Abstract

Rock typing is an essential part of building geological model for an asset. Millions of dollars are invested in logs, core measurements, SCAL studies and geological interpretation that result in definition of different rock types. In most cases rock types that are identified in a reservoir do not have crisp boundaries and display overlapping characteristics. During the upscaling process, multiple rock types that have been identified in a high resolution geological (geo-cellular) model are approximated into a dominant rock type for any grid block in a reservoir simulation flow model. This defeats the original purpose of performing detail geological and petrophysical studies as far as reservoir flow models are concerned. The objective of this study is to develop a new upscaling methodology based on fuzzy set theory principles. Fuzzy rock typing refers to taking into account the inherent uncertainties and vagueness associated with rock typing in hydrocarbon bearing reservoirs.

In this paper a numerical simulator has been used as the control environment in order to set up multiple studies that would demonstrate the difference between using conventional approach of implementation of geological models in the reservoir flow simulation studies and the new approach that is the subject of this study. By using the numerical reservoir simulator as the control environment it is intended to study the complexities that exist in geological model at much higher resolution and then compare simulation in large grid blocks using two different approaches. The problem has been set up in the form of upscaling study.

First, the study was performed using conventional upscaling practices and then it was carried out using the proposed technique. The results then have been analyzed in order to demonstrate the difference between the two techniques and the advantages and disadvantages of each have been identified.

This manuscript has been organized in several sections. In the literature review section the current practices in upscaling dynamic reservoir properties such as relative permeability and capillary pressure are reviewed as well as basic definitions of rock typing. A brief section on fuzzy set theory is also presented in this section. The problem is defined in more details and some background information is presented in the “Introduction” Section. The approaches used to perform the study are presented in the “Methodology” section. Details results are presented and discussed in the “Results & Discussion” section and the manuscript is completed providing some concluding remarks.

Literature Review

Upscaling Dynamic Reservoir Characteristics- A variety of approaches for upscaling high resolution geocellular models for flow simulation are reviewed. The number of cells which can be handled in a typical reservoir simulator are highly dependent on the type of simulation to be performed and are usually between 105 to 106 cells. On the other hand geological models which are referred to as geocellular models, geostatistical models or fine grid models contain 107 to 108 cells. Computing time, cost and capabilities all restrict our ability to use high resolution geocellular models for reservoir fluid flow simulation. As a result there is a need to cluster data into smaller sets of characteristics that represent the most significant aspects of reservoir. This process is called upscaling.

Depending on the situation, different upscaling procedures might be appropriate. The simulation question being addressed, production mechanism and level of details which can be considered in the coarse model, will define the idyllic process to use (1).
Upscaling techniques can be categorized based on different factors. One classification is based on the types of parameters upscaled. This category contains single phase upscaling used for moderate degrees of coarsening and two phases upscaling usually used for higher degrees of coarsening. Upscaling the relative permeability and capillary pressure data are usually reflected on high degrees of coarsening. The second classification is in accordance with the way in which the abovementioned parameters are computed.

Under the third classification, the upscaling methods are divided into analytical and numerical according to the method used. The only parameters to be upscaled in the single phase flow are porosity, absolute permeability (or transmissibility). However, in two phase flow case, relative permeability can be upscaled as well.

Nevertheless some engineers have always believed in simulating the low resolution two phase models only by taking into account the absolute permeability (or transmissibility) and porosity. This approach is referred to as single phase upscaling. In models of this type, the geocellular scale relative permeabilities are used directly on the coarse scale (1).

Some publications have shown that this is not enough to capture the effects of heterogeneity on two phase fluid simulation using upscaling only permeability particularly if the correlation length of the heterogeneity not represented on the fluid flow simulation grid is significant compared with the well spacing (2; 3). This often happens when long, thin, high-permeability channels, thin, high-permeability layers, or extensive, but thin, shale barriers are present in the reservoir (4).

With reference to pressure and saturation equation, it can be said that single phase upscaling only the pressure equation is modified while in two phase upscaling parameters in both pressure and saturation equations are altered.

In the second type of classification, two different approaches of purely local procedure and global upscaling techniques can be defined. In purely local procedure only the fine scale area equivalent to the coarse block parameters are considered for upscaling. Conversely in the global upscaling technique the coarse model parameters are computed after simulating the high resolution model.

Baker and Thibeau have summarized different dynamic pseudo relative permeability methods, their properties and limitations in their work (4). The role of pseudo relative permeabilities is determining the output flow rate of each phase from each grid block. The flow rate and pressure gradient between each grid block and its neighbor is related using the pseudo relative permeabilities. If the flow is dominated by gravity forces, vertical equilibrium pseudo can be calculated (5). On the other hand, if the capillary pressure is dominated, the pseudo may be calculated by upscaling the permeability of each phase and dividing by the scaled up absolute permeability (6).

One of the well known methods for calculating the pseudo relative permeability curves is Kyte and Berry method (7). In this method the values of average pressure for each coarse gridblock and total flow rates of each phase between each pair of neighboring coarse gridblocks are computed from the fine-grid simulation results. These values are substituted in the coarse-grid Darcy equations to conjecture the coarse-grid (pseudo) relative permeability values that would be required to reproduce the fine-grid flows. Some problems can happen if the net flow of a phase is in the opposite direction to the average pressure gradient (7).

Stone used the total mobility as a way to overcome the problems with Kyte and Berry method (8). He suggested calculating average mobility and net fractional flow. His method is not valid when the effect of capillary pressure and gravity is not neglected (4).

The other method which is widely used is the weighted relative permeability method. This method is used in the upscaling program sold ECLIPSE reservoir simulation software, and gives smooth pseudos with values between 0 and 1. In this method, the pseudo relative permeability of a phase is simply calculated by averaging the relative permeabilities of that phase in certain blocks of the fine grid model. There is not enough validation of reproducing the same results as fine scale model, using this method, despite its popularity (4).

**Rock types and Flow Units** A need to define quasi geological/engineering units to shape the description of reservoir zones as storage containers and reservoir conduits for fluid flow have been recognized by petroleum geologists, engineers, and hydrologists. “Flow units” are resultant of depositional the depositional environment and diagenetic process, and different authors have defined them in different words (9).

Understanding complex variation in pore geometry within different lithofacies rock types is the key to improving reservoir description and exploitation. Core data provide information on various depositional and diagenetic controls on pore geometry. Variation in pore geometrical attributes in turn defines the existence of distinct zones (hydraulic units) with similar fluid-flow characteristics. Hear et al. defined flow unit as a reservoir zone that is laterally and vertically continuous, and has similar permeability, porosity, and bedding characteristic. Gunter et al. defined flow unit as a stratigraphically continuous interval of similar reservoir process that honors the geologic framework and maintains the characteristic of the rock type (10).
Taghavi et al. have defined flow units as a lithofacies or group of lithofacies which have the same petrophysical and flow parameters (11). Petrophysical properties include porosity and permeability. However some other parameters such as capillary pressure and relative permeability are comprised in the flow parameters category. Defining the flow units in carbonate reservoirs is relatively difficult due to small scale depositional heterogeneities together with post depositional diagenesis and fractures which can substantially alter the flow potential of the depositional unit. They have used both the static and dynamic reservoir data to identify the flow units in a carbonate reservoir in south west of Iran. Ultimately, they have shown that even after considering the porosity-permeability cross plot and capillary pressure data the overlaps of different flow units still exists.

The geologist will also identify various “facies” within the reservoir. This term is used to describe a sedimentary body having distinct physical, chemical and biological attributes (12). Within a given facies the reservoir properties can vary significantly. This variation has lead to a further subdivision known as Flow Units (FU). Flow units are regions in the sedimentary sequence that are judged to control the movement of injected or produced fluids within the reservoir (13).

Bear defined the hydraulic (pore geometrical) unit as the representative elementary volume of the total reservoir rock within which the geological and petrophysical properties of the rock volume are the same (14).

Ebanks defined hydraulic flow units as a mappable portion of the reservoir within which the geological and petrophysical properties that affect the flow of fluid are consistent and predictably different from the properties of other reservoir rock volume (15).

Some other authors believe that a hydraulic unit is defined as the representative volume of the total reservoir rock with geological properties that control fluid flow. It is a reservoir zone that is laterally and vertically continuous and has similar flow and bedding characteristics (16).

The Rock Type concept was introduced by Archie who classified carbonate rocks on the basis of grain type and the amount of visual porosity. Rock types usually were corresponded to flow units in terms of productivity. In fact Rock Types are defined as units of rock deposited under similar conditions which experienced similar diagenetic processes resulting in a unique porosity-permeability relationship, capillary pressure profile and water saturation for a given height above free water in a reservoir (17).

Porosity, permeability, mercury injection capillary pressure, relative permeability and mineralogical data are usually utilized to portray the reservoir pore system into rock types having similar flow capacity and storage capacity. Characterization of reservoir into rock types in order to determine flow units incorporate geological, petrophysical and production data (18).

Different group of scientists and engineers have defined rock types in different words (19). Geologists have defined rock type as rock volumes having similar depositional and diagenetic environment identified using core description and core analysis in cored wells (Lithofacies). Petrophysicists believe rock types are rock volumes having similar responses of log measurement in a whole well profile (Electrofacies). In reservoir Engineers’s point of view rock type are rock volumes having similar pore size distribution, capillary pressure and relative permeability curves at a given wettability.

A review of the studies performed, shows that different authors have usually used the words “rock types”, “flow units” and “hydraulic units” interchangeably. Nevertheless, some have pointed out their differences and compared them. Bessa, for instance believes that rock types can be used to link depositional facies, diagenesis, reservoir properties and wireline log response. While, hydraulic units are related to geological facies distribution but do not necessarily coincide with facies boundary (16).

Rock type distribution identification is conspicuous, since it is key information to define layering and select the best option for production test interpretation (19). Gunter et al. pioneered a graphical method for quantifying reservoir flow units based on geological framework, petrophysical rock/pores types, storage capacity, flow capacity, and reservoir process speed (20).

Amaefule et al. introduced the concept of reservoir quality index (RQI), considering the pore-throat, pore and grain distribution, and other macroscopic parameters (21).

Asgari et al. have performed a study in which he has used a new approach for development of rock type characterization (19). As they have cited, common rock type either are based on petrophysical facies classified by log responses, core description and single phase data such as porosity and permeability (Static Rock Typing), or SCAL defined rock types at two phases. The second method takes capillary pressure and relative permeability into account.

**Fuzzy Set Theory** - One can view fuzzy sets as a generalization of classical sets, or crisp sets as they are sometimes called. Classical sets and their operations are particularly useful in expressing classical logic and they lead to Boolean logic and its applications in digital systems. Fuzzy sets and fuzzy operations, on the other hand, are useful in expressing the ideas of fuzzy logic leading to applications such as fuzzy controllers.
In crisp logic the boundary of the sets are precise while this is not true for fuzzy logic. In FL this requirement is relaxed and therefore the set boundaries in this case are vague. A fuzzy set is a set where degrees of membership between 1 and 0 are permitted; it allows partial membership. The fuzzy logic Venn diagram does not have a crisp boundary, and boundary zones appear as shading (22). Having the set X as the universe and set A as a fuzzy subset of the universe, the value μA(x) is called the membership value or the grade of membership of x ∈ X. The membership value represents the degree of x belonging to the fuzzy set A. The value of the characteristic functions for crisp sets is either 0 or 1, but the membership value of a fuzzy set can be an arbitrary value between 0 and 1.

Fuzzy sets can thus better reflect the way intelligent people think. For example, an intelligent person will not classify people into two categories of friends and enemies. These categories are two extremes while there are some people who can be considered in ranges between these categories. It should be noted that there are degrees in every trait can lead to error in decisions (23).

Fuzzy sets are the tools which convert the perceptions of fuzzy logic into algorithms directing to functions. They are used to state accurately what one means by vague terms such as hot, cold, tall, and short. By allowing fractional membership, fuzzy sets can provide computers with algorithms that expand their binary logic and enable them to make human-like decisions.

The term fuzzy in this context does not mean imprecise, but exactly the opposite. It may appear difficult to settle the argument that the objective of fuzzy sets is to enable computing with words with the fact that fuzzy sets are of a mathematical nature. Do humans think in expressions of triangular membership functions, Cartesian multiplications, etc.? Certainly not, but one may think of fuzzy sets and the related mathematics as the media through which the way we think is transferred to a computer, rather than trying to accommodate our thinking to the computer needs. Of course, it would have been more efficient to have a way for direct relocate of thoughts without the transitional stage of mathematics.

The evasion of mathematics occurs in the way to describe a system. Attempting to transfer our way of thinking into fuzzy set formulation could have an interesting side effect. It gives us an opportunity to consider our own thoughts and actions and reflect on the astuteness of our choices and verdicts.

Background

Reservoir rocks having similar texture, grain size, sorting etc, can be classified (purely geologically) into lithofacies classifications. Each lithofacies indicates a certain depositional environment with a distribution trend and dimension. Petrophysical groups are classified by porosity, permeability, capillary pressure and pore throat size distribution. A Rock Type combines both these classifications by linking petrophysical properties and lithofacies as part of the reservoir rock type definition. According to previous works done, it has been proved that a static rock type can not be used to simulate the fluid flow behavior in the reservoir.

There are a unique set of properties that define the productivity of hydrocarbon in a reservoir. These properties are discussed under the reservoir characterization concept. There is a link between the geological theory and reservoir engineering/management. Reservoir characteristics can be put in two categories, as far as reservoir scale is considered, namely microscale and macroscale. Microscale properties include pore types, pore connectivity, and capillary and electrical properties, etc., whereas macroscale properties include lateral and vertical connectivity of reservoir layers, flow units, etc. However all these properties are controlled by three geological inputs: depositional texture, diagenesis and tectonic features.

The size and shape of the grains, their packing and sorting characteristics, and the nature of any mud matrix are all described using depositional texture. Together these variables define individual lithofacies and the nature and distribution of primary porosity. Diagenesis modifies the depositional texture to either enhance or reduce reservoir potential through dissolution and cementation (including lithification and compaction) respectively.

The rock type (lithotype) classification which is usually used is only based on the depositional texture and grain size, sorting, effective pore type and diagenesis. According to this criteria, the data needed to define the rock types such as pore throat size distribution can be identified using throat size distribution plot and thin section analysis for each lithotype.

Varavur et al. (24) identifies significant shortcomings in the current rock typing method used. Some of them are summarized as follows:

1. Significant degrees of overlap between various rock-types observed on the Porosity/Permeability cross plots.
2. No success proof of the attempts for predicting these lithotypes using conventional logs and a combination of high technology tools.
3. Having no input data from uncored wells for defining Rock Type and consequent definition of them for the core wells and spatially distributing them (24).

Varavur et al. (24) have used a new method to define the dynamic rock type in a giant reservoir that is different with the old scheme which only honors the geological reservoir properties. The mercury injection data has been vastly used in their work. The classification generated by clustering of Mercury Injection data has unique Porosity/Permeability correlation for each class. In this paper apart from the static parameters of the rock types (porosity and permeability), their dynamic values have been considered as well.

The other issue discussed in this work with affiliation to rock typing, is the upscaling. Building geologic models for an asset require rock typing as an essential part. Information necessitated for defining rock types are obtained from logs, core measurements, SCAL studies and geological interpretation. Millions of dollars are invested to attain this information. Upon definition of rock types for series of geological formation, geo-scientists are asked to use approximation and identify a dominant rock type for any given grid block in a reservoir simulation model. This defeats the original purpose of performing detail geological, petrophysical and geophysical studies as far as reservoir flow models are concerned. This approximation of multiple and overlapping rock types into one dominant rock type becomes even more notable when realizing that a typical grid block in a reservoir flow model is almost the size of six football fields, while most of the rock typing studies are performed at the core scale.

Each rock type is associated with a series of relative permeability and capillary pressure curves. Values identified in this study will be used in a fuzzy aggregation method in order to identify the way relative permeability and capillary pressure curves should be used to generate values that are used in the reservoir flow model for a particular grid block. It is important to note that the methodology and the results presented in this paper marks the start of a larger study that has been initiated to develop a new upscaling technology for reservoir simulation and modeling by integrating reservoir characterization, geology, petrophysics with the state of the art in artificial intelligence and data mining. As such the results presented here should be considered preliminary and part of a work in progress.

Methodology

This study included several stages and models. For the purposes of brevity only two of the models that had been studied are presented in the article. Readers are encouraged to refer to the thesis published at West Virginia University (25) for the complete study.

A commercial reservoir simulator has been used (26) to model a single well. The modeled reservoir is consisted of three different rock types. Specific relative permeability and capillary pressure curves have been assigned to each of the rock types. Figure 1 shows the three overlapping rock types selected for this study in a permeability-porosity cross plot. The detailed explanation for the procedure is shown below.

It is obvious from Figure 1 and confirmed by results of some sensitivity analysis that rock type 3 has the most contribution to fluid flow throughout the reservoir. The objective is to study the impact overlapping rock types on flow of fluid in the reservoir and test a new upscaling technology that would minimize the impact of the upscaling in the outcome of the fluid flow in the reservoir and compare this new technology with the conventional techniques currently being used. To accomplish this task following steps are implemented:

1. Build a high resolution model with multiple rock types. Run the model and establish a flow rate profile for the well for the high resolution model.
2. Upscale the model using conventional upscaling technique (identifying one rock type as the dominant rock type for each upscaled grid block). Run the upscaled model and establish a flow rate profile for the well for the low resolution (conventionally upscaled) model.
3. Upscale the model using the Fuzzy Rock Typing (FRT) upscaling technique (the details to be followed). Run the FRT upscaled model and establish a flow rate profile for the well for the FRT low resolution model. Compare the three flow rate profiles namely the high resolution model(representing the geocellular model) with the two upscaled models, the conventional and the FRT upscaling.
4. Modify the percent of dominant rock type in the high resolution model and repeat steps 1, 2, and 3. The point is that as the percent of the dominant rock type in the high resolution model decreases (from 90% to 50%), the conventional rock type would still pick the rock type with larger share as the dominant rock type without a distinction on the role it
plays in the overall fluid flow and the results of the upscaling will not change. The FRT upscaling method, on the other hand, will take into account the contribution of each rock type to the fluid flow during the upscaling process.

Case 1

A) High Resolution Model- First the high resolution model is built and run. This model is representing the high resolution geocellular model with fine scale data. The general properties of the high resolution model are presented in Table 1.

The Winland plot used for this study is shown in Figure 1. As shown in this figure the grid blocks in the high resolution model are consisted of three distinct but overlapping rock types denoted as RT1, 2, 3. “Winland Plot” is a semi-log crossplot of permeability (mD) versus porosity (%), with isopore throat lines (R35 Ports). “R35 Ports” correspond to the calculated pore throat radius (microns) at 35% mercury saturation from a mercury injection capillary pressure test. They can be calculated directly from Winland’s equation (Equation 1) or other equations based on permeability and porosity (27; 28). In this equation, permeability is input in milidarcies and porosity in percent.

\[
\log R_{35} = 0.732 + 0.588 \times \log(K) - 0.864 \times \log(\varphi)
\]

\[\text{Equation 1}\]

R35 pore throat radii is a function of entry size and pore throat sorting, and is a good measure of the largest connected pore throats in a rock with intergranular porosity. As explained before, each rock type is associated with certain dynamic reservoir properties (relative permeability and capillary pressure characteristics). The abovementioned curves for three rock types used in this study are demonstrated in Figure 2.

<table>
<thead>
<tr>
<th>Table 1. High Resolution Model Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Property</strong></td>
</tr>
<tr>
<td>Δx</td>
</tr>
<tr>
<td>Δy</td>
</tr>
<tr>
<td>Δz</td>
</tr>
<tr>
<td>nx</td>
</tr>
<tr>
<td>ny</td>
</tr>
<tr>
<td>nz</td>
</tr>
<tr>
<td>Reservoir Top</td>
</tr>
<tr>
<td>Bubble point pressure</td>
</tr>
<tr>
<td>Initial reservoir pressure</td>
</tr>
<tr>
<td>Initial oil saturation</td>
</tr>
<tr>
<td>Water saturation</td>
</tr>
</tbody>
</table>

Figure 1. Winland Plot for Case 1
The high resolution model will be upscaled 75 times. This implies that 75 grid blocks from the high resolution model will create one low resolution grid block in the upscaled model. Table 3 displays the degree of contribution for all rock type in terms of the number of grids belonging to each of the 75 high resolution blocks.

In this case the porosity value is the same for all the rock types. Using this value and the porosity- permeability relationship in each rock type, the permeabilities are calculates to be 1.8 mD, 4.9 mD and 7.8 mD for rock types 1, 2 and 3 correspondingly (see Figure 1).

**B) Conventionally Upscaled Model** The geological models, referred to as fine grid models, geostatistical models or simply geocellular models, represent geological variation on very fine scales vertically, though their areal resolution is still relatively coarse. For example, a typical geostatistical model might contain layering of thickness 1 ft or less, though cell sizes in the areal direction might be about 50 - 100 ft. Thus, fine grid geological descriptions can be expected to grow further, so the need for reliable upscaling techniques will continue.

In this study a high resolution model was built to symbolize a high resolution replica of the reservoir made based on fine scale geocellular model data. The geocellular models should be upscaled in order to be run in the reservoir simulators.

The upscaling is performed by the magnitude of 75. The low resolution model has three grid blocks in each of X and Y direction. Every three layers in Z direction is upscaled to one layer. Therefore 75 high resolution grids create one low resolution block; consequently the low resolution model has 243 grid blocks while the high resolution one was consisting of 18225 grids.

In conventional upscaling process, the rock type that has the higher number of grids in 75 high resolution block will compel its properties to the whole block. As it was explained in the last sections, rock type 3 is the dominant among all, in all cases. As a result, all 243 blocks will belong to rock type 3 after carrying out the upscaling. Since it is a fact for all the cases, the upscaled model achieved by this methodology will be indistinguishable for all of them regardless of different rock type distributions.

**C) Fuzzy Upscaled Model** Each rock type is associated with a series of relative permeability and capillary pressure curves. The approximation of multiple and overlapping rock types into a dominant rock type results in defeating the original purpose
of performing a detailed geological, petrophysical and geophysical studies as far as reservoir flow models are concerned. The approach proposed in this research is based on fuzzy set theory. Base on this method, a membership value is defined for each rock type. This value is calculated based on the quantity of the grids belonging to each rock type \((\mu_i)\). For instance if out of 75 grid blocks, 38 of them belong to rock type 3, and rock types 5 and 1 have a share of 3 and 27 apiece, the membership value for rock types 3, 5 and 1 will be 60, 4 and 36 percent correspondingly.

This membership value has been used to define new rock types after upscaling. These rock types are expected to be more realistic and have closer results to the high resolution models’ outcomes.

The porosity, permeability, relative permeability and capillary pressure data associated to the new rock types have been determined using the membership values.

A logical assumption leads us to the fact that each rock type should have an effect in the upscaled block and this effect is rooted in their share of the high resolution grids and fuzzy membership functions. Using the fuzzy set theory this behavior is trying to be mimicked.

In this case there will not be a unique low resolution model for all the high resolution realizations. The single rock type high resolution model will be upscaled to a single rock type low resolution model identical to the conventionally upscaled one.

Since the rock type distribution in each 75 grid blocks is identical to the distribution to the other 75 grids, the fuzzy rock type created will be similar for 243 low resolution blocks of a case, but different from another case. Following table shows the fuzzy membership and permeability values before and after upsampling for the case with 60% of grids fitting in rock type 3.

**Table 2. Permeability values before and after fuzzy upscaling (60% of rock type 3)**

<table>
<thead>
<tr>
<th>Property</th>
<th>Number of High Resolution Grids</th>
<th>Fuzzy Membership Value</th>
<th>Value before Upscaling</th>
<th>Value after Fuzzy Upscaling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kx (mD)</td>
<td>RT 1: 27</td>
<td>RT 1: 0.26</td>
<td>RT 1: 1.78</td>
<td>FRT 1: 5.54</td>
</tr>
<tr>
<td></td>
<td>RT 2: 3</td>
<td>RT 2: 0.04</td>
<td>RT 2: 4.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RT 3: 45</td>
<td>RT 3: 0.60</td>
<td>RT 3: 7.84</td>
<td></td>
</tr>
</tbody>
</table>

**D) Modifying the High Resolution Block** - The percent of each rock type in the high resolution block has been modified. The new cases have been created according to Table. These models have gone through upscaling using two different approaches explained.

**Table 3. Number of grid blocks for each rock type out of 75 grids**

<table>
<thead>
<tr>
<th>Percentage of RT3</th>
<th>Number of RT3 Grid Blocks</th>
<th>Number of RT5 Grid Blocks</th>
<th>Number of RT1 Grid Blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>75</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>90%</td>
<td>68</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>80%</td>
<td>60</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>70%</td>
<td>53</td>
<td>3</td>
<td>19</td>
</tr>
<tr>
<td>60%</td>
<td>45</td>
<td>3</td>
<td>27</td>
</tr>
<tr>
<td>50%</td>
<td>38</td>
<td>3</td>
<td>34</td>
</tr>
</tbody>
</table>

Case 2

The difference of this case with the previously discussed case is in the sample used for the rock types and the approach followed in calculating the fuzzy upscaled values.

**A) High Resolution Model** - The high resolution model is created according to the properties presented in Table 1. As indicated in Figure 3, all rock types have the same porosity and permeability values of 13% and 8.14 mD respectively. The sample used is fallen where the rock types have overlapped. These rock types differ in dynamic reservoir properties. Several realizations of rock types distribution have been studied as explained in the preceding case.
B) Conventionally Upscaled Model- As explained in the last sections, the high resolution model is used as a representation of the fine scale geological model which should be upscaled in order to be run by the reservoir simulators. The upscaling was performed to the magnitude of 75. Given that conventional upscaling was used for upscaling, the properties of the dominant rock type (rock type 3) were dispensed to all the grid blocks.

C) Fuzzy Upscaled Model- Apart from calculating the membership values based on the participation of each rock type in making fine scale model grids ($\mu_v$), another membership value has been computed using the fuzzy membership functions for permeability ($\mu_k$).

The triangular membership function used in this case can be expressed as:

$$
\mu(x) = \begin{cases} 
    a \frac{(b-x)}{(b-c)}; & b \geq x \leq c \\
    a \frac{(d-x)}{(d-c)}; & c \geq x \leq d \\
    0 & \end{cases}
$$  \hspace{2cm} \text{Equation 2}

The membership value used at the end is the integration of effect of each rock type in making the high resolution model and its influence in the Winland plot. This values for different case have been presented in Table 4. Since the porosity and permeability values are the same for all rock types, only the dynamic reservoir properties (relative permeability and capillary pressure) will be fuzzy upscaled.

D) Modifying the High Resolution Block- After modifying the high resolution model by changing the percent of each rock type, the steps C and D were repeated. Table 4 displays the membership values calculated for each case.
Table 4. The membership values used for different cases

<table>
<thead>
<tr>
<th>RT</th>
<th>µκ</th>
<th>µν</th>
<th>New Membership Value</th>
<th>Normalized Membership Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>90% of RT3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RT1</td>
<td>0.267</td>
<td>0.050</td>
<td>0.013</td>
<td>0.049</td>
</tr>
<tr>
<td>RT2</td>
<td>0.456</td>
<td>0.040</td>
<td>0.018</td>
<td>0.066</td>
</tr>
<tr>
<td>RT3</td>
<td>0.267</td>
<td>0.910</td>
<td>0.243</td>
<td>0.885</td>
</tr>
<tr>
<td>80% of RT3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RT1</td>
<td>0.267</td>
<td>0.160</td>
<td>0.043</td>
<td>0.156</td>
</tr>
<tr>
<td>RT2</td>
<td>0.456</td>
<td>0.040</td>
<td>0.018</td>
<td>0.066</td>
</tr>
<tr>
<td>RT3</td>
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<td>0.214</td>
<td>0.778</td>
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<td>70% of RT3</td>
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<tr>
<td>60% of RT3</td>
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<td>0.360</td>
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<tr>
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<td>0.160</td>
<td>0.583</td>
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<tr>
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<td>0.267</td>
<td>0.600</td>
<td>0.160</td>
<td>0.583</td>
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<tr>
<td>50% of RT3</td>
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<td>0.136</td>
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<tr>
<td>RT3</td>
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<td>0.510</td>
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</table>

Results and Discussion

Two cases were discussed in this work. The results are discussed for both cases.

Case 1—Figure 4 compares the cumulative oil production for different high-resolution models created based on the percentage of each rock type. As explained before rock type 3 has the most contribution in the flow, rock types 5 and 1 come after in sequence. Hence, the more percentage of rock type 3 is, the higher the oil production will be. This is attested in the following figure.

In fact the reduction in number of grids belonging to the rock type 3 is the occasion of decrease in amount of produced oil.
Rock type 3 was identified as the dominant rock type; thereby its properties were assigned to all coarsened block using the conventional upscaling technique. The upscaled model was run a flow rate profile for the well for the low resolution (conventionally upscaled) model was established. These results were compared with the outcome of low resolution model upscaled using fuzzy rock typing technique, and the high resolution model. The results for the models having 90% and 60% of the dominant rock type (rock type 3) are demonstrated in Figure 5 and Figure 6 respectively.

The errors caused by upscaling using two explained approaches are compared in Figure 7.
It can be observed that the error in conventional upscaled model goes up as the contribution of the dominant rock type in the high resolution model reduces. This originated from the fact that the properties of the dominant rock type have been dispensed through all coarsened blocks in the conventional upscaling approach.

The error in fuzzy upscaled model decreases to almost 1% in the case having 70% of rock type 3. This number increases for after that which can be explained as a function of the rock type allocation in the high resolution model and direct contact of them with wellbore. Nevertheless, in all cases the percent of error caused by fuzzy upscaled model is astonishingly less than the error generated by conventional upscaling technique.

**Case 2**- The same analysis explained in the preceding section has been carried out for this case as well. As it can be observed in Figure 8, decrease in the number of grids associated with rock type 3, causes reduction in oil production. Referring to the role of each rock type in hydrocarbon production, this behavior can be easily explained.
The high resolution and upscaled models results have been compared. The results for the cases having 90 and 60 percents of rock type 3 have been demonstrated here as an example.

![Figure 9.3RHR-90% and 3RLR-90% Models Comparison- Oil Production](image)

![Figure 10.3RHR-60% and 3RLR-60% Models Comparison- Oil Production](image)

Figure 11 is the graphical representation of the amount of difference between the high resolution model result and both low resolution models’s outcomes, after ten years of oil production.
As it is demonstrated in Figure 11, the error caused by conventional upscaling is significantly more than fuzzy upscaling. As the percent of rock type 3 in high resolution model decreases, the error increase drastically in conventionally upscaled model. However the error flows a descending trend for fuzzy upscaled models, except for the case having 50% of rock type three grid blocks in high resolution model. This might be rooted in the geometry of rock type distribution in the reservoir. The blocks that the well is drilled in, and the rock types they belong to play an important role in generating this difference.

In accordance with the results shown in Figure 7 and Figure 11, when overlap of the rock types is higher, the results obtained by fuzzy upscaling model are better in comparison with the conventional upscaling method.

**Conclusion**

Different realizations have been generated using commercial reservoir simulator to mimic the behavior of a hypothetic reservoir.

Using multiple studies, the differences between employing conventional approach of implementation of geologic models in the reservoir flow simulation studies and a new approach have been demonstrated. The new methodology used in this study is based on fuzzy set theory.

The intention of this investigation was to establish a new technique for impersonating the reservoir behavior, while the uncertainties have been tried to be taken into account.

According to the outcomes in all cases the fuzzy upscaled model results are by far closer to the high resolution model. The difference between the conventionally and fuzzy upscaled models becomes more conspicuous when the percentage of the grids belonged to each rock types gets close. In this case the share of the grids for the dominant rock type is not significantly higher than the other’s.

According to the analysis performed, the higher the overlap, the better is the result.

In reference to the results, this methodology seems to be feasible. It can be studied under other reservoir circumstances to find more about its applicability.

**Acknowledgement**

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**References**


