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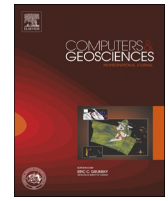

Derivative analysis for layer selection of geophysical borehole logs ☆

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ABSTRACT

Analysis of geophysical borehole data can often be hampered by too much information and noise in the trace leading to subjective interpretation of layer boundaries. Wavelet analysis of borehole data has provided an effective way of mitigating noise and delineating relevant boundaries. We extend wavelet analysis by providing a complete set of code and functions that will objectively block a geophysical trace based on a derivative operator algorithm that searches for inflection points in the bore log. Layer boundaries detected from the operator output are traced back to a zero-width operator so that boundaries are consistently and objectively detected. Layers are then classified based on importance and analysis is completed by selecting either total number of layers, a portion of the total number of layers, selection of minimum layer thickness, or layers detected by a specified minimum operator width. We demonstrate the effectiveness of the layer blocking technique by applying it to a case study for alluvial aquifer detection in the Gascoyne River area of Western Australia.

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1. Introduction

When examining information from boreholes, we often combine the use of drillers' lithological with geophysical borehole logs to determine relevant properties of the earth. However, the lithology record from the drilling process may be in error. This can be due to the type of drilling process used, such as a mud rig in a clay-rich environment, whereby discrimination of earth materials from drilling mud may be difficult or impossible, or it may be because drilling samples are only taken every metre to half-metre; and thereby information is lost during the drilling process. By comparison, geophysical logs are taken after the borehole has been drilled (and developed, in the case of water bores) and the tools are lowered to record information continuously. However, noise in the measurement of geophysical properties can be an issue, and the natural identification of layer boundaries may therefore be difficult or problematic. In addition, the actual resolution ability of the borehole device may be limited, so that layers from geophysical logs are smeared out. This can often be the case for natural gamma logging, which takes continuous recording over time intervals while being lowered; but it can also affect apparent conductivity logging. The separation of the transmitting coil from the receiving coil limits the minimum layer resolution in the well-log (e.g., Kaufman and Dashevsky, 2003).

Recent advances on the natural identification of borehole layers and boundaries have been made with the use of wavelet transforms of geophysical well-logs (see for example Cooper and Cowan, 2009; Webb et al., 2008; Choudhury et al., 2007; Cowan and Cooper, 2003). Wavelet analysis transforms the profile data into depth and transform information which, in the case of geophysical logs, shows the power of the log signal as a function of the depth under ground. The efforts of these authors, which rely mostly upon the Morlet and Mexican Hat wavelets, have shown that wavelet analysis is an effective tool for de-noising and blocking geophysical log data. Cowan and Cooper (2003) use Haar and Morlet wavelets to examine magnetic susceptibility data in Western Australia. The Haar wavelets effectively limited high-frequency noise from the downhole logs, and showed clear images of the long-wavelength variations in the subsurface. Continuous wavelet transforms were also applied to density and susceptibility data in drillcore measurement by Webb et al. (2008), revealing statistical patterns in the density data that were previously undiscovered. The work of Cowan and Cooper (2003) was expanded upon several years later, where Cooper and Cowan (2009) use the continuous transform Mexican Hat Wavelet to analyse magnetic susceptibility log data in Australia for banded-iron formations in Hammersley Basin. They compare wavelet analysis to median and mean filtering with favourable results, and show that the Mexican Hat continuous wavelet transform is as effective as, or more effective than, using a mean or median filter for automated layer selection of data.

In this paper, we further develop the concept of Cooper and Cowan (2009) by applying a derivative-type analysis based on a

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piecewise-linear approximation to the Mexican Hat wavelet transform. Instead of focussing on the frequency and signal content of the geophysical log, we examine the other primary purpose of wavelets of this shape: derivative analysis. Our wavelet, which acts more as an operator, effectively takes the second derivative of any geophysical bore log. Layer boundaries are objectively detected by looking for the inflection points in the log, and boundaries of layers in the transformed space are then traced back to zero-width derivative operators. We briefly explain how the derivative operator transforms the borehole trace, and how the transformed data is analysed for blocking. We provide tools for examining the blocked trace, and hierarchically classify layers based on layer-importance, proportion of total layers, and layer thickness. We show that the derivative analysis can be used for a variety of post-processing analysis techniques, including forward modelling for other complementary geophysical measurements and improving lithology layers from drilling records. We present a freely available, complete, working and annotated Matlab code package for the geophysical community under the Creative Commons Attributions CC-BY licence 3.0 (Creative Commons, 2013).

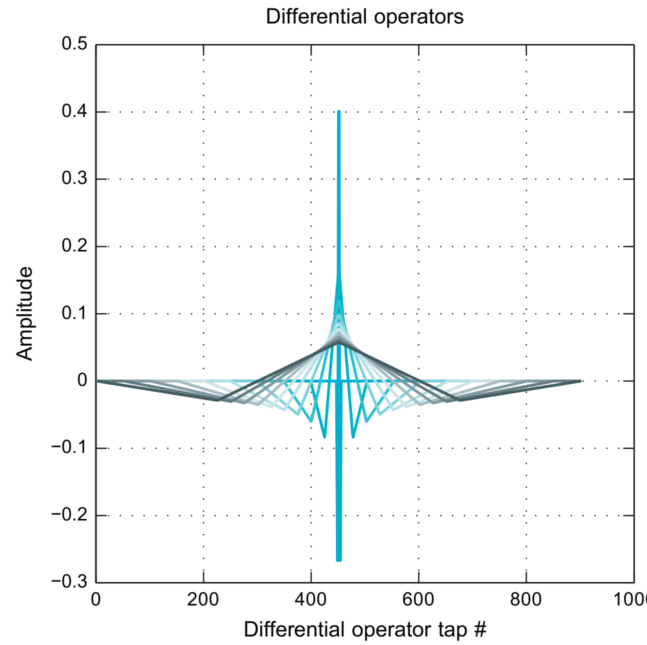

Fig. 1. Selection of 10 of the 224 differential operators used in the Gascoyne River case study (Section 3). Range is from $\boldsymbol{w_1}$ (light blue) to $\boldsymbol{w_{224}}$ (grey). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

2. Method

In this section, we describe our method of obtaining a modified vector of the geophysical borehole trace in order to perform the derivative analysis. Here, we also describe how we construct the matrix of differential operators that are used to find inflection points in the data that represent layers or boundaries in the geophysical data. The geophysical borehole log is convolved with successively wider and wider differential operators in order to find inflection points in the data. Since convolution in the real domain is equivalent to multiplication in the Fourier domain, we convert all data to Fourier domain data for the calculations, and back to real space for the analysis.

2.1. Algorithm for calculating derivatives

We begin with a borehole trace of geophysical data that is sampled in discrete steps of increasing depth Δd_t. The geophysical trace data is N points long, where N is an even number, and we denote an individual sample of the total trace $\boldsymbol{x}$ at depth i as x_i occurring at depth d_i. For the derivative analysis, an extended ensemble of the data is created by padding the original data and subtracting its mean: $\boldsymbol{x_e} = [0, -(\boldsymbol{x}'-\bar{x}), 0, \boldsymbol{x}-\bar{x}]$, where $\boldsymbol{x}'$ is the reverse order of the borehole trace data. The new trace $\boldsymbol{x_e}$, which is of length $2N+2$, is then transformed to the Fourier domain using the discrete Fourier transform $\mathcal{F}(\boldsymbol{x_e})$.

Our method of layer analysis is similar to the use of the wavelet blocking technique in geophysical borehole logs (Cooper and Cowan, 2009; Cowan and Cooper, 2003). Instead of the 'Mexican Hat' continuous wavelet transform, we use a simple approximation that is linearly piecewise-continuous. For our process, we use even-numbered interpolations of the primary wavelet $\boldsymbol{w_p} = [-1/2, 1, -1/2]$ which is, in its simplest interpretation, a double derivative operator. Our first differential operator, $\boldsymbol{w_1}$, is formed as follows: beginning with a minimum operator of eight taps, we interpolate vector $\boldsymbol{w_p}$ with eight evenly spaced samples, and pad the left and right sides of the operator $\boldsymbol{w_1}$ with 0 s so that it is also of length $2N+2$. Each successive vector is constructed in the same way, stepping up by four taps at each new operator, until the final operator vector is $2N+2$ points long, and there are at most two zeros in the differential operator trace. For every operator, we normalise the area under the positive section of the curve by dividing by the total number of points that create the wavelet. As an example, Fig. 1 shows 10 differential operators used in the blocking case study from the Gascoyne River (Section 3). The width of the positive section of each operator (i.e., the section of the operator window that is greater than 0 in the vector) is $2N/3$ points long, and the total number of operators is $M = \lfloor x \rfloor - 1$. We define the width of the operator as the total number of points in the positive section of the operator window multiplied by the depth-step value in the geophysical bore-log. The resulting operator matrix $\boldsymbol{W}$, which is $((2N+2)\times M)$ in size, also gets transformed into the Fourier domain, resulting in $\mathcal{F}(\boldsymbol{W})$.

As stated earlier, each application of the derivative transform operates on the geophysical borehole trace to pick out inflection points in the data. Since the operators act on the data as a filter, we can easily express the calculation of the double derivative as a convolution of data. This is most easily calculated in the Fourier domain; however, transformation of data to the Fourier domain implies that our data is cyclic in nature: something that is clearly not true of the original trace. It is for this reason that we have modified the borehole trace to $\boldsymbol{x}'$, which includes a mean-subtracted, reverse trace of the borehole data coupled to a mean-subtracted forward trace of the data (with buffers of 0 between each sub-trace). The addition of the reversed discrete data ensures that the differential operators will discover boundary inflections at the beginning and end of the original geophysical trace, and that the circular convolution of the application of the differential operators in the Fourier space will not overlap layers near the beginning and ending of the original data set. The differentiation product matrix, which is the result of the application of each differential operator vector in $\mathcal{F}(\boldsymbol{W})$ to the extended borehole trace $\mathcal{F}(\boldsymbol{x}')$, is then transformed back to real space and concatenated back to an $(N\times M)$ matrix which contains the derivative information for the geophysical borehole trace. This process is explained in the procedure below, where the symbol $\circ$ represents the Hadamard entry-wise product:

1. From $\boldsymbol{x}$, construct $\boldsymbol{x_e}$ and replicate it into matrix $\boldsymbol{X_e}$ of size $(2N+2\times M)$.
2. Create the $(2N+2\times M)$ derivative matrix $\boldsymbol{W}$.

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