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Velocity analysis with local event slopes related probability density function

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ABSTRACT

Macro velocity model plays a key role in seismic imaging and inversion. The performance of traditional velocity analysis methods is degraded by multiples and amplitude-versus-offset (AVO) anomalies. Local event slopes, containing the subsurface velocity information, have been widely used to accomplish common time-domain seismic processing, imaging and velocity estimation. In this paper, we propose a method for velocity analysis with probability density function (PDF) related to local event slopes. We first estimate local event slopes with phase information in the Fourier domain. An adaptive filter is applied to improve the performance of slopes estimator in the low signal-to-noise ratio (SNR) situation. Second, the PDF is approximated with the histogram function, which is related to attributes derived from local event slopes. As a graphical representation of the data distribution, the histogram function can be computed efficiently. By locating the ray path of the first arrival on the semblance image with straight-ray segments assumption, automatic velocity picking is carried out to establish velocity model. Unlike local event slopes based velocity estimation strategies such as averaging filters and image warping, the proposed method does not make the assumption that the errors of mapped velocity values are symmetrically distributed or that the variation of amplitude along the offset is slight. Extension of the method to prestack time-domain migration velocity estimation is also given. With synthetic and field examples, we demonstrate that our method can achieve high resolution, even in the presence of multiples, strong amplitude variations and polarity reversals.

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1. Introduction

Subsurface macro-model seismic velocity estimation and seismic imaging are the two main procedures of seismic data analysis (Yilmaz, 2001). Velocity analysis on common-midpoint (CMP) gathers using semblance (Taner and Koehler, 1969) is a basic step towards the detailed inversion of velocity model. The first round of velocity analysis is done by the field engineers once seismic data is acquired. The accuracy of the velocity picking depends on the engineers' abilities and on the quality of data. The velocity model is updated iteratively in the later indoor seismic processing, which makes it one of the most labor-consuming tasks. Velocity analysis is also affected by the resolution of the semblance spectra and by the accuracy of the selected equation in approximating the behaviors of the seismic events (Zhang et al., 2014). Conventional semblance can be interpreted as a correlation with a constant, which implies the assumption that there is no amplitude variation along offset (Sarkar et al., 2002; Luo and Hale, 2012). The semblance is effective for most cases. It might fail in the case of amplitude-versus-offset (AVO) anomalies. To suit the presence of strong amplitude variations and polarity reversals, AB semblance (Fomel, 2009) is derived as a correlation with an amplitude trend. However, it may be difficult to differentiate the semblance energy peaks of primary reflections from those of the interfering events such as multiples. Weighted semblance (Luo and Hale, 2012) is developed as a high resolution method to better distinguish different sets of semblance energy peaks. Eigenvalue decomposition (Biondi and Kostov, 1989) and singular value decomposition (SVD) (Spagnolini et al., 1993) can be applied to improve SNR by separating signal and noise into different subspaces. The multiple signal classification (MUSIC) is also a high resolution semblance estimator, defined as the inverse of one minus a normalized coherence measurement. With the first eigenimage, a reduced semblance coefficient and the corresponding MUSIC is derived by Ursin et al. (2014).

Semblance by scanning a set of parameters can be avoided in seismic velocity analysis tasks once local event slopes are estimated. Local event slopes contained in seismic data and seismic images can be used for depth domain velocity model inversion, such as common-reflection-surface (CRS) stack (Hertweck et al., 2007), normal-incidence-point (NIP) wave tomography (Duveneck, 2004), and stereotomography (Billette and Lambaré, 1998; Lambaré, 2008). Time-domain imaging

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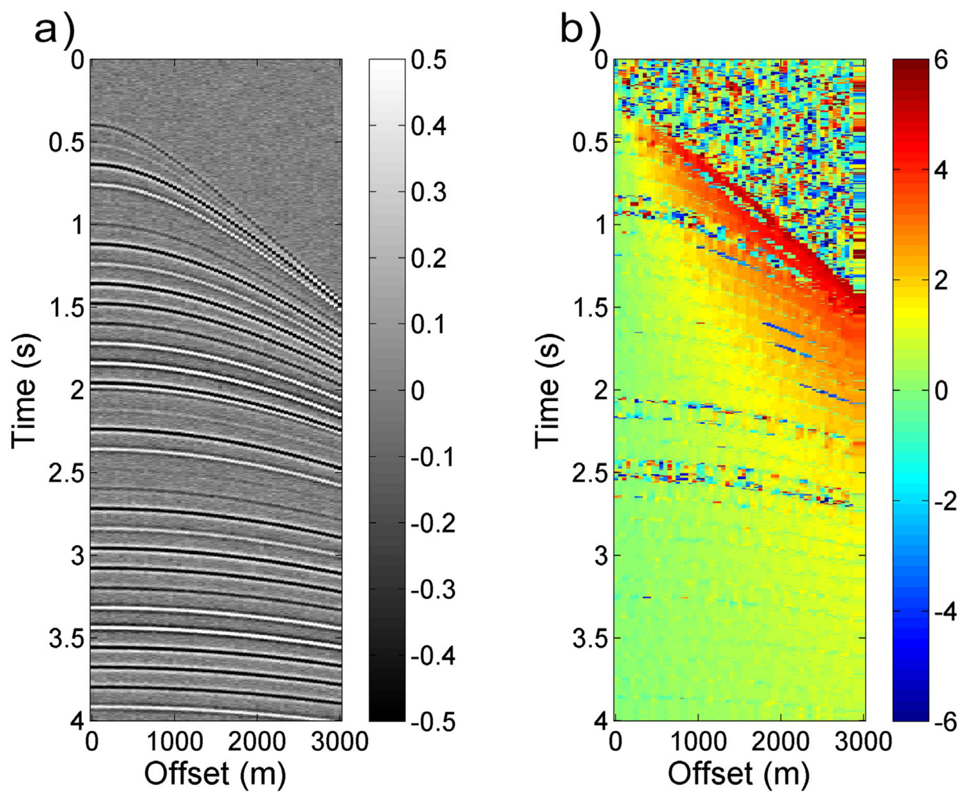

Fig. 1. Synthetic example with random noise. (a) Synthetic CMP gather with random noise, (b) estimated slopes with phase method.

and velocity estimation can also be done with local event slopes (Fomel, 2007; Cooke et al. 2009). On a single CMP gather, normal moveout (NMO) velocity becomes an attribute that can be directly derived from the local event slopes. Averaging filters (Cooke et al. 2009) and velocity map by image warping (Glasbey and Mardia, 1998; Fomel, 2007) have been implemented to perform the local event slopes related time-domain velocity estimation. Averaging filters are deployed on the mapped velocity values along the offset direction. It implicitly assumes the mapped velocity value errors are distributed symmetrically for one seismic event. Velocity map by image warping can be viewed as a kind of semblance. To get the unbiased estimation, image warping assumes that the amplitude varies slightly along offset. These methods have poor performance in the presence of multiples and AVO. Local event slopes estimation is the keystone of applying local event slope related velocity analysis. Various algorithms have been developed to extract local event slopes, such as local slant stack (Ottolini, 1983), plane-wave destruction (PWD) filters (Fomel, 2002; Schleicher et al., 2009; Chen et al. 2013a and 2013b), and Hilbert transform (Barnes, 1996; Cooke et al. 2009; Zhang et al. 2013; Wang et al. 2015).

To pick velocity values manually requires the skill and experience of the data processor. Automatic velocity analysis has been developed with various strategies in the past decades. Toldi (1989) describes one of the first automatic velocity analysis algorithms, in which the velocity model is represented by possible interval velocity values. Least-square optimization is implemented to obtain the best model that has maximum stacking power along the moveout curves. Zhang et al. (2014) further extend the method to the case of non-hyperbolic moveout. Velocity picking on semblance image can be viewed as a variational problem (Fomel, 2009). By taking the energy on semblance spectra as slowness, the first arrival ray path from the top to the bottom of semblance corresponds to an optimal picked velocity. The performance of this approach is further studied by Almarzoug and Ahmed (2012) with real seismic datasets.

In this paper, we propose a method for velocity analysis with local event slope related probability density function (PDF). In the proposed method, we first estimate local event slopes in the Fourier domain with phase information. A frequency adaptive filter is added to improve the performance of slope estimation in the low SNR situation. Then, histogram analysis is implemented on the attributes mapped from local event slopes to obtain an estimate of NMO velocity PDF. Automatic velocity picking based on first arrival ray path with straight-ray segments assumption is performed to obtain the velocity model. Extension of the proposed method to anisotropic velocity analysis, prestack time migration velocity estimation is straightforward. Synthetic and field examples are given to validate the performance of our method.

2. Theory

In this section, we illustrate our method with the simple hyperbolic moveout case for simplicity and give an extension to prestack time-domain velocity analysis. This method is also extendable to the case of non-hyperbolic moveout caused by reflector curvature, heterogeneity, or anisotropy (Alkhalifah and Tsvankin, 1995).

2.1. Local slope estimation by phase method

Various techniques have been proposed to estimate the local event slopes. Fomel (2007) measures local slopes with PWD filters. Since PWD filters calculating local event slopes with the minimum global misfit criterion, it may lose local property to some extent. Instantaneous temporal frequency and instantaneous spatial frequency obtained from Hilbert transform can give the instantaneous p values (Barnes, 1996; Cooke et al. 2009), which are equivalent to local slopes.

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