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# Characterization of Reservoir Rock Types in a Heterogeneous Clastic and Carbonate Reservoir

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## Abstract

Identifying reservoir rock types and their most significant vertical and horizontal heterogeneities is an essential component of reservoir characterization process, which are among the key input parameters into a three-dimensional geological and flow simulation models. A reservoir classification and rock typing study were carried out on the Asmari formation of a mixed siliciclastic and carbonate reservoir in Iran. Detailed core analysis data including capillary pressure, core porosity, core permeability and core description supplemented by well logs revealed a complete vertical sequence of seven distinct clastic and carbonate reservoir rock types. Identification of the reservoir intervals and pay zones was carried out by means of the above results. Core based reservoir rock types were examined for each cored wells and log based reservoir rock types were selected and assigned in the uncored wells. The above data were applied as input parameters in a method based on Fuzzy Logic inference. The Fuzzy Logic technique was calibrated in 4 cored wells and blind tested in the other cored wells to determine the reservoir rock types. After the secondary calibration of the Fuzzy Logic against the core data, this technique was applied on 28 wells without any core data. The results reveal a very good match between the core data analyses and the Fuzzy Logic determination of the reservoir rock types. This technique can be applied to reduce the uncertainty of determination of the rock typing or as a very good predictor in uncored wells.

**Keywords***:* Rock types, Capillary pressure, Permeability, Petrophysical logs, Fuzzy logic.

## Introduction

It is well known that accurate reservoir simulation and management requires a quantitative model of the spatial distribution of reservoir properties and an understanding of the nature of reservoir heterogeneity at many scales.

Reservoir rock type determination has presented a challenge for cases whenever no direct measurements of reservoir rock type are available. The direct determination of reservoir rock type will be carried out though the core analysis while indirect determination will be carried out through the log analyses. Typically, few wells in a field may have laboratory information such as core analysis data whereas most of wells may have electronic logs data. Wells without core are usual due to various reasons such as, time and cost associated with coring, and or impractical coring in many situations, such as in horizontal wells.

However, a method was applied based on the Fuzzy Logic inference, in some wells where core data are not available, to determine the reservoir rock types from wire-line logs data in the Asmari formation of a heterogeneous reservoir in Iran.

The Asmari formation in the southwest of Iran is one of the most important reservoirs in the world. This formation is predominately a carbonate unit, but in the central area of the Dezful Embayment, it is a mixed siliciclastic and carbonate reservoir.

## Core Study

The core study approach was conducted on:

1) Sedimentological description of more than 2000 m of cores from 17 wells.
2) Microscopic study of more than 6000 thin sections from different cored wells.
3) Study of 16 samples from different reservoir rock types by Scanning Electron Microscopy (SEM).
4) Conventional core analysis of more than 1500 core plugs.
5) Mercury Injection Capillary Pressure (MICP), curve analysis on 16 core plugs.

## Mineralogy, Rock Fabric and texture

Thin section petrographical analysis were carried out to determine mineralogy, rock fabric, texture, pore geometry and distribution, grain characteristics, diagenetic features and sedimentary structures for more than 6000 side wall core thin sections from 17 wells.

For a detailed identification of the above characteristics, Scanning Electron Microscopy (SEM) analysis was carried out on 16 samples selected from various reservoir rock types of wells.

Based on the petrographic observations, the rock composition of the Asmari reservoir varies between siliciclastic and carbonate lithologies. In this reservoir quartz and dolomite are dominant minerals where calcite, anhydrite, clay minerals, potassium feldspar and iron oxides are among other abundant minerals. Carbonate rocks in the reservoir show a highly variable depositional fabric and texture. In the present study, the Dunham's (1962) classification, was applied. Fabric and textural characteristics in this method depend on the depositional environments and particle types. Most of petrophysical properties, such as porosity, permeability, water saturation, mercury injection and capillary pressure data depend on fabric and textural characteristics. Siliciclastic sediments show a relatively consistent depositional fabric. In the silicilastic rock study, the great emphasis was placed on textural attributes such as: grain size, sorting, roundness, puerility and maturity. Grain size is a highly variable and ranges in extreme cases between silt and very coarse sand grade. Sorting of various sediments ranges from poor to very well sorted with a mode of moderately well sorted.

### Porosity-Permeability relationship

The permeability-porosity relationship by means of cross-plots was studied for various rocks types. In summary graphs presented in Figures 1-2, permeability-porosity trends for siliciclastic and carbonate reservoir rock types were plotted together. The results from these cross-plots study reveal that the permeability of the sandstone (Fig. 1) is well defined by the porosity, whereas in the carbonate (Fig. 2) has a more diffused clouds which indicating to other major factors affecting the permeability. High porosities in carbonates can be observed that does not give rise to high permeability. This property of carbonates is well known as poor connectivity of the vugs.

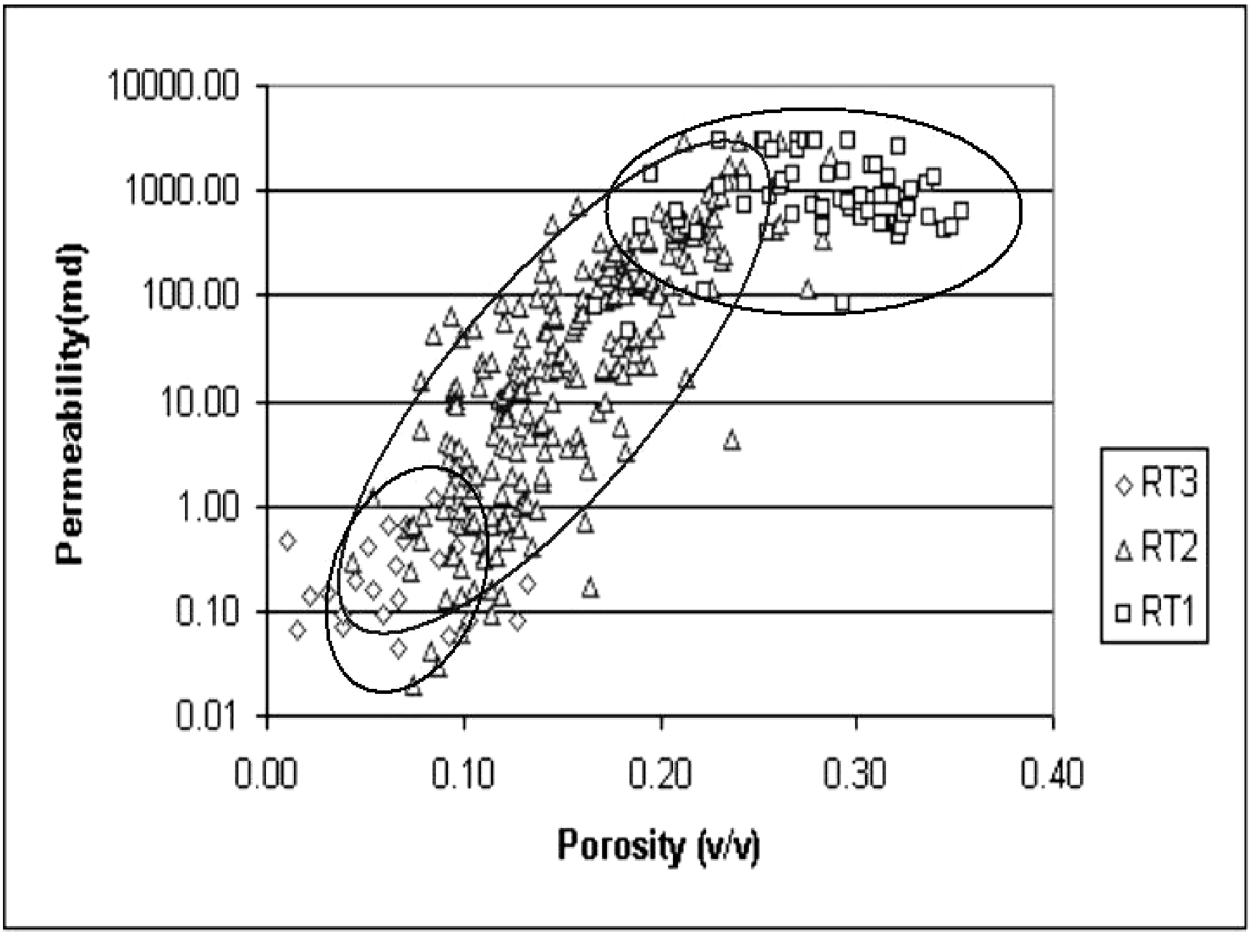

**Fig. 1. Permeability versus porosity, siliciclastic reservoir rock types.**

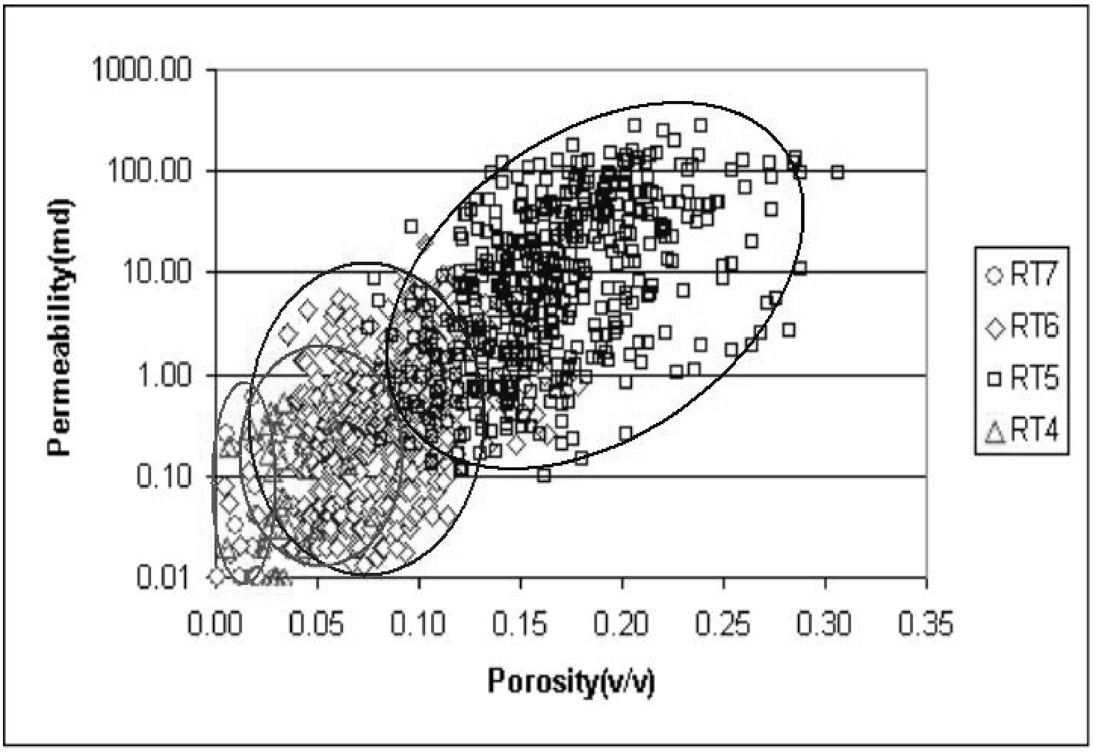

**Fig. 2. Permeability versus porosity, carbonate reservoir rock types.**

In the clay cemented sandstones, high porosity can be observed. This high porosity is mainly in the form of micro–porosity filled with chemically and physically (capillary) bound water, which is immobile. Since this high porosity does not take place in fluid flow, the permeability in the clay-cemented sandstones is low.

However the clusters of points for each reservoir rock type are not totally distinct from each other. The overlapping of depositional lithofacies in these graphs is probably caused by a number of factors including diagenesis, fracturing, similarity in pore structure produced by different depositional environment and the somewhat subjective nature of specifying reservoir rock type based on hand specimens.

## Mercury Injection Capillary Pressure Curves

Mercury injection capillary pressure (MICP) curves were applied to determine the pore geometry and the pore throat size of porous rocks in the reservoir. Sixteen samples, were selected, described, photographed and made into thin sections for mercury injection capillary pressure analysis. These samples were prepared from conventional core plugs when routine core analysis was carried out on them. The reservoir samples were converted from laboratory air/ mercury system to the subsurface brine/ hydrocarbon system of the reservoir then the mercury injection data was applied to the reservoir samples. MICP results and pore throat size curves for selected samples are shown in summary graph, Fig. 3, and summarized in Tab. 1. Capillary pressure data were applied to distinguish between reservoir and none-reservoir rocks, pay and none-pay, on the basis of none-wetting-phase saturations (see Tab. 1). This will be carried out by study of the displacement of capillary pressure curve, while pore throat radius was applied to categorize the rock by pore-type, e.g. nanno, micro, meso, macro and mega.

## Identifying Reservoir Rock Types in Cored Wells

Development of a rock–fluid model in the Asmari reservoir was carried out with the input data from the geological and petrophysical results. The results were applied to identify various reservoir rock types in the reservoir, poor reservoirs or non-reservoir rocks. A reservoir rock type is defined as an interval of rock with unique pore geometry, determined mineralogical composition and is related to certain specific fluid-flow characteristics.

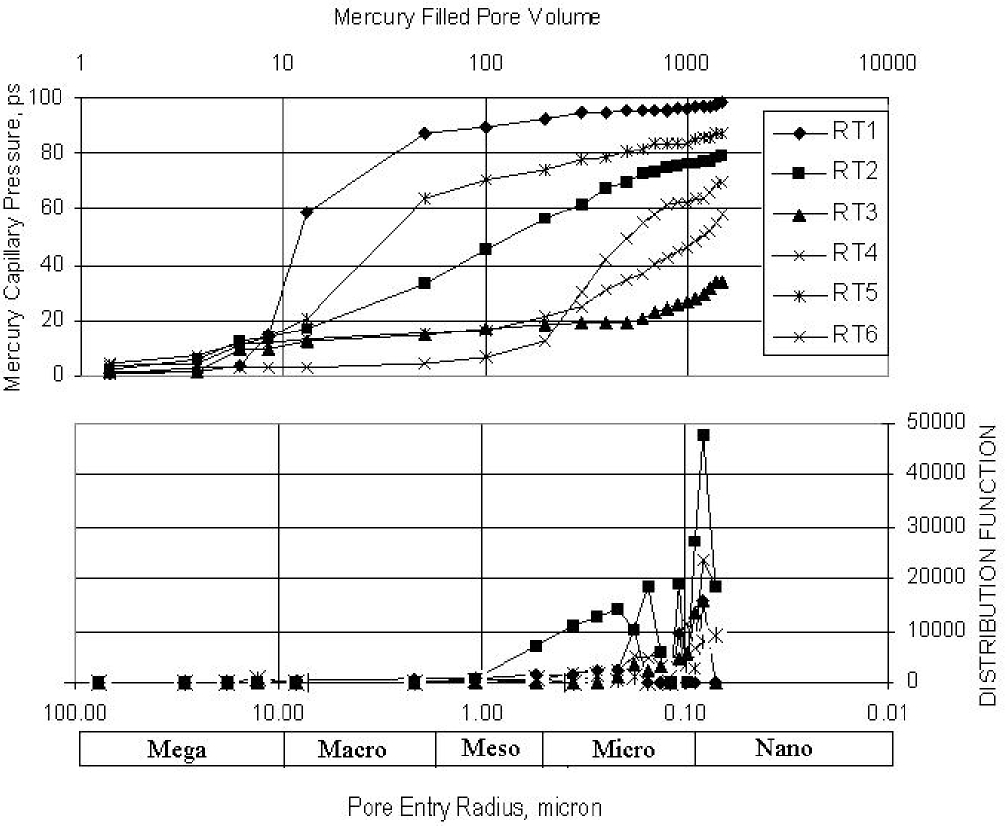

**Fig. 3. Capillary pressures, mercury injection curves show pore size distribution and mercury filled pore volume for various rock.**

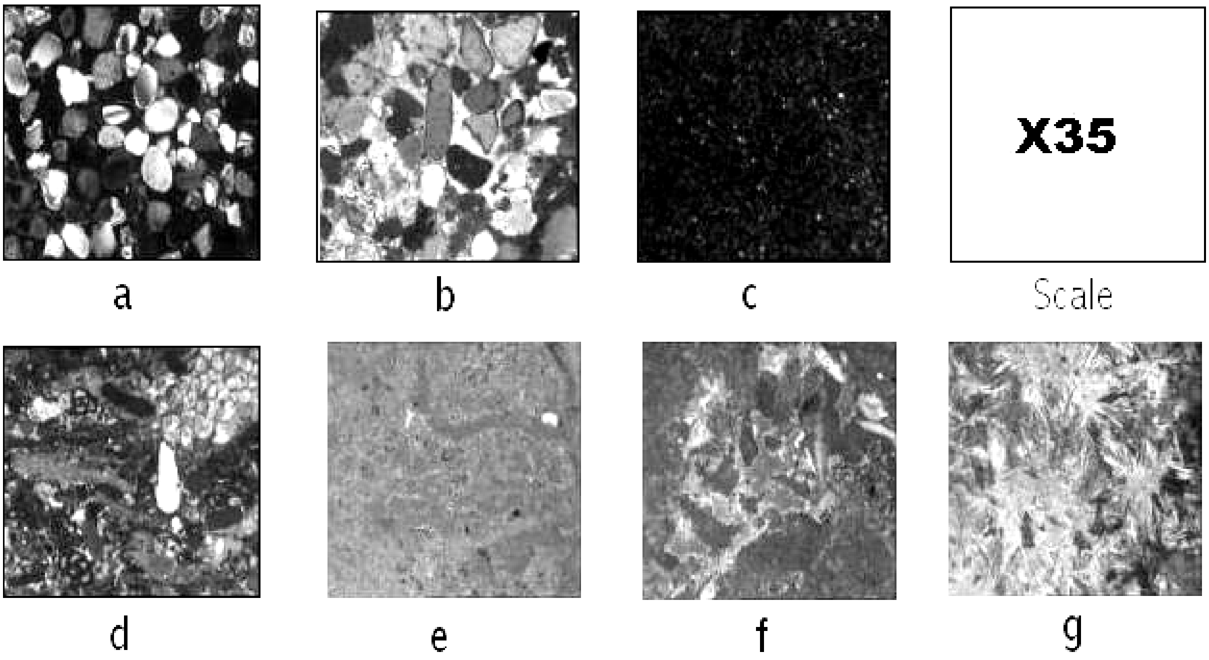

**Fig. 4. Thin sections photomicrographs showing: a- RT1: well sorted and well rounded fine grain clean sands. b- RT2: partially cemented subangular fine to medium grain sandstone. c- RT3: sandy and clay siltstone. d- RT4: Limestone with grainstone/packstone fabric. e- RT5: porous dolomite. f- RT6: sandy dolomite with anhydritic cement. g- RT7: anhydritic patches with chicken wire fabric.**

**Tab. 1. Summary of petrophysical and geological properties for various rock types.**

| ROCK TYPES / PETROPHYSICAL PARAMTERS | | RT1 | RT2 | RT3 | RT4 | RT5 | RT6 | RT7 |
|---|---|---|---|---|---|---|---|---|
| **LITHOFACIES** | | Frible to Partially Cemented Sandstone | Anhydritic Consolidated Sandstone | Claystone, Silticlaystone and clayey siltstone | Grainstone Packstone | Crystalline Dolostone/sandy Dolostone | Anhydritic Dolostone/ Sandy Dolostone | Nodular Anhydrite |
| **POROSITY CHARACTERISTICS** | Maximum Air Porosity (%) | 35.4 | 29.2 | 29.3 | 22.3 | 30.7 | 17.6 | 17.8 |
| | Minimum Air Porosity (%) | 12 | 1 | 0.4 | 0.2 | 1.9 | 0.4 | 0.1 |
| | Average Air Porosity (%) | 27.4 | 13.4 | 11.6 | 7.4 | 15.3 | 7.4 | 2.4 |
| | Air Porosity | Excellent | Moderately | Moderately | Fair | Good | Fair | Low |
| | Interparticle Porosity (%) | 95.8 | 84.6 | 100 | 29.3 | 9.9 | 9.7 | 50 |
| | Vuggy Porosity (%) | 4.2 | 14.1 | 0 | 42.7 | 65.4 | 72.2 | 0 |
| | Interaparticle Porosity (%) | 0 | 0 | 0 | 25.6 | 9.9 | 6.9 | 0 |
| | Moldic Porosity (%) | 0 | 0 | 0 | 1.2 | 11.1 | 6.9 | 0 |
| | Intercrystaline Porosity (5) | 0 | 1.3 | 0 | 1.2 | 3.7 | 4.2 | 50 |
| **PERMEABILITY CHARACTERISTICS** | Maximum Helium Permeability (md) | 3000 | 1243 | 63.3 | 233 | 577.72 | 41.53 | 23.25 |
| | Minimum Helium Permeability (md) | 2.15 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 |
| | Average Helium Permeability (md) | 690.04 | 81.73 | 7.08 | 4.31 | 23.32 | 1.83 | 0.83 |
| | Helium Permeability | Excellent | Good | Fair | Fair | Good | Fair | Low |
| **MICP CHARACTERISTICS** | C-factor (measure of pore sorting) | Medium | Medium | Good | Medium | Poor | Medium | Medium |
| | Sm (Unsaturated pore volume) | Low | Medium-High | High | High | Medium | High | High |
| | Pd (Entry Pressure) | Very Low | Medium | Medium | High | Low | High | High |
| | Pore Size Distribution (MICPM) | Meso-Mega | Micro-Meso | Micro | Micro-Meso | Micro-Mega | Micro-Meso | Nano-Micro |
| **RESERVOIR QUALITY** | | **Net Pay** | **Net Pay** | **None reservoir** | **None reservoir** | **Net Pay** | **None reservoir** | **None reservoir** |

The first attempt in this study was to apply porosity-permeability ratio criteria from the routine core analysis to classify the reservoir rock type. Then these criteria were compared with visual porosity and rock fabric characterized from microscopic studies in addition to the results based on log data. MICP curves were analyzed to confirm validity of the reservoir rock type classification. The capillary pressure data was also applied to distinguish reserveoir rock from none-reservoir rock and pay from none-pay. A better understanding of the behavior of capillary pressure curves will be achieved when it is integrated with the information provided by the thin sections and SEM micrographs. The reservoir rock porosity, permeability and pore throat radius ranges, by reservoir rock type are presented in Tab. 1. Fig. 4 show thin section photomicrographs from various rock types. Grain characteristics and pore filling materials for various rock types can be achieved from SEM photomicrographs presented in Fig. 5.

However, in this study seven reservoir rock types was designated and identified from RT1 to RT7 with individual pore geometries, mineralogy, and fluid-flow characteristics, in the Asmari reservoir. In addition, by applying these criteria, the reservoir was divided into seven zones.

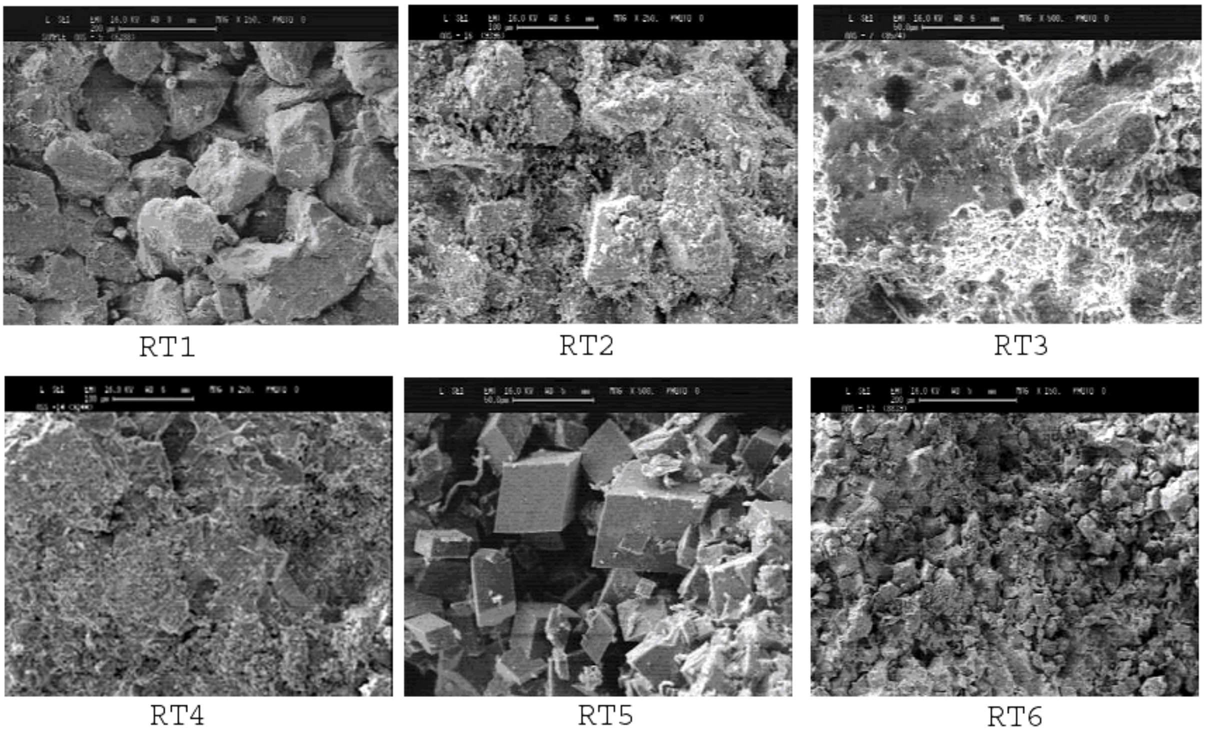

**Fig. 5. Scanning Electron Microscope photomicrographs showing grain characteristics (RT1, RT2 and RT5) and pore filling materials (RT2, RT3, RT4 and RT6).**

## Estimation of reservoir rock types applying Fuzzy Logic

Fuzzy logic is an extension of conventional Boolean logic (zeros and ones) developed to handle the concept of “partial truth” values between “completely true” and “completely false”. In contrast to binary-valued (bivalent) logic, truth is ascribed either 0 or 1, multivalent logic can ascribe any number in the interval [0,1] to represent the degree of truth of a statement. This is a normal extension of bivalent logic, and it is a form of logic that humans practice naturally. Zadeh introduced it in the 1960's as a means to model uncertainty.

More common use of fuzzy logic is to describe the logic of fuzzy sets (Zadeh 1965). These are sets that have no crisp, well-defined boundaries, and which may have elements of partial instead of full membership. For fuzzy sets, elements are characterized by a membership function that describes the extent of membership (or the degree of fit) of each element to the set. Such a membership function maps the entire domain universe to the interval [0, 1].

Fuzzy mathematical techniques have been applied to solve various petroleum engineering and geological problems in the past, involving mainly classification, identification, or clustering. Toumani *et al.* (1994) used fuzzy clustering to determine lithology from well logs in Upper Carboniferous coal deposits of the Ruhr basin. Cuddy (1997) used fuzzy logic to predict permeability and lithofacies in uncored wells to improve well-to-well log correlations and 3-D geological model building. Saggaf & Nebrija (2003) used fuzzy logic approach for the estimation of facies from wire-line logs in a field in Saudi Arabia.

## Application to well data

The Fuzzy Logic inference method was applied to identify and determine the kind of reservoir rock type in the uncored wells based on data from wire-line logs in the Asmari-reservoir. Reservoir rock type determination applying the Fuzzy Logic is based on the fact that a known reservoir rock type can give any log reading although some readings are more likely than others. In this method several conditions based on wire-line data were applied to determine the reservoir rock type and reduce the uncertainty of the determination. As an example, two reservoir rock type will be discussed here, partially cemented sand (RT1) and shaly sandstone (RT3). Partially cemented sand has most likely high porosity and low gamma ray radiation while shaly sandstone has low porosity with high gamma radiation.

It is obvious that the Fuzzy Logic inference is not just a simple probabilistic method. It is based on measured data.

The membership functions are based on determination of reservoir rock type applying the wire-line data and core description. The core determinations were derived from examination of known reservoir rock type of cored wells in the area. These membership functions will be applied to identify the reservoir rock types in an uncored well by means of wire-line log. There is no limitation on the number of input logs in this method. However, the additions of further curves may not reduce the uncertainty of the determination of reservoir rock type, but, it is important to have a consistent set of logs in all wells. A sensitivity study was carried out based on five selected logs due to their relative importance in rock typing. These logs are: gamma ray (GR), effective porosity (PHIE), neutron porosity (NPHI), density (RHOB) and sonic (DT). The membership distribution for effective porosity log in RT1 and RT6 as an example are presented in Fig. 6. The membership functions were calculated from the logs and core-derived reservoir rock types in four cored-wells (B, C, D and E). In order to test the uncertainty of the determination of reservoir rock type by Fuzzy Logic method the cored-well A was selected and core data from other wells were applied in this well. The core description in this well was applied for a comparison with the result from the Fuzzy Logic and calibration of the input data of the method. The core-derived determination of reservoir rock types from well B displays in the last track of Fig. 7 while the Fuzzy Logic determination displays in the last but one track. The logs of the test well A were passed through the Fuzzy Logic inference system to determine the reservoir rock types in this well. This determination was compared with core description from this well (see Fig. 8). The determination of reservoir rock type based on the Fuzzy Logic is in agreement with the result from core analysis. This comparison between two methods reveals a good to very good results. The core analyses from 5 cored-wells were applied to determine reservoir rock types in 28 uncored wells with the geometry of the reservoir to construct a representation of the initial (static) state of the reservoir, having a specified resolution, quality and accuracy. The section is shown in Fig. 9, represents the estimated reservoir rock types over the whole field applying a geostatistical method.

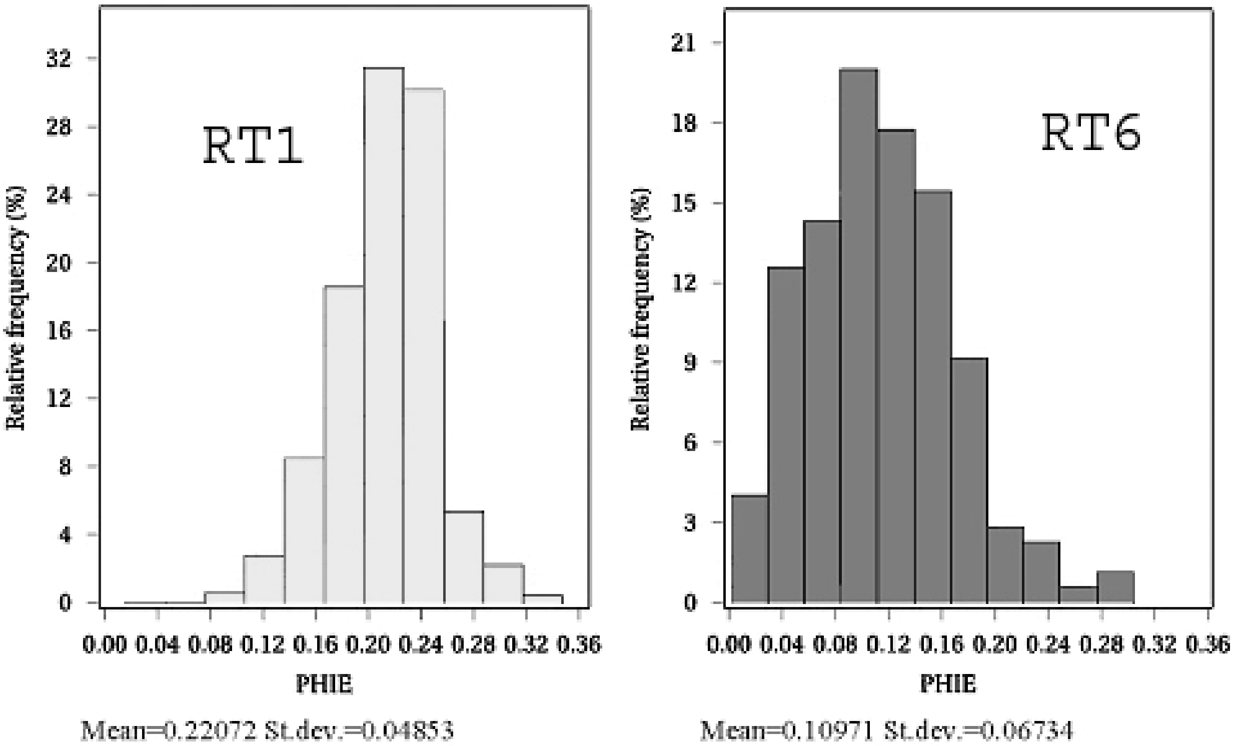

**Fig. 6. Membership distributions for porosity log in RT1 and RT6, examples of reservoir and none reservoir rock types.**

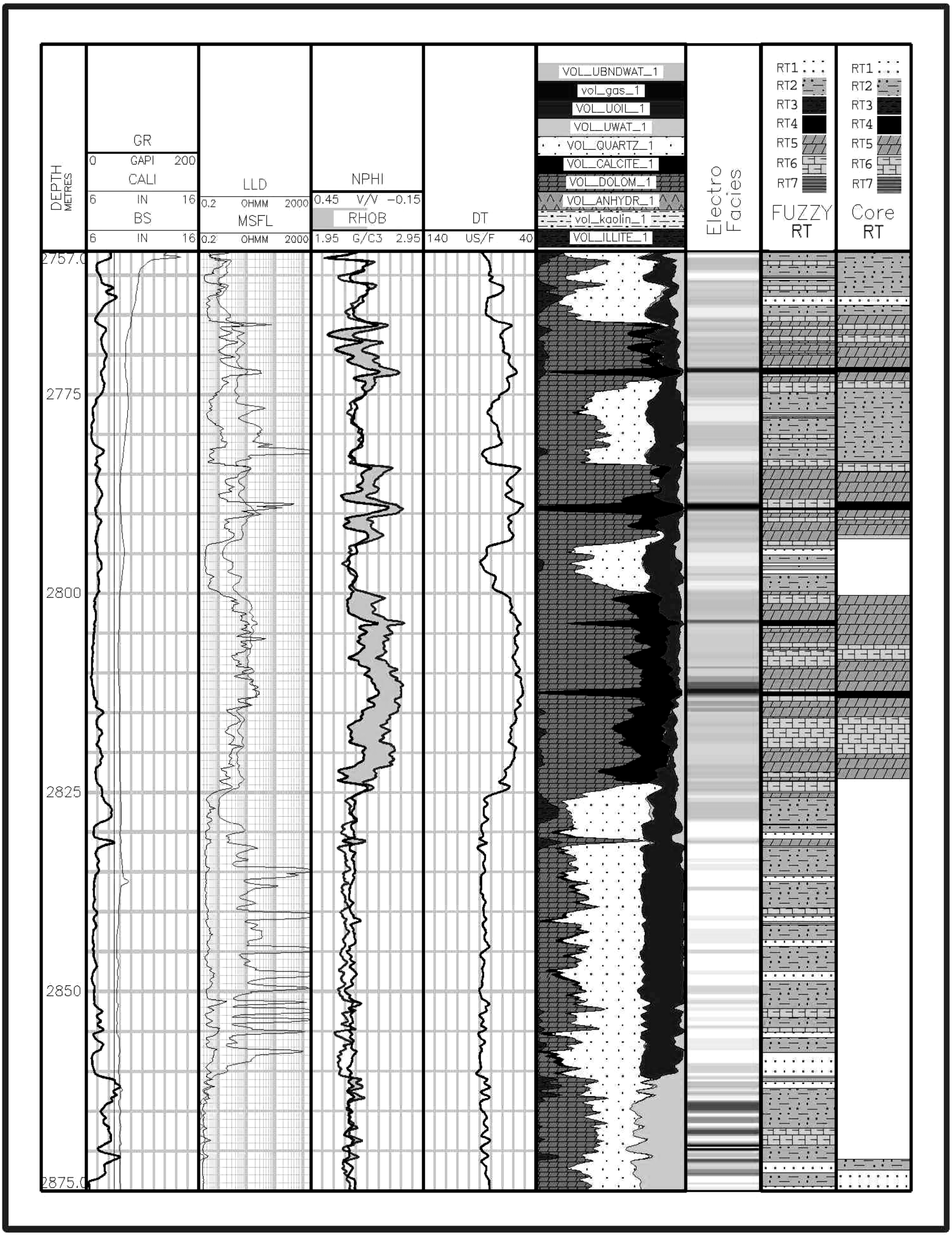

**Fig. 7. Comparison of the reservoir rock types determination between the Fuzzy Logic inference method and reservoir rock type determination based on core analyses, the two last tracks. The first six tracks represents log data and interpreted lithology and facies, respectively.**

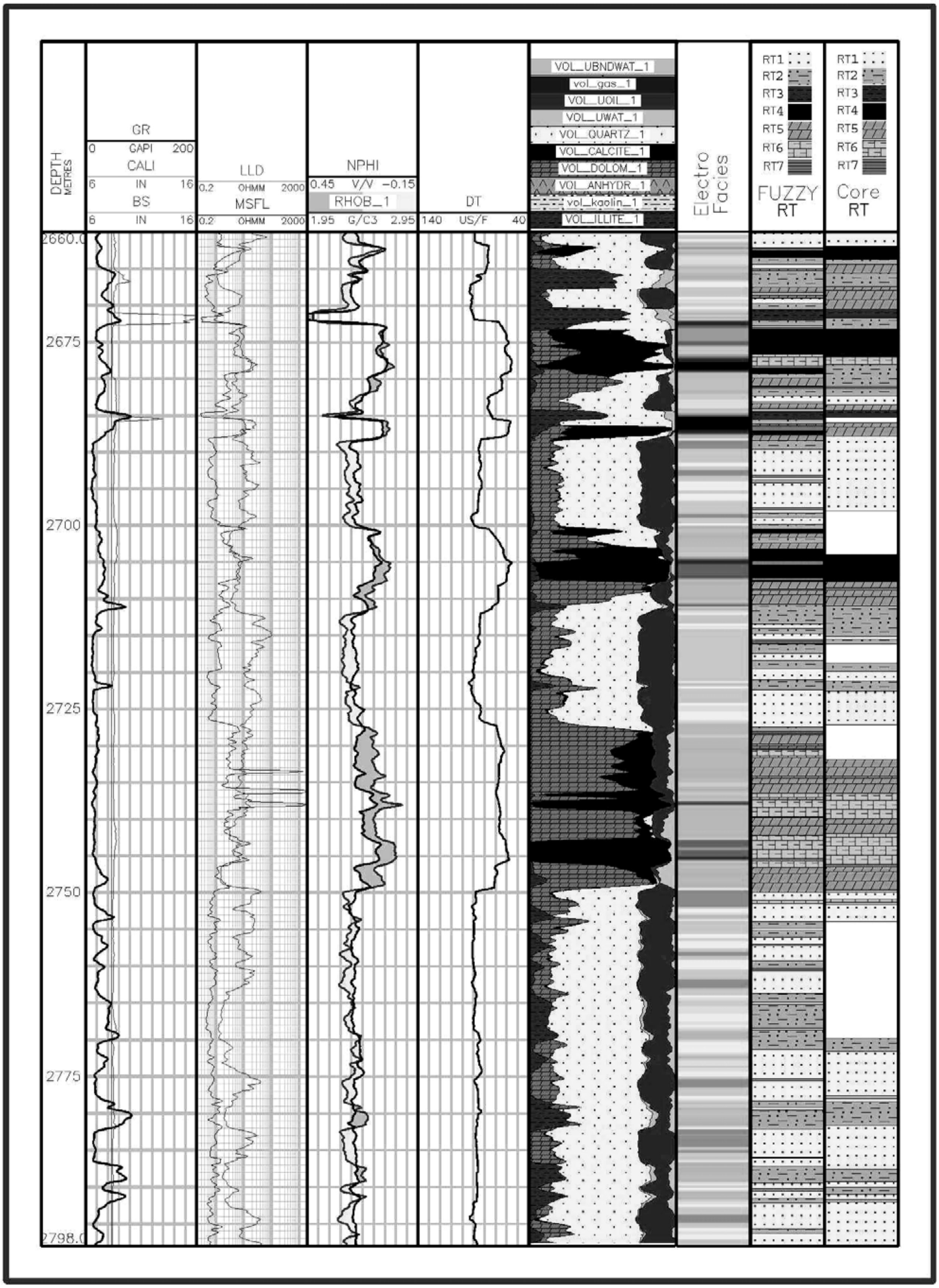

**Fig. 8. Blind-testing prediction in the test well A.**

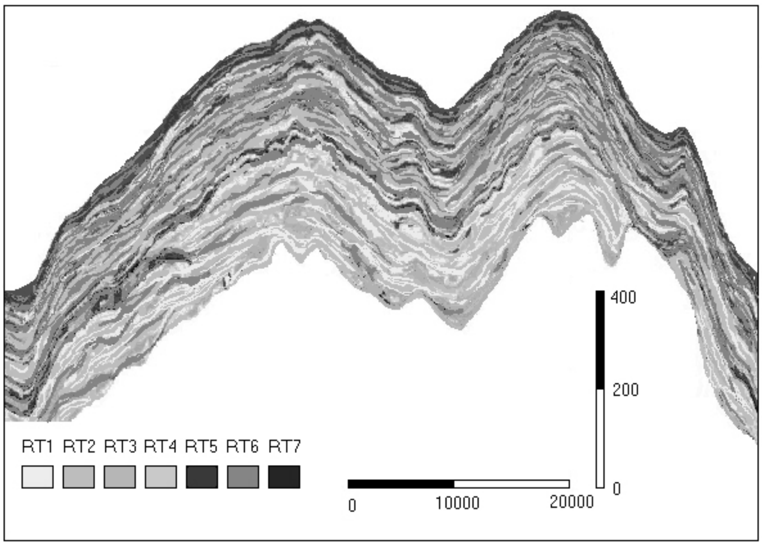

**Fig. 9. Cross section showing estimated reservoir rock types over the field.**

## Conclusion

High uncertainty occurs when the determination of the reservoir rock type in an uncored well will take place. Rock typing was applied for well correlation and as input data to build a 3D model of the reservoir. In this study an intelligent method was applied for rock-type analysis through the integration of core, conventional open-hole logs and geological data.

The Fuzzy Logic is inherently well suited to characterizing vague and imperfectly defined knowledge, and it can thus yield a simple and more accurate description. The Fuzzy Logic inference system allows an engineer to incorporate his basis and previous knowledge and experience, as well as general engineering principles and notions, into the inference process. Application to well data indicates that the method can determine the reservoir rock types of uncored wells with a good accuracy that rivals those of other methods, such as methods based on statistics. This method can be applied to reduce the uncertainty of determination of the reservoir rock type or as a very good predictor in uncored wells.

Applying this method requires only the standard electronics logs such as porosity and density than complex and special logging system.

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