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Method Images Small-Scale Fractures

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HOUSTON–In 2000, shale gas represented only 1 percent of U.S. natural gas supplies. Today, it is 30 percent and that percentage keeps increasing. The technology to drill and fracture shale formations is being exported to the rest of the world, increasing national oil and gas reserves in many other countries.

Productivity in 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, detecting naturally occurring faults and fractures–and their interaction with the hydraulic fracturing process–are key areas of investigation.

The thickness of shale formations is often only 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. High-resolution imaging of small-scale fractures in shale reservoirs has the potential to improve production and recovery efficiency, reduce field development costs, and decrease the environmental impact of developing the field by using fewer wells to optimally produce the reservoir.

Diffraction imaging (DI) is a novel technology that uses diffractions to image with super-resolution small subsurface elements that produce diffractions such as small-scale faults and fractures. 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 (the minimum resolvable detail) of half a seismic wavelength.

Diffraction imaging can be used to complement the structural images produced by conventional processing by generating an additional image volume of high-resolution unconformities. By identifying the areas with increased natural fracture density, reservoir engineers can

FIGURE 1A

Specular Reflection and Diffraction Imaging Comparison

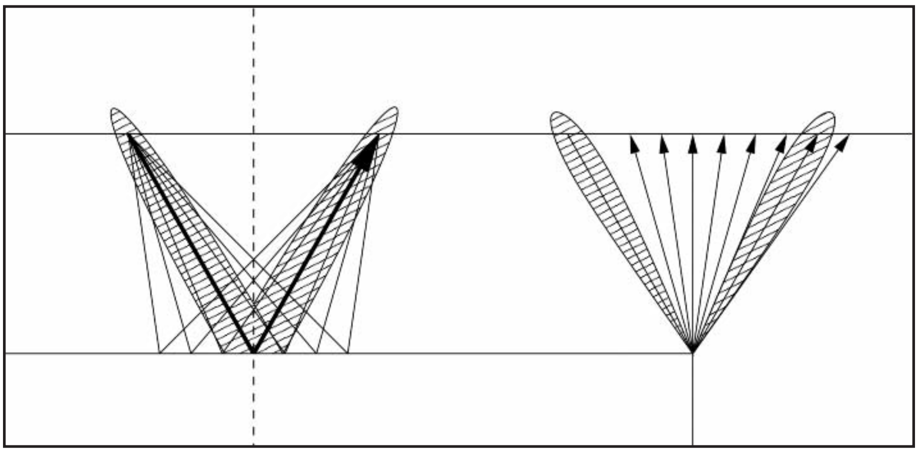
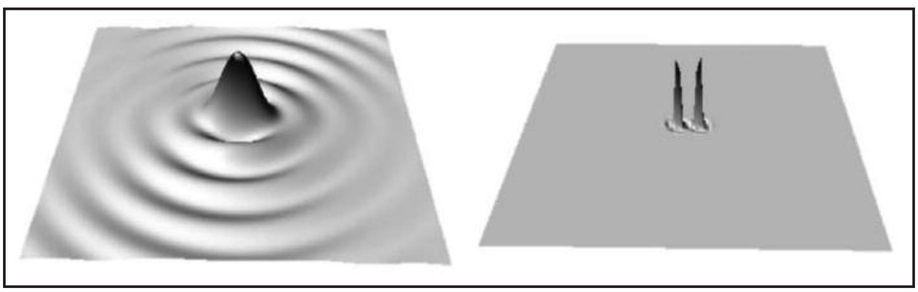


FIGURE 1B

Resolution of Kirchhoff Migration (left) versus Diffraction Imaging (right)



Source: Gelius and Asgedom, 2011

design an optimal well placement program that targets the sweet spots and areas with increased production, while minimizing the total number of wells used for a prospective area.

'Super-Resolution' Information

DI 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 that are small compared to the seismic wavelength. An important property of DI is that it provides super-resolution information. We observe the super-resolution primarily in depth or time slices, because diffraction imaging does not have the contribution from reflected rays at small angles in the vicinity of the specular reflection.

To illustrate this effect, Figure 1A shows the difference between a conventional pure specular reflection and a higher-resolution pure diffraction imaging case. The Fresnel zone for the reflection is depicted by the hatched area. The diffractions offer higher-resolution details of discontinuities, such as natural fractures occurring in rocks.

Figure 1B depicts the difference in resolution between a standard Kirchhoff migration on the left and DI on the right, when imaging two closely spaced scatterers. The diffraction imaging result shows much higher resolution and the ability to differentiate two very small diffractors that are grouped by the Fresnel zone in the Kirchhoff image.

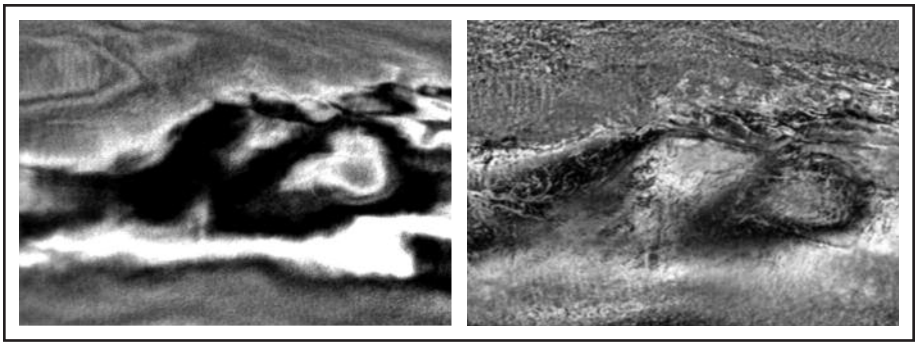
The main goal of conventional time and depth seismic processing is to enhance specular reflections. There are many time processing steps designed to increase the lateral coherency of the reflections, from interpolation, F-XY deconvolution and F-K filtering, to wave-equation 5-D binning. Since diffractions have a different move-out than reflections, many processing steps designed to enhance reflections end attenuating the diffractions.

Seismic methods generally are limited in their resolving power to about one-half of the dominant wavelength at the target. When sand or shale layers are thinner than half of the wavelength, tuning and multiple-reverberation effects make stratigraphic interpretations 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, which causes the attenuation of the high-frequency component of the seismic wave field.

Furthermore, the high frequencies that are present in the data are often lost during standard processing. Figure 2 shows the difference in detail between a depth slice through a Kirchhoff migrated data volume (left) in the Eagle Ford Shale, and the same depth slice through a 3-D diffraction imaging volume (right). In the DI depth slice, much higher resolution discontinuities can be seen in areas that appear fairly smooth in the Kirchhoff constant depth slice.

FIGURE 2

Kirchhoff Depth Slice (left) and DI Depth Slice (right) Comparison (Eagle Ford)



Crucial Structural Details

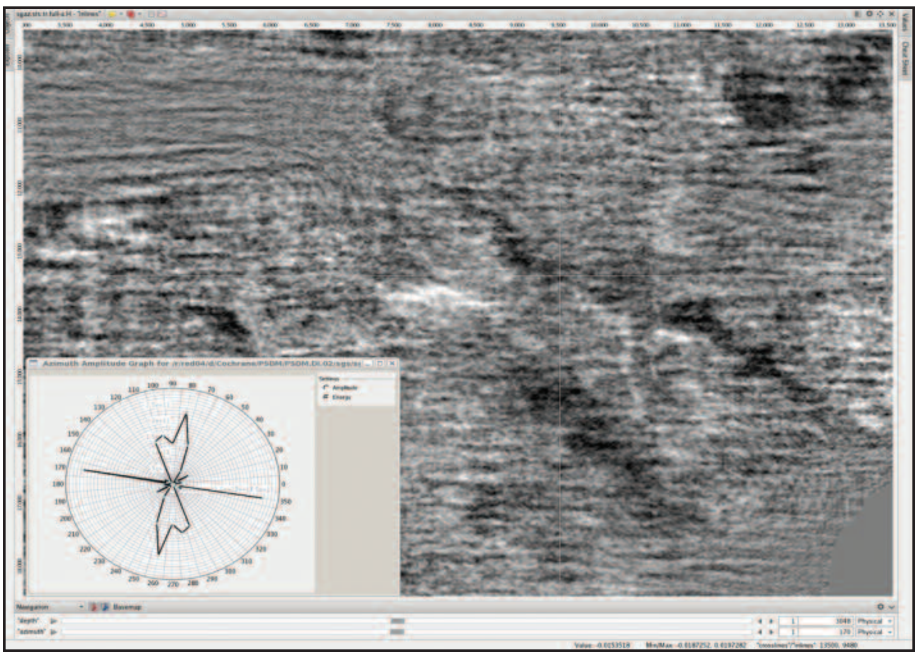
Although the importance of diffractions in high-resolution structural imaging is well understood in geophysics, diffraction imaging is still not a widely used tool in seismic interpretation. In fact, most of the algorithms that are used to process seismic data enhance reflections and suppress diffracted energy. The goal of diffraction imaging is not to replace these traditional algorithms, but to provide interpreters with an additional attribute to fill in the small, yet potentially crucial, structural details.

Several DI techniques have been proposed. They fall into two categories. The first category consists of methods that separate 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. It is important to keep in mind that there is no sharp distinction between reflection and diffraction waves (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 instead use a different image forming technique that suppresses reflecting surfaces in the image. Our implementation falls in the second category

FIGURE 3

Diffraction Amplitudes with Azimuth



of methods, and can be expressed as a reflection-suppressing kernel for Kirchhoff migration.

Standard approaches to obtain high-resolution information, such as coherency analysis and structure-oriented filters, derive attributes from stacked, migrated images. By comparison, diffraction imaging acts on the prestack data. The seismic events from a prestack seismic dataset are migrated to proper depth and location using the final velocity model obtained after the velocity model building process, but the output is assigned to separate bins according to the value of a specific parameter called specularity.

The specularity gathers can be post-processed using a plane wave destructor filter to attenuate the contribution coming from specular reflectors. The improvement using specular gathers comes from the fact that specular reflections and diffractions can be differentiated at small angles. Previous methods simply eliminated the energy at small reflection angles from both reflectors and diffractions, because it could not be differentiated. This ability, in turn, leads to higher resolution in imaging of diffractions and less artifacts. The key is that diffractions have a long tail in specular gathers, while reflections only exist at small angles.

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 prestack data, the diffractor amplitude can be enhanced while attenuating specular reflections.

An interesting property of diffractions is that the amplitude of the diffraction varies with azimuth when the diffraction is on an edge, fault or fracture. The amplitude of the diffraction is larger perpendicular to the fault or fracture, and weaker along the fault. From a physical point of view, it makes sense that rays perpendicular to a fault will reflect back with strong amplitude, while rays parallel with the direction of the fracture may have weaker reflections. Point diffractors have a regular distribution of amplitude with azimuth.

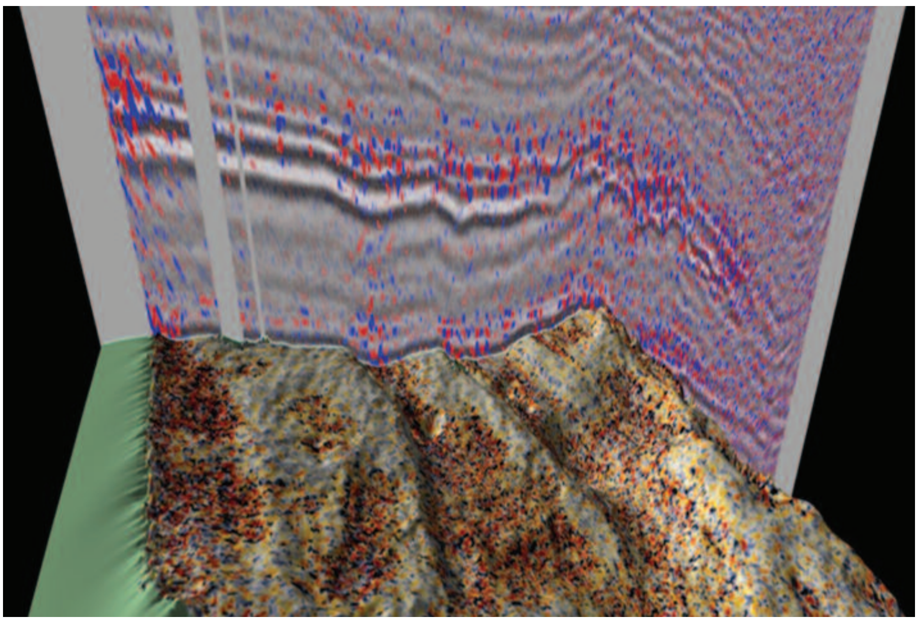
Figure 3 shows an example of diffractor amplitudes with azimuth. In this case, the diffractor was situated on a fracture, with the amplitude stronger perpendicular to the azimuth of the fracture. The background is the sum of all diffraction imaging amplitudes with azimuth, and the interpeter can point the cursor on the image to visualize the distribution of amplitudes with azimuth at a particular location. This brings into focus the interesting application of using the azimuth variation of diffraction amplitudes to visualize the main fracture direction, and then infer the principal stress direction in certain formations. Such information is useful for designing the direction of horizontal wellbores and optimizing hydraulic fracturing programs.

Eagle Ford, Niobrara Examples

Figures 4 and 5 demonstrate the application of DI technology on a 3-D seismic survey in the southwestern area of the Eagle Ford Shale play, while Figure 6 shows DI results from a 3-D survey in

FIGURE 4

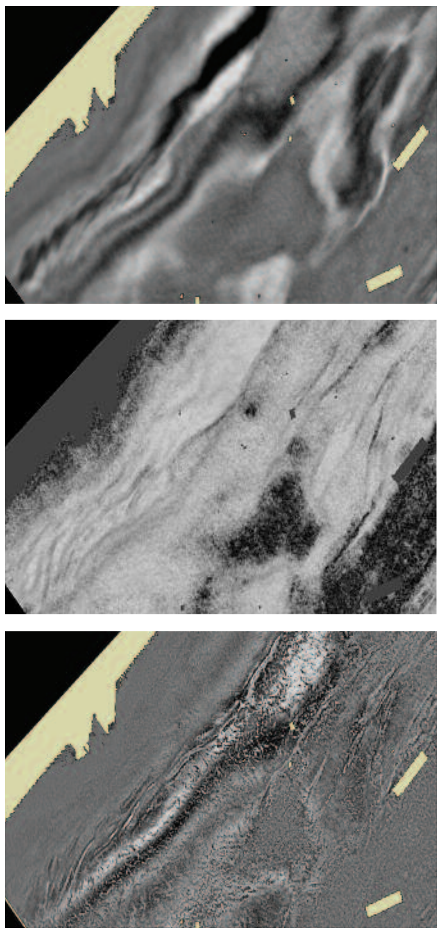
Diffraction Imaging Overlaid on Structural Image (Eagle Ford)



Data courtesy of Seitel

FIGURE 5

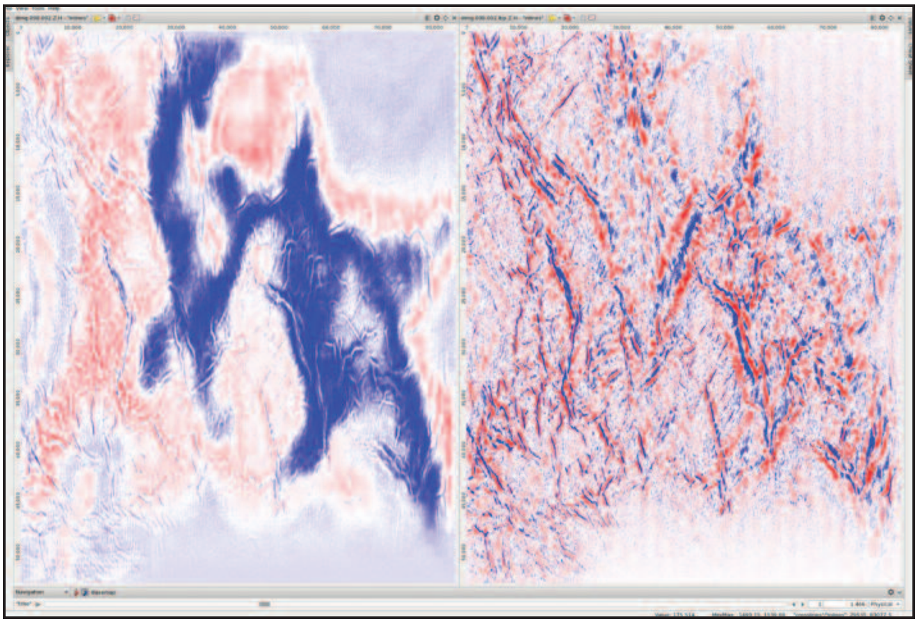
DI (bottom), Coherence (middle) And PSDM (top) Depth Slice Comparison (Eagle Ford)



Data courtesy of Seitel

FIGURE 6

PSTM Amplitudes (left) and DI (right) Time Slice Comparison (Niobrara)



Data courtesy of Geokinetics and Geophysical Pursuit Inc.

the Niobrara play. Both survey areas are characterized by a relatively uncomplicated, horizontally stratified velocity trend.

As a result, there were no important challenges for depth imaging, such as the multipathing of energy. Therefore, both areas were suitable for further deploying diffraction imaging technology, and represent a step toward its application in more complicated structural geometries.

Figure 4 shows an overlay of diffraction imaging in color over the structural image in grayscale. The diffraction imaging amplitudes are shown along a horizon where areas with higher DI amplitudes potentially indicate zones of higher fracture density.

The depth slices in Figure 5 compare the diffraction image with both the standard depth migration image and a coherence cube extracted from the same depth image through Eagle Ford data. The DI depth slice (bottom) shows much more detail than either the PSDM depth slice (top) or the equivalent coherency depth slice (middle).

The time slices in Figure 6 compare prestack time migration amplitudes on the left with DI amplitudes on the right in the Niobrara 3-D dataset.

Diffraction imaging is a novel high-resolution imaging technology designed to enhance the definition and resolution of discontinuities in 3-D seismic data, particularly imaging small-scale fractures in shale reservoirs such as the Eagle Ford, Niobrara, Bakken, Utica, Woodbine, Horn River and Montney. DI has the potential to improve production and recovery efficiency, reduce field development cost, and decrease the environmental impact of developing lease positions by using fewer wells to optimally produce the reservoir. The technology is a fundamental advance in any seismic processing system that images 3-D prestack data for complex geological structures, which have become the focus of modern oil and gas exploration. ❐

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