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High Resolution Diffraction Imaging of Small Scale Fractures Fields in Unconventional Shale Plays

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Abstract

Summary

In 2000, shale gas represented just 1 percent of American natural gas supplies. Today, it is 30 percent and the percentage keeps increasing. The technology to drill and fracture the shale formations is now exported to the rest of the world, increasing the national oil and gas reserves in many other countries. The thickness of the shale formations is often just a few hundred feet, so new high-resolution technologies are needed to visualize the structure and the natural fracture distribution and orientation in these thin shale layers. Diffraction imaging can be used to complement the structural images produced by conventional processing - by generating an additional image volume of high resolution unconformities - such as small scale faults, pinch-outs, or salt flanks.

Introduction

High resolution imaging of the small scale fractures in shale reservoirs improves production and recovery efficiency, reduces field development cost and decreases the environmental impact of developing the field by using fewer wells to optimally produce the reservoir. This technology is not yet deployed in the industry and is a fundamental advance in high resolution 3-D prestack data imaging of complex geological structures. Current diffraction imaging research has identified a new approach to image small scale faults, pinch-outs, salt flanks, reflector unconformities, in general any small scattering objects, by using diffraction imaging as a complement to the structural images produced by reflection imaging

Diffraction imaging can be used as a complement to the structural images produced by conventional processing, to image and visualize the structure and the natural fracture distribution and orientation in thin shale layers. Diffraction imaging is simply the process of using diffractions to focus and image the structural elements that produced diffraction surfaces. 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 goal of diffraction imaging is to provide interpreters with an additional 3-D or 4-D volume to fill in the small, but potentially crucial, structural details.

The main goal of conventional time and depth seismic processing is to enhance specular reflections. There are many time processing steps 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, end up attenuating the diffractions.

Seismic methods are generally limited in their resolving power to about one half of the dominant wavelength at the target. When the shale layers are thinner than half 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. High resolution imaging is of great value to an interpreter, for instance to enable identification of small scale faults, and to locate formation pinch-out positions. 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 and image super-resolution structural information.

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 focus and image the structural elements that produced diffraction surfaces. 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 (Shitvelman and Keydar 2004, Taner, Fomel and Landa 2006, Fomel, Landa and Taner 2006, Khaidukov, Landa and Moser 2004, Moser and Howard 2008, Moser 2009), 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 3-D or 4-D volume to fill in the small, but potentially crucial, structural details. Figure 1 shows a comparison of a detail in a structurall images compared with the diffraction image.

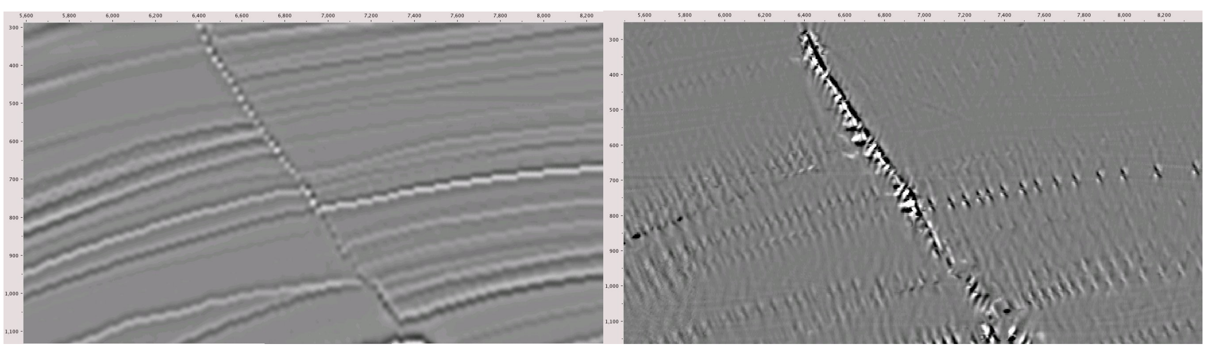

Figure 1: Details on a fault from a synthetic model. (Left) Kirchhoff migration stack using the exact velocity model (Right) Diffraction imaging stack of the same data..

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, Landa and Moser 2004, Taner, Fomel and Landa 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" (using 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. A conventional full wave Kirchhoff migration forms a seismic image as:

$$V_{kirch}(x) = \sum_{s,r} \int U(t,s,r)\delta(t - t_d(s,x,r))dt \quad , \quad (1)$$

where, δ is the Dirac delta function, the sum is over all source and receiver pairs *(s,r)*, *U(t,s,r)* is the seismic data and $t_d(s,x,r)$ is the stacking traveltime trajectory given by the traveltime from the source to the image point and back to the receiver,

$$t_d(s,x,r) = T(s,x) + T(x,r), \quad (2)$$

For a sufficiently dense grid covering the source-receiver acquisition, the traveltimes *T(s,x)* and T*(x,r)* are pre-computed by ray tracing in the velocity model, and stored on disk as traveltime tables for subsequent use in forming the image (1). The idea behind Kirchhoff diffraction imaging is to modify the image to be given by:

$$V_{diff}(x) = \sum_{s,r} \int w(s,x,r)U(t,s,r)\delta(t - t_d(s,x,r))dt \quad , \quad (3)$$

where all of the quantities are the same as before, except for the addition of the weight function *w(s,x,r)*. This weight is used to suppress reflections and is obtained by the following steps. First, using standard Kirchhoff migration we find the seismic image $V_{kirch}(x)$ by equation (1). This image will include both reflections and diffractions, but as mentioned before, the reflections are the most dominant part of the image. The second step is to analyze the structures in the Kirchhoff image and determine the normal vector *n* to these structures at each image point. With this information we can define the weight function by:

$$w(s,x,r) = 1 - \left|\frac{\hat{n}\cdot(p^s+p^r)}{\|p^s+p^r\|}\right|, \quad (4)$$

where $p^s(x) = \nabla_x T(s,x)$ and $p^r(x) = \nabla_x T(x,r)$ are the gradients of the traveltimes from the source to the image point and from the image point to the receiver respectively. The logic behind this weight function is that the normal vector $(p^s + p^r)/||p^s + p^r||$ is the angle bisector of the of wave vectors for the incoming and outgoing waves. For a (specular) reflector, this direction is collinear with the normal vector to the reflector, thus the weight function will be nearly zero. At a diffraction point, since the seismic waves propagate in all directions, the weight function will not be zero, at least for most of the wave propagation directions. As a practical implementation, we introduced a gain function in order to moderate the filter for angles close to zero and 90 degrees.

The analysis of the structures in the Kirchhoff image (1) is the most challenging part. We are using here the plane wave destruction (PWD) filter technique, introduced by Claerbout, 1992, and improved by Fomel, 2002. In our implementation, the dips in the image are found as solutions of local least square problems for the plane wave destruction misfit. The degree of localization of these dips can be defined by the user and can generate a certain smoothness of the dip field.

Applications

The method was first tested and calibrated on several synthetic datasets. The Kirchhoff migrations were performed using Z-Terra's prestack depth migration program, in which the diffraction imagining method was implemented in a special migration kernel. One of the synthetic datasets, the Cassis model has been previously investigated in Moser and Howard (2008) using a slant stack method for the dip field estimation. Figure 2 shows the Kirchhoff migration stack compared to the diffraction imaging stack. All the discontinuities visible in the full-wave stack are enhanced in the diffraction image while all the specular reflections are almost completely attenuated. In Figures 3 we show some details from from the same model. Figure 4 shows the results of a real data set where Diffraction Imaging was used to obtain a 3-D volume of discontinuities through the Eagle Ford shale. Such volumes can be used to map the natural fractures distribution in the reservoir, and are useful in mapping the areas with possible higher production, optimize the hydraulic fracturing stages, and in general optimize the field production.

Conclusions

Diffraction imaging can be used as a complement the structural images produced by conventional processing, to image and visualize the structure and the natural fracture distribution and orientation in thin shale layers. We used the reflector dip field extracted from a full-wave pre-stack Kirchhoff migration image to modify the weighting function of the migration kernel. As a result we enhanced the diffraction component of the image, while almost completely attenuating the specular reflections. We calibrated the methods on several synthetic datasets, then we applied it on 3-D real data to obtain spectacular super-resolution results.

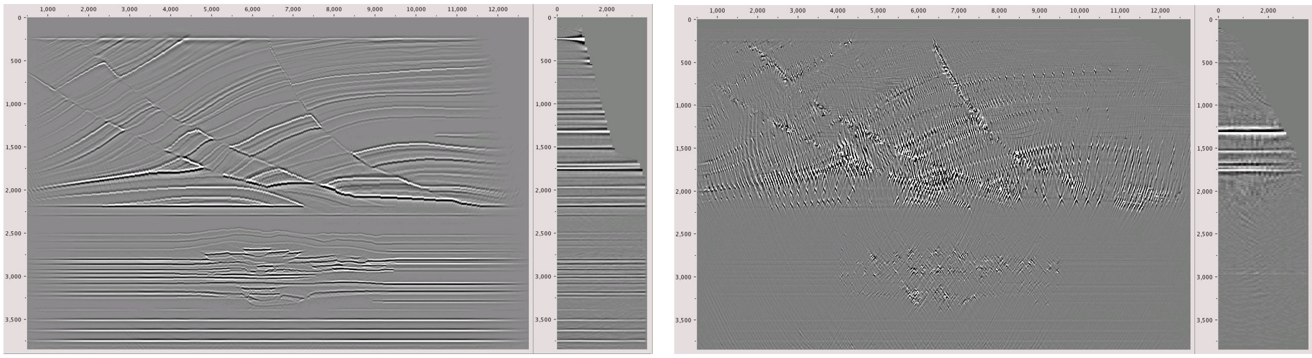

Figure 2: (Left) Kirchhoff migration stack and offset gathers using the exact Cassis velocity model. (Right) Diffraction imaging migration result.

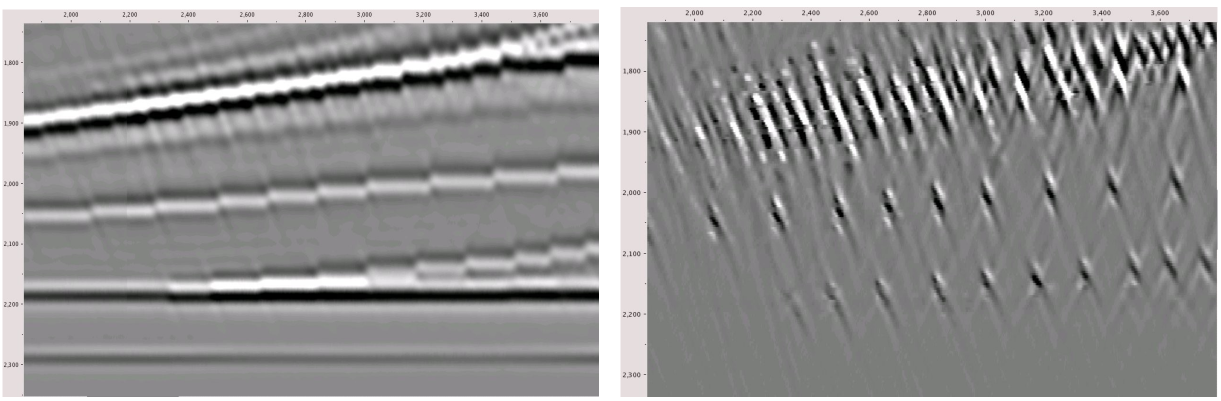

Figure 3: Details on a pinch-out from the Cassis model. (Left) Kirchhoff migration stack using the exact Cassis velocity model. (Right) Diffraction imaging migration result using the exact model.

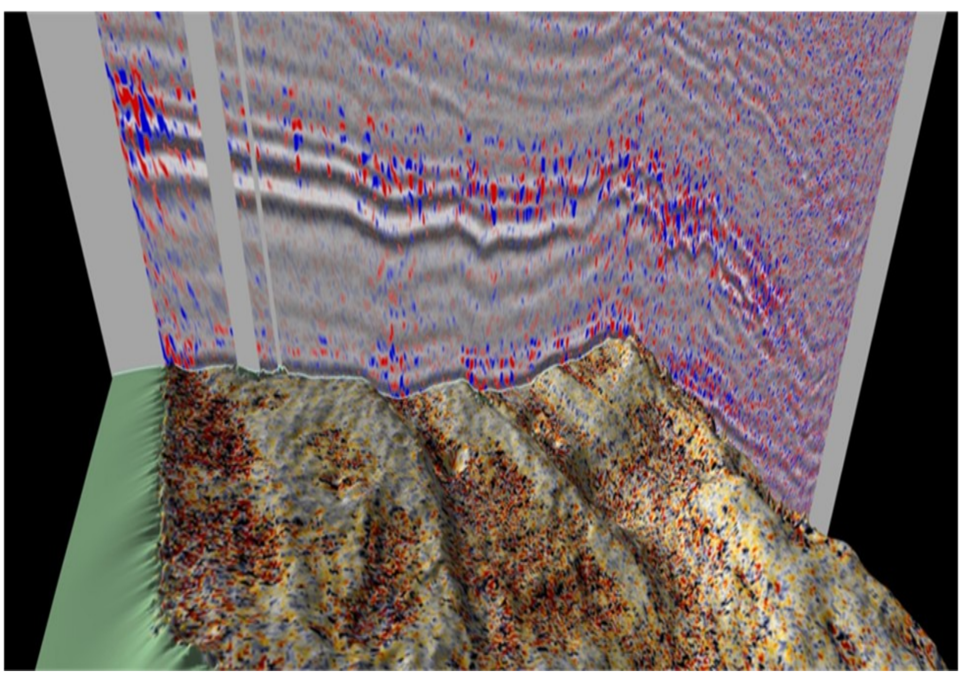

Figure 4: Diffraction imaging along horizon showing the areas with larger fracture density, overlayed on the structrural image. Data courtesy of Marathon and Seitel.