CORE IMAGE ANALYSIS: RELIABLE PAY ESTIMATION IN THIN-BEDDED RESERVOIR UNITS

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ABSTRACT

Robust pay measurements can be difficult to obtain from thinly bedded clastic reservoirs. The resolution of conventional log suites is too low to calculate net pay where bed thicknesses are less that 30-60cm. Many exploration targets are in areas where bed thicknesses are considerably less and yet there is the potential for significant yield. There have been a number of improvements in the analysis of logs and the logging tools themselves, but they are up against a hard limit, below which the signal represents a convolution of information from contrasting lithotypes and contrasting petrophysical signatures. Image analysis has been used to generate pay logs and estimate net pay from image logs, but such estimates are only as good as the imagery and the methods used to validate the imagery. Estimates from image logs are limited by the resolution of the tool (~0.5cm), log quality, and what can be a weak or chaotic petrophysical contrast between beds.

The following is an illustration of the methods used to estimate pay in thin-bedded units using high-resolution core imagery, the data integration used to validate the imagery, and the image analytic procedures developed to extract pay information. Unlike most calculations of pay, no consideration is given to the height of the hydrocarbon column. The goal here is to estimate the potential for pay from the core at the macro scale. In effect the result represents Net Reservoir, or “net reservoir with porosity and permeability greater than my petrophysical cut offs”. The height of the hydrocarbon column, and the positions of gas/oil/water interfaces are large-scale phenomena that generally can be discerned on the logs.

INTRODUCTION

Thinly bedded reservoirs are found throughout the world and can be expected in many of the fluvial, deltaic and deep-water formations that are currently targets of exploration and development. Much of the reservoir may be massive sands, but there is usually a significant portion of the reservoir that contains thin beds which exist below the resolution of the logs. Net pay estimates are traditionally derived from well logs and while the integration of log analysis and statistical modeling has led to apparent improvements in the estimation of pay from thinly bedded clastics (e.g. Claverie, et.al., 2007 and Lìu, et.al., 2007), well logs cannot resolve thinly bedded units.

With the advent of borehole imagery, image logs have also been used for pay estimation, but the resolution of the imagery is coarse with pixelssizes approximating 0.2 in. As pixel size increases, the effective resolution of the imagery decreases and systematic overestimation is expected. Lawrence (2002) in a comparison of pay estimates from acoustic imagery and core found that results from the acoustic logs tended to be 5% greater than those derived from core. Knecht, et. al. (2004) used the core/image log comparisons as a training class to tailor log analysis methods to the formation. Such methods have tremendous value in the characterization of reservoir units in uncored wells, but they are all validated through comparison with core. The following is meant to illustrate the analysis of core.

IMAGE PROCESSING

The direct method of calculating pay from core would be to simply measure the length of rock material in each tube, then measure the thickness of any contained sand beds and calculate net sand ratio, but this neglects the role of measurement error, fractures, and complexity. Most of these units can be quite complex and the thickness of any one bed can vary considerably depending upon where it is measured. When these sources of error are compounded over hundreds or thousands of individual thin beds, the total error can be quite large.

Image analysis provides a more accurate means of assessing pay. First, each core image is segmented into a ‘sand mask’ and a ‘fracture mask’. During validation, the sand mask is refined into a ‘pay mask’ through comparison with petrologic and petrophysical data obtained from analysis of core plugs. The fracture mask is used to ensure that pixels associated with fractures are not tallied as either ‘pay’ or ‘not-pay’. Net pay is then measured using two different methods: ‘Run-Length’ and ‘Pay Ratio’. The former measures the actual length of core material and ‘pay’ using a pair of counters for each column of the image. The Pay Ratio method subdivides the core into a series of discrete, non-overlapping windows. A pay ratio is calculated for each window. As all of the windows are the same size, net pay can then be calculated from the mean pay ratio multiplied by the length of the interval. The latter method neglects the shortening associated with fractures and gaps and is a means of accounting for the rock material (‘kerf’) that is removed when the core is sawn into tubes.

Image Segmentation

The resolution of the original imagery, whole-tube images digitized at 10x resolution, was too high for image segmentation based upon color. At the micro-scale, light colored sand consists of a collection of light and dark grains, many of which can be the same color as the intervening shale beds. While the proportion of these grains may be low, the exclusion of them would constitute a systematic underestimation.

Prior to segmentation, the true length of core material in each image was measured and the length of the image was rounded up to the nearest centimeter, creating a variable width gap in the core. It is a means of approximating the contribution of missing rock material at the ends of the tubes. All of the images were then projected down to 150dpi and then smoothed using a median filter to mute the effect of sand texture (Figure 1). The images were then segmented using HSI thresholding (Crabtree, et.al., 1984). Unlike simple gray-level thresholding HSI uses the entire color space. Fracture masks were also created for each tube and are used to ensure that fractures are not tallied as either 'Sand' or 'Not-Sand'.

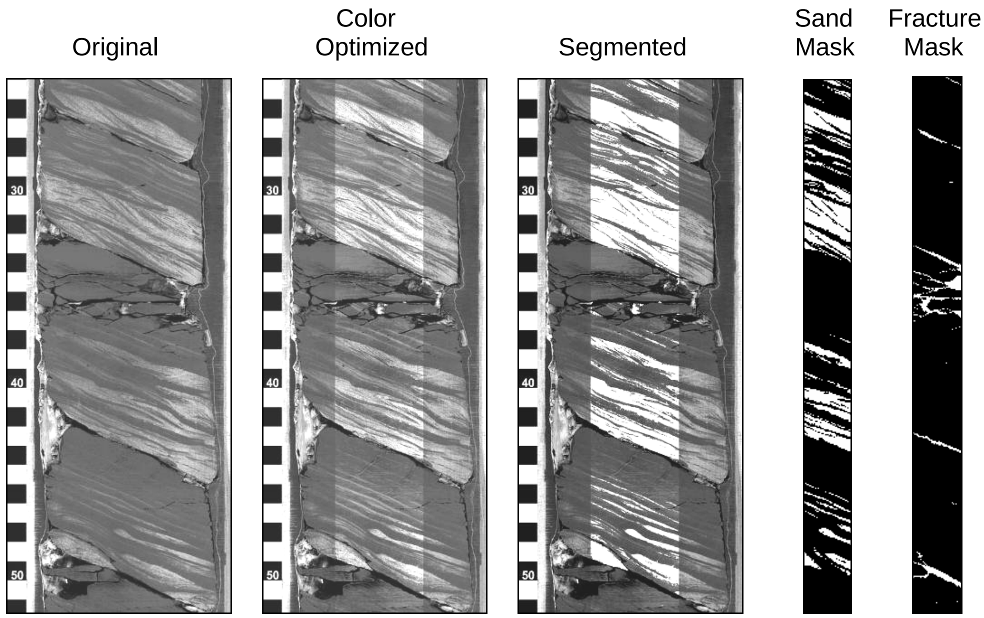

Figure 1 – An example of the segmentation procedure: The original image (smoothed) was color-optimized in a stripe 1.5- 2.0 inches wide. HSI thresholding was then used to segment the image (white: sand, everything else: not-sand). A similar filter was used to image the fractures. The results were converted to binary images 1-inch (150 pixels) in width.

Image Validation

Before any meaningful analysis can proceed the sand masks must be transformed into pay masks. There are two stages. First each image is inspected for 'bleed' and reasonableness. Color bleed is a common problem in the application of any thresholding filter. The procedure is always a trade-off between excluding objects that are 'not sand' while not excluding too many of those objects that are 'sand'. The result is that each image requires close inspection and touch-up. An example of reasonableness can be found in Figure 2, in the fractured zone just above the center of the interval. It contains a small chip of sand. While the chip is undoubtedly sand it does not seem reasonable that it is part of the fractured shale zone in which it is found.

The second stage of validation is to check the sand mask against data measured from core plugs, including porosity and permeability, detailed thin section petrography, SEM, and QXRD. All of the images segmented for sand were overlain on the originals and then the plug points were added in a separate image layer. The data is used to identify both pay and non-pay lithotypes throughout the length of the interval. The 'featureless' sandstone shown in figure 2 is an example. The dry core surface is light-colored and featureless. It is possible to discern darker sand grains, but it was not until the surface was wet that it was possible to observe any fabric. The availability of high resolution imagery proved to be valuable.

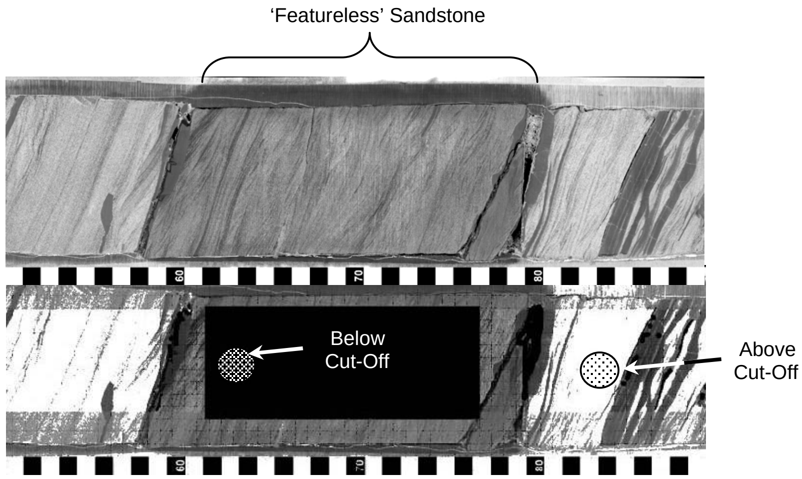

Figure 2 – Highly cemented 'featureless' sands with plug points overlain. The name arose from the character of the dry core surface. It was very light-colored tan and completely featureless. In the core image above the surface was wetted with Isopar to discern the fabric. The unsuitability of this lithotype became obvious when plug points were overlain.

The limitation of validation with plug data is that it is point data. High resolution imagery proved to be valuable for distinguishing subtle transitions between core plugs. Figure 3 shows a transition from normal 'pay' sand, to non-pay 'calcite-cemented sand', and then to 'featureless' sand. At 10x magnification, the grain color is virtually identical, but the grain size is smaller, and the grains are outlined by white calcite. The presence of the calcite in the interstices between grains translates into significant difference in image texture at the micro-scale which translates into a very subtle variation in color describing an arcuate transition between the two types of sand.

Image Analysis

All of the images from any one continuous interval are processed as a group, forming a continuous image. Using the run-length method, a pair of counters is initialized for each column of the aggregate image. The first one is used to tally the number (or length) of non-fracture pixels in the column, the second is used to count the number of non-fractured pay pixels. The result is a total length and a reservoir length for each column of the image, which are then used to calculate a mean reservoir length and pay ratio.

Using the Pay Ratio method, the aggregate image is subdivided into discrete, non-overlapping windows and the pay ratio, the number of non-fracture, 'pay' pixels to the number of non-fracture pixels. The result is a pay log, a vertical record of pay. These logs can be enhanced to provide a means to assess down-core uncertainty (Prince, 2002), and can be prepared at any window size. Figure 4 contains an example of logs from the Gulf of Mexico prepared using window sizes above and below the resolution of most logging tools.

For the purposes of net pay estimation, the window size is set to 1cm, the pay ratio is calculated for each subsample sample, and a mean pay ratio is calculated for the entire interval. Net reservoir is the mean pay ratio multiplied by the length.

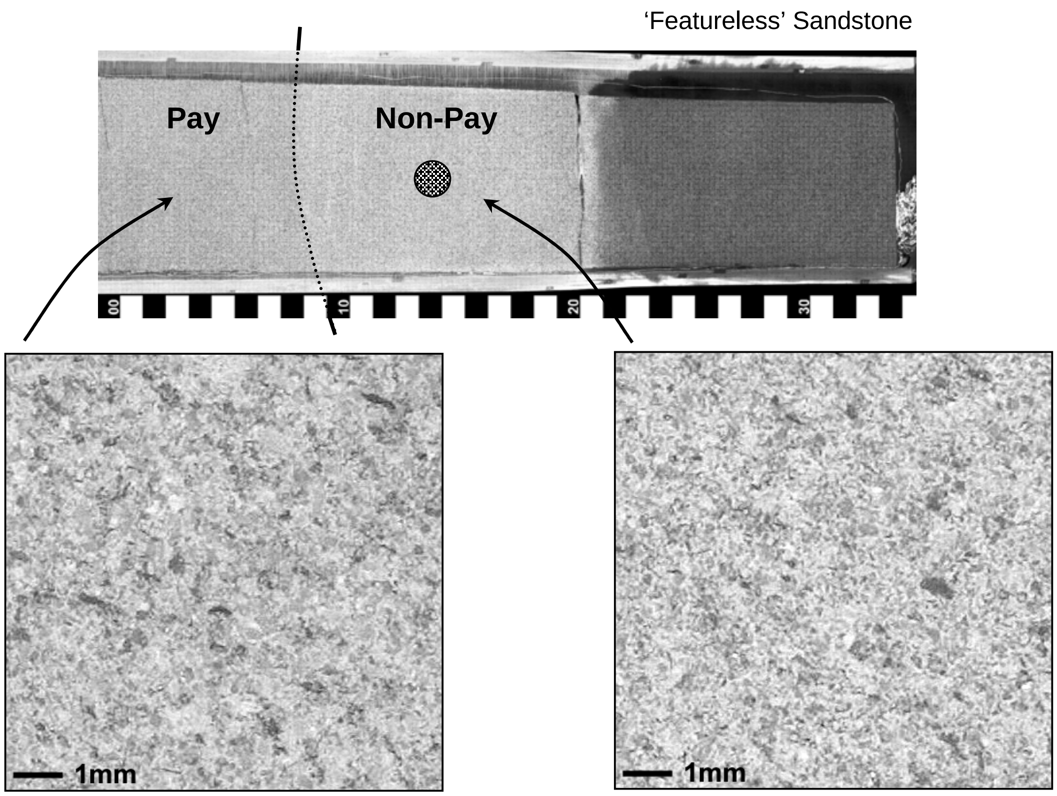

Figure 3 – A Transition zone between 'Pay' sand, 'Calcite-Cemented' sand and then 'featureless' sandstone. The color of the sand grains is virtually identical, but the calcite cement in the interstices between grains imparts a slightly brighter tone and different texture when viewed at 10x.

RESULTS AND DISCUSSION

The preceding has been an illustration of the methods used to estimate thin-bedded pay directly from core. The specific method of image segmentation is up to the investigator, but the critical part, image validation, must be carried out regardless of the method of segmentation.

The preceding also illustrates two different image analytic approaches. As comparison of the two methods, they were both applied to a series of twelve discrete thin-bedded intervals from a 200+ meter core from southern Asia. The intervals ranged from 2 to 33m in length and represented only those portions of the core containing thin beds (approximately 40% of the pay). A comparison of core length with run length revealed fractures, and kerf accounted for approximately 4% of the core length. A comparison of the calculated pay lengths showed that the run-length method tended to underestimate pay by 3%. The divergence increased with the length of the interval as the number of gaps in the core and the number of fractured zones increased. Regardless of the image analytic methods employed, careful examination of a core is vital to obtaining a precise estimate of pay, and serves as the basis for up-scaling those measurements to the scale of a well log.

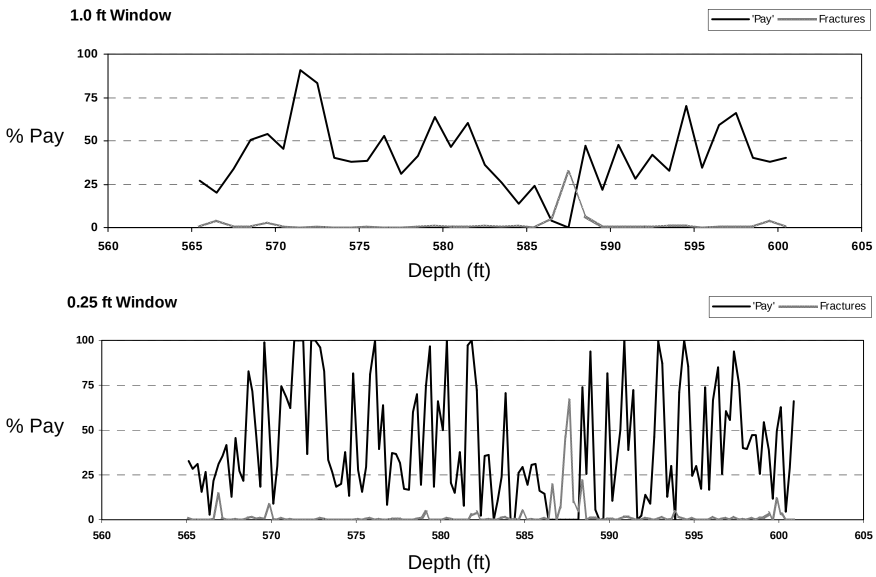

Figure 4 – Pay Logs from the Gulf of Mexico at approximately the resolution of a well log (1ft) and one taken well below the resolution of a well log (0.25 ft).

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