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A method for aquifer identification in petroleum reservoirs: A case study of Puerto Ceiba oilfield

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ABSTRACT

The paper describes an efficient multi-stage data-driven method for aquifer and water influx pattern classification. It is based on statistical multivariate analysis techniques, Principal Components Analysis and Cluster Analysis. The main advantage of the proposed method is the integration of the analysis of static (water and oil properties) and dynamic (production series) data in order to understand the water-related behavior of the oilfield. For oilfield aquifers classification, oil and water physicochemical properties are used. Water influx pattern classification consists of three steps. Firstly, single-well production data analysis techniques are applied: (1) conventional decline curve analysis; and (2) a novel water-cut curve analysis with a logistic growth equation. Secondly, the obtained parameters are employed for the statistical multivariate analysis of the field. Finally, logistic-type equation parameters are used for qualitative identification of velocity of water entrance, water amount and first date of water entrance. The proposed method is discussed and illustrated using Puerto Ceiba case study. The work is a step forward towards the introduction of data-driven approaches in the engineering practices of water control.

1. Introduction

Water is one of the most effective oil production driving mechanisms either as bottomwater-drive or edgewater-drive. Water associated with hydrocarbon – known as natural brine or formation water – is water trapped in underground formations that is commonly produced along with oil and gas. As the reservoir pressure depletes, water production increases. When the amount of produced water becomes excessive, oil production drops reducing the lifespan of most hydrocarbon wells (Bailey et al., 2000; Seright et al., 2003). As a recovery process to increase the amount of extracted oil, water may also be injected into the formation with the purpose of improving oil displacement in the reservoir.

The nature, chemical properties and volume of produced water all have a direct impact on oil recovery factor and underline the need to understand the behavior of water associated to oil. For a successful oilfield water control, it is important to identify the aquifer, i.e., the origin of the produced water and the flow path directions. Unfortunately, the construction of a hydrological model for the reservoir is not a common practice in petroleum engineering; water control is usually carried out empirically (Seright et al., 2003). In Sheremetov et al. (2007) a hybrid intelligent system called SMART-Agua proposed to diagnose water invasion problems and analyze the likely impact of available solutions for each well was presented. The authors experience makes it clear that to develop efficient water control strategies detailed knowledge of each well must be integrated into the oilfield perspective. In this respect, the origin of the formation water is one of the main issues. Moreover, if water production is excessive, the water influx mechanism should also be evaluated (Bailey et al., 2000).

There are several physically-based approaches to analyze these issues that range from geochemical approaches to hydrological modeling and aquifer identification (Birkle et al., 2002; Birkle and Torres-Alvarado, 2010), pressure tests to study hydraulic communication between wells (Renard, 2005), tracing tests to determine fluid directions (Zemel, 1995; Bingyu et al., 2002). Most of these approaches require expensive and time-consuming tests and are not risk free.

In the case of mature fields, recollection of physicochemical and production data is a standard daily practice. Systematic approaches to data analysis have emerged to account for uncertainty of both static and dynamic variables. Statistical analysis has a welth of applications in petroleum engineering, including curve fitting for Type Curve Matching, non-linear regression for pressure test analysis, and multivariate estimation of distribution algorithms for automatic history matching among others. The application of

Abbreviations: AMS, Accelerated Mass Spectrometry; DCA, Decline Curve Analysis; DCT, Decline Curves vs. Time; FA, Factor Analysis; GOR, Gas to Oil Ratio; HCA, Hierarchical Cluster Analysis; ICPMS, Inductively Coupled Plasma–Mass Spectrometry; IPT, Interference Pressure Test; LC, Lower Cretaceous; LGC, Logistic Growth Curve; PCA, Principal Components Analysis; UJ_{Kim}, Upper Jurassic Kimmeridgian; UJ_{Tit}, Upper Jurassic Tithonian; WOR, Water-to-Oil Ratio

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Nomenclature

a	a positive constant related to the limiting value of the water entrance
b	exponent varying from 0 to 1
d_E	Euclidean distance
d_M	Manhattan (city block) distance
D_i	initial decline rate
F_w	water cut in %
k	a positive constant related to the shape coefficient of the logistic curve
$Q(t)$	daily oil production
q_i	initial oil production
t_c	positive constant related to the center of water input
xi and yi	are the values of the i-th variable, at points x and y respectively.

these methods has been detailed elsewhere (Damsleth et al., 1992; Gaskari et al., 2006; Schulze-Riegert and Ghedan, 2007; Kabir et al., 2007; Johansen, 2008; Abdollahzadeh et al., 2011) for a single reservoir. For hydrological modeling the use of statistical methods range from the analysis of correlation between producer response and injection profile for water control to flow-simulation with the Monte Carlo (MC) algorithm (Chou et al., 1994; Wong and Shibli, 2001; Narayanan et al., 2003; Kebede-Gurmessa and Bárdossy, 2009). Data-driven analysis methods are thus a viable alternative for water control and provide an important additional tool for aquifer and water influx identification.

In the paper we present and illustrate a fast data-driven method that uses multivariate statistical techniques for aquifer and water influx pattern identification in the following way:

- First, multivariate statistical methods such as Principal components analysis (PCA), and hierarchical Cluster analysis (CA) are applied to oil and water physicochemical properties to evaluate the number of the aquifers associated to the oilfield.
- Second, these statistical methods are applied for water influx pattern identification. For this task, single-well production data analysis techniques such as: (1) Decline Curve Analysis (DCA) (Arps, 1956; Fetkovich, 1980); and (2) a logistic growth curve (LGC), proposed as novel water-cut curve analysis (Banks, 1993) are applied. The parameters of each curve (DCA for oil rate and LGC for water cut) are integrated to describe the water influx patterns.
- In addition, linguistic variables are proposed to qualify water entrance.

The method is based on the following assumptions:

1) Variability of aquifer's properties is associated with the oil properties variability.
2) Variability depends on formation characteristics and historical migration of the fluids.
3) Water entrance mechanisms depend upon formation characteristics and operational conditions.
4) The maximum amount of water affects the oil rate.

The method is illustrated for the case of the Puerto Ceiba oilfield of the Bellota-Jujo asset (Bellota-Chinchorro before) located in the coastal swamps of the Gulf of Mexico.

The rest of the paper is organized as follows. In Section 2, a necessary background is briefly presented. The proposed method is described in Section 3. Section 4 shows the results of its application to Puerto Ceiba oilfield including the validation of the aquifer classification. Discussion of the results is presented in Section 5. Finally, conclusion remarks summarize our results in the last section.

2. General background

Through geological time, the original sea water composition undergoes a series of changes depending on the burial and hydraulic conditions of the formation. Brine evolution from buried sea water within sedimentary rocks associated with hydrocarbon involves a series of processes such as dissolution of minerals from adjacent sediments; cation exchange between water and minerals; concentration of dissolved compounds through evaporation or filtration; retention of dissolved cations by clay minerals; and infiltration of meteoric water. Formation water tends to be more saline in undeformed basins or in areas where the sedimentary sequence contains evaporite rocks. Additionally, formation water characteristics and physical properties vary depending on hydrostatic conditions, i.e. geographic location of the field, geological formation, and the type of hydrocarbon produced. Brine properties and volume can also vary throughout the lifetime of the reservoir. The salinity of oilfield water usually increases with depth but the opposite may also occur especially in sandstone formations. The Ca/Mg ratio indicates the degree of interaction of water with the surrounding minerals (dissolution) (Hyeong and Capuano, 2001), while Na/Cl ratio is useful to classify water type (Collins, 1975).

After the original buried organic material completes its thermal maturation, petroleum undergoes additional geochemical processes as well as physicochemical and bacteriological alteration during its migration, events occurring over the geologic time and affecting its final composition (Collins, 1975; Chapman, 1983).

Hydrological systems and in particular groundwater systems are complex and difficult to observe because the main sources of influence are the soil and rocks the water evolves in. The geological structures and specially their heterogeneity can influence greatly the flow of water by creating preferential paths where water can flow faster.

Conventional practice in petroleum engineering usually assumes that given a formation or oilfield there is only one aquifer associated. Although this hypothesis may generally be true, several oilfields have revealed the existence of more than one aquifer (Birkle et al., 2002), which may be segregated at the beginning but mixed later as a consequence of reservoir exploitation. Chemical properties of formation water are the result of spatial and temporal geochemical processes and have been used to identify the number of aquifers at play in the oilfield and also the likely water migration trends (Birkle and Torres-Alvarado, 2010).

From the hydrochemical point of view, Birkle et al. (2002) describe a method for local and regional hydrodynamic model construction based on measuring the water ^{14}C content along with the analysis of major and trace elements (ions and isotopes), that require accelerated mass spectrometry (AMS) and inductively coupled plasma–mass spectrometry (ICPMS) techniques available only at specialized laboratories. Variations in the chemical and isotopic composition of groundwater samples can be related to: (1) the geochemical evolution of a single aquifer; (2) the affiliation between different aquifer systems as a consequence of formation properties distribution such as permeability and porosity; (3) rock contact and dissolution.

The use of water major ions is a common method to delineate flow trends and indicate the partition of the water samples (from each well) into aquifer types of similar chemical composition. The