NUMERICAL SIMULATION OF OIL/OILY-CONTAMINANT MIGRATION AND ENTRAPMENT IN A LENTICULAR RESERVOIR

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ABSTRACT. Numerical simulations show that water and oil/oily-contaminant migration are controlled by regional fluid-potential fields which may be modified locally by highly permeable lenses and buoyancy. In addition, fluid potentials are coupled to the distribution of oil/oily-contaminant via relative permeability and capillary-pressure curves. As saturation distributions evolve through space and time, so do the water and oil fluid-potential surfaces.

The importance of capillary forces in oil contaminant migration and entrapment is illustrated by the fact that, in certain cases, lenses fill from above, even when the migrating fluid is lighter than water. Capillary forces operating in conjunction with lenticular reservoirs create excellent dynamic oil traps by allowing free passage of water, while retaining and concentrating oil.

The analysis of oil (oily-contaminant) migration using numerical modeling and potentiometric-surface techniques is useful for the prediction of migration pathways and potential accumulation sites. On the other hand, identifying actual accumulations from fluid-potential measurements (via inverse modeling) is not possible because fluid potentials are not uniquely dependent on saturation.

RÉSUMÉ. Des simulations numériques montrent que l’écoulement de l’eau et la migration d’hydrocarbures sont contrôlés par les champs hydrauliques régionaux; ceux-ci peuvent être modifiés localement par des lentilles à forte perméabilité et par la flottabilité des hydrocarbures. De plus, les potentiels sont couplés à la distribution des hydrocarbures par la perméabilité relative et par la pression capillaire. La distribution de la saturation évolue dans le temps et dans l’espace; il en est donc de même des surfaces du potentiel eau-hydrocarbure.

L’importance des forces capillaires dans la migration et le piégeage des hydrocarbures est illustrée par le fait que dans certains cas les lentilles sont remplies par le haut, même si le fluide polluant est plus léger que l’eau. Les forces capillaires, en association avec des réservoirs lenticulaires constituent d’excellents pièges dynamique à hydrocarbures en permettant le libre passage de l’eau et en fixant et en concentrant les hydrocarbures.

L’analyse de la migration des hydrocarbures à partir de la modélisation numérique et des techniques des surfaces potentiométriques est très utile pour prédire les trajets de migration et les sites d’accumulation potentielle. Par ailleurs, l’identification des accumulations actuelles à partir de mesures de potentiel de fluide n’est pas possible parce que ces potentiels ne dépendent pas uniquement de la saturation.

INTRODUCTION

For many years, hydrogeologists have exploited, and/or explored for, groundwater resources using mapped fluid-potential distributions in aquifers. Although the importance of the genetic relationship between hydrogeology and petroleum geology has been widely recognized (Hubbert, 1953; Schowalter, 1979; Tóth, 1980; Dahlberg, 1982; England et al., 1987; Garven, 1989; Bethke et al., 1991; Harrison and Summa, 1991), there have been few published examples of the applications of standard hydrogeological exploration techniques to petroleum geology. Only more recently have hydrogeological techniques been
applied to petroleum geology for exploration purposes (Zawisa, 1986; Wells, 1983; Vugrinovich, 1988; Toth and Otto, 1989; Thompson and Tóth, 1990).

One example of a hydrogeological technique applicable to hydrocarbon exploration is potentiometric surface analysis. Tóth (1962), Obdam and Veling (1987), and Fitts (1991) showed that a highly permeable sandstone lens encased in a low-permeability matrix will cause characteristic distortions in the surrounding groundwater flow field (Figure 1). Tóth and Rakhit (1988) showed that these potentiometric anomalies were dependent on the lens geometry, the matrix-to-lens permeability contrast, and the regional fluid-potential gradient. Tóth and Rakhit's work also demonstrated how computergenerated anomalies could be compared to field-derived potentiometric surfaces with predictions made as to the location(s) of reservoir-quality lenses.

Figure 1. Schematic of the effect of a highly permeable lens on a uniform flow-field (modified after Tóth and Rakhit, 1988).

However, all the above-mentioned studies considered only water, i.e., single-component flow. No consideration was made for the presence of a hydrocarbon component (oil or gas), and the associated changes in relative permeability (Schwaller, 1979), or capillary-pressure effects (Craig, 1971; Berg, 1975; Duliea, 1979; Watts, 1987). A potentiometric surface analysis that is based on a single-fluid component was found to be suitable for the search for rock bodies of high permeability but not for reservoirs filled with oil.

This paper presents results from a followup study which investigated the effects of multiple fluid components on the temporal evolution of the potentiometric surface in and around a highly permeable lens. We used a numerical model to simulate secondary migration of oil in a horizontal carrier bed and the subsequent filling of a lens-shaped reservoir situated within the bed. The model incorporated the three main driving forces of migration: advection, bouyancy, and capillary forces (Rostron, 1990a; Bethke et al., 1991; and Rostron, 1992). The fully coupled solution technique also enabled examination of the "feedback" effects of changes in oil saturation on capillary pressures and relative permeabilities.

First, we shall briefly review the basic fluid-potential equations and the way the numerical model was used to produce the potentiometric surfaces. Then, we present the hydraulic head distributions for the steady-state (pre-migration) stage, followed by descriptions of the oil saturation, and hydraulic head surfaces for water and oil through time, representing the migration stage. Particular emphasis is placed on the effect of changes in oil saturation on the oil and water potentiometric surfaces. Space limitations prevent the presentation of all the results obtained. Instead, we will limit our presentation to four representative cases which show the basic results and include a sensitivity analysis of variations in fluid density and the isotropy and intrinsic permeability of the flow medium. The final section of the paper presents the implications of the work in terms of oil migration in general, the effect of oil on potentiometric surface analysis, and possible implications to contaminant hydrogeology.

MULTIPHASE FLUID-POTENTIAL ANALYSIS

Hubbert (1940) showed that fluids flow according to their own potential-energy fields. In a fluid mixture consisting of two or more immiscible components, the fluid potential (or mechanical energy per unit mass), \( \Phi \), for each component, \( f \), is given by:

\[
\Phi_f = g z + \frac{P_f}{\rho_f} = gh_f
\]

(1)

where: \( \Phi \) is fluid potential, \( g \) is gravitational constant, \( z \) is position above a common datum, \( P \) is fluid pressure (gage), and \( \rho \) fluid density, with the subscript denoting the individual component. The detailed derivations of