A DENSITY-BASED IMAGING TECHNIQUE TO SUPPLEMENT FMI IMAGES FOR SEDIMENTARY FACIES MODELING

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Abstract

Formation Micro-Imager (FMI) logs provide a detailed image of the rocks on all sides of the wellbore by measuring resistivity. The high-resolution FMI logs provide valuable information regarding bedding surfaces and bed boundaries. Typically FMI images are combined with conventional log analysis data for sedimentary facies recognition and modeling. However, there is always some uncertainty surrounding the interpretation of FMI images and from time to time it is needed to validate the results by comparison with core data. Visual description of the surface of the core is not always sufficient to compare against the FMI data since some heterogeneous features impacting the FMI data may not be obvious enough in visual inspections. For several years Computerized Tomography (CT) has been used by the industry as an effective non-destructive tool for reservoir characterization. A CT-scan slice represents a two-dimensional disk of mostly electron density data (depending on X-ray energy used) at each scan location in the core. By combining several slices, it is possible to reconstruct the whole core in three-dimensions. This paper discusses the development of a practical algorithm for extracting data from near the external surface of the three dimensional density based images for comparing against the corresponding FMI logs. Practical applications of this technique proved to be extremely useful in characterizing some of the interesting facies in a Lower Aptian reservoir in the Middle-East.

Introduction

Cores collected during the exploration and development phases of carbonate reservoirs provide very important petrophysical, paleontological, sedimentological, petrographic, and diagenetic information. Unfortunately, prior to a thorough examination of the cores, they are typically damaged by plugging and slabbing activities, both of which may spoil the original fabric of the identifying fossils and possibly lead to inaccurate interpretations of the depositional facies.

A Lower Aptian carbonate reservoir in Saudi Arabia was recently developed with several horizontal and vertical wells. While coring was limited to only a few vertical wells, an extensive logging program was used to get maximum amount of information from each well. Rudist fossils from this reservoir have been used to aid in the interpretation of the lithofacies and reservoir facies in uncored horizontal development wells. The rudists are sufficiently large fossils that they provide well developed and easily identified images on CT-scans of cores (see Figure 1). Their CT images, combined with the core-based fossil information, can be used to interpret the images represented on the FMI logs. This procedure is important because the various rudist species are known to have preferentially occupied different environments during the deposition of these carbonates. Ongoing studies are involved in refining the interpretation of the depositional regime in such wells, as there are significant associations between depositional and reservoir facies. The ultimate goal of this work is to combine core description and CT techniques to improve the understanding of the depositional behavior in carbonate reservoirs to improve the interpretation by FMI logs, especially in horizontal wells.

Formation Micro-Imager Logs

Image logs are resistivity or acoustic devices that measure certain physical properties of the rock at or near the well that can be displayed as images of the wellbore, which can then be interpreted on a computer. Typically rock properties are controlled by factors such as variations in composition, diagenesis, grain size, grain orientation, pore fluid variations, etc. Image logs can provide detailed picture of the wellbore that represent the geological and petrophysical properties of the section being logged. In the late 1980's Schlumberger introduced the concept of borehole electrical images by processing variations of the shallow microresistivity of wellbore walls recorded by modified versions of its Stratigraphic High Resolution Dipmeter Tool™. Called the Formation Micro-Scanner™ (FMS), the tool measured closely spaced arrays of focused shallow resistivity readings that are related to changes in rock composition and texture, structure, and fluid content [Serra, 1989]. Processing the data, in which a range of colors are assigned to the lateral (side-to-side) and vertical variations of the microresistivity along the wellbore, produces an image of the borehole wall.

The current generation of tools, called the fullbore Formation Micro Imager™ (FMI), records an array of microresistivity measurements from 192 sensors on eight pads mounted on four orthogonally placed caliper arms. The spacing and position of the pads provides 80% coverage of an eight-inch diameter hole and a resolution of 5 mm. Other oil field wireline service companies have since developed similar high-resolution electrical borehole imaging tools. The FMI yields a continuous, high-resolution electrical image of a borehole (color-coded for resistivity values), and therefore complements whole cores cut in the same well. If the FMI-derived image is of sufficient quality and calibrated against the core, it can provide a continuous survey of the formation in places where core is not cut, there was no core recovery, or when a core has been damaged through handling, transportation, or plugging.

CT-Scanning

Since the early '80s CT-scanning has been used as an effective tool for evaluating reservoir cores. A CT-scanner can generate an image along any slice plane of a core. Several CT-scans at adjacent slice planes can give a three-dimensional picture of the entire core. Because the CT-scanning is non-destructive, it is attractive to geologists and reservoir engineers alike, as the integrity of the cores is not compromised during the scanning process. Using CT, the bulk density and lithology differences in a core can be determined. CT number, the parameter measured by all medical-based CT-scanners, is a relative scale of attenuation coefficients (uses the value of -1000 for air and 0 for water). For a properly calibrated artifact-free system, the CT number generally varies linearly with the bulk density of a rock. Details of generating artifact-free CT data, suitable for quantitative research can be found in the literature [Hunt et al., 1988; Vinegar and Wellington, 1987]. CT-scanning has been used at Saudi Aramco for almost 10 years, mainly for selection of appropriate SCAL plugs. Currently CT-scanning is used more and more for integrated core-log activities such as detailed core description, core quality assessment, lithology identification, heterogeneity determination, etc. As CT-scanning of preserved cores is the very first operation conducted on the cores, the three-dimensional density data generated remain available for any future qualitative and quantitative use, even if the core becomes subjected to extensive slabbing and plugging.

Density-Based FMI-Type Images Using CT

In addition to generating slice images, a typical petrophysical CT-scan software would only generate slab images, orthogonal with each other, along the length of the core. For comparing

CT-data against the FMI data a special algorithm was developed. First, the data corresponding to each core tube were read and converted to bulk densities using suitable linear transforms applicable to that well. Then the slices were aligned with one another and using a circular region-of-interest tool, the largest possible circle (i.e. near the periphery) was drawn within the core material on each slice. The software was then programmed to read all the density values on the circle and plot them on a two-dimensional plane. Each slice was represented by a thin strip of density data corresponding to the thickness of the X-ray beam passing through the core. The next step involved stacking the data and attaching depths to them. The core depths must be shifted to match with log depths using gamma-scan or similar procedures, without which the comparison with FMI logs will not work very well. This way density-based FMI-type images can be generated for comparison with the actual FMI logs.

Results

A total of eight cores (about 60 ft each) were cut from a vertical well in the Lower Aptian reservoir studied. Each core was cut into about 22 short pieces (about 2.8 ft each), each of which was than preserved in brine inside a larger PVC core tube. The well was then logged using conventional logging tools as well as the FMI. After depth shifting the core data, the CT slices can be placed side by side with the FMI images to reveal the details of features seen by FMI images. Figure 2 shows the potential of CT slices to properly capture various features seen in the FMI images. A section containing the rudist bearing part (mostly in Core #2) of the reservoir was chosen for detailed study. Figure 3 is an FMI image of the section representing Core #2, and Figure 4 is a montage of all CT slices corresponding to the 22 core tubes from Core #2 out of which the 12 lowermost tubes showed rudist-like features. After confirmation from the surface data during physical inspection, these 12 core tubes were selected for detailed studies using CT. Until recently, the application of CT in this reservoir has been focused on the engineering aspects, with scanning done at the classic 2-inch spacing. For this detailed study however, a 5-mm spacing, with a 5-mm beam width, was used to provide full coverage of the 12 core tubes. Virtual vertical sections through each core tube using this technique become far more accurate. Figure 5 shows the CT-scan slices from the detailed study (5-mm spacing) for Tube #1 of Core #2.

Figure 6 illustrates a comparison between the core, CT scan and FMI images to illustrate the images related to the vertical distribution of macrofossils in the reservoir studied. The two FMI images (A) illustrate a "wrap-around" pseudo-core view of Tube #1 in an attempt to closely compare the FMI log with the core photograph (B). Four individual FMI logs for each receiver pad are included (E). The FMI color scale presents a range of resistivities from conductive (black) to resistive (white). Two CT scan synthetic vertical images or slabs (C), at 90º have been colored to closely match the FMI tones and a density-based FMI-type image or a pseudo "wrap-around" view (F) has also been generated. The rudists are clearly depicted as highly resistive (light toned) features, and the elevator habit of one of the varieties, as identified in the core, is clearly seen. The critical advantage of the FMI log is clearly evident in this example as additional information is provided over the section where actual core coverage is incomplete. Once calibrated in this way, rudists in elevator growth position can be clearly recognized and confidently used to infer a particular depositional environment.

Conclusions

A practical functioning algorithm was developed for extracting data from near the external surface of the three dimensional density based images for comparing against the corresponding

FMI logs. The combination of CT slice, slab and FMI-type images along with core photos and actual FMI logs were successfully used to discriminate various types of rudists in a Lower Aptian reservoir and to get valuable supplementary information on the depositional environment by discriminating in-situ from displaced assemblages of rudists [Hughes et al., 2002]. Their identification in the horizontal well FMI images should provide important contributions to the interpretation of the three dimensional distribution of various lithofacies and their associated reservoir facies, that can be used to develop and improve reservoir models.

The use of core and CT scan - calibrated FMI logs in cored vertical wells is providing valuable assistance to facies determination in the horizontal, uncored development wells where conventional logs cannot yet provide such information. From detailed geological work we can sometimes get good slab images but lot of information is either lost or may not be seen. By combining CT-scan slice and FMI-type logs together, we can derive maximum amount of information from a core. Another advantage is that a series of such images can be generated for any number of circular sections, which may be useful for cores contaminated near the surface with barite mud, filtrates, etc.

Acknowledgments

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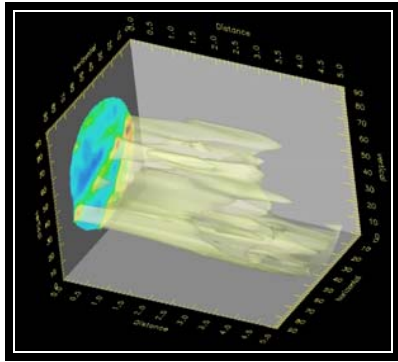
Figure 1: A CT-scan generated three-dimensional image of a rudist inside a small (1-1/2" diameter × 2" long) core plug from the Lower Aptian reservoir studied.
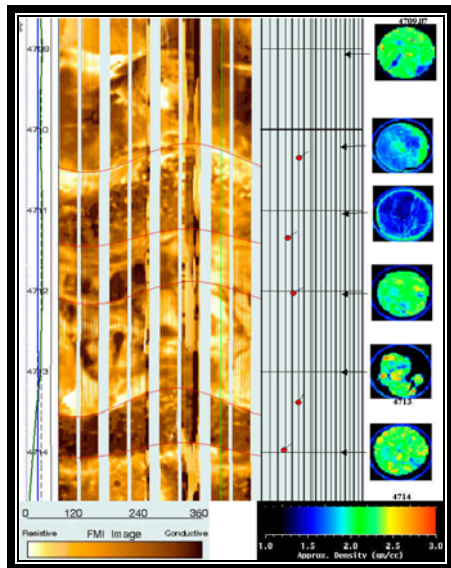

Figure 2: Comparison between FMI images and CT-slices. The effect of dipping is slightly evident in the second slice from the top.
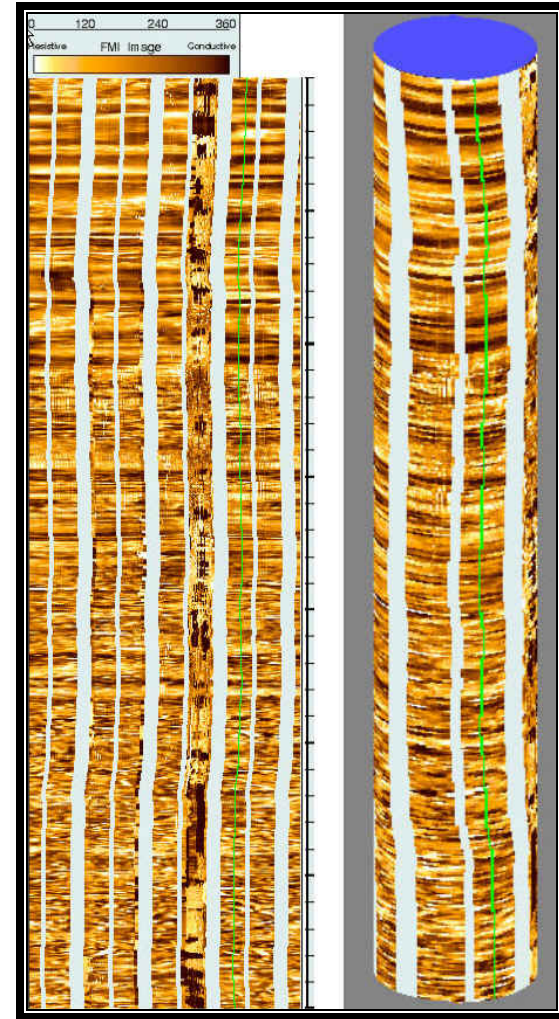

Figure 3: FMI image of the 60 ft section representing Core #2. On the left, a dynamic FMI image, on the right, a "Core View" simulating a core. The FMI color scale presents a range of resistivities from conductive (black) to resistive (white).
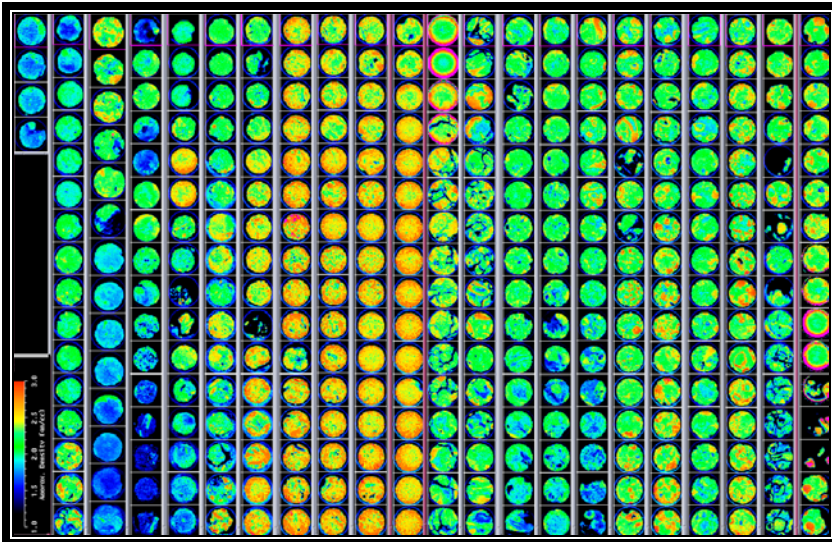
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Figure 4: A composite image showing the density variations in Core #2 (dark blue representing low-density; red and orange representing high-density) as seen by CT. The circular CT slices (2" apart from each other) are generated by scanning 22 core tubes, each represented by a column containing a maximum of 16 slices. The depth increases from top to bottom, in each column, then from left to right. The occasional red rings represent artifacts caused by steel reinforcements in the fiberglass tubes.
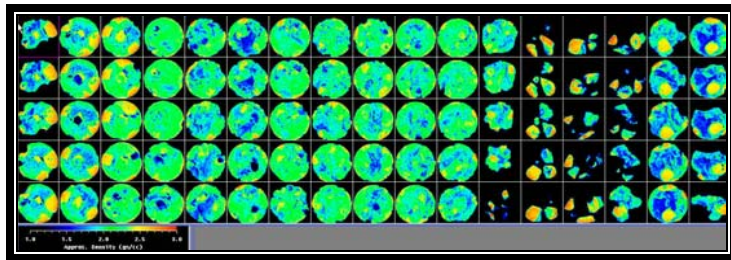

Figure 5: Detailed CT-scan slices (5-mm spacing, 5-mm beam width) of Tube #1 from Core #2 showing the rudists (yellow). The depth increases from top to bottom, in each column, then from left to right.
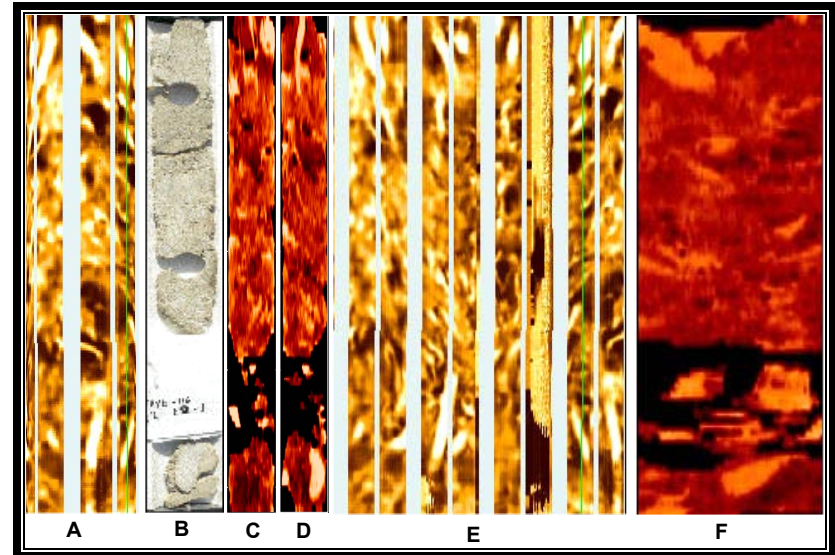

Figure 6: A montage of the images from Tube #1 of Core #2. A and E are FMI images. The FMI color scale presents a range of resistivities from conductive (black) to resistive (white). B is the core photograph. C and D are orthogonal reconstructions (CT-generated slabs), and F is the CT-generated density-based FMI type log, presented as a cylinder opened and displayed in two dimensions. Here the CT-scan color scale in C, D and F represents a range of computed densities from zero (black) to high (light orange).