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Inference of strata separation and gas emission paths in longwall overburden using continuous wavelet transform of well logs and geostatistical simulation

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ABSTRACT

Prediction of potential methane emission pathways from various sources into active mine workings or sealed gobs from longwall overburden is important for controlling methane and for improving mining safety. The aim of this paper is to infer strata separation intervals and thus gas emission pathways from standard well log data. The proposed technique was applied to well logs acquired through the Mary Lee/Blue Creek coal seam of the Upper Pottsville Formation in the Black Warrior Basin, Alabama, using well logs from a series of boreholes aligned along a nearly linear profile.

For this purpose, continuous wavelet transform (CWT) of digitized gamma well logs was performed by using Mexican hat and Morlet, as the mother wavelets, to identify potential discontinuities in the signal. Pointwise Hölder exponents (PHE) of gamma logs were also computed using the generalized quadratic variations (GQV) method to identify the location and strength of singularities of well log signals as a complementary analysis. PHEs and wavelet coefficients were analyzed to find the locations of singularities along the logs.

Using the well logs in this study, locations of predicted singularities were used as indicators in single normal equation simulation (SNESIM) to generate equi-probable realizations of potential strata separation intervals. Horizontal and vertical variograms of realizations were then analyzed and compared with those of indicator data and training image (TI) data using the Kruskal–Wallis test. A sum of squared differences was employed to select the most probable realization representing the locations of potential strata separations and methane flow paths.

Results indicated that singularities located in well log signals reliably correlated with strata transitions or discontinuities within the strata. Geostatistical simulation of these discontinuities provided information about the location and extents of the continuous channels that may form during mining. If there is a gas source within their zone of influence, paths may develop and allow methane movement towards sealed or active gobs under pressure differentials. Knowledge gained from this research will better prepare mine operations for potential methane inflows, thus improving mine safety.

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1. Introduction

Stress-relief fractures that occur during longwall mining provide extensive pathways for gas migration from gas-bearing strata or environments with accumulations of methane—such as abandoned workings, uncased shafts, or wellbores—into sealed and active areas. Due to high conductivity of bedding plane separations, methane emissions can occur suddenly with large gas quantities inundating the ventilation system and changing the properties of the mine atmosphere over large areas. To evaluate the likelihood of methane migrations from different sources into the sealed and active gobs, and to effectively control methane in the overburden, it is important to estimate intervals of strata separations and to identify paths that these emissions may follow.

The presence of mining-induced bedding plane separations has important implications beyond ground control objectives; these fractures generally have very high conductivity for fluid flow, as demonstrated by Karacan et al. (2007) and Karacan and Goodman (2009). Well test analyses of gob gas venthole production showed that average permeabilities in the fractured zone of gob may vary between 1000 and 15,000 millidarcies (md) (Karacan, 2009a). The author noted, however, that the properties of individual heterogeneities were all lumped together in this analysis to represent an effective average since analyzed flow came from a long interval of the gob. Therefore, permeability of individual fractures may be even higher. Later, Karacan and Goodman (2011) conducted further work by studying measured casing strain

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during mining and by analyzing production data during this period. They determined that one of the major strata separations could be as much as 0.55 ft with a permeability of ~80,000 md, while the effective average of the rest of the fractured gob interval could have permeability values of ~20,000 md. These are significant values for potential gas flow within the gob and between active and sealed portions of the mine, if strata separations and fractures intercept gas sources within the zone affected from the mining stresses. Therefore, the ability to predict strata separation intervals is critical in this zone for effective control of methane gas in underground coal mining operations.

Existing methods to locate intervals of strata separations rely on empirical and numerical methods. An empirical method proposed by Palchik (2003, 2005) is based on the correlation of the presence and absence of estimated horizontal fractures with uniaxial compressive strength and thickness of rock layers, distances from the extracted coal seam to the rock layer interfaces, and the thicknesses of extracted coal. His observations on the existence of horizontal fractures at different overburden rock-layer interfaces indicate that the probability of fracturing increased with the compressive strength difference between neighboring rock layers. It should be noted that, according to these observations, not every strata interface—not even every one of the strong-weak rock interfaces—is prone to separation.

Numerical models, on the other hand, are mostly geomechanical models that require exhaustive data sets of strata and interface properties to produce accurate results. By using such models and input data sets Whittles et al. (2006) conducted studies on the effect of different geotechnical factors on characteristics of fracturing, gas sources, and gas flow paths for longwall operations in the United Kingdom. Gale (2005) simulated rock fracture, caving, stress redistribution, and induced hydraulic conductivity enhancements around longwall panels. He reported that the horizontal conductivity can be significantly enhanced along bedding planes within and outside the panel, thereby increasing the potential of methane migration from affected regions. Guo et al. (2012) monitored strata displacement, stress, and water pressure changes at longwall overburden, and modeled stress changes, permeability conditions, and gas flow dynamics.

Empirical or numerical approaches for determining intervals of strata separation are difficult, time consuming, and require highly dependable input data, which may or may not be readily available. In addition, these methods are deterministic, producing results that are absolute and without any room for uncertainty. In consideration of the significant permeability values that strata separations may have, it is correct to say that the ability to predict the intervals and uncertainties of strata separations can help not only to control and capture methane more effectively, but can also assess an imminent methane in-flow danger at an active mine.

The aim of this work is to infer strata separation intervals in longwall overburden by an alternative method that relies only on well logs as the input data and on signal processing and stochastic geostatistical simulation techniques. Well logs and geophysical techniques have been applied to address various issues related to oil and gas reservoirs, as well as coal mining (e.g., Hatherly, 2013; Karacan, 2009b and the references therein). Therefore, uses of well logs for conventional formation evaluation purposes will not be reviewed and repeated here. Instead, researchers will examine well logs, in particular the gamma log, from a signal interpretation and processing perspective, and will aim to model its singularities using geostatistical approaches to infer strata separation intervals with associated uncertainty.

2. Motivation, approach to the problem, and the general workflow

2.1. Motivation

The motivation behind this work is the premise that geological stratigraphic sequences contain localized weaknesses, either at the interfaces between formations or within formations due to inclusions or concentration of different layers of minerals. Such weaknesses, which may not be evident to geologists or engineers using conventional techniques, can create fractures, i.e. strata separations, under mining-induced stresses. Once these locations fail, they may prevent strata separation at other locations that at first glance are deemed better candidates for fracturing since stresses will be relieved at those weak locations. Therefore, locating and mapping these weaknesses with their spatial distribution can better predict intervals of strata separations that will occur under mining-induced stresses and can identify the resulting flow paths of strata gas.

Fortunately, the locations of strata weaknesses can manifest themselves by abrupt changes in magnitudes and/or frequencies of well log signals. These are termed singularities in signal processing language and are easily distinguished using localized amplitude-frequency analyses of well logs. These singularities can be the precursors for strata separations. Well logs are merely signals recorded as responses of geologic formations to various inputs, or signals that originate from various properties inherent to the formations along the boreholes. Moreover, they are nearly exact measures of relevant data with relatively high resolution along the axis of measurement. Therefore, putting them under a mathematical microscope to detect singularities may enable us to use well logs to predict intervals of strata separations to assist geomechanical models or empirical approaches.

2.2. Methodology and workflow

In this work, a profile that intercepted six boreholes along its horizontal length in the studied area within the Brookwood and Oak Grove coalbed methane fields in Alabama, USA, was selected. Gamma and density logs acquired in these boreholes are shown in Fig. 1. Continuous wavelet transform (CWT) was used to detect singularities in the gamma log data of the boreholes from their wavelet coefficient maps. In theory, if a wavelet is stronger in identifying locations, it is weaker for the identification of scales, and vice versa. For instance, the Morlet wavelet provides a better localization of frequencies that correspond to uniformities or singularities, whereas the Mexican hat wavelet provides a better location of the depths that correspond to those changes. In this work, both were utilized to take advantage of their specialized properties in locating singularities and scales at which they could be analyzed. As it will be shown in Section 4.2, scale 40 was found as the appropriate scale for identification of singularities from the wavelet coefficient maps. In the identification of this scale, the coefficients in the scalograms of Mexican hat and Morlet wavelets were analyzed together. The criterion was to mark the scale as the boundary where singularities actually showed up and continued to lower scale values with diminishing coefficients. Haar wavelet, which is a member of Daubechies wavelet family and is a special case known as D2, is another mother wavelet that is proposed for the purpose of identification of abrupt changes in signals (Perez-Muñoz et al., 2013). However, it has not been used in this work due to its discontinuous and thus non-differentiable nature.

Pointwise Hölder exponents (PHE), which are the measure of the strength of the singularities in a signal, were also determined using the generalized quadratic variation (GQV) method as complementary to the CWT analyses. In the GQV method of PHE computation around each log data, a gamma value of 0.7 with geometric sampling using a minimum of 1 and a maximum of 16 values were employed. Therefore, up to 16 values in the neighborhood of each data were used to generate a PHE for each data point. These parameters were used to generate approximately 1600 PHE in the neighborhood of approximately 1600 individual data points of each of the well logs.

Both CWT and PHE are used in hydrology (Gaucherel, 2002), in atmospheric sciences (Domingues et al., 2005), and in biomedical sciences (Humeau et al., 2007) among others. CWT and waveform analyses techniques, in particular, are used in oil fields for facies recognition (López and Aldana, 2007), stratigraphic identification of formation interfaces (Pan et al., 2008), multiscale analysis of log measurements (Briqueu