Processing of anisotropic images for upscaling and fracture detection
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Summary

We present a processing technique for upscaling and fracture detection using seismic anisotropy images and log data. Attribute and multi-resolution analyses are applied to quantify fracture patterns (FPs). The image is then decomposed into FPs on different scales. Both upscaling and multi-scale fracture detection are performed by using a theoretical expression which relates the characteristics of fracture-induced anisotropy at three adjacent scales.

Introduction

Recently, de Hoop et al. (1999) have shown how the vector image \( m \) of optimal combinations of anisotropic parameters in spatial and/or temporary coordinates \( r \) may be obtained from seismic data. The objective of this paper is to provide a way of image processing for the delineation of fractured zones by multi-scale decomposition, upscaling, and inversion of the vector \( m \). This study integrates the following image processing tools: (i) attribute analysis (e.g. Barnes, 1999) with an emphasis on FP-related attributes, (ii) multi-resolution analysis and wavelet-based upscaling of seismic/log data, and (iii) rock physics transformations using theoretical relationships between the parameters of fractures and the associated fracture-induced anisotropy.

Localization of fracture zones

For a gridded array \( m(r) \), we start by creating an image matrix \( M \), which can be partitioned into a set of submatrices \( M_n, n = 0, 1, 2, \ldots, \) associated with noise trains, fault systems, or FPs. All such submatrices are susceptible to digital image processing analysis. We design meaningful attribute plots of \( M \) in the hope of revealing a possible FP (say, \( M_0 \)) not visible in the original section. All attributes are computed using the analytic image \( M + \imath M^H \), where the imaginary part \( M^H \) is derived from \( M \) by convolution with a 2-D Hilbert transform operator. The instantaneous attributes are then calculated including reflection strength, phase or perigram, and frequency. We show that their colour diagrams represent a valuable aid to FP detection in the first stage of our processing scheme.

Multi-resolution analysis

The FP matrix can be expressed as \( M_0 = S_0 + S + N \), where \( S \) is the multi-scale FP, \( S_0 \) is the background layered medium, and \( N \) is the noise component. The purpose of multi-resolution analysis (second step) is twofold: firstly, filtering of the noise \( N \) in a time-frequency sense; secondly, the time-scale or scale-space decomposition of the image \( S = S^{(0)} + S^{(1)} + \ldots \) to invert the data with respect to scale (Li et al., 1996). Classical Fourier processing techniques are not applicable in this situation due to the coupling between adjacent scales. Recently developed wavelet transforms (WT) overcome this resolution limitation and offer superior spectral decomposition. The simplest wavelet basis studied here is the Haar basis. It is too coarse for studying prestack seismic data. However, it is useful for image processing. The 2-D WT transforms the image into 3-D space, providing a mechanism for analyzing data at different \( r \) and different scales. Filtering in the scale domain consists of zeroing WT coefficients corresponding to the noise energy. The multi-resolution analysis of \( S \) is based on the assumption that the FP under consideration should intrinsically have scale dependence. When the window function has a broad width, a gross picture of the FP is obtained (upsampling). When the analysis window becomes narrow, the detailed properties of the FP become enhanced (micro-structure detection).

Multi-scale fracture detection

Finally, we estimate fracture parameters from the input images \( S = S^{(m)} \) at different WT scales \( m = 0, 1, \ldots \). In doing so, we define the FP-related scale \( q \geq 0 \) and the corresponding \( 6 \times 6 \) anisotropy matrix \( C \). The FP-scale decomposition is achieved by expressing this matrix through \( 6 \times 6 \) anisotropy matrices \( C_1 \) and \( C_2 \) representing two intersecting FPs at scale \( q + 1 \) (Schoenberg and Sayers, 1995). These two matrices may be further subdivided into another two matrices at scale \( q + 2 \) and so on.
Let us consider a material composed of two arbitrary anisotropic phases: the embedded medium \( C_1 \) and the system of aligned fractures \( C_2 \) with fracture density \( \varepsilon \). The stress-strain matching conditions for such a two-phase composite material leads to the following equation

\[
C(\varepsilon) = \sum_{\alpha=1}^{2} B_{\alpha}(\varepsilon) F(C_{\alpha}, \varepsilon)
\]

with diagonal matrices \( B_{\alpha} \) and matrix function \( F \) defined by Druzhinin (1997). A particular example is an orthorhombic structure composed of two orthogonal FPs with isotropic phases. In this example, each individual phase can be simulated by a simple model of parallel slip interfaces (Schoenberg and Douma, 1988) or by a more complicated model involving the non-linear coupling between fractures (Thomsen, 1995).

In FP inversion, the key parameter is the fracture density \( \varepsilon \). This parameter is estimated from the Taylor series expansion

\[
C = C_1 + \sum_{j=1}^{\infty} C^{(j)} \varepsilon^j
\]

by using the non-linear iterative inversion technique (Druzhinin and Hanuya, 1998). In the above expansion, the Taylor coefficients

\[
C^{(j)} = \partial^j C(0)
\]

are determined explicitly by differentiating equation (1) with respect to \( \varepsilon \). The first-order coefficient \( C^{(1)} \) is useful for studying the sensitivity of effective parameters prior to inversion.

Conclusions

In this work, the long-wavelength scaling behaviour of anisotropic images and log data was examined by means of attribute analysis and wavelet decomposition. We integrate these tools to distinguish fracture properties at different scales. In addition, we proposed a strategy to quantify the scale-dependent fracture patterns from vector images of anisotropic parameters and to search for the optimal parameters.

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