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Rock boundries selection from more than one geophysical log using principal component and derivative analyses

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Summary

Down-hole geophysical measurements provide a continuous, high resolution log trace which reflects the variation of physical properties of subsurface lithological units. Inflection points at geophysical log correspond to rock boundaries. Thus, zero values in the second derivative of the log trace indicate rock boundaries. Density and gamma ray response logs measured at the Victoria property were used in this research. As the derivative method is a uni-variable technique, principal component analysis was used to extract one variable that is indicative of the variation of gamma ray response and density logs. Using the wavelet analysis, the log trace was blocked and rock boundaries were plotted based on different criteria including 25% of total detected boundaries, layer importance, and operator width. The lithological units logged by geologists had excellent correlation with the boundaries detected by the wavelet method. The results showed more detailed and accurate information of variation of physical properties within and between layers.

Introduction

Down-hole geophysical log measurements can provide continuous, high-resolution data that represents the physical properties of rocks surrounding the borehole. Despite this, the interpretation can be adversely impacted by high noise levels, local heterogeneities, and aliasing of high frequency variations. As layer boundaries can correspond to inflection points in the measured properties, one way of detecting the rock boundaries is to compute the second derivative of the log and then identify zero values. A simple calculation of the second derivative can be used, but the result might be confusing due to the noise content of the data (Cooper and Cowan, 2009).

Ideally, we would like a method to produce a smooth, and unchanged log through homogenous units, while keeping the edges between individual units sharp. This process is called blocking or zoning which conventionally was performed using a median filter with adjustable window size. The results depend on the window size used. The continuous wavelet analysis has been applied to block the geophysical logs. It analyzes the log at different scales to evaluate the variation of frequency content with distance. The resultant denoised log produced by the CWT has completely flat segments with sharp boundaries (Cooper and Cowan, 2009).

This technique has been successfully applied on geophysical logs measured in sedimentary environments (Cowan and Cooper, 2003; Cooper and Cowan, 2009 and Davis and Christensen, 2013). Down-hole density and gamma ray response measured within hole FNX1182 at Victoria property, Sudbury were used to evaluate how effectively this technique can be applied to more than one physical property measurement in a complex igneous/metamorphic environment.

Theory and/or Method

The continuous wavelet transformation $\boldsymbol{Wf}$ of a geophysical log $\boldsymbol{f}(\boldsymbol{t})$ is represented as a function of scale (s) and position (u):

$$\boldsymbol{Wf}(\boldsymbol{u},\boldsymbol{s}) = \int_{-\infty}^{\infty} \boldsymbol{f}(\boldsymbol{t}) \frac{\mathbf{1}}{\sqrt{\boldsymbol{s}}} \boldsymbol{\Psi}^{*}\left(\frac{\boldsymbol{t}-\boldsymbol{u}}{\boldsymbol{s}}\right) \boldsymbol{dt}$$

where $\boldsymbol{\Psi}$ indicates wavelet used and * represents the complex conjugate. 'Mexican hat' wavelet, which is the second derivative of a Gaussian function, is used as $\boldsymbol{\Psi}$ (Cooper and Cowan, 2009):

$$\boldsymbol{\Psi}(\boldsymbol{t}) = \frac{\mathbf{2}}{\boldsymbol{\pi}^{\mathbf{0.25}}\sqrt{\mathbf{3}\boldsymbol{\sigma}}}\left(\frac{\boldsymbol{t}^{\mathbf{2}}}{\boldsymbol{\sigma}^{\mathbf{2}}} - \mathbf{1}\right)\boldsymbol{e}^{-\frac{t^2}{2\sigma^2}}$$

In this work, instead of the Mexican hat its piece-wise linear approximation is used as an operator to take the second derivative of the log. In order to convolve the log with the differential operator in the space-domain, the Fourier transform of the log is multiplied by the Fourier transform of the operator, and then the convolved result is transformed back to the space domain. This process results in a matrix including the transformed data at each depth for different operator widths. Figure 1.a shows transformed data as a function of depth for a range of scales from 1 to 800 m. In this plot, zero contours represent edge points detected at different scales, u. To locate the positions of lithological boundaries, a scale needs to be selected, and only the zero contours intersecting the scale should be traced back to the operator width of zero. There are many contours on smaller scales because edge points related to high frequency noise events are detected as boundaries. On larger scales, the log is analyzed to detect more significant edge points. The properly selected scale should not be too small, (as it will be impacted by many noise events), or too large (as legitimate boundaries will be missed (Davis and Christensen, 2013).

This technique is a univariate analysis, so the number of variables should be reduced to a single variabe capable of adequately representing the variation in the data. Principal component analysis (PCA) is a statistical tool which is used to reduce the dimensionality of the data (Krzanowski, 2000).

The derivative analysis was performed on data using a Matlab code written by Davis and Christensen (2013). The range of operator width was assigned between 1 and 800 m as the maximum width should be two-thirds of the length of the trace to make sure the longest wavelength variation is analyzed (Davis and Christensen, 2013).

Examples

Down-hole gamma-ray response and density measurements were used to identify lithological boundaries within hole FNX1182. The PCA was performed on these two data sets, and a component representing more than 95% of the variation in density and gamma-ray response measurements was extracted. The variation of the component scores along the hole is shown in Figure 1.b. The trace of component scores is transformed with a range of operator width from 1 to 800 m. The color image of the transformed data for each operator width is plotted in Figure 1.a. Positive and negative deflection zones are indicated by red and blue colors, and black contours correspond to zero values which indicate the inflection point in the log data. As illustrated in Figure 1.a, the number of inflection points (layer boundaries) detected by wider operators are less than for a smaller operator width. To locate the detected boundaries at a specific operator width on the log, the intersected contours should be traced back to the operator width of zero. For example, the operator width of 700m intersects the black contours at three points. If these contours are traced back, three boundaries are located at depths of 291m, 452m, and 1099m.

The proper operator width selection is a critical step in this work as a scale that is too small tends to detects inflection points related to noise content of the data, and a value too large only detects very significant (large scale) boundaries. The blue line in Figure 1.b shows the lithological boundaries detected when using an operator width of 30m. This width is subjectively determined to be away from boundaries related to noise content of the log trace. The number of detected boundaries is determined by the operator width which can be selected subjectively.

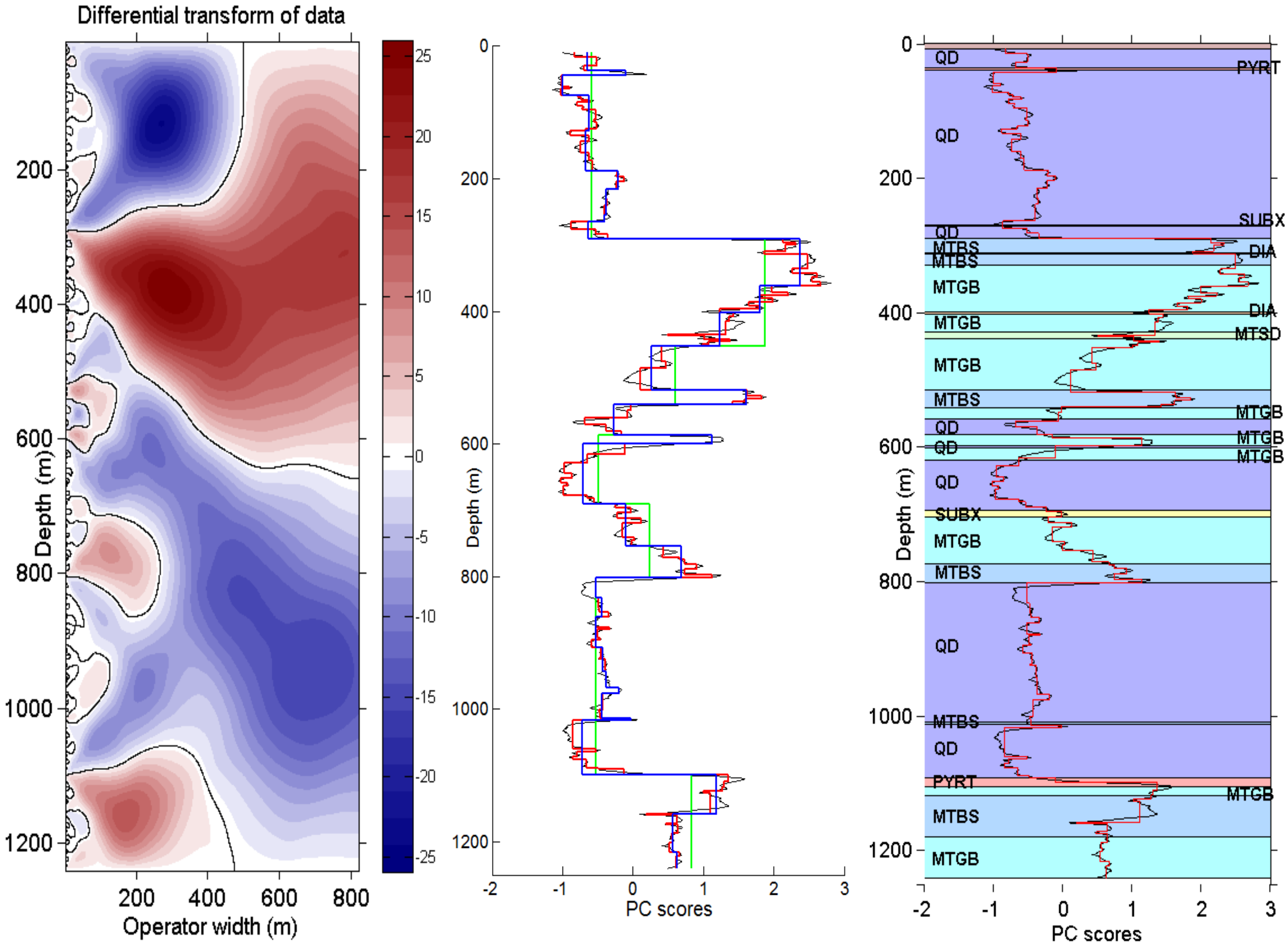

Figure 1- a) differential transform of the PC scores along the hole. Negative and positive deflections of the trace are represented by blue and red regions, respectively. Black contours indicates where a deflection occurs; b) Black line: the original trace of PC scores; green line: seven most important boundaries; red line: 25% most important detected boundaries; blue line: layer boundaries detected by operator width of 30m; c) lithological boundaries logged by geologists and boundaries detected by derivative analysis.

To avoid the subjective result, proper criteria are required to pick the layers based on their importance. High deflection of a log trace relative to neighboring values of the trace indicates important layers. The layer importance is the average value of the transformed data within each region shown in Figure 1.a. All detected layers are ordered in Figure 2 based on their normalized relative importance (Davis and Christensen, 2013). As illustrated, the importance of layers shows a significant drop after the 7th layer. The seven most important lithological boundaries are plotted with the green line in Figure 1.b.

Davis and Christensen (2013) suggest a threshold of 25% to pick a portion of layers with high importance. The 25% most important detected layers are shown in Figure 1.b and repeated in Figure 1.c for comparison with the lithological boundaries logged by geologists (black horizontal lines). All geological boundaries between rock types are detected with the PCA wavelet technique, although they are slightly misplaced compared with the geologists' results. When there is a 20cm interval of measurement, the results of wavelet analysis can enhance the accuracy of the boundaries selected.

Aside from the major boundaries, the boundaries plotted within a rock unit add more details about the heterogeneity of rocks. These variations might reflect slight heterogeneity of the rock types, like those seen within the quartz diorite (QD) units; or they may represent significant layers with different physical properties like sub-layers detected within metagabbro (MTGB) at 450m and 750m.

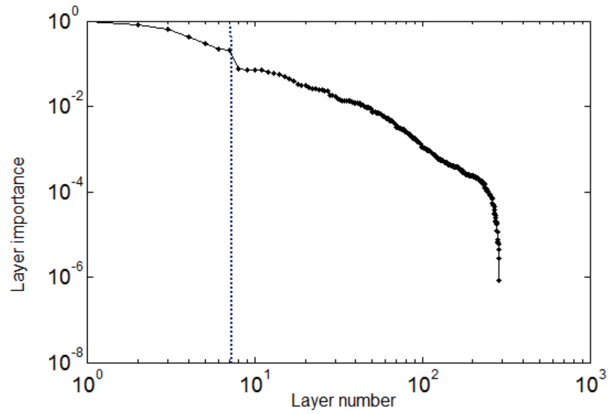

Figure 2- Normalized layer importance for all detected layers by derivative analysis in a decreasing order. Dashed line indicates the significant drop after the 7th layer.

Conclusions

Down-hole geophysical logs provide valuable information about the physical properties of rock surrounding a drillhole. Inflection points on these logs can correspond to layer boundaries which separate two layers or lithological units with distinct physical properties. A piece-wise linear approximation of the Mexican hat wavelet is an operator to compute the second derivative of the log. We extend the method by applying it to principal component scores obtained from density and gamma ray response logs. Applying the operator with a range of operator widths to transform the data can be used to analyze variations in log trace at different scales. Wider operators detect significant changes in the log, while smaller operators look for higher frequency variation. The proper operator width is the one which represents more detailed information, while disregarding the boundaries related to high frequency noise content of the data. The operator width selection is a subjective way to pick the layers. Layer importance provides useful information to pick those layers objectively related to significant deflection in the log trace. When selecting the 25% most important interfaces, we found a good agreement with the lithological boundaries identified by a geologist, demonstrating that this technique can detect boundaries even within an igneous/metamorphic environment. The results can be used to modify the rock boundaries previously logged by geologists.

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