AAPG Annual Meeting
March 10-13, 2002
Houston, Texas

Automated Facies Estimation from Integration of Core, Petrophysical Logs, and Borehole Images

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Introduction

This study represents a robust approach that integrates log characteristics and textural signatures from image data in a pragmatic facies classification validated by core. The objective is to integrate information from core with conventional logs and borehole images through a neural network system. This provides a facies database that can be used to predict facies from log measurements in adjacent uncored wells. The present study was done on a well in the Sabriyah Field in the Mauddud Reservoir of Kuwait. Conventional porosity logs, textural information from Combinable Magnetic resonance (CMR*) pore size data, and borehole image (Fullbore Formation MicroImager - FMI*) derived heterogeneity curves were used as inputs in the neural network application *RockCell**. The results were successfully calibrated with eight dominant core derived-facies described over the reservoir section based on Dunham's classification. Several networks were trained iteratively and the one with the least training/cross validation error was selected for facies estimation over the entire logged interval. The resulting log derived facies is validated with the core-derived classification, illustrating the feasibility of this technique.

Facies Analysis and Reservoir Heterogeneity

Borehole imaging tools are being more widely used for visual texture and to identify rock types. The high vertical resolution of the resistivity imaging tool *FMI** permits detection of subtle variations in the rock fabric due to changes in conductivity. The borehole image analysis application *BorTex** quantitatively describes these images and relates this to a description of reservoir heterogeneity. Conventional porosity and lithology logs, pore size distributions from Nuclear magnetic resonance logs, in conjunction with

BorTex outputs can be used to zone a reservoir section into a number of facies or texturally consistent zones. The neural-network application *RockCell* is used to create a database of these logs, NMR and FMI texture consistent intervals and relate them to facies types. For example, a carbonate texture could be described as layered or massive with strong diagenetic imprints and porosity types can be attributed to vugs, moulds, karsts, inter or intra-particle porous patches resulting from diagenesis, bioturbation or preferential cementation. Being resistive, the dense limestone areas or porous section with residual hydrocarbon have lighter shades on the images, and shale, mud invaded porous rocks, vugs, and moulds have darker shades.

BorTex processing involves iterative runs to optimize the parameters used for extraction of textural information from the images and the results are validated by visual examination of the FMI images. The final outcome is a heterogeneity map of the borehole wall in terms of conductive and resistive events. The results of FMI image-derived heterogeneity analysis are depth-indexed continuous curves for the proportion and size of each type of formation heterogeneity. The proportions of resistive spots are picked in dark blue while the large resistive patches are designated in cyan (see figures 1 and 2). The conductive events are further classified into three types, large patches, connected spots, and isolated spots. Their proportions are displayed in different colors along the images as magenta, red, and orange respectively (see figures 1 and 2). These curves are averaged over 1.0 ft window and output at 6 inches to be consistent with other conventional logs.

Facies Analysis Work Flow

The BorTex *processing was carried out on the FMI images to extract the textural information of the formation heterogeneity. The core was described using Dunham's classification to reflect the texture of the carbonate formation.* RockCell, *neural network classification and estimation technique was then run for a comprehensive albeit automated facies delineation. Conventional open-hole logs, pore size distribution (Micro-Texture) from NMR logs, and the FMI image-derived (Macro-texture) curves from* BorTex *were used as inputs in the neural network facies classification scheme. The* RockCell *interpretation module comprises of the following steps:*

1. Model Generation:

   Intervals representing various key open-hole based lithology/porosity data, NMR pore size distribution, core based textural facies, and FMI image based macro-texture are selected as inputs to generate a model.
2. Network training:
   The model is then used to train a network relating the designated facies to the log signatures.

3. Facies Estimation:
   Final phase is to assign the most likely facies to the entire logged interval and generation of a facies probability log.

For the present well the facies categorization that were made are textural or morphofacies from images, electrofacies from the conventional open-hole logs, and micro texture from the NMR data. The morphofacies classification using *BorTex* was made based on the proportions of conductive and resistive events/heterogeneities of different size and connectivity. To derive this type of classification the neural network was trained to identify isolated conductive spots, connected conductive spots, large conductive patches or events, resistive spots, and resistive patches. For open-hole log derived electrofacies, the neural network was trained for conventional open-hole logs (gamma ray, neutron porosity, density, compressional sonic, CMR pore size bins, total CMR porosity, and CMR permeability logs.

Facies Description

Eight characteristic rock types were identified based on core observations and are consistent with the facies descriptions used in the Mauddud Reservoir. They are Mudstone (Mb/Ml), clay bearing skeletal Wackestone (Lwc), clean Packstone (Lpb), glauconitic Packstone (Lpgl), skeletal Packstone (Lpc; profuse and diffused clay bearing), bioturbated/laminated skeletal/peloidal Grainstone (Lgb), bioturbated Sandstone (Sb), and laminated Sandstone (Sl).

The typical FMI, NMR log response, and core appearance for a typical grainstone and packstone facies are presented in figures 1 and 2. The calibration of the core-based lithological facies and FMI image-derived facies has been the basis for launching the log-based neural network facies analysis. Based on the dominant heterogeneity type and CMR pore size distribution characteristics the eight facies are summarized in Table 1. The salient sedimentary features based on FMI image appearance/core description characterizing the unique nature of these facies are also included.

Conclusion

This study presents a novel automated approach for high-resolution facies analysis through the integration of core, NMR, conventional open-hole logs, and wellbore images. This neural network facies modeling technique has great potential in estimating facies in uncored wells to assist in establishing the stratigraphic model across a field.

Facies	*BorTex* **Heterogeneity**	**Sedimentary Structure from Image**	**CMR T2 Distribution Pattern**	**CMR Bin Porosity**
Mb/ML	Conductive and resistive events forming alternate bands	Laminated	Mostly low amplitude bimodal, with restricted distribution halfway to the left; well sorted pores	Mostly micro to clay sized pores
Lwc	Alternate resistive and conductive events with pronounced resistive spot. Subequal proportion of conductive patch and conductive connected spot	Bedded	Very low amplitude bimodal with first mode corresponding to small pores with micro to clay sized pores. Moderately sorted pores	Finer size classes predominant with common small and some medium pores
Lpb	Subequally distributed resistive spots and patches with significant proportion of conductive heterogeneities	Isolated to diffuse nodules floating in dendritic conductive channels	Broad based, low amplitude, centered unimodal with occasional insignificant 2nd mode. Poorly sorted pores	Subequal distribution of small, micro, and clay sized pores with some medium to rare large pores
Lpgl	Patchy distribution of conductive and resistive events with pronounced resistive spots	Massive to irregular lamination	Broad-based, centered, low amplitude, bimodal to plateau-top unimodal; moderate to poor sorting of pores	Subequal distribution of small, micro, and clay sized pores with minor medium pores
Lpc	Subequally distributed resistive and conductive events	Patchy/nodular	Broad-based, very low amplitude, unimodal distribution at the center trailing to the left; moderate sorting of pores	Subequal distribution of micro and small pore size with consistent clay sized pores
Lgb	Subequal resistive spots and patches	Massive with irregular	Almost bimodal with insignificant second mode. Medium	Subequal proportion of different size classes indicating

		wavy resistive stringers	amplitude skewed to the right; poorly sorted pores	poor sorting
Sb	Predominant resistive events with common conductive spots	Well laminated	Mostly bimodal, very low amplitude with restricted distribution to the extreme left with occasional small and medium pore size classes; moderate sorting of pores	Clay sized pores predominate with other pore sizes only at the top forming a small coarsening upward cycle
Sl	Alternating resistive and conductive events with high proportion of resistive spots and conductive patches	Very well laminated with occasional cross lamination	Broad based bimodal, medium amplitude with occasional 3rd mode; very poor sorting of pores	Subequal distribution of different size classes indicating very poorly sorted pore size distribution

Table 1: Detailed description of identified facies namely Mudstone (Mb/Ml), Wackestone (Lwc), clean Packstone (Lpb), glauconitic Packstone (Lpgl), skeletal Packstone (Lpc), Grainstone (Lgb), bioturbated Sandstone (Sb), and laminated Sandstone (Sl) in the control well.

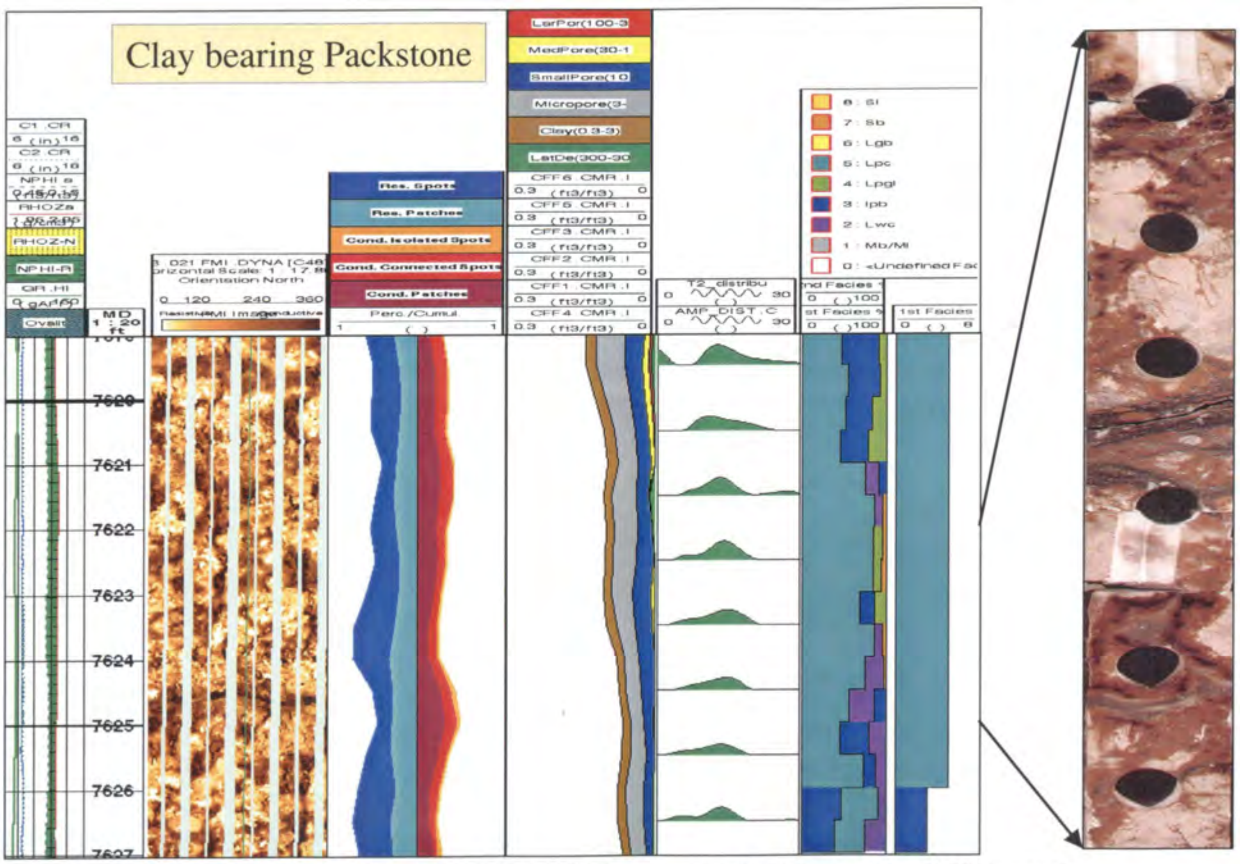

Figure 1: Typical FMI image, open-hole logs, proportion of conductive versus resistive heterogeneities, CMR bin porosity, T2 distribution, and core example defining Facies 5, Clay bearing Packstone. This facies is commonly skeletal with diffused/ pronounced clay mostly concentrated into compactionally modified partings. Black arrows represent tie points between image and core.

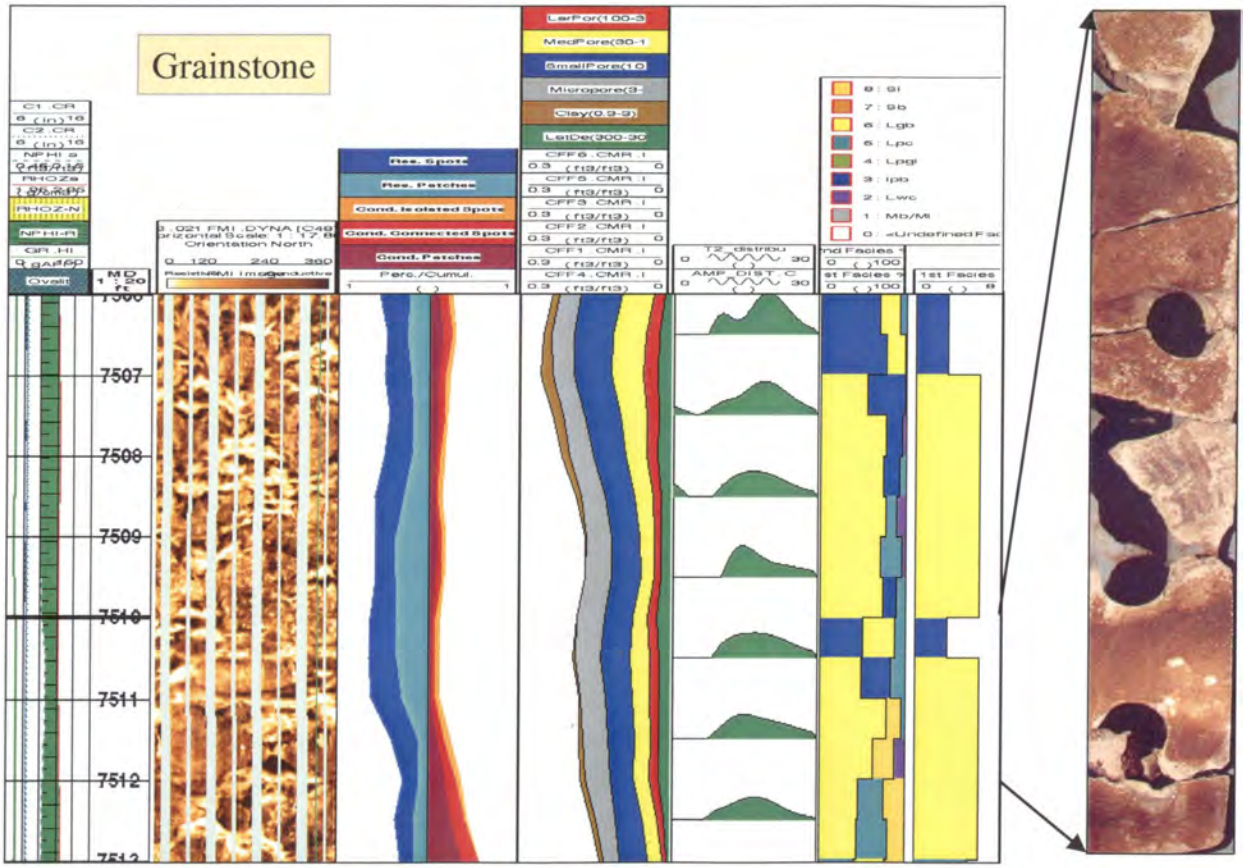

Figure 2: Typical FMI image, open-hole logs, proportion of conductive versus resistive heterogeneities, CMR bin porosity, T2 distribution, and core example defining Facies 6, Grainstone. It is characterized by skeletal, peloidal limestone with occasional bioturbation and rare lamination. Black arrows represent tie points between image and core.