Calculating Permeability from FMI Images in Oil Sand Deposits

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This paper presents a methodology to calculate vertical and horizontal permeability curves from FMI images in Oil Sand deposits. First, a sand / shale indicator model is calculated from the FMI image. Then, sequential indicator simulation is used to calculate a realization that is conditional to the 2D cylindrical sand / shale indicator model. Then, a 3D permeability model is calculated using the porosity and Vshale values from local windows of data. Finally, vertical and horizontal permeability curves are calculated from the 3D permeability model.

Introduction

Fullbore Formation MicroImaging (FMI) data is often gathered as part of the exploration process in Oil Sand projects. However, many times little if anything is done with the FMI images themselves. However, this is valuable information that could be better utilized. In this paper we discuss a method for calculating vertical and horizontal permeability curves from FMI images in Oil Sand deposits. The FMI is not an image in the sense that it is not a picture. Instead, the FMI is an "image" of the microresistivity of the wall of the borehole. The image is cylindrical based on data gathered from all 360 degrees of the borehole wall.

In order to calculate the permeability curves, first a sand / shale indicator model is calculated from the FMI image. The dark parts of the image are coded as shale and the light parts are coded as sand. The result is a 2D cylindrical indicator model as shown in Figure 1. Then sequential indicator simulation is used to simulate a sand / shale indicator model on a 3D grid that uses the 2D cylindrical model as conditional data. Finally local windows are used to calculate permeability based upon local porosity and Vshale values from the 3D indicator model. Then averaging techniques are used to calculate vertical and horizontal permeability curves with depth.

There are four steps required to calculate the permeability curves from the FMI data:

1. Convert the FMI data to ASCII format
2. Calculate the sand / shale indicators using location dependent thresholds
3. Calculate FMI quick logs for checking and quick interpretation
4. Calculate FMI horizontal and vertical permeability

Step 1 is performed manually using an image editing software such as GIMP. Steps 2 through 4 can be automated using three programs that have been constructed: PGM2ANG (for steps 1 and 2), FMIQL for step 3 and FMI-K (for step 4).

Step 1: Convert the FMI Data to ASCII Format

The original FMI image is obtained in a .tiff file format complete with a header as well as a multitude of other information. An example of a FMI image with the header and other extraneous information is shown in Figure 2. The original image is cropped to the limits of the actual FMI image (i.e. the header and all other information are cropped out of the image). Then the cropped image is saved as a .pgm image (portable grey map) using ASCII encoding (rather than raw encoding). The result is an image file that can be opened in a text editor. The first two lines in the pgm file are header information. The third line in the file contains two numbers that are the number of image pixels in the x and y direction, respectively. The fourth line in the file will usually be the number 255, which is the maximum possible image value, corresponding to white. After the fourth line, each line contains one grayscale value between 0 and 255. A value of 0 is black and corresponds to shale. A value of 255 is white and corresponds to sand.

Tip: The open source image editor GIMP makes Step 1 very easy. GIMP makes zooming and cropping the image very easy and the output .pgm file contains only 1 grayscale value per line. Other image editors may output variable numbers of grayscale values per line, making it difficult to deal with the image data in later steps.

Step 2: Calculate Sand / Shale Indicators Using Location Dependent Thresholds

The end result of this step is a 2D cylindrical sand / shale indicator model of the borehole wall calculated from the FMI data. A program called PGM2ANG has been constructed to complete this step. The image is

read in by the program and the grayscale values are calculated as either sand or shale based upon an initial threshold value that is specified by the user. The "goodness" of the sand / shale model can be assessed in two ways:

1. The core photos can be visually compared with the sand / shale indicator model. The images can be examined to ensure that key sand / shale features match up in both photos.
2. The Vshale can be calculated for the indicator sand / shale model. Then the calculated Vshale can be compared with the geophysical log Vshale for differences.

However, there are usually many intervals where core photos are missing and cannot be compared with the indicator model. In addition, the image comparison is subjective and hard to quantify. Comparison of the Vshale profiles can be done quantitatively based upon the difference between the two profiles at the threshold locations.

We have found that to obtain a good match between the Vshale profiles, thresholds need to be specified at many different depth locations in the borehole (approximately 1 threshold location per metre depth, more in hard to match areas). The thresholds must be between 0 and 1 (corresponding to grayscale values of 0 and 255, respectively) and a reasonable starting threshold is 0.7. A threshold is needed at every depth location and there could be more than 12,000 pixels in the y-direction so a threshold is calculated at every depth in the y-direction based upon a linear interpolation between the specified threshold above and below the depth location.

The thresholds could be specified and iterated manually to obtain a good match between the two Vshale profiles; however, the process is time and labor intensive. Instead, the program PGM2ANG implements a type of simulated annealing process to iteratively calculate the optimal thresholds as follows:

- A threshold location is randomly selected.
- The threshold at that location is increased or decreased by a small amount.
- Then an objective function based on the error between the two Vshale profiles is calculated:

$$OBJ.FUNC. = \sum_{i=1}^{n} \left| Actual\, Vshale_i - Calculated\, Vshale_i \right|$$

- If the changed threshold results in a decrease in the objective function (which implies that the change results in a better match between the two profiles) then the changed threshold is accepted.
- These steps are repeated for a specified number of times.

Initial testing indicates that approximately 40 to 50 iterations are needed for each threshold location. So, for a 20 m long FMI image, 1000 iterations in total should be performed.

The program PGM2ANG outputs:

- A sand / shale indicator model in an angular format that is later used as an input to the FMI-K program.
- A sand / shale indicator model in GSLIB style format, which can be viewed using the GSLIB program PIXELPLT.
- The final calculated "best" thresholds used to calculate the final indicator model.
- The Vshale log for the indicator model.

An example of this step is shown in Figure 3. Note the excellent match between the log Vshale and the indicator model Vshale.

Step 3: Calculate the FMI Quick Logs for Checking and Quick Interpretation
The program FMIQL can be used to calculate "FMI Quick Logs". The quick logs provide preliminary results for quick estimation and checking and calculates a number of values that can be plotted as logs. FMIQL will output the following information with depth:

- Volume of shale (Vshale)
- Porosity
- Vertical variogram range
- Horizontal variogram range
- Kh from EPF formalism

- Kv from EPF formalism

The user chooses a calculation interval and window size. Vshale is determined simply by calculating the fraction of shale pixels from the indicator model within the calculation interval. Porosity is calculated based on the indicator Vshale as follows:

$$Porosity = 0.5175(1 - Vshale)$$

The vertical and horizontal permeability can be estimated by assigning an elementary scale permeability based on the local Vshale and applying a small scale Kv/Kh ratio of just under 1.0. The formula to calculate the permeability is:

$$\log\left(\overline{K}_{sand}(V_{SH})\right) = \log(\overline{K}_{clean\,sand}) - \frac{V_{SH}}{0.25}\left[\log(\overline{K}_{clean\,sand}) - \log(\overline{K}_{0.25})\right]$$

The equation above comes from a calibrated relationship between Vshale and Kh as illustrated in Figure 4. It is important to realize that the calculated indicator model is really a 2D cylindrical grid. However, in order to flow simulate we require a 3D x,y,z grid based model. This is illustrated in Figure 1. Thus, in step 4 we will use sequential indicator simulation (SIS) to simulate a full 3D sand / shale indicator model for the length of the hole. The SIS requires variograms, and FMIQL fits the variograms based on the variogram derivative at short scale (as shown in Figure 5):

$$\gamma(h) = \frac{3h}{2a} - \frac{h^3}{2a^3}$$

$$\frac{d\gamma(h)}{dh} = \frac{3}{2a} - \frac{3h^2}{2a^3}$$

Step 4: Calculate FMI Horizontal and Vertical Permeability

The program FMI-K is used to complete the fourth and final step.

In order to calculate a permeability model, first we must use indicator simulation to simulate a 3D grid of sand / shale indicators. Local window are used to read the data as required. Then variogram derivatives are used to simulate a facies realization conditional to the 2D cylindrical indicator model calculated from the FMI data. Future work may consider MPS for the 3D indicator simulation with core photos used for the training image. For now, SIS is used since it is a reliable and proven technology.

Next, permeability values are assigned to the 3D grid based on local porosity and Vshale based on a flow simulation. The vertical solution provides Kv and a combination of the two horizontal solutions provides Kh as follows:

$$Kh = \sqrt{Kx\,Ky}$$

The output of the FMI-K program is Vshale, Porosity, Kh, Kv and the Kv/Kh ratio for each depth.

For the FMI example shown in Figure 3, the horizontal and vertical permeability profiles are shown in Figure 6. Preliminary sensitivity analysis has shown that the permeability curves are not very sensitive to the choice of areal grid size (in the indicator simulation), the local window size for VShale calculation or stochastic randomness caused by the simulation process.

Conclusions

In this paper, a methodology is presented to calculate permeability curves in the vertical and horizontal directions based on FMI data. First, the original image must be converted to a portable grey map file format. Then, a 2D cylindrical sand / shale indicator model can be calculated from the image based upon location dependent thresholds. The thresholds are initially specified by the user, and are iterated using a modified simulated annealing approach to calculate thresholds which minimize the differences between the geophysical Vshale and the model Vshale. Next, a 3D sand / shale indicator model is simulated, conditional to the 2D cylindrical indicator model. The 3D model is simulated using SIS and variograms calculated based upon the derivatives of the short scale variogram. Then permeability is assigned to 3D grid cells using the local Vshale and porosity values from specified windows. Then vertical and horizontal permeability are calculated for each depth.
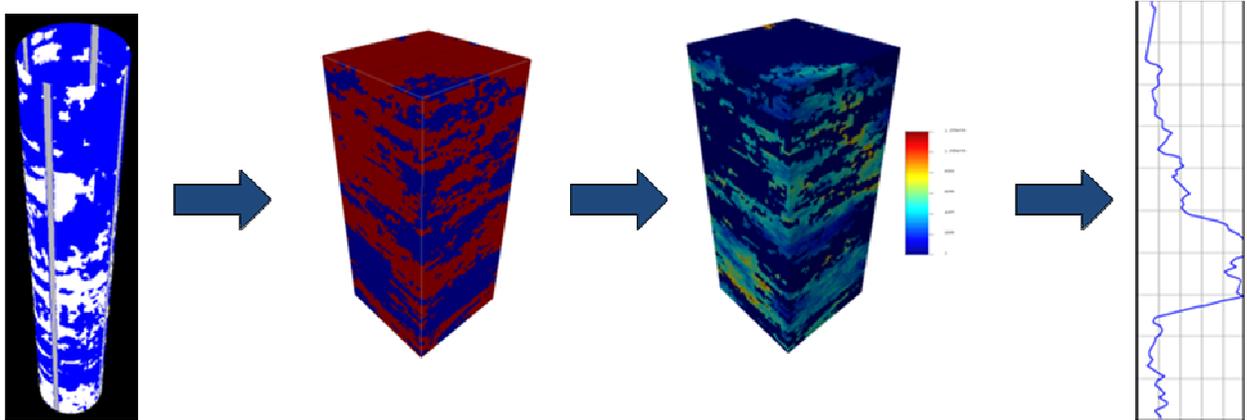
Figure 1: From left to right: a) the 2D cylindrical indicator sand / shale model calculated from the FMI image. b) the indicator simulated 3D grid. c) the permeability model. d) the vertical permeability curve.
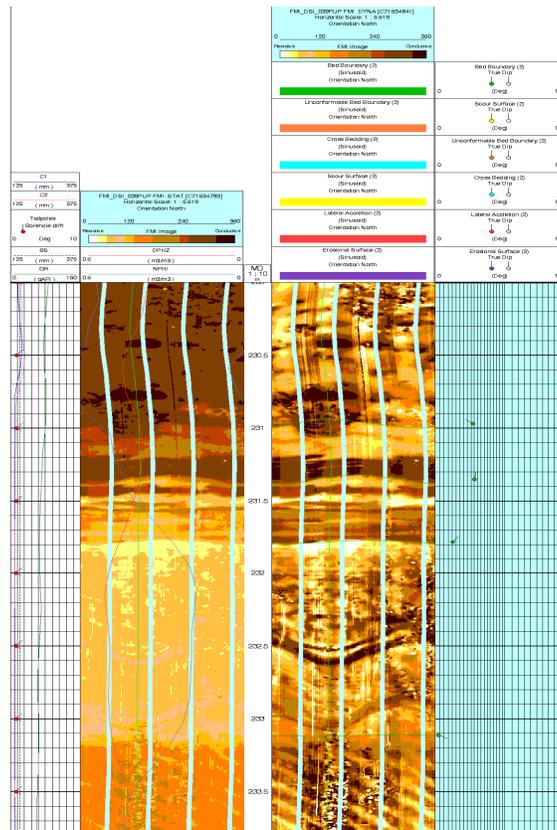
Figure 2: An example of an original FMI image showing the header and other information
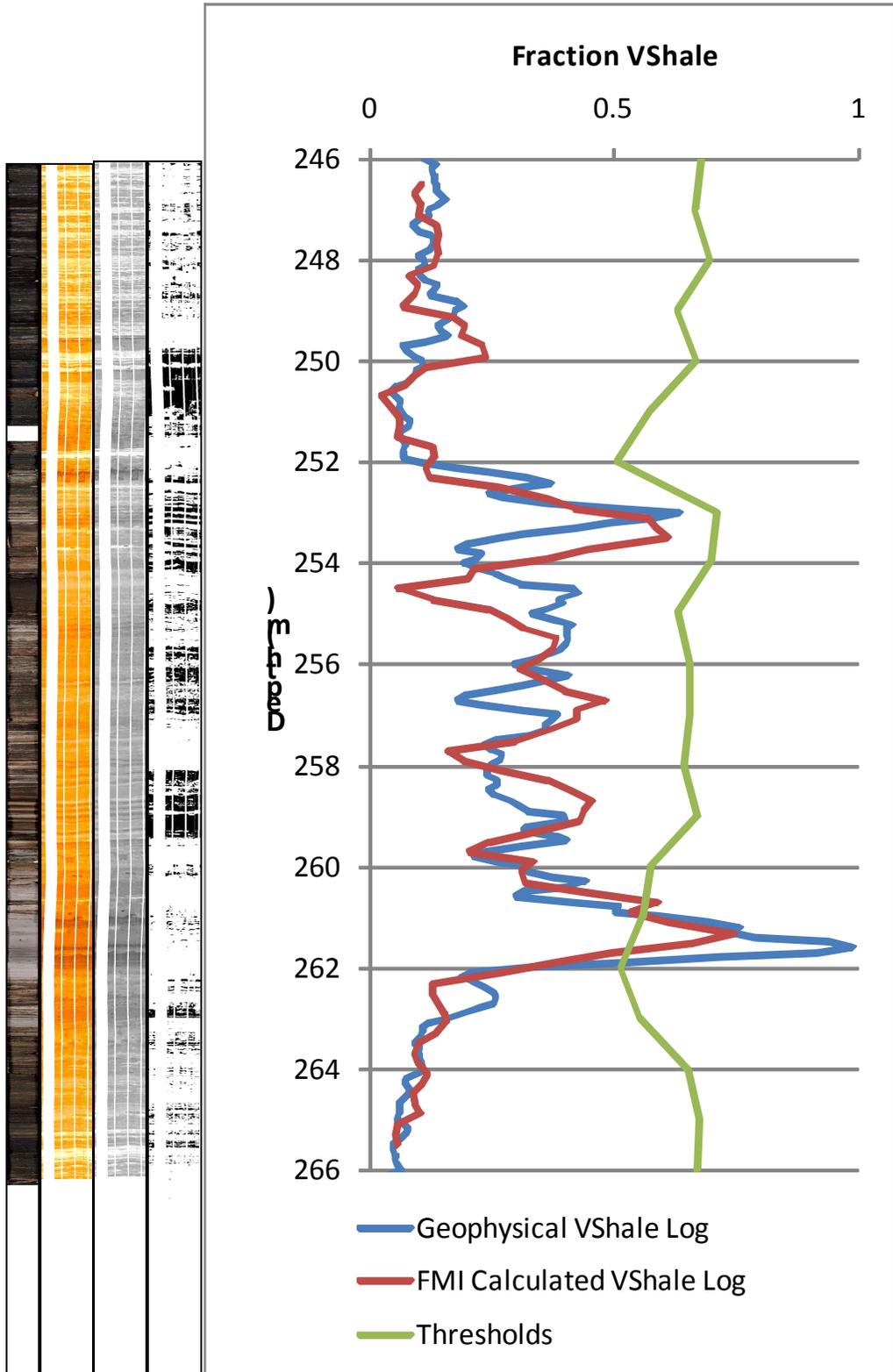
Figure 3: From left to right: a) Core photo b) raw FMI c) grayscale FMI d) 2D sand / shale indicator model e) the geophysical log Vshale is shown in blue. A 5 point moving average of the calculated indicator Vshale is shown in red. The thresholds used to calculate the indicator model is shown in green.
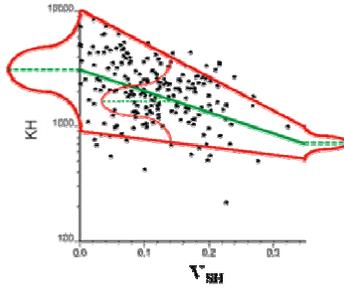
Figure 4: Calibrated relationship between Vsh and Kh
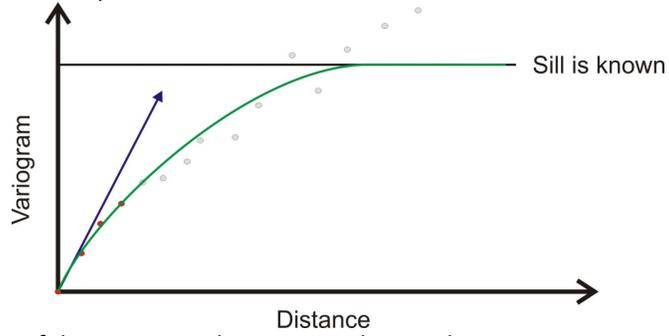
Figure 5: An illustration of the variogram derivative at short scale
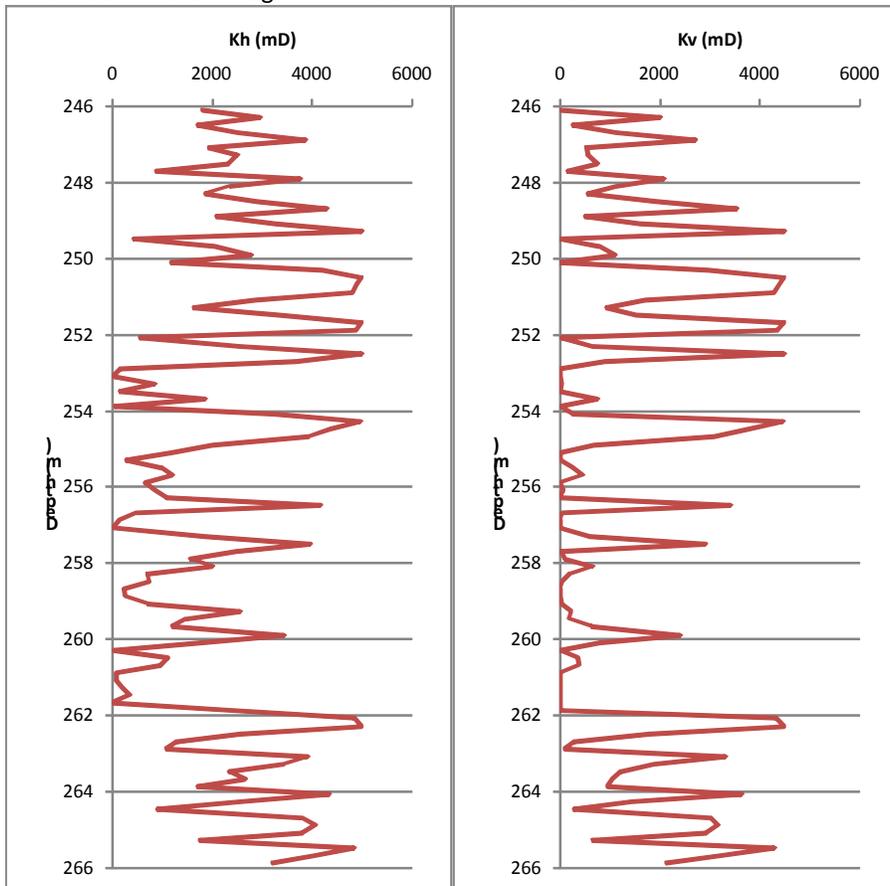
Figure 6: Horizontal and vertical permeability profiles for the FMI shown in Figure 3