Separation, imaging, and velocity analysis of seismic diffractions using migrated dip-angle gathers

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SUMMARY

There exists a clear distinction between seismic diffractions and reflections in the post-migration dip-angle gather domain. We analyze this distinction and show the possibility of using it for separating and imaging seismic diffractions with only single-offset data as input. When observed in dip-angle gathers, diffraction events are also significantly more sensitive to velocity errors, which opens up the possibility of using them for velocity analysis. We demonstrate the proposed technique on synthetic and real-data examples.

INTRODUCTION

Diffracted waves contain valuable information about small objects such as faults, pinchouts, fractures, etc. (Landa et al., 1987; Kanasewich and Phadke, 1988; Liu et al., 1997; Landa and Keydar, 1998; Bansal and Imhof, 2005). Diffraction analysis is a challenging problem because the energy retained by these events is typically one or two orders of magnitude weaker than the energy retained by the reflections. Several authors have suggested that diffractions should be separated from reflections before analysis (Harlan et al., 1984; Khaidukov et al., 2004). Correct identification and use of diffraction events are important also for velocity estimation, which can be carried out in the prestack as well as in the poststack domain (Sava et al., 2005; Taner et al., 2006; Fomel et al., 2007).

The post-migration dip-angle domain has gained some attention lately and was shown to be of great importance to the quality of depth imaging in complex geological areas (Audebert et al., 2002; Reshef and Rüger, 2005). In this paper, we propose to use the dip-angle domain for development of methods to extract and analyze diffraction data. In particular we suggest using diffraction data in this domain for velocity analysis, in both time and depth migration.

We describe first dip-angle-domain data decomposition after migration and show how diffraction and reflection events behave in this domain. The ability to use single offset to generate dip-angle common image gathers (CIGs) is also demonstrated. We then present, using synthetic and real-data examples, the separation and imaging of seismic diffractions and the influence of velocity errors on the appearance of migrated diffractions in the dip-angle domain.

SIMPLE THEORY OF REFLECTIONS AND DIFFRACTIONS IN MIGRATED DIP-ANGLE GATHERS

To explain the difference between reflections and diffractions in dip angle gathers, we consider, for simplicity, the case of post-stack migration in a constant velocity medium. A similar analysis can be extended to prestack migration.

In a 2-D zero-offset constant-velocity situation, the mapping between model coordinates $\{x,z\}$ and data coordinates $\{y,t\}$ is provided by the following geometrical relationships:

$$y = x + z\tan\alpha \quad (1)$$

$$t = \frac{2z}{v\cos\alpha}\,, \quad (2)$$

where v is the medium velocity and α is the dip angle (Figure 1).

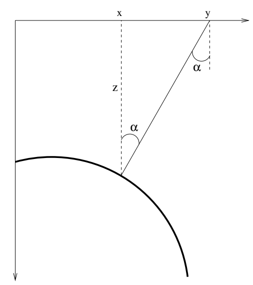


Figure 1: Zero-offset reflection (a scheme).

Migration amounts to the inverse transformation

$$x = y - \frac{v_M t}{2}\sin\alpha \quad (3)$$

$$z = \frac{v_M t}{2}\cos\alpha\,, \quad (4)$$

where v_M is the migration velocity.

Let us consider a plane reflector with dip α_0. If this reflector is described by the function

$$z(x) = z_0 + x\tan\alpha_0\,, \quad (5)$$

its response in the data, according to equations (1–2), is

$$t(y) = \frac{2\,(z_0\cos\alpha_0 + y\sin\alpha_0)}{v}\,, \quad (6)$$

and its image, according to equations (3–4), is defined by

$$x = -\frac{v_M}{v} z_0\cos\alpha_0\sin\alpha + y\left(1 - \frac{v_M}{v}\sin\alpha_0\sin\alpha\right) \quad (7)$$

$$z = \frac{v_M}{v} z_0\cos\alpha_0\cos\alpha + \frac{v_M}{v} y\sin\alpha_0\cos\alpha\,. \quad (8)$$

Eliminating y from equations (7–8), we obtain an image of the plane reflector in the dip-angle coordinates

$$z_\alpha(x,\alpha) = \frac{(z_0\cos\alpha_0 + x\sin\alpha_0)\, v_M\cos\alpha}{v - v_M\sin\alpha_0\sin\alpha}\,. \quad (9)$$

For a fixed x, equation (9) describes the response of a dipping reflector on a dip-angle image gather. The response has the form of a smile with a stationary point. If the migration velocity is correct, the stationary point occurs at $\alpha = \alpha_0$. It is easy to verify that, in this case, the derivative at the stationary point

$$\frac{\partial z}{\partial\alpha} = \frac{(z_0\cos\alpha_0 + x\sin\alpha_0)\,(v_M\sin\alpha_0 - v\sin\alpha)}{(v - v_M\sin\alpha_0\sin\alpha)^2} \quad (10)$$

becomes zero, and that $z_\alpha(x, \alpha_0) = z(x)$. Summation of the dip-angle gather over angle produces then a correct image according to the stationary phase principle.

Now let us consider a diffraction point with coordinates $\{x_0, z_0\}$. It is convenient to parametrize its response in the data by ray angle β. According to equations (1–2), the response is

$$y = x_0 + z_0 \tan\beta \tag{11}$$

$$t = \frac{2\,z_0}{v\cos\beta}\,, \tag{12}$$

which resolves, by eliminating β, to the familiar equation of a hyperbola

$$t(y) = \frac{2\sqrt{z_0^2 + (y-x_0)^2}}{v}\,. \tag{13}$$

According to equations(3–4), the image of a diffraction point is

$$x = x_0 + z_0\,\frac{v\sin\beta - v_M\sin\alpha}{v\cos\beta}\,, \tag{14}$$

$$z = z_0\,\frac{v_M\cos\alpha}{v\cos\beta}\,, \tag{15}$$

or, eliminating β,

$$z_\alpha(x, \alpha) = \frac{v_M \cos\alpha\,\left[(x-x_0)\,v_M\sin\alpha + D\right]}{v^2 - v_M^2\sin^2\alpha}\,, \tag{16}$$

where $D = \sqrt{z_0^2\,(v^2 - v_M^2\sin^2\alpha) + (x-x_0)^2\,v^2}$. When the migration velocity is correct ($v_M = v$), and the dip-angle gather is observed directly at diffraction point $x = x_0$, the response is a flat line $z_\alpha(x_0, \alpha) = z_0$, which corresponds to illuminating the diffractor uniformly from different angles. Otherwise, the response is a curve and may not have a stationary point.

Our theoretical derivations are depicted in Figures 3–5, which show theoretical dip-angle gathers for a model with two plane reflectors and a diffractor (Figure 2). The diffraction response is shown as a dashed curve and appears flat in an angle gather above the diffraction point when the migration velocity is correct (Figure 3). It becomes curved when the migration velocity changes (Figures 4 and 5).

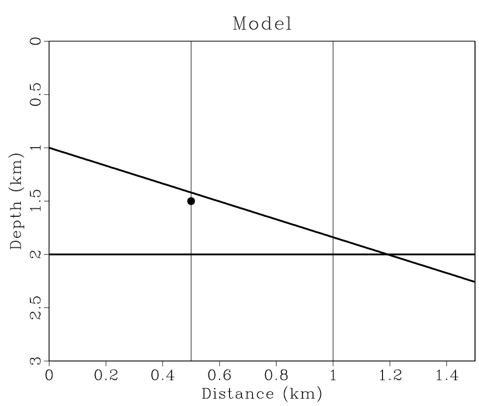


Figure 2: Theoretical model with two plane reflectors and a diffractor.

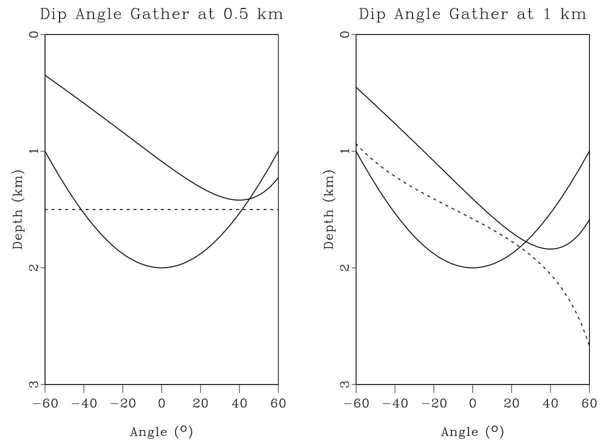


Figure 3: Theoretical dip-angle gathers for migration with the correct velocity. (a) At 0.5 km (above the diffractor). (b) At 1 km (away from the diffractor).

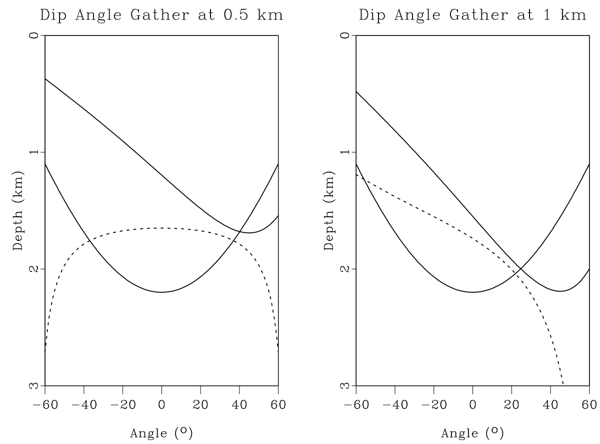


Figure 4: Theoretical dip-angle gathers for migration with 10% higher velocity. (a) At 0.5 km (above the diffractor). (b) At 1 km (away from the diffractor).

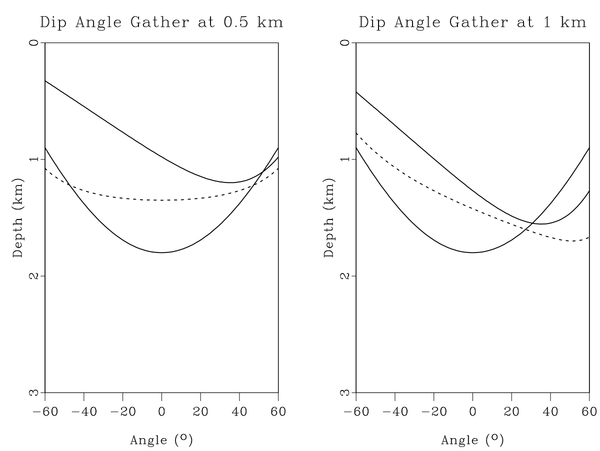


Figure 5: Theoretical dip-angle gathers for migration with 10% lower velocity. (a) At 0.5 km (above the diffractor). (b) At 1 km (away from the diffractor).

SEPARATION AND IMAGING OF SEISMIC DIFFRACTIONS IN MIGRATED DIP-ANGLE GATHERS

Figure 6a shows a dip-angle gather created by prestack depth migration with a correct velocity of the Sigsbee synthetic dataset. This gather is situated at one of the artificial diffraction points inserted in the model. The flatness of the diffraction events is clearly visible. Taking advantage of the local dip discrepancy between reflection and diffraction events, we separated them using plane-wave destruction (Fomel, 2002). The separated sections are displayed in Figures 6b and 6c.

When the velocity used for the migration is the correct one, the migrated diffractor will be horizontal only at the gather located right above it. In Figure 7, a set of dip-angle gathers is shown with the two arrows pointing to the lateral position of the diffractors. Even on the CIGs not above the diffractors, the diffractions (elongated dipping events) are distinguishable from the concave reflectors. Applying our separation technique to a number of dip-angle gathers and stacking the separated events, we obtain an image of diffractions (Figure 8(a)). The described method of separating and imaging diffractions in the post-migration domain is a powerful alternative to separation in unmigrated data, as proposed by Fomel et al. (2007).

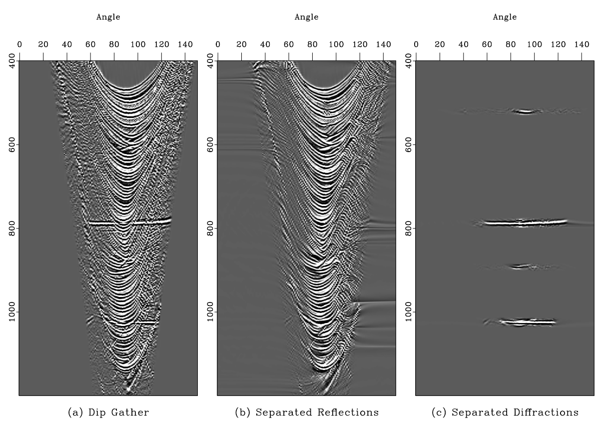


Figure 6: Dip-angle gather generated for Sigsbee synthetic data (a) separated into contributions from reflections (b) and diffractions (c).

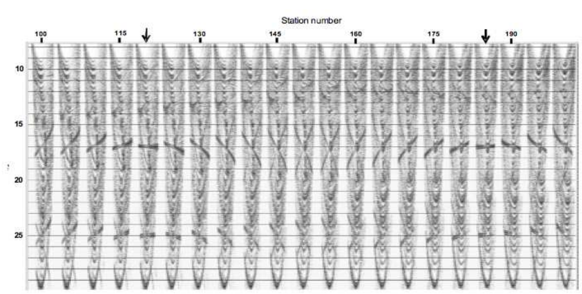
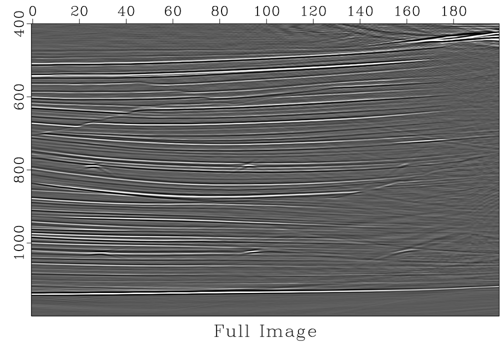
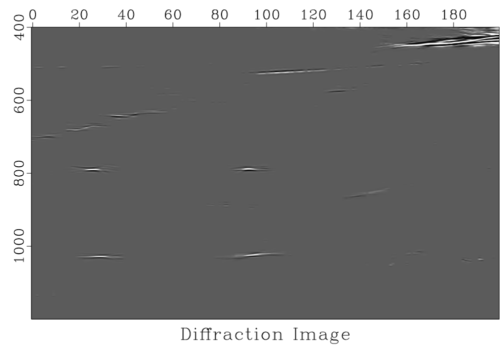


Figure 7: Identification of the diffractors position from a set of dip-angle CIGs.



(a)



(b)

Figure 8: Portion of a seismic image for the Sigsbee synthetic data. (a) Full image. (b) Image of separated diffractions.

VELOCITY ANALYSIS WITH MIGRATED DIFFRACTIONS USING DIP-ANGLE GATHERS

After prestack depth migration, reflections in the dip-angle domain will always have a concave shape, regardless of migration velocity (Reshef, 2007). It means that there is no easy way to use the reflections in this domain for velocity analysis. The effect of velocity errors on diffractions is completely different and is demonstrated by Figure 9, which presents a dip-angle CIG after prestack depth migration with a wrong velocity. Note that reflections are shifted up and down (with respect to low/high velocity) and maintain the same concave shape, while the diffractions show the familiar "smiling" and "frowning". Unlike the asymmetry of the concave reflections, which is related to their dip (Audebert et al., 2002), the asymmetry of the diffractions is due to lateral velocity variations and location of the CIG with respect to the diffractors. We can assert that, in this domain, continuous events with convex shape are most likely to be diffractions migrated using a too-high velocity.

The sensitivity of diffractions to velocity errors can be used for velocity analysis, as shown in Figure 10. Using the ability to generate dip-angle gathers from a single offset, we applied poststack time migration to a portion of the marine data stack shown in the figure. The single-offset input (zero offset in this case) was migrated into a set of dip-angle CIGs. One of the CIGs, located right above a diapir (arrow in the top image), is shown after application of prestack time migration

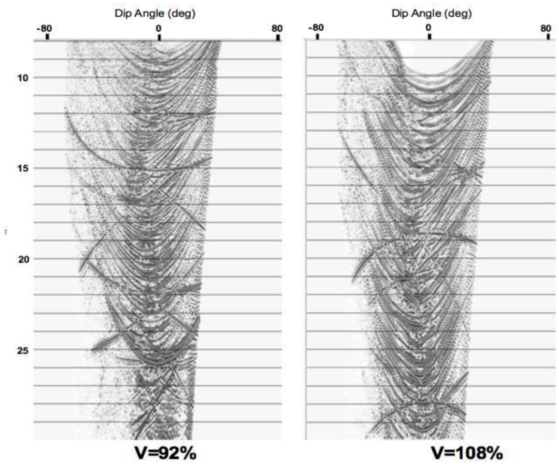


Figure 9: Dip-angle CIG after PSDM with wrong velocity.

with four different migration velocities ($V_4 > V_3 > V_2 > V_1$). Examination of the migrated diffraction at 0.7 s indicates that the second velocity (marked by V_2 in the figure) is the optimal one and produces the flattest event. As in the depth domain, diffractions exhibit the classical effect of shape changes with migration velocity.

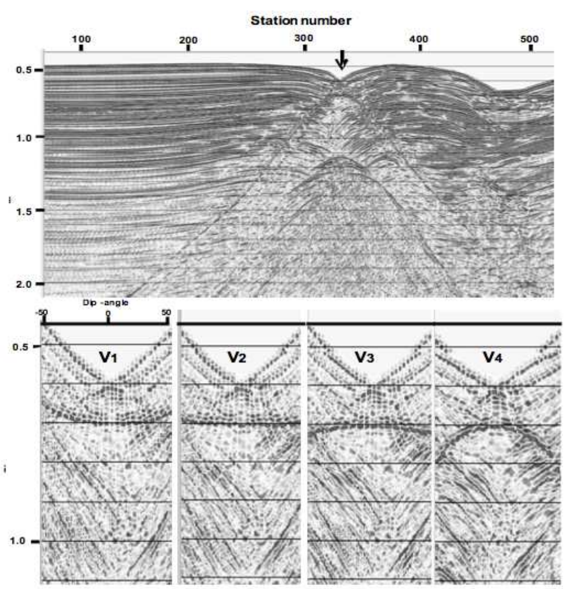
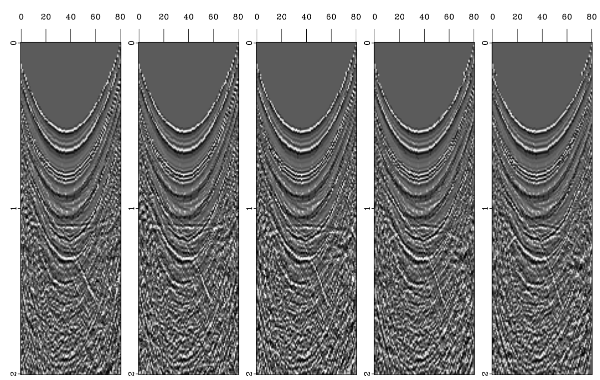


Figure 10: Poststack velocity analysis using diffractions. Top: migrated image. Bottom: dip-angle gather above a diffraction point migrated using different velocities.

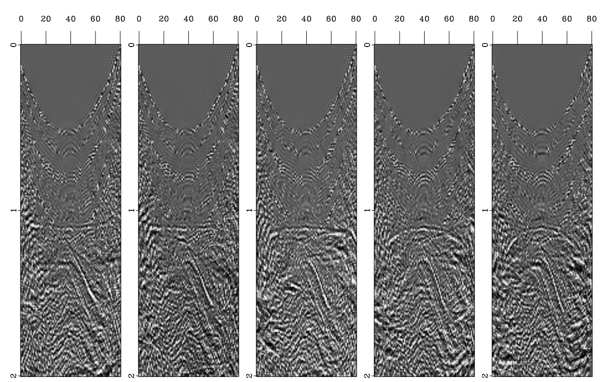
Figure 11 shows another set of dip-angle gathers from time migration with different velocities before and after diffraction separation. The separated diffraction events noticeably change their shape with changes in migration velocity and thus can be employed directly for migration velocity analysis.

CONCLUSIONS

There are two major advantages to migration into dip-angle common-image gathers. First, appearance of data in this domain is the same whether the input data are multi- or single-offset. Second, diffractions appear significantly different from reflections, which makes it possible to separate and image them using local slope analysis. Unlike reflections, diffractions are also significantly affected by velocity errors. These two characteristics can be used in application to efficient migration velocity analysis using diffraction events. The analysis can be applied to time or depth migration and requires only a single offset (such as zero offset) as input. The distinct difference between reflections and diffractions in the migrated dip-angle domain suggests that this domain is preferable for separating and imaging these two types of waves.



(a)



(b)

Figure 11: Dip-angle gather above a diffraction point migrated with different velocities (a) and diffractions separated by plane-wave destruction (b).

ACKNOWLEDGMENTS

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EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2008 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Audebert, F., P. Froidevaux, H. Rakotoarisoa, and J. Svay-Lucas, 2002, Insights into migration in the angle domain: 72nd Annual Internaional Meeting, SEG, Expanded Abstracts, 1188–1191.

Bansal, R., and M. G. Imhof, 2005, Diffraction enhancement in prestack seismic data: Geophysics, **70**, V73–V79.

Fomel, S., 2002, Applications of plane-wave destruction filters: Geophysics, **67**, 1946–1960.

Fomel, S., E. Landa, and M. T. Taner, 2007, Poststack velocity analysis by separation and imaging of seismic diffractions: Geophysics, **72**, U89–U94.

Harlan,W. S., J. F. Claerbout, and F. Rocca, 1984, Signal/noise separation and velocity estimation: Geophysics, **49**, 1869–1880.

Kanasewich, E. R., and S. M. Phadke, 1988, Imaging discontinuities on seismic sections: Geophysics, **53**, 334–345.

Khaidukov, V., E. Landa, and T. Moser, 2004, Diffraction imaging by focusing-defocusing: An outlook on seismic superresolution: Geophysics, **69**, 1478–1490.

Landa, E., and S. Keydar, 1998, Seismic monitoring of diffraction images for detection of local heterogeneities: Geophysics, **63**, 1093–1100.

Landa, E., V. Shtivelman, and B. Gelchinsky, 1987, A method for detection of diffracted waves on common-offset sections: Geophysical Prospecting, **35**, 359–373.

Liu, E., S. Crampin, and J. A. Hudson, 1997, Diffraction of seismic waves by cracks with application to hydraulic fracturing: Geophysics, **62**, 253–265.

Reshef, M., 2007, Velocity analysis in the dip-angle domain: Presented at the 69th Annual International Conference and Exhibition, EAGE.

Reshef, M., and A. Ruger, 2005, Influence of structural dip on interval velocity analysis: 75th Annual International Meeting, SEG, Expanded Abstracts, 2245–2248.

Sava, P. C., B. Biondi, and J. Etgen, 2005, Wave-equation migration velocity analysis by focusing diffractions and reflections: Geophysics, **70**, U19–U27.

Taner, M. T., S. Fomel, and E. Landa, 2006, Prestack separation of seismic diffractions using plane-wave decomposition: 76th Annual International Meeting, SEG, Expanded Abstracts, 2401–2404.