Anisotropy estimation based on the grey level co-occurrence matrix (GLCM)

Christoph Georg Eichkitz¹, Johannes Amtmann¹, Marcellus Gregor Schreilechner¹ and Sarah Schneider² focus on the application of textural attributes to estimate volumetric anisotropy based on the grey level co-occurrence matrix (GLCM).

Anisotropy refers to directional properties. In geophysics, we often refer to seismic anisotropy, the dependence of velocity on direction or upon angle (e.g., Crampin 1981, 1985; Lynn and Thomsen, 1990; Willis et al., 1986, Martin and Davis, 1987; Thomsen, 1986; Alkhalifah and Tsvankin, 1995). Variation in seismic velocity with direction may reflect lateral changes in facies, the presence of faults or fractures, or differences in pore fillings, among many factors that may influence velocity. In principal, seismic data can be used to estimate volumetric anisotropy (Simon, 2005). In this work we focus on the application of textural attributes to estimate volumetric anisotropy. The grey level co-occurrence matrix (GLCM), initially described by Haralick et al. (1973) as a tool for image classification, is a measure of how often different combinations of pixel brightness values occur in an image. This method has widely been used for classification of satellite images (Franklin et al., 2001; Tsai et al., 2007), sea-ice images (Soh and Tsatsoulis, 1999; Maillard et al., 2005), and magnetic resonance and computed tomography images (Kovalev et al., 2001; Zizzari et al., 2011). This methodology can also be applied to seismic data to describe facies, reservoir properties, and fractures (Vinther et al., 1996; Gao, 1999, 2003, 2007, 2008a, 2008b, 2009, 2011; West et al., 2002; Chopra and Alexeev, 2005, 2006a, 2006b; Yenugu et al., 2010; de Matos et al., 2011; Eichkitz and Amtmann et al., 2012b, 2013, 2014, Eichkitz and de Groot et al., 2014; Eichkitz et al., 2015a, 2015b). GLCM-based attributes can be calculated in different directions, yielding an array of radial responses. By comparing these different results it is possible to determine anisotropy in the seismic data. Here, directional GLCM-based attributes are used for the description of channel structures and for the interpretation of fractured reservoirs.

Workflow for anisotropy detection

The GLCM methodology belongs to the group of second-order texture classification methods in which the relationships between two sample points are measured. Usually, the sample points are neighbours, but the offset can be larger. The sample points being compared are aligned in different directions. For a simple 2D image and a standard offset of one pixel, the number of neighbouring pixels is eight and the number of possible directions is four (Eichkitz et al., 2015a, 2015b). Eichkitz et al. (2013) described how GLCM calculations could be expanded to three dimensions. For 3D data and a sample offset of one, there are 26 neighbouring samples that are aligned in 13 different directions. Increasing the sample offset increases the number of neighbouring samples. A sample offset of two means that the direct neighbouring samples are skipped and comparisons are made with the next sample points. Then, a centre sample point has 98 second-neighbouring samples and these are aligned in 49 directions (Figure 1).

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Figure 1 For an offset of one, each sample point has 26 neighbouring cells (a). These neighbouring cells are aligned in 13 directions. For an offset of two, the number of neighbouring pixels increases to 98, aligned in 49 directions (b).
are written into a symmetric matrix having the same size as the number of grey levels used. GLCM-based attributes are based on a normalized version of this matrix, found by dividing all matrix entries by the total number of co-occurrences. This produces a matrix of proportions that may be regarded as a kind of probability matrix. A number of attributes can be calculated based on this probability matrix (Haralick et al., 1973) and assigned to the central point of the analysis window. To determine GLCM-based attributes for the entire dataset, this procedure is repeated within a moving window.

Calculations performed in different directions will give slightly different results. Based on this observation, a workflow can be developed that automatically detects such directional differences for an entire seismic cube. The workflow consists of three main steps (Figure 2). First, parameters for the calculations must be defined, including the number of grey levels, the vertical and horizontal size of the analysis window, and the sample offset. Depending on the sample offset, GLCM calculations will be done in 13 directions (offset = 1) or 49 directions (offset = 2). Next, in step 2 of the workflow, one GLCM based attribute is calculated in all directions, producing either 13 or 49 attribute cubes. In the final step, these 13 or 49 attribute cubes are compared. For each sample point, the minimum and maximum values of the attribute cubes are determined and the directions in which these values occur are stored.

The maximum and minimum values can be used as indicators of anisotropic areas. Dividing the maximum values by the minimum yields a new attribute, the anisotropy factor. The anisotropy factor is an expression of the anisotropy present at each sample point. In the very rare circumstance that both the maximum and minimum are the same, the anisotropy factor equals 1 and area is isotropic. The range of the anisotropy factor depends on the scale of the GLCM attribute used. For GLCM energy, the anisotropy factor ranges between 1 and 10. Attributes such as GLCM variance will yield a smaller range in anisotropy factor.

As the value of 1 for the anisotropy factor can rarely be found, this may lead to an overestimation of the anisotropy in some areas. To avoid this, the final results can be conditioned by applying a threshold or cut-off value. All areas where the anisotropy factor is below a certain threshold value are set to undefined, while other other areas are assigned their minimum and maximum values and the corresponding directions of the minimum and maximum values.

For a definitive description of seismic anisotropy, this procedure should be repeated using several GLCM–based attributes and the results combined. It is then possible to describe areas that have greater directional variability, which may be an indicator of changes in lithology, pore filling, or density of fractures.

**Application of the workflow**

This workflow was tested for two different applications. The first is a suspected channel system in Miocene sediments of the Vienna Basin in Austria. The objective of the study was to describe the channel system using GLCM–based attributes and obtain information about the internal structure of the channels. The second case study is fracture detection within the Carboniferous (Pennsylvanian) Tensleep Formation at Teapot Dome in Wyoming, USA. In this study, the aim was to map fracture intensities and orientations in terms of fracture dip and azimuth.

A channel system was identified at depth of approximately 1000 ms by conventional coherence attribute analysis (Eichkitz et al., 2012a) in a seismic survey of the
Figure 4 (Upper) Amplitude and coherence for time-slice shown in Figure 3. (Lower) Anisotropy directions and anisotropy factor calculated for four GLCM-based attributes. Best results are achieved with GLCM-based energy and homogeneity, which also show higher differences between maximum and minimum values (see scale on images).

Figure 3 Calculation of GLCM-based energy in 13 directions. In the time-slices small variations are observable. The channel structure is especially visible in calculations done with 0° dip. Dotted lines indicate channel system interpreted on coherence cube (Eichkitz, et al., 2012a).
Figure 5 Anisotropy factor based on GLCM energy for five different stratigraphic intervals at Teapot Dome. In the Opeche Shale there are only a few areas with higher anisotropy factor. There are more areas with a high anisotropy factor in Tensleep A Sandstone, Tensleep B Dolomite, Tensleep B Sandstone and Tensleep C1 Dolomite. The anisotropy factor can be correlated with fracture intensities in these areas.

Figure 6 Azimuth direction of maximum values of GLCM-based energy. In combination with the information from Figure 5, these directions can directly be used as indicators of fracture directions.
have been published (e.g. Gilbertson, 2006; Zhang, 2005; Wilson et al., 2013b, 2015, Schwartz, 2006). The use of seismic attributes to describe Tensleep fractures has been investigated by Ouenes et al. (2010), Gao (2013), Wilson et al., (2012, 2013a, 2013b, 2015), Di and Gao (2014), and Thachaparambil (2015).

In this study, post-stack seismic attributes including coherence, curvature, and spectral decomposition (Schneider, et al., 2015) were used in addition to GCLM-based attributes. The parameters for the GLCM-based attribute calculations were similar to those used in the channel study with 64 grey levels and an analysis window of 3 x 3 x 15. Calculations were made in 13 directions and the results compared with each other. The anisotropy factor was especially important because it is an indicator of fracture intensity. In this case study, the anisotropy factor should be highest in the Tensleep B stratigraphic zone and lower in the Tensleep C and in the Opeche Shale where fracturing is known to be less intense. This is clearly apparent in Figure 5, which shows maps of the anisotropy factor for the Opeche Shale, Tensleep A Sandstone, Tensleep B Dolomite, Tensleep B Sandstone, and Tensleep C1.

In addition to the anisotropy factor, the workflow produces directions of anisotropy that can be correlated with the strike and dip of fractures. Depending on the GLCM-based attribute, the strike direction is either perpendicular to the direction of maximum value or is parallel. For GLCM-based energy, the strike direction is perpendicular to the direction of maximum value, so energy-based azimuths and dips must be shifted to obtain fracture dip and azimuth. In Figure 6, corrected fracture azimuths based on GLCM energy are shown for the Opeche Shale, Tensleep A Sandstone, Tensleep B Dolomite, Tensleep B Sandstone, and Tensleep C1.

The objective of the second case study was to characterize a fractured reservoir. Teapot Dome, located in central Wyoming, is the extension of a large structural complex with the Salt Creek anticline to the north and the Sage Spring Creek and Cole Creek oil fields to the south (Doelger et al., 1993; Gay, 1999; Cooper et al., 2001). Stratigraphic units of interest are the Pennsylvanian Tensleep Formation and Opeche Shale. The Tensleep Formation serves as a reservoir interval in several Rocky Mountain oil fields and consists predominantly of naturally fractured sandstone. Numerous studies of fracturing in the Tensleep Formation have been published (e.g. Gilbertson, 2006; Zhang, 2005; Wilson et al., 2013b, 2015, Schwartz, 2006). The use of seismic attributes to describe Tensleep fractures has been investigated by Ouenes et al. (2010), Gao (2013), Wilson et al., (2012, 2013a, 2013b, 2015), Di and Gao (2014), and Thachaparambil (2015).

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Image logs from four wells are available at Teapot Dome, so it is possible to compare the results of seismic attribute calculations with fracture rose diagrams based on image log data. This is done in Figure 7 which compares GLCM-based attributes to interpretation based on image logs and also to spectral edge attribute calculations by Thachaparambil (2015). The GLCM–based attributes show very good correlation within the limitations imposed on them by the seismic resolution. For 13 directions, it is only possible to resolve in 45° increments in the horizontal and vertical planes. The resolution could be improved by increasing the number of directions used in the calculations.

Conclusion

Textural attributes are a useful addition to seismic attribute interpretation. One important benefit of textural attributes based on the GLCM is the possibility to doing calculations in different directions. Using the anisotropy factor workflow, it is possible to determine the presence of anisotropy in seismic reflection data and also determine the major and minor axes of anisotropy. The anisotropy factor, an indicator of the degree of anisotropy, can be calculated from such data.

A case study demonstrates the use of GLCM textural attributes in interpreting facies and internal structure of a channel detected seismically. A second case study illustrates the applicability of the method to a fractured reservoir, where it was possible to determine fracture intensity and the strike and dip of fractures. In both case studies, only 13 directions were used; performing GLCM-based anisotropy calculations in 49 directions would enhance the results.

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