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Directional filter aided sub-basalt interpretation: A case study from the Faroe-Shetland basin

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ABSTRACT

In complex geological settings, post-stack image processing aids geological interpretation. This case study shows how directional filtering, which is a spatial convolution that focuses energy along a pre-determined direction, can be used for post-stack processing. Application of coherency filtering can improve the mappability of both horizon and fault when applied in the following manner. One or more Region of Interest (ROI) are identified in the stack image and isolated for processing. Within a ROI, the directional filter is applied along the dominant horizon dip. For each ROI the coherency attribute, which provides an image of the discontinuities (e.g. faults), is also generated. The directional filtering is applied to the coherency image along the dominant dip of the faults/fractures. Finally, for each ROI, the filtered coherency image and the filtered stack are co-rendered. The co-rendered image can be merged with the unprocessed stack for a more complete interpretation of the geology. This simple yet intuitive workflow can greatly aid geological interpretation. Here, direction filtering is demonstrated on sub-basalt stratigraphy using a 2D profile from the Faroe-Shetland Basin but the methodology is applicable to any setting.

1. Introduction

Mapping faults and horizons forms the backbone of seismic interpretation. In essence, presence of both horizons and faults in a seismic section indicates a stratigraphical or structural change in geology. Horizons indicate change in seismic impedance across two layers while faults indicate change in continuity of a horizon. Conventionally, an interpreter maps faults and horizons by visually identifying them in a seismic section/volume. Recently, there has been a surge of automated mapping algorithms, ranging from deterministic (Pedersen et al., 2002, Randen et al., 2001) to stochastic (Aminzadeh and Chatterjee, 1984, Tingdahl and De Rooij, 2005). Although automated mapping is beneficial from an economic perspective, it is in common knowledge that its success depends on the noise content of the data. Automated algorithms tend to perform better with higher resolution and cleaner datasets. Post-stack image enhancements can greatly assist in automated mapping and therefore is being widely explored (Hale, 2013, Love and Simaan, 1985, Bondar, 1992, Sibille et al., 1984). Among a variety of image enhancement methods, filters with edge detection capability have been found to be particularly effective (Lu and Cheng, 1990, Huang, 1990, Luo, 1999, Luo et al., 2002). Bakker et al. (1999) have shown that the detection may not be limited to linear edges; they combined Gradient Square Tensor (Waagstein, 1988) and Kuwahara filter to develop filters with "steering" capabilities.

Image enhancement can be particularly advantageous for interpreting sub-basalt settings where data quality is generally poor. Scattering and absorption by overlying high-velocity fractured basalt greatly reduce energy penetration (Martini and Bean, 2002) and do not allow a very clean and coherent image of the underlying sediments to be produced (Kiørboe and Petersen, 1995, Ziolkowski and Fokkema, 2006). When basalt flows interfinger with sediments seismic energy is also lost through internal multiples (Fliedner and White, 2003), which are very difficult to account for in processing. Further, layered basalt intrusions also act like lenses that progressively distort the wavefield (Reshef et al., 2003). However, layered intrusion, such as in the Faroe-Shetland Basin, might form hydrocarbon traps and therefore sections containing basalt layers can be valuable imaging targets.

Sub-basalt imaging is usually done in an iterative manner where interpretation and velocity model building are coupled. This, however, also presents an interpreter with a circular problem. A poor sub-basalt image cannot support reliable interpretation but unless the interpretation is improved, it is difficult to improve the velocity model itself. For enhancing sub-basalt interpretation without having to rebuild the velocity model, researchers have attempted supplementing seismic with electromagnetic (MacGregor and Sinha, 2000) and gravity datasets (Colombo et al., 2012). Results from such joint analysis have been insightful but limited only to resolving the large-scale features of the geology. For a detailed geological model that includes subtle features such as

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fault splays and pinch-outs, the need of improving the seismic image cannot be circumvented.

In this paper we present a generalized approach of enhancing a linear feature in seismic image through spatial convolution. The method, known as “directional filter” is borrowed from the broader field of image processing. Use of spatial filters for highlighting features of interest is fairly state-of-the-art in image processing applications (Gonzales and Woods, 2002). The choice of the spatial filter is target-dependent. For example, when the continuity of an interface needs to be enhanced, a Coherency filter is used. On the other hand, for enhancing discontinuity, a Laplacian filter is applied (Shukla and Saha, 2011). Directional filter is a rather general term for operators that can enhance lineaments along any predetermined orientation. More simply, directional filtering can be compared to throwing a beam of light in different directions using a flashlight which will illuminate differently oriented features. Its application, limited in this paper to a grayscale representation of 2D stack, is as follows. A grayscale image is a matrix of integers ranging between 0 (black) and 255 (white). When the larger image matrix is convolved with the smaller filter matrix, hereafter referred to as the *kernel*, features along a particular direction get highlighted based on the kernel composition. This simple yet intuitive approach can be used to enhance mappability (ease of identification) of both faults/fractures and horizons.

The novelty of this paper is in the way the processing is done – while the horizons are improved on the stack, to improve the fault/fracture definition, the coherency attribute (Bahorich and Farmer, 1995, Chopra, 2002) is used. Coherency provides an image of the discontinuities (faults, fractures, etc.) as zones of higher (or lower depending on scaling) values compared to the background. The key in this paper is applying the directional filter along the dominant dip of the feature of interest, be it a fault or horizon. Our workflow is as follows (Fig. 1). First, we identify one or more Region of Interest (ROI) in the stack that require enhancement. The ROI is isolated for processing. Then, within an individual ROI, we apply the directional filter along the dominant horizon dip. We also compute the coherency attribute for every ROI and apply the directional filtering to the coherency image along the dominant dip of the faults/fractures. Finally, for each ROI, we co-render the filtered coherency and the filtered stack images. Co-rendering provides a powerful visualization of how faults and the horizons interact. The co-rendered image is then merged with the unprocessed stack for a more complete interpretation. The workflow is generic allowing an interpreter to select a ROI based on the image complexity. Here, although we have demonstrated the direction filtering on sub-basalt stratigraphy using a 2D profile from the Faroe-Shetland Basin (Fig. 2a), it is applicable to any setting and, in principle, extendable to a 3D volume.

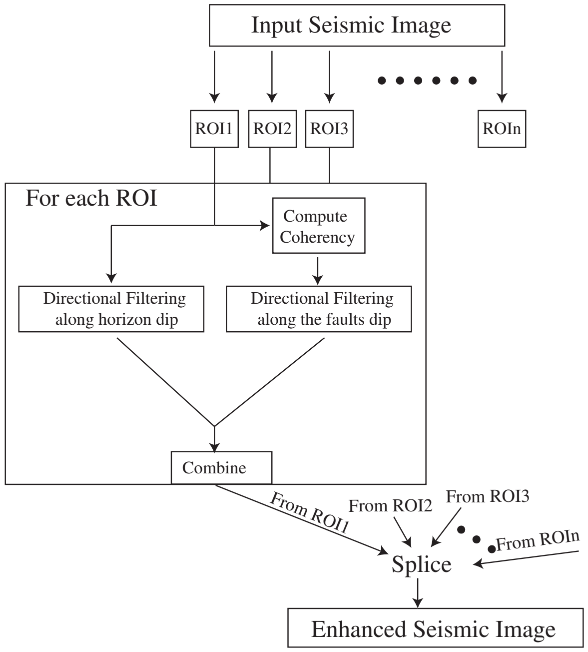

Fig. 1. Directional filter application workflow.

2. Study area

The Faroe–Shetland Basin is located offshore northwest Scotland on the SE margin of the Atlantic Ocean. The basin hosts a number of mini-basins separated with intra-basin highs that have been locations of significant hydrocarbon discoveries. The basalt cover in the basin is attributed to a Paleogene mantle plume. An episodic but rapid uplift of the Faroe-Shetland Basin during the Paleocene through Eocene followed by a rapid subsidence defines its overall architecture (Dam, 1998, Smallwood and Gill, 2002, Champion et al., 2008, Gariépy et al., 1983, Waagstein, 1988). A basalt layer overlies prospective Paleocene and Mesozoic strata. In the parts of the basin outside the basalt layer, hydrocarbons have mainly been found in the Jurassic sandstone reservoirs particularly within late Jurassic stratigraphic traps. How basalt effected the petroleum system in the Faroe-Shetland Basin is not very clear. Structural changes from basalt interfingering are very likely (Ligtenberg, 2003, 2005, Ligtenberg and Connolly, 2003). Therefore, mapping the sub-basalt faults and fractures is important not only for understanding the later hydrocarbon migration but also reconstructing the local basin architecture.

3. Method

At its core, directional filtering is a convolution operation and can be graphically understood as follows. Consider an input image as a matrix of n rows and m columns and a filter kernel of 3 rows and 3 columns. Also consider an output image which is initially the same as the input image. The kernel can be centered at a user-desired location in the input image. The overlap between the kernel and the input image will be a 3 × 3 matrix. The convolution operation involves multiplying the corresponding elements of the overlapped matrices and adding them. The sum is assigned to the output image at the location of the kernel's central element (Fig. 3). The kernel is then moved to a new location and the process is repeated and the output image gets progressively updated.

It is easy to see that if the middle row of the kernel is zero, only the horizontal features will be enhanced. In this application we are assuming the horizontal direction as 0° and clockwise rotation as increasing angle. Thus, if the middle column or the diagonal elements are zero, only the vertical features or features oriented at 45° will be enhanced. More generally, the kernel for enhancement along angle θ is as follows (Pratt, 2001):

$$\begin{bmatrix} (\cos\theta + \sin\theta) & (\cos\theta) & (+\cos\theta - \sin\theta) \\ (\sin\theta) & (0) & (-\sin\theta) \\ (-\cos\theta + \sin\theta) & (-\cos\theta) & (-\cos\theta - \sin\theta) \end{bmatrix} \tag{1}$$

As suggested by Eq. (1), the kernel matrix has two key characteristics. First, its central element is zero and second, the sum of its elements is also zero. This prevents bias. Examples of kernels for four orientations, 90°, 100°, 110° and 135°, are presented in Fig. 4.

How direction filter behaves can be understood using the following demonstration. Fig. 5a shows the image of a human face. The texture of the faces comprises straight and curved lines. In Fig. 5b, we blurred the face using a 10 × 10 matrix. As a result, it is difficult to outline its parts such as the ear and eyes. Fig. 5b is intended to conceptually represent a migrated image where the energy has not been focused, say, for