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Image point transform method for VSP data in VTI medium

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ABSTRACT

Image point (IP) transform method is a very useful tool for VSP data processing and signal enhancement, wavefield separation and imaging because reflection events are mapped onto points by IP transform, and thus, they can be easily identified and separated from other events like direct waves and noise in IP domain. However, in practice, applying IP transform directly to seismic data for anisotropic media leads to misinterpretation because the propagation velocity varies depending on propagation angle in anisotropic media. In order to overcome this problem, we proposed an anisotropic IP transform method for vertical transversely isotropic (VTI) medium by calculating traveltime of incident and reflected wave path separately. During the calculation of traveltime for segmented ray path, the geometrical information of reflection points can be derived analytically. This information for reflection point can be directly used for the purpose of reflector imaging. In determining ray velocities of both waves, we applied bisection method to determine phase angle for a given propagation angle without any weak anisotropy approximation. We applied and validated anisotropic IP transform to numerical VSP data for dipping reflector model and reconstructed the reflectors' image using the information for reflection point that are determined during anisotropic IP transform.

1. Introduction

Vertical seismic profiling (VSP) is widely adopted for the purpose of reservoir characterization and fracture imaging. Because of high frequency signal attributes and unique geometry of source and receiver, VSP shows better resolution than surface seismic method for not only horizontal layered structures but also complex structures like salt dome.

Although conventional methods like F–K filter, median filter and VSP–CDP mapping have been commonly used for VSP data processing, IP transform method has also been widely used as VSP data processing tool for signal enhancement and reflector imaging for instance since it was proposed by Cosma and Heikkinen (1996) as a process for signal enhancement of weak reflections in VSP data.

IP transform is a kind of Radon transform (τ-p transform) but has different integral path compared with Radon transform. Since Radon transform takes straight line with specific slowness (1/velocity) as integral path, it maps reflection waves to elliptic lines in τ-p domain. On the other hand, IP transform which takes hyperbolic integral path maps reflection events onto points in IP domain. Because the reflection events are condensed to points in IP domain, they are easily identified from others like noise, direct waves and multiples. Cosma and Enescu (2004) and Cosma et al. (2006) used IP transform to separate reflection wave by inverse IP transform after some filters like dip filter in IP domain. Cosma et al. (2010) also proposed a new migration scheme that uses IP transform under the assumption that a reflector can be regarded as the superposition of small planar reflectors and showed its usefulness by applying it to 3D VSP data. Lee et al. (2010) expanded and generalized IP transform for VSP geometry to IP transform for reverse VSP geometry by adopting the concept of IP transform of all data to a certain line which is perpendicular to the strike of a reflector plane. They also proposed the mid-point method as a new scheme for fracture imaging.

The most of seismic data processing including VSP processing are based on isotropic assumption that seismic properties such as P and S wave velocities are the same along any direction of measurements. However many researchers reported that the seismic properties of underground are not isotropic but anisotropic (Crampin et al., 1984; Makeeva et al., 1990; Thomsen, 1986). Helbig (1984) and Crampin et al. (1984) argued that the seismic anisotropy is related with wavelength and the small scale of structures, and/or small inhomogeneity in medium compared with wavelength. Crystalline rock also often shows anisotropy depending on the anisotropic properties of composition minerals or their directional alignments and isotropic layered system also shows anisotropy. Seismic anisotropy is also shown in case that a small scale of crack and a set of fracture system is aligned with a certain direction and filled with fluids such as water, gas and oil (Babuska and Cara, 1991; Crampin, 1985; Lynn, 1996).

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Cosma and Heikkinen (1996) applied IP transform to multi-azimuthal 3D VSP data. Although they analyzed directional differences of seismic velocity in crystalline rock, their IP transform analysis assumed that the medium is isotropic. In this case, an anisotropic IP transform method is highly recommended to avoid potential misinterpretation.

In this paper, we derived an anisotropic IP transform method for VTI medium and described the difference between anisotropic and isotropic IP transform. We also examined the applicability and characteristics of anisotropic IP transform by applying it to numerical VSP data for wave separation and reflector imaging.

2. Image point transform in VTI Medium

Following the convention of Cosma and Heikkinen (1996), IP transform and its inverse transform in isotropic medium are expressed as below.

$$\Gamma(\zeta,\rho) = \int_{z_{\min}}^{z_{\max}} g(z, t = t_r(\rho,\zeta;z))dz \quad (1)$$

$$g(z,t) = \frac{d}{dt}\mathrm{H}\int_{\zeta_{\min}}^{\zeta_{\max}} \Gamma(\zeta,\rho = \rho_r(z,t;\zeta))d\zeta \quad (2)$$

where, $g(z,t)$ and $\Gamma(\zeta,\rho)$ are a common shot gather and its IP transform, respectively, and H is Hilbert transform.

Eq. (1) corresponds to a generalized form of integral transform along a selective path given by t_r In case of Radon transform, the integral path constraint t_r is given as a straight line having a specific slowness and intercept time. In IP transform, t_r is given as a hyperbolic path that satisfies a two-way travel time relation of reflection events.

For isotropic medium, reflection traveltime can be easily calculated by dividing the distance form image point to receiver by the velocity (V) of medium. Considering the generalized geometrical relation between an image point and a pair of source and receiver as shown in Fig. 1, it is given by simple equation as follows:

$$t_r = \sqrt{\rho^2 + z^2 - 2z\zeta}/\mathrm{V}. \quad (3)$$

For anisotropic medium, on the other hand, we need to divide the traveltime in Eq. (3) into incident and reflected part. Geometrically, the distance from an image point (IP) to a receiver (D) is equal to the sum of the distance from a source (S) to a reflection point (RP) and the distance from RP to a receiver (D). On the contrary to isotropic case where the velocity of incident and reflected ray are the same, the velocity of incident ray is different from that of reflected ray unless the axis of symmetry is parallel or perpendicular to the reflector plane depending on the ray angle in anisotropic medium. Consequently, the Eq. (3) should be modified to Eq. (4) for anisotropic medium where the ray velocity depends on the propagation angle.

$$t_r = \sqrt{\rho^2 + z^2 - 2z\zeta}/\mathrm{V} = \left|\vec{RP} - \vec{S}\right|/\mathrm{V}(\varphi_1) + \left|\vec{RP} - \vec{D}\right|/\mathrm{V}(\varphi_3). \quad (4)$$

Considering geometrical relation illustrated in Fig. 1 and introducing the strike angle (φ), then the relations between propagation angles of incident wave (φ_1) and reflection wave (φ_3) can be expressed as follows:

$$\tan\varphi_1 = \left(\vec{RP} - \vec{S}\right)\cdot(\cos\phi, \cos\phi, 0) \Big/ \left|\vec{RP} - \vec{S}\right| \quad (5)$$

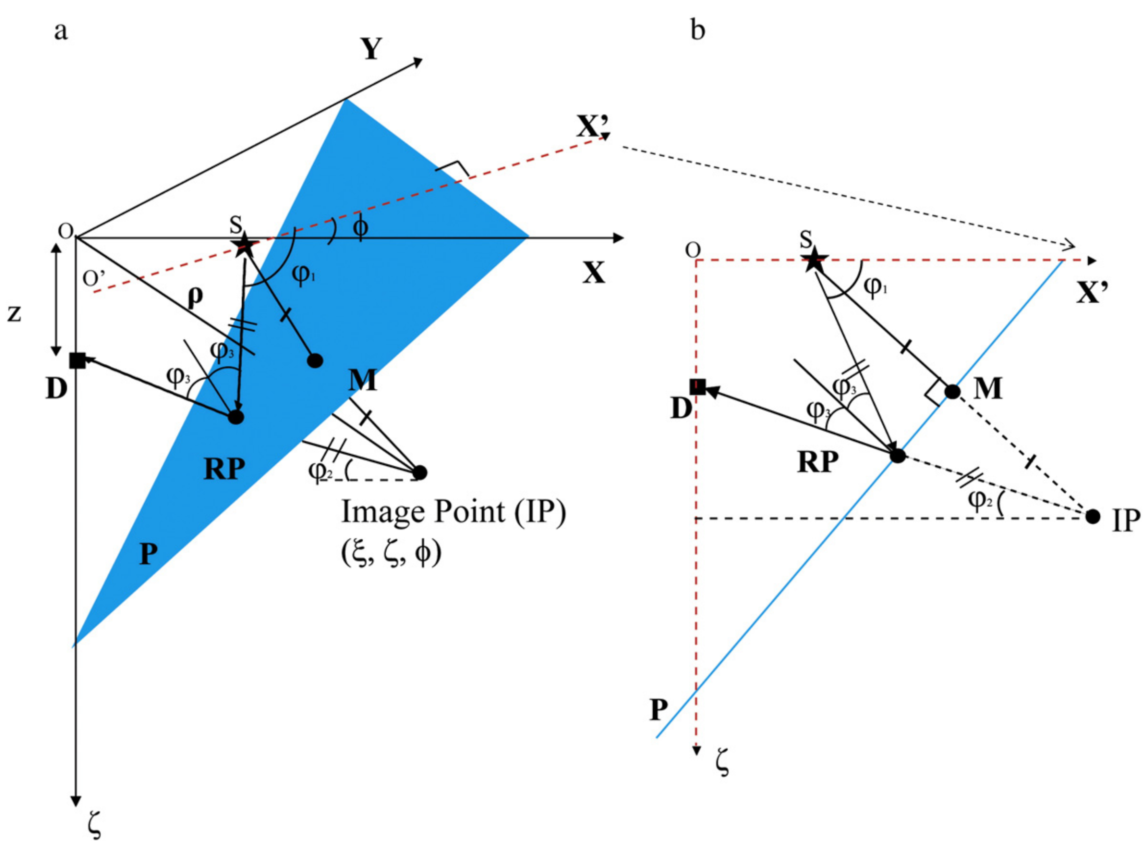

Fig. 1. 3D geometrical relation between an image point and a pair of source and receiver point (a). S is a source on surface, IP is the image point of S to plane reflector R. D is a receiver in borehole, RP is the reflection point on reflector plane P and M is the midpoint between the source S and its image point IP. (b) 2D projection on to the virtual plane perpendicular to the strike direction. (X′–ζ plane) and φ_1, φ_2 and φ_3 are defined on this plane.