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Diffractions - Yesterday, Today, and Tomorrow

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SUMMARY

Seismic diffractions are the response of important small scale elements in the subsurface such as faults, karsts, fractures. We distinguish between reflective and diffractive contributions to the wavefield and recognize the diffractive component as a key ingredient in establishing resolution. We present past, present and future of using the diffractions for seismic imaging and illustrate it with many interesting and exiting examples.

Introduction

Being long time "the abandoned stepchildren of traditional seismic processing and imaging" (Khaidukov et al., 2004), diffractions start receiving the attention they deserve. The importance of diffracted waves in seismic has long been recognized (Krey, 1952, Hagedoorn, 1954). But theoretical understanding of the detailed behaviour of diffractions started after fundamental works of Trorey (1970) and Klem-Musatov et al. (1972) (detailed analysis and references on seismic diffractions can be found in Klem-Musatov, 1994).

Several early attempts to use diffraction events for fault identification and model parameter estimation were carried out in the USSR. Kovalevsky (1971) noted and experimentally confirmed the existence of the seismic anomalies associated with small-amplitude faults in the subsurface. He successfully explained the relevant wave mechanism at the empirical level.

Landa (1978) proposed to estimate parameters of small amplitude faults by minimizing the difference between the observed and calculated wavefields. Modelling of the diffraction events plays a crucial role in computing the subsurface response and convergence of the optimization process. In fact, it was one of the first attempts to perform full waveform inversion.

Landa and Maksimov (1980) presented results of the physical modelling of the wave propagation through the media containing scattering objects. They demonstrated the possibility identifying diffraction events in seismic data and using them for detection of small scale structural elements such as faults, pinchouts, unconformities etc.

In the late eighties and the nineties publications on diffractions were rare and rather exotic. Landa et al. (1987) and Kanasewich and Phadke (1988) proposed to construct a diffraction time image (D-section) by stacking the signal along a diffraction trajectory instead of conventional common midpoint (CMP) hyperbola. In his controversial and interesting series of papers, Neidell (1997) distinguished between reflective and diffractive contributions to the wavefield and recognized the diffractive component as a key ingredient in establishing resolution. Papziner and Nick (1998) extracted diffraction energy from ground-penetrating radar (GPR) data to detect small objects in georadargrams. Landa and Keydar (1998) used diffractions to monitor the digging of tunnels.

Over the last decade there has been an increasing interest to use diffractions as a direct indicator of various reflector discontinuities, faults, carsts, fractures etc. The main interest now is concentrated on efficient separation between specular and scattered wavefields and the subsequent imaging of the diffractive component. Goldin et al. (2000) try to separate weak diffractions from strong regular reflections by downward wavefield continuation using Gaussian beams. They proposed to construct selective images which highlight the elements that backscatter wave energy at certain angles.

Khaidukov et al. (2004) claim and illustrate that diffractions have been ignored in the conventional processing sequence. They promote diffraction imaging as a supplement to the conventional reflection imaging and propose diffraction biased imaging algorithm. The crucial point of such algorithm is the diffracted and reflected wave separation. The approach proposed is based on focusing reflected waves to their imaginary source points and then muting them from the full wavefield. Sava et al. (2004) proposed a method for estimating interval velocity using the kinematic information in defocused diffractions by extracting velocity information from defocused migrated events analyzing their residual focusing in physical space. Bansal and Imhof (2005) recognizing that diffraction events contain valuable information and could be used for imaging and interpretation, proposed a data processing workflow to enhance these events while suppressing reflections. Fomel et al. (2007) developed an integrated approach for extracting and imaging diffracted events. They used stacked zero-offset data and produced time-migrated images with separated and optimally focused diffracted waves as output. They also introduced diffraction events focusing as a criterion for migration velocity analysis, as opposed to the usual flat gather criterion used in seismic imaging. Focusing analysis is applicable not only to multicoverage prestack data but also to poststack or single-offset data. Taner et al. (2006) suggested separating diffractions in the full prestack data using the simulated plane wave section. Moser and Howard (2008) further develop and elaborate on ideas presented in Khaidukov et al. (2004) showing the diffraction imaging in the depth domain and in the context of a conventional prestack depth migration and migration velocity analysis workflow. They apply the fact that the classical migration loop can be subdivided into a part that accounts for specular reflections and a part that excludes specular reflections. By designing an additional weighting function to the migration kernel, which consists in suppressing specular reflections, the migration results in a diffraction image.

Gulunay (2008) suggested using kinematic properties of diffracted events for suppressing source energy scattered in the shallow part which contaminates the weak earth signals arriving from the deep target areas. Landa et al. (2008) and Reshef and Landa (2009) proposed a novel approach to improve the velocity analysis process by performing the analysis in a non-conventional dip-angle migrated domain and to use diffractions instead of reflection. The method is based on the clear distinction between diffractions and reflections in the post-migrated dip-angle domain. The attractive possibility to perform the analysis using only single common offset data opens a way to work efficiently in 3D case and with wide azimuth data by using stacked data for velocity model estimation.
Berkovitch et al. (2009) presented a method for imaging local heterogeneities of the subsurface using a new local time correction. This time correction which is based on the multifocusing method accurately describes the moveout for diffracted events, valid for arbitrary subsurface model and for arbitrary source-receiver configuration. The method consists of optimal stacking of seismic data along actual diffraction time curves and producing a section in which diffraction events are emphasized and specular reflections are attenuated.
Several recent publications report on imaging scattering objects and fractures using azimuthal binning (Chen and Hilterman, 2007), reflection and diffraction separation combined with curvelet-based subtraction (Verschuur et al., 2007), or the local image matrix in prestack migration (Zhu and Wu, 2008).
In this paper we present past, present and future of diffraction imaging. We also present an interesting and never previously published attempt to use full waveform inversion where diffractions play an important if not crucial role.

Small-amplitude fault parameter estimation using full waveform inversion

A naïve attempt to use full waveform inversion for parameter estimation was carried out in Landa, 1978. Although the idea of fitting seismograms is quite trivial, there are two main aspects which prevent use of optimization strategy to be practical and useful in seismic. The first and the principal one is to have an adequate and computationally efficient solution for forward modelling (see the story of the stealth technology!). The second (more technical) aspect is to be able to minimize a strongly non-linear objective function. Development of an asymptotic solution for wavefield propagation in models containing sharp changes of geometrical or physical properties in the early 70's (see for references Klem-Musatov, 1994) allowed in principle to consider optimization method for identification and parameter estimation of a small scale scattering objects such as faults. A simplified model of a fault assumes a known overburden and is characterized by the following unknown parameters: horizontal position X_0, vertical amplitude Δh, horizontal shift δ, reflector local dip φ and the fault azimuth α (Fig. 1).

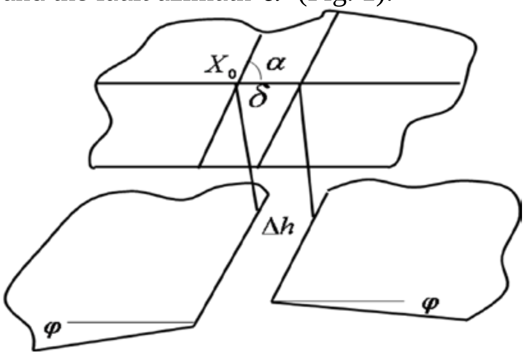
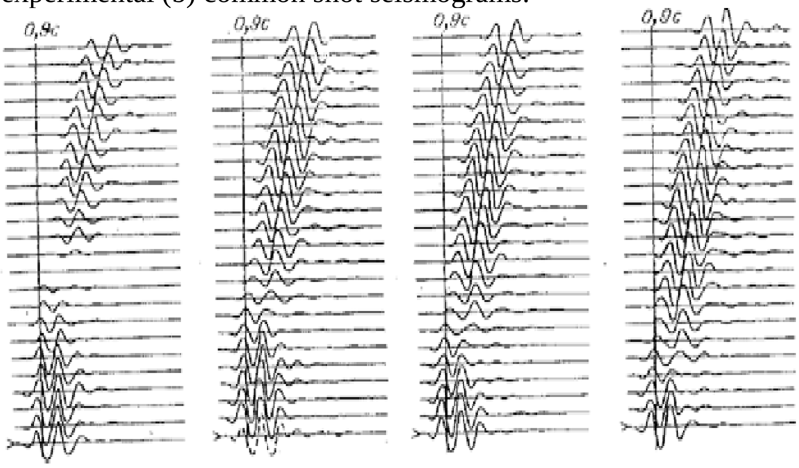


Fig. 1. Geometrical model of fault. (Adopted from Landa (1978)).

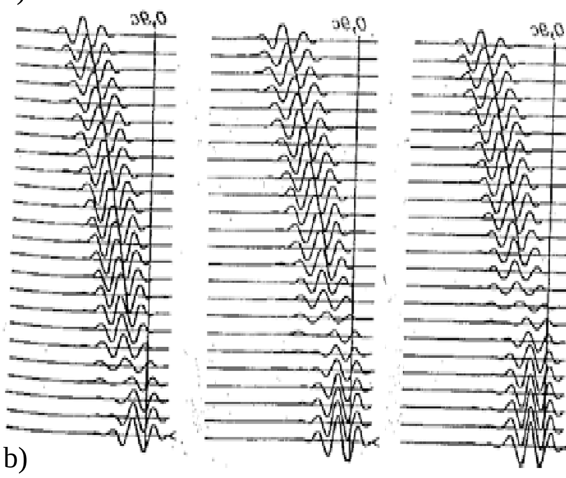
The inversion method consists of:

a) Computing the full wavefield for an initial model
b) Computing misfit objective function
c) Minimizing of the objective function
d) Accounting for a priori information

Testing the method on synthetic data showed that the position and the vertical amplitude of the fault can be estimated reliably if a priori information on the overburden model and geometry of the reflector is accurate. At the same time estimations of the azimuth and the horizontal shift strongly depend on amount and azimuthal distribution of the observed data. Experiments with physical modelling showed very good correspondence between the observed and mathematically modelled data and confirmed the ability to estimate small number of parameters comparing the wavefields in target time windows and using a priori information. Fig. 2 illustrates several synthetic (a) and experimental (b) common shot seismograms.



a)



b)

Fig.2 Synthetic (a) and experimental (b) seismograms (Landa and Maximov, 1978)

Discussion and Conclusions

Diffractions are reliable indicators of small structural and lithological elements of the subsurface. Diffractions open a different perspective on seismic image resolution. Traditional seismic imaging methods giving considerations only to reflections may safer in quality and resolution. They regard the diffractive wavefield component as noise and practically ignore the information it conveys. At the same time, the diffractive component of the full wavefiled is a key ingredient in establishing resolution. The main challenge of diffraction analysis is that real diffractions are typically one or two orders of magnitude weaker than specular reflections. There are several methods to separate them from the full wavefiels before analysis and imaging. These methods work in time or depth domain and can be model dependent or independent.

Finally, if diffractions receive the attention they deserve, we will be able to see the invisible.

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