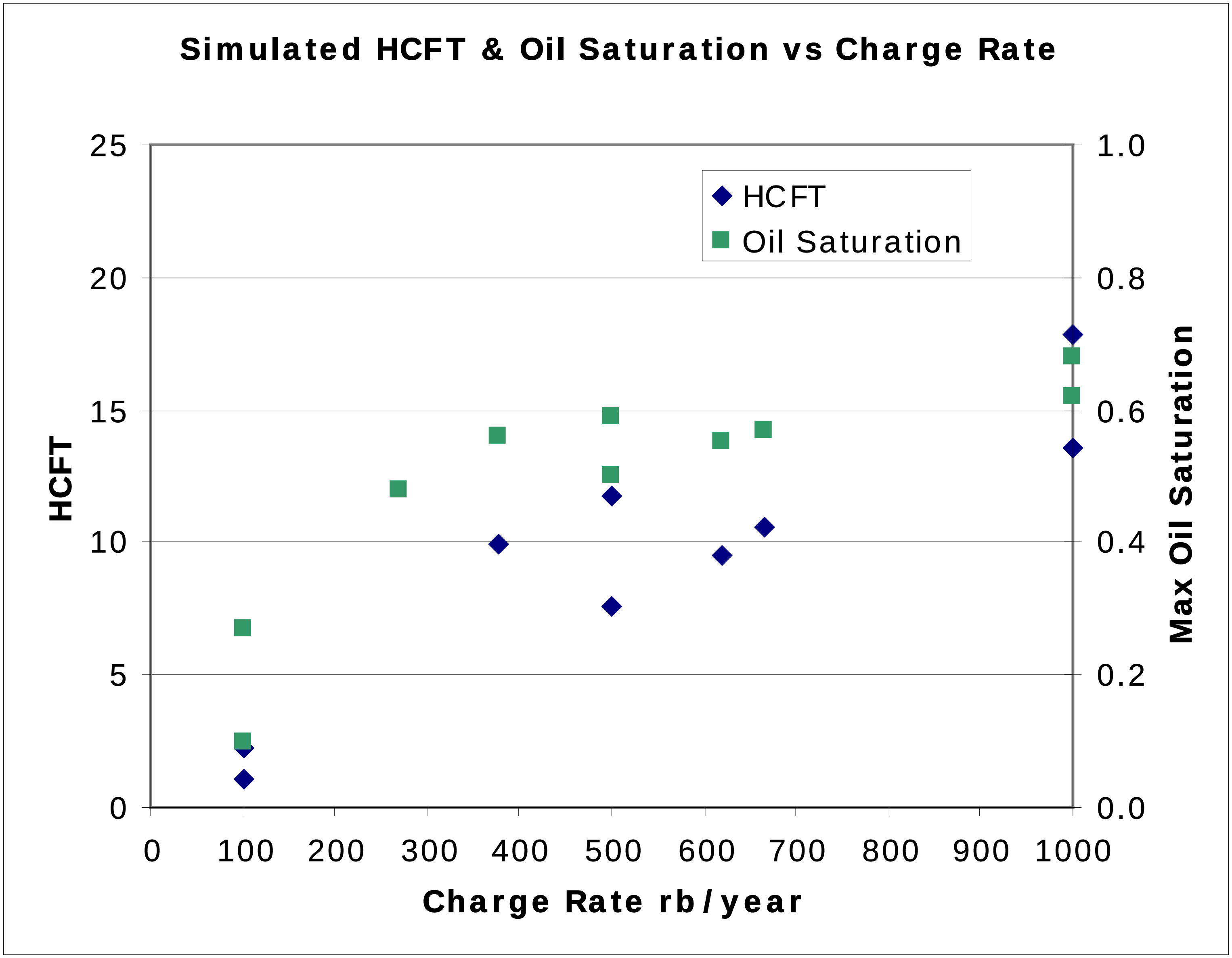

Figure 3. Simulated oil saturation and oil feet of an ‘on-the-move’ oil accumulation for a range of charge.

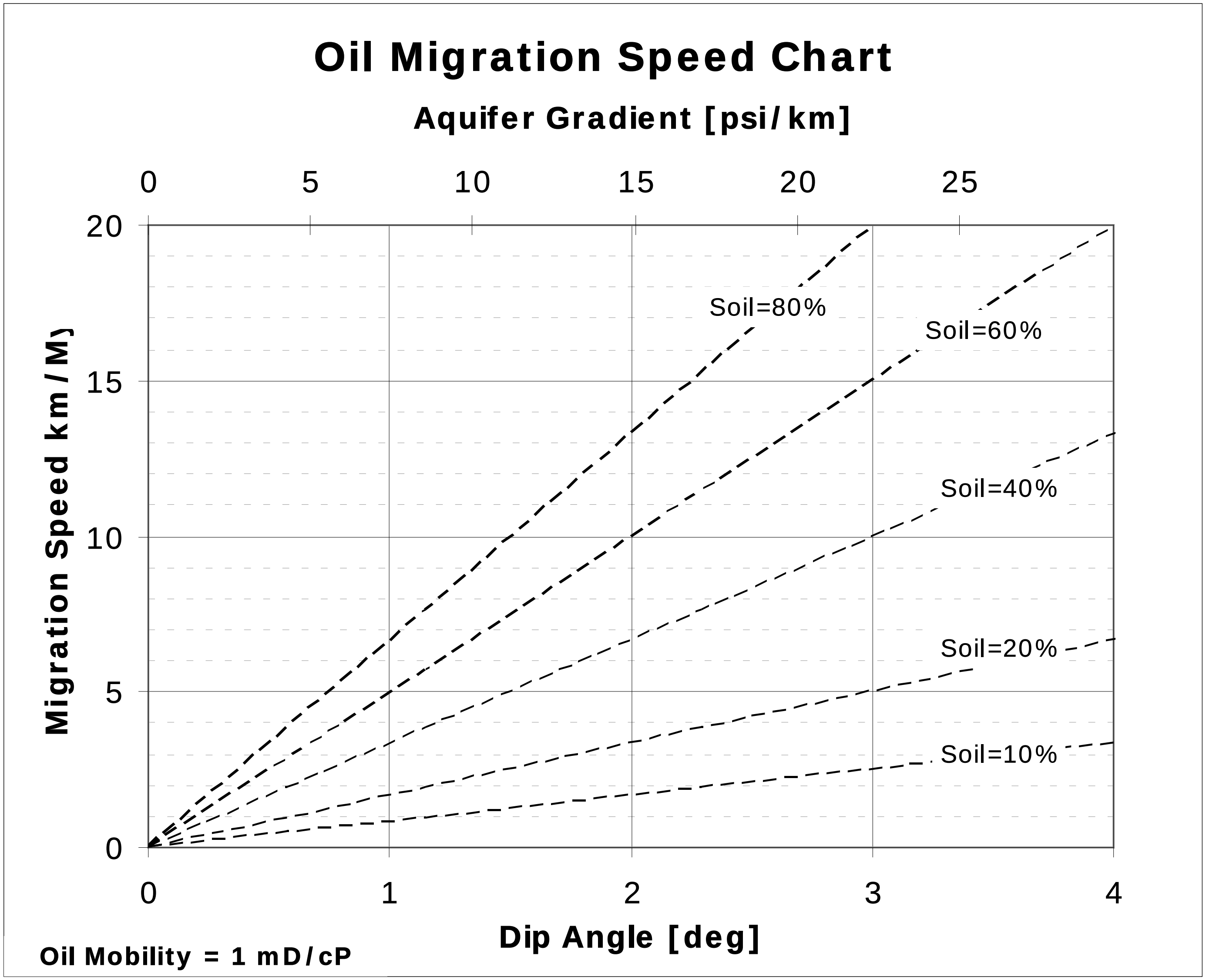

Figure 4. Oil migration speed resulting from buoyancy and/or aquifer flow for increasing oil saturations.