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High Resolution Diffraction Imaging of Small Scale Fractures in Shale and Carbonate Reservoirs

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SUMMARY

Current research in the field of seismic depth imaging has identified a new approach to image with super-resolution fractured zones, fault edges, small scale faults, pinch-outs, reef edges, channel edges, salt flanks, reflector unconformities, near surface scattering objects and in general any small scattering objects, by using Diffraction Imaging as a complement to the structural images produced by reflection imaging. Diffraction Imaging is the imaging of discontinuities in the earth. Diffractions are the seismic response of small elements (or diffractors) in the subsurface of the earth, such as small scale faults, fractures, near surface scattering objects and in general all objects which are small compared to the wavelength of seismic waves. We show results in different areas of the world, in fractured carbonate and unconventional shale reservoirs. Using Diffraction Imaging to identify areas with increased natural fracture density, which correlate with increased production, the reservoir engineers can design an optimal well placement program that targets the sweet spots and minimizes the total number of wells used for a prospective area.

Introduction

Current research in the field of seismic depth imaging has identified a new approach to image with super-resolution fractured zones, fault edges, small scale faults, pinch-outs, reef edges, channel edges, salt flanks, reflector unconformities, injectites, fluid fronts, caves and karst, and in general any small scattering objects, by using Diffraction Imaging as a complement to the structural images produced by reflection imaging. Diffraction Imaging is the imaging of discontinuities in the earth. Diffractions are the seismic response of small elements (or diffractors) in the subsurface of the earth, such as small scale faults, fractures, near surface scattering objects and in general all objects which are small compared to the wavelength of seismic waves. We show results in different areas of the world, in fractured carbonates and unconventional shale reservoirs. Using Diffraction Imaging to identify areas with increased natural fracture density, which correlate with increased production, the reservoir engineers can design an optimal well placement program that targets the sweet spots and minimizes the total number of wells used for a prospective area.

Diffraction Imaging is a novel high-resolution imaging technology designed to image and identify in very fine detail the small scale fractures in shale and carbonate reservoirs that form areas of increased natural fracture density. These areas may be associated with higher production wells (Schoepp et. al., 2015). Diffractions are the seismic response of small elements (or diffractors) in the subsurface of the earth, such as small scale faults, fractures, near surface scattering objects and in general all objects which are small compared to the wavelength of seismic waves. The diffraction imaging is the direct response to subsurface discontinuities and is in most cases obtained from pre-stack, pre-migration data rather than post-stack, post-migration images. The diffractions volume can be used as a complement to the structural images produced by reflection imaging (Khaidukov, Landa and Moser, 2004; Taner, Fomel and Landa, 2006; Moser and Howard, 2008; Koren, Ravve and Levy, 2010; Dell and Gajewski, 2011; Moser, 2011).

Standard approaches to obtain high-resolution information, such as coherency analysis and structure-oriented filters, derive attributes from stacked, migrated images. Diffraction imaging in comparison, acts on the pre-stack data, and has the potential to focus super-resolution structural information. Diffraction images can be used as a complement to the structural images produced by conventional reflection imaging techniques, by emphasizing small-scale structural elements that are difficult to interpret on a conventional depth image.

We show that operating in a migration framework on pre-stack data, using procedures which complement those used to enhance specular reflections, allows us to obtain higher resolution information, which is lost in conventional procedures. An efficient way to obtain diffraction images is to first separate the migration events according to the value of specularity angle, in a similar way to offset gathers; diffraction images are produced subsequently using post-processing procedures. The high-resolution potential is demonstrated by several case histories in carbonate reservoirs and unconventional shales, showing much more detail than conventional depth migration or coherence. Productivity in the shale plays depends on many factors including total organic content, the susceptibility of the reservoir to hydraulic fracturing and factors in the well design and completion processes. However, since reservoir porosity is exclusively fracture porosity, the detection of naturally occurring faults and fractures and the interaction of these with the hydraulic fracturing process are key areas of investigation.

Theory and Method

Diffractions are the seismic response of small elements (or diffractors) in the subsurface of the earth, such as small scale faults, near surface scattering objects and in general all objects which are small compared to the wavelength of seismic waves. Diffraction imaging is simply the process of using diffractions to determine the locations of the small subsurface elements that produced them. Since diffractors are, by definition, smaller than the wavelength of seismic waves, diffraction imaging provides super-resolution information, which consists of image details that are beyond the classical Rayleigh limit of half a seismic wavelength. The importance of diffractions in high-resolution structural imaging has been emphasized in many recent publications (Shtivelman and Keydar 2004, Tanner et al. 2006, Fomel et al. 2006, Khaidukov et al. 2004, Moser and Howard 2008, Moser 2009, Popovici et al., 2014), however, diffraction imaging is still not a widely used tool in seismic interpretation. In fact, most of the algorithms that are used to process seismic data enhance reflections and suppress diffracted energy. The goal of diffraction imaging is not to replace these traditional algorithms, but rather to provide interpreters with an additional image to fill in the small, but potentially crucial, structural details.

An important point to note is that a true diffraction image is not optimally obtained by post-processing of a traditional seismic image, even if the seismic image is obtained by an algorithm that does not suppress diffractions. While diffractors will appear in the image, usually in the form of discontinuities, they have much lower amplitudes than reflecting structures. By imaging diffractors using the pre-stack data, the diffractor amplitude can be enhanced while the specular reflections can be attenuated. Furthermore, and more importantly, discontinuities in the seismic image can appear for a variety of reasons other than diffractions, including small errors in the velocity model of the earth that was used to obtain the image.

Several techniques for diffraction imaging have been proposed (Khaidukov et al. 2004, Tanner et al. 2006, Moser and Howard 2008, Moser 2009). They fall into two categories. In the first category are methods that separate the seismic data into two parts, one that contains the wave energy from reflections and the other that contains the wave energy from diffractions. Each component is used to provide an image through traditional seismic imaging methods. We have to keep in mind that there is no clear distinction between "reflection waves" and "diffraction waves." By Huygens' principle a reflector can be represented by a series of point diffractors that are positioned on its surface. In the second category are methods that do not separate the input seismic data, but rather use a different image forming technique that suppresses reflecting surfaces in the image (Moser and Howard 2008, Moser 2009). We will focus on the second category of methods, specifically on the method of Moser and Howard, which can be expressed as a reflection suppressing kernel for Kirchhoff migration.

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Since diffractors are, by definition, smaller than the wavelength of seismic waves, diffraction imaging provides super-resolution information. In Figure 1, we illustrate the difference between the conventional specular reflection and the higher resolution diffraction imaging. The Fresnel zone is depicted by the hatched area.

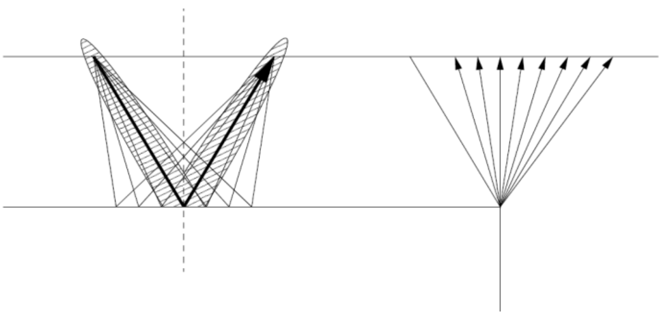

***Figure 1**: Comparison between a pure specular reflection and a pure diffraction case. The Fresnel zone for the reflection is depicted by the hatched area. The diffractions offer higher resolution details of discontinuities, such as the natural fractures occurring in rocks.*

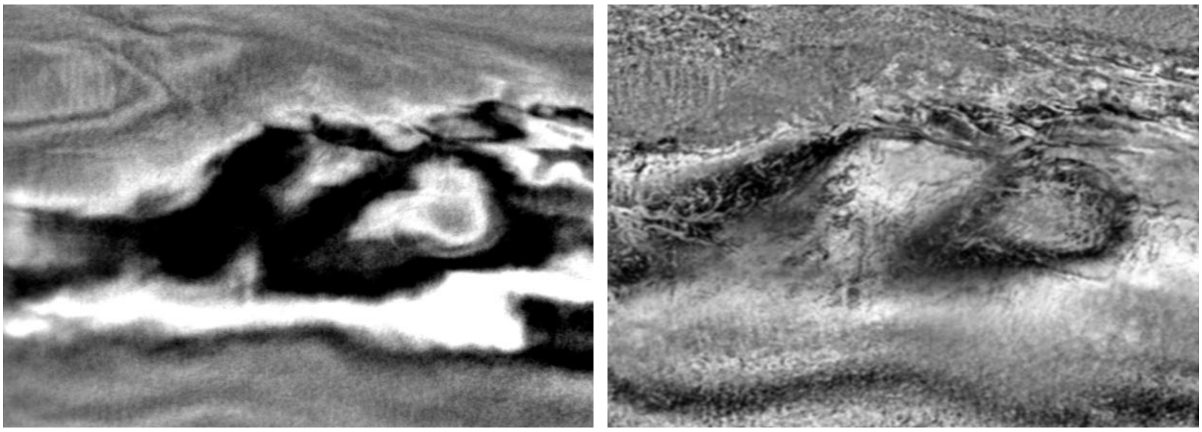

***Figure 2**: Comparison between a Kirchhoff PSDM depth slice and a Diffraction Imaging (DI) depth slice. The DI slice shows higher resolution details of discontinuities. Data courtesy of Seitel.*

The main goal of conventional time and depth seismic processing is to enhance specular reflections, which follow Snell's law and for which the angle of incidence equals the reflection angle. Many time processing steps are designed to increase the lateral coherency of the reflections, from interpolation, FXY deconvolution and FK filtering, to wave-equation binning. Since diffractions have a different move-out than reflections, many processing steps designed to enhance reflections result in attenuating diffractions.

Seismic methods are generally limited in their resolving power to about one half of the dominant wavelength at the target. When the sand or shale layers are thinner than half of the wavelength, tuning and multiple-reverberation effects make the stratigraphic interpretation of the images difficult and unreliable. Decreasing the wavelength of the seismic waves reflected at the target is nearly impossible in surface seismic surveying because of the dissipative nature of the overburden that causes the attenuation of the high-frequency component of the seismic wavefield. Furthermore, the high frequencies that are present in the data are often lost during standard processing.

Small-scale faulting

If we examine the spatial distribution of the diffraction response relative to the major faults, we note that the diffractivity tends to be organized in north-east south-west trending bands running parallel to the major fault trends. We interpret the area of high diffractivity to be small-scale faults or fractures antithetic to the major faults. These features occur at the seismic scale but are too small to be observed on the conventional reflection seismic. Moreover, the dense diffraction distribution could be associated with an even finer scale of faulting and fracturing not detectable via the seismic method, beyond the resolution of surface seismic data.

Conclusions

We discuss the implementation in image domain of Diffraction Imaging, a method of imaging discontinuities in the earth like fractured zones, fault edges, small scale faults, pinch-outs, reef edges, channel edges, salt flanks, reflector unconformities, near surface scattering objects and in general any small scattering objects.

We use Diffraction Imaging as a complement to the structural images produced by reflection imaging. Diffractions are the seismic response of small elements in the subsurface of the earth, objects which are small compared to the wavelength of seismic waves. We show results in different areas of the world, in fractured carbonate and unconventional shale reservoirs.

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