Specular/diffraction imaging by full azimuth subsurface angle domain decomposition

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Summary

This work presents a new seismic imaging system for generating amplitude preserved, three-dimensional directional gathers. The proposed method is based on directional angle decomposition that enables the implementation of both specular and diffraction imaging in real 3D isotropic/anisotropic geological models, leading to simultaneous emphasis on both continuous structural surfaces and discontinuous objects, such as faults and small-scale fractures. Structural attributes at each subsurface point, e.g., dip, azimuth and continuity, can be derived directly from the directional angle gathers. The proposed approach is most effective for imaging and analysis below complex structures, such as subsalt and subbasalt, high-velocity carbonate rocks, shallow velocity anomalies, and others.

Introduction

Diffraction imaging in the pre-stack time domain has been intensively studied (e.g., Khaidukov et al., 2004, Shtivelman and Keydar, 2005, Fomel et al., 2006, and others). Kozlov et al. (2004) presented diffraction imaging in depth using a "side wave" Kirchhoff-type migration, where the migration aperture was tapered to filter out the specular energy. Moser and Howard (2008) presented the implementation of diffraction imaging in depth for 2D models, providing a comprehensive review and insight of the potential of diffraction waves to obtain high-resolution images of small-scale discontinuous subsurface objects. Recently, Reshef and Landa (2009) showed the application of diffraction energy within dip gathers for high-resolution velocity analysis, especially in areas containing discontinuous objects or along irregular interfaces.

Our study is based on the ability to decompose the recorded seismic wavefield into continuous full azimuth directivity components in situ at the subsurface image points (Koren et al., 2008). The proposed method follows the concept of imaging and analysis in the Local Angle Domain (LAD) in isotropy/anisotropy subsurface models. Using an asymptotic ray-based migration/inversion "point-diffractor" operator, ray paths, slowness vectors, traveltimes, geometrical spreading, and phase rotation factors are calculated from the image points up to the surface, forming a system for mapping the recorded surface seismic data into the LAD at the image points. The strength of the proposed imaging system is mainly in its ability to construct highquality, continuous, full-azimuth, directional angle gathers in real 3D space. The ability to decompose the specular and diffraction energy from the total scattered field obtained within the full-azimuth directional angle gathers is the core

component of our imaging system. It is based on estimating a directivity-dependent specularity attribute, computed along 3D directional gathers, which is primarily used as a weighted stack filter. Two types of images are constructed: Specular weighted stacks for emphasizing subsurface structure continuity, and diffraction weighted stacks, which emphasize discontinuities of small-scale objects such as faults, channels and fracture systems. Note that full-azimuth directional angle decomposition does not necessarily require a wide-azimuth acquisition geometry system; rather, a large migration aperture is needed to allow information from all directions. Moreover, in many cases it is sufficient to use small offsets to create directional angle gathers. For example, it has been shown that nearly vertical faults and salt flanks can be detected via simulated corner (duplex) waves established with directional angle decomposition, where the integration is performed on narrow opening angles (narrow cones) only (Kozlov et al., 2008). In this work we present the method used to decompose the specular and diffraction energy from the total scattered field, and its application for both specular and diffraction imaging on real 3D datasets.

Local Angle Domain

Imaging systems involve the interaction of incident and scattered (reflected/diffracted) wavefields at the image points. Each wavefield can be decomposed into local plane waves (or rays), indicating the direction of propagation. The direction of the incident and scattered rays can be conventionally described by their respective polar angles. Each polar angle includes two components - dip and azimuth.



Figure 1: Ray pair and four LAD angles

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The imaging stage involves combining a huge number of ray pairs representing the incident and scattered rays. Each ray pair maps the seismic data recorded on the acquisition surface into the four-dimensional Local Angle Domain (LAD) space. In our notation, these angles are dip v_1 and azimuth v_2 of the ray-pair normal, opening angle γ_1 and opening azimuth γ_2 (Figure 1).

Directional Angle Gathers

The reflectivity/diffractivity I_v at the image point is a function of the ray pair normal dip v_1 and azimuth v_2 ,

$$I_{\nu}(m,\nu_{1},\nu_{2}) = \cos^{2}\nu_{1} \int \frac{W_{\nu}(m,\nu_{1},\nu_{2},\gamma_{1},\gamma_{2})}{V_{S}(m)V_{R}(m)} \cdot \frac{D_{3}(S,R,\tau_{D})\sin\gamma_{1}}{A(m,S)A(m,R)} d\gamma_{1}d\gamma_{2}$$
⁽¹⁾

where $S = S(m, v_1, v_2, \gamma_1, \gamma_2)$ and $R = R(m, v_1, v_2, \gamma_1, \gamma_2)$ are the source and receiver coordinates on the surface. These coordinates are established by the diffraction rays

These coordinates are established by the diffraction rays that connect the given image points with the given source and receiver locations. The dependency of the source and receiver locations on the background velocity model and the set of LAD angles for each image point makes the implementation of this output-driven approach extremely challenging. Parameters A(m,S) and A(m,R) are the amplitudes of Green's functions for the shot and receiver, $D_3(S, R, \tau_D)$ is the filtered data, and $\tau_D = \tau_D(S, m, R)$ is the diffraction time. $V_S(m)$ and $V_R(m)$ are the phase velocities of the incident and scattered rays, respectively, at the image point. The function W_V is the integration weight, inversely proportional to the hit counts (illumination). In our implementation, the 3D directional gathers are displayed in a cylindrical coordinate system, where the radius is the dip angle.

Specularity Attribute

The 3D cylindrical directional gathers are used to compute specularity attributes. Each data point in the gather represents a specific depth and direction (dip and azimuth) on a unit sphere. We assign a three-dimensional window that includes the vertical range and the solid angle. The proximity on the surface of the unit sphere is a small spherical cap around the varying central direction. Each component of the specularity attribute is calculated as a weighted energy local stack,

$$E = \sum_{ijk} w_{ijk} A_{ijk}^2$$
(2)

where *i* and *j* are indices of direction for the normal to the reflection surface studied, and *k* is the depth index within the window. A_{ijk} is the seismic data of the original directional gather and w_{ijk} are the specularity attributes to be computed. In our analysis we test the potential of each direction to be a normal to a true local continuous planar reflector. In case such a reflector exists, in addition to the energy of the central normal ray, there are contributions from shifted normal rays reflected from the same surface at slightly shifted reflecting points. Below we explain the distribution of the neighboring specular energy along the directional gather. Consider the ray diagram plotted in Figure 2. Two specular normal rays are plotted: Central ray *AB* with traveltime t_0 and shifted ray *CF*. *AC* is the







Figure 3: Specular energy surface

shift of the reflection point along the reflecting plane. It is assumed that a neighboring ray *EF* starting at the same lateral location as the central ray, but at a different depth and different take-off direction, arrives to the same point *F* on the surface and shares approximately the same traveltime $t_{ijk} = t_0 + \Delta t_{ijk}$ as the shifted specular ray. The shifted specular path is split into two intervals, *CD* and *DF*. Let point *B* be the surface point of the central specular ray and point *F* be the surface point of the shifted specular ray. Point *D* is the projection of point *B* on the direction of the shifted specular ray near the surface. We assume that the traveltime through the interval *CD* of the shifted ray is the same as the full traveltime of the central ray t_0 . To obtain the additional traveltime along the path DF, we compute the projection of the horizontal vector $\Delta \vec{R} = BF$ between the surface points of the central and shifted specular rays on the direction of the shifted ray near the surface. The direction; therefore, the additional traveltime reads

$$\Delta t_{ijk} = p_x \Delta R_x + p_y \Delta R_y , \qquad (3)$$

where p_x and p_y are slowness components of the central ray at the surface. The resulting traveltime of the shifted central ray is $t_S = t_0 + \Delta t_{ijk}$. We compare it with the traveltime of the neighboring ray t_{ijk} and obtain the difference, $\tau_{ijk} = t_S - t_{ijk} = t_0 + \Delta t_{ijk} - t_{ijk}$. The time lag τ is then normalized by the time of the central ray. For a true specular surface, the time lag τ should be close to zero. Thus, in order to identify the true specular direction, one can stack the energies (magnitudes A_{ijk} squared) through the window, using the weights

$$w_{ijk} = \exp\left(-\tau_{ijk}^2\right) \,. \tag{4}$$

Generally, the computation of τ requires the following ray attributes: Traveltimes, surface slowness vectors, and surface arrival locations for all 3D gather points. However, for the assumption of a constant background velocity, the ray attributes can be internally estimated. In Figure 2, z_0 is the depth of the scattering point A, and $\Delta z = AE$ is the upward shift of the scattering point of the neighboring ray. This value is always positive, $0 \le \Delta z/z_0 \le 1$. The surface of the vanishing time lag may be presented as $\Delta z(v_1, v_2, \Delta v_1, \Delta v_2)$, where v_1, v_2 are dip and azimuth of the central ray, while $\Delta v_1, \Delta v_2$ are the dip and azimuth differences, respectively, between the neighboring and shifted central rays. This leads to a result of

$$\frac{z_{0} - \Delta z}{z_{0}} = \frac{\cos\nu_{1}\cos(\nu_{1} + \Delta\nu_{1})}{1 - \sin\nu_{1}\sin(\nu_{1} + \Delta\nu_{1})\cos\Delta\nu_{2}} \quad .$$
(5)

The dip of the neighboring ray varies in the range of $0 \le v_1 + \Delta v_1 \le \pi/2$. The surface described by this equation is schematically plotted in Figure 3, for a dip of the reflection surface $v_1 = 60^\circ$. The radius in the cylindrical frame corresponds to the dip of the neighboring ray, and the azimuth is the difference Δv_2 .

Shifted Normal Ray

The shift AC (in Figure 2) of the normal ray in the reflection plane can be expanded in two orthogonal components: d in the direction of projection of the vertical

axis z on the reflection surface element, and s in the horizontal direction. For a constant reference velocity, the shift components are

$$\frac{d}{z_{0}} = \frac{\sin(v_{1} + \Delta v_{1})\cos\Delta v_{2} - \sin v_{1}}{1 - \sin v_{1}\sin(v_{1} + \Delta v_{1})\cos\Delta v_{2}},$$

$$\frac{s}{z_{0}} = \frac{\cos v_{1}\sin(v_{1} + \Delta v_{1})\sin\Delta v_{2}}{1 - \sin v_{1}\sin(v_{1} + \Delta v_{1})\cos\Delta v_{2}}.$$
(6)

For fixed dip angles of both central and neighboring rays, $v_1 = \text{const}, \Delta v_1 = \text{const}$, and varying azimuthal lag Δv_2 , the trace of the take-off point of the shifted normal ray is elliptic,

$$\frac{(d-d_{\rm o})^2}{A_d^2} + \frac{s^2}{A_s^2} = 1 \qquad , \tag{7}$$

where d_0 is the shift of the ellipse center relative to the take-off point of the central normal ray,

$$\frac{d_{\rm o}}{z_{\rm o}} = -\frac{\sin v_1 \cos^2(v_1 + \Delta v_1)}{1 - \sin^2 v_1 \sin^2(v_1 + \Delta v_1)} \quad , \tag{8}$$

while A_d and A_s are the minor and major semi-axes, respectively,

$$\frac{A_d}{z_o} = \frac{\cos^2 \nu_1 \sin(\nu_1 + \Delta \nu_1)}{1 - \sin^2 \nu_1 \sin^2(\nu_1 + \Delta \nu_1)} ,$$

$$\frac{A_s}{z_o} = \frac{\cos \nu_1 \sin(\nu_1 + \Delta \nu_1)}{\sqrt{1 - \sin^2 \nu_1 \sin^2(\nu_1 + \Delta \nu_1)}} .$$
(9)

The major semi-axis does not exceed the depth of the central normal ray $A_d \leq A_s \leq z_0$. For a fixed dip of the central ray only $v_1 = \text{const}$, and varying neighbor dip and azimuthal lag, we obtain a family of non-intersecting ellipses with different shifts, semi-axes and eccentricities. Contours of smaller neighbor dips $v_1 + \Delta v_1$ are completely inside the contours of larger dips. We comment on three particular cases. For a flat reflector $v_1 = 0$, the shift d_0 vanishes, and the trace reduces to a circle of radius $z_0 \sin \Delta v_1$. For a vertical neighbor ray $\Delta v_1 = -v_1$, the trace squeezes to a single point: Semi-axes A_d and A_s vanish, and the shift becomes $d_0 = -z_0 \sin v_1$. For a nearly horizontal neighbor ray $v_1 + \Delta v_1 = \pi/2$, the shift vanishes, and the trace becomes a circle of maximum radius, z_0 .

Field Example: Specular Energy Enhancement

Figure 4 shows two depth migrated sections from 3D land data in Northwest Germany following the creation of directional angle gathers. Figure 4a shows the direct stack of the directional angle gathers, and Figure 4b shows the specular energy weighted stack of these gathers,

$$I_{\text{spec}}(m) = \sum_{\nu_1, \nu_2} I_{\nu}(m, \nu_1, \nu_2) \cdot f_{\text{spec}}^{p}(m, \nu_1, \nu_2) \quad , \quad (10)$$

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Figure 4: Depth migrated section from 3D transition area



Figure 6: Depth slices from a fractured carbonate reservoir

where $f_{\text{spec}}(m, v_1, v_2)$ is a computed specularity gather that measures the high-energy reflectivity from continuous surfaces, and p is an amplifying power index. The highenergy values associated with the specular directions sharpen the image of the structure, and the improvement in the continuity of the structural information throughout the volume is clearly seen in Figure 4b. Figure 5 shows an example of a directional angle gather in the vicinity of the salt. Two areas of specular energy are clearly visible, indicating subsurface points which are in the vicinity of conflicting dips, such as uncomformities and pinchouts. This shows that the common assumption that every image point is characterized by a single directivity is somewhat naïve, and that we must also consider all the energetic directions.

Field Example: Diffraction Energy Enhancement

Figure 6 shows two depth slices from a fractured carbonate reservoir in the North Sea. Figure 6a demonstrates the resolution that can be obtained using a standard Kirchhoff migration. Figure 6b shows a high-resolution image of the same reservoir, emphasizing the fracture system and the channels, that were obtained by using diffraction energy weighted stack, as opposed to the specular energy weighted stack shown in the previous example,



Figure 5: Specularity directional gather

$$I_{\text{diff}}(m) = \sum_{\nu_1, \nu_2} I_{\nu}(m, \nu_1, \nu_2) \cdot f_{\text{diff}}^{p}(m, \nu_1, \nu_2) \quad , \quad (11)$$

where

$$f_{\text{diff}}(m, v_1, v_2) = 1 - f_{\text{spec}}(m, v_1, v_2)$$
 (12)

is an operator that decays the specular energy.

Conclusions

This work presents a new seismic imaging system for generating and extracting high-resolution information about subsurface angle dependent reflectivity, with simultaneous emphasis on both continuous structural surfaces and discontinuous objects, such as faults and small-scale fractures. The new directional image gathers allow automatic extraction of geometrical attributes, such as dip, azimuth and specularity/continuity, and enable the generation of different types of images by weighting either specular or diffraction energy. It has been shown that several specular directions may coexist at the same image point, associated with conflicting dips (unconformities and pinchouts). Both continuous structure surfaces and discontinuous subscale small objects, such as channels and fractures, can be detected, even below complex geological structures.

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