PAPER J

WHY WE USE PRESTACK REVERSE-TIME MIGRATION

Le-Wei Mo and Jerry M. Harris

INTRODUCTION

This paper serves as an introduction to the two following papers (Mo and Harris, 1993a, 1993b). It answers the question why we have used prestack reverse time migration to process crosswell seismic data.

Crosswell seismic survey places sources and receivers in the subsurface close to the target. Its distinct difference over the other survey configurations, e. g., surface reflection seismic and VSP, is that wavefields do not propagate through the severe attenuating weathered surface layer before being received. The advantage is that it permits the recording of seismic data with frequencies from a few hundred Hertz up to a few thousand Hertz (Harris, 1988; Paulsson, 1988). This frequency is an order of magnitude higher than what can be achieved with the standard surface reflection seismic or VSP configurations. The spatial resolution limit (a few feet) is thus an order of magnitude smaller than what can be achieved with the standard surface reflection seismic or VSP configurations. Despite its high resolution, the compromise between well damage and energetic downhole source dictates that the area that can be effectively surveyed is limited, at most up to 1000 ft in lateral dimension with given present technology. Thus crosswell imaging fills in a gap between large scale, low resolution surface seismic surveys and small scale, high resolution log and core measurements. It is mainly used as a tool of production seismology.

GOAL

An important parameter of the earth is velocity (Vp and Vs). Velocity variation can be decomposed into a low wavenumber (wavenumber is spatial frequency) component and a high wavenumber component (Claerbout, 1985). To extract the low wavenumber component of the velocity spectrum, many researchers (McMechan et al., 1987; Harris, 1988; Bregman et al., 1989; Chen et al., 1990; Luo and Schuster, 1991; Lines, 1991) have developed methods of transmission traveltime tomography to produce smooth velocity cross-sections between the two wells. Cross-well transmission traveltime tomography allows us to constrain velocities much better than with classical surface reflection seismology methods, because with precisely located downhole sources and receivers we avoid the velocity/depth ambiguity that is common with surface methods. Thus provided good coverage, accurate low wavenumber component of the velocity spectrum is recovered by cross-well transmission traveltime tomography. But transmission traveltime tomography uses only the traveltimes of the first arrivals, which represent only a small fraction of the total information contained in the data. And it suffers from coverage limitations both at the top and the bottom of the survey, where the crossing ray paths between sources and receivers are sparse.

The high wavenumber component of the velocity spectrum remains to be found. However, it turns out to be much more difficult to be realized. Scattered events in seismic records, such as reflections and diffractions, carry rich lithologic information. Inversion for the high wavenumber component of the velocity spectrum requires the application of these scattered events, which promises resolution of the scale of wavelength. Two categories of methods have been proposed for the extraction of high wavenumber component of the velocity spectrum. They all use the full wavefields of the recorded data, thus often collectively called full-waveform methods. One category of methods, inversion (Tarantola 1986) and diffraction tomography (Harris, 1987; Pratt and Worthington, 1990), proposed to perform full waveform inversion of seismic scattered data directly for rock physics parameters (Vp, Vs, and density). Even though alluring, these methods suffer from not being robust enough to handle practical noisy seismic data. The other category of method, migration (Berkhout, 1985; Claerbout, 1985), proposed to image the impedance reflectivity first, thus reducing the data volume and increasing the signal to noise ratio. A further inversion of the impedance reflectivity images gives the rock physics parameters (Vp, Vs, and density). Methods in the two preceding papers (Mo and Harris, 1993a, 1993b) fall in this last category, and are designed to retrieve the subsurface impedance reflectivity images of multi-elastic wavemodes (P-P, P-S, S-P, and S-S). Further inversion for the rock physics parameters (Vp, Vs, and density) remains to be done.

Crosswell seismic data recorded with our acquisition system contain a rich variety of elastic wave modes, P-P, P-S, S-P, and S-S, the bandwidths of which range from a few hundred Hertz up to a few thousands Hertz (Harris et al., 1992). Subsurface impedance reflectivity images of multi-elastic wavemodes (P-P, P-S, S-P, and S-S) will be useful for seismic reservoir characterization. Aside from showing the structures of the subsurface, high resolution images of these multi-elastic wavemodes may be indicative of lithology, subsurface physical states (e. g., pressure and temperature), and pore-fluid content. Those types of information will be useful in reservoir management (infill drilling and field extension), and monitoring time-variable reservoir production and enhance oil recovery (EOR) processes.

PREVIEW

In field and water-tank crosswell survey configuration, complex wavefields (P-P, P-S, S-P, and S-S) are being recorded. From these complex wavefields, we can extract various types of geological information. However, if not properly processed, these complex wavefields act as noise to any processings. This explains why the present delay of migration theory being applied to crosswell seismic data.

VSP-CDP mapping (Wyatt and Wyatt, 1981), as a robust method, has been applied to crosswell seismic data (Stewart and Marchisio, 1991; Lazaratos, 1993). The assumption of 1-D geology in VSP-CDP mapping makes it unable to image 2-D geology correctly. And its lateral resolution is limited because ray-theoretic VSP-CDP mapping does not focus diffraction energy, and thus does not collapse Fresnel zone. A better method would be wave equation prestack reverse time migration coupled with transmission traveltime tomography. Transmission traveltime tomography gives an accurate background velocity model, which represents the low wavenumber band of the velocity spectrum. Reverse time migration can honor an arbitrary velocity model and accurately image reflecting structures of arbitrary dips, which represent the high wavenumber band of the velocity spectrum. In this last category, several researchers have attempted the application of migration, and or inversion, Beydoun et al. (1988) by inversion, Hu et al. (1988) by second-order-in-time and space central finite difference reverse time migration and Gray and Line (1992) by Kirchhoff VSP depth migration. Even though these methods have been tested with synthetic data or acoustic laboratory data, we need more accurate numerical method to process field data. And after migration, we still need to do a series of processings before we arrive at good stack images.

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The reverse-time migration (McMechan, 1983) is highly accurate and versatile. And it should be implemented with a fast finite difference wave equation solver. We have a good and fast finite difference wave equation solver (Mo and Harris, 1993a). Thus we use the reverse-time migration algorithm (McMechan, 1983) in our crosswell data processings. The cost of reverse-time migration is reduced by the virtue that we obtain images of two elastic wavemods (P-P and S-P, or P-S and S-S) by one migration pass in field data (Mo and Harris, 1993b).

OVERVIEW

Mo and Harris (1993a) shows how prestack reverse-time migration is performed, and the vertical and horizontal resolution that can be achieved by crosswell seismic survey. We have applied second-order-in-time, eighth-order-in-space staggered-grid finite difference method (Virieux, 1986; Dablain, 1986; Etgen, 1989) to solve the two-way acoustic wave equation for wave propagation. This numerical method warrants coarse grid computation. Spatial sampling rate of about five points per wavelength is enough to avoid numerical dispersion, as oppose to sampling rate of fifteen points per wavelength that is required by second-order in time and space finite difference method (Alford et al., 1974). And computation is thus fast. And we have applied the finite difference method (Van Trier and Symes, 1990) to compute the direct wave traveltime used as the excitation time imaging condition for the prestack reverse time migration (Claerbout, 1985; Hu and McMechan, 1986).

Mo and Harris (1993b) shows prestack reverse-time migration of field data. We perform prestack migration on all the common receiver (or shot) gathers to obtain an image cube. Even though migration has the merits of correct imaging of dipping reflectors and collapsing of Fresnel zone, it has long be scolded for it smears noise around. However, it is just this so-called "shortcoming" of migration that helps subsequent dip-filtering on migration images to remove noises. In a constant velocity medium, the prestack migration impulse response is that one data point is spread into a whole ellipse with the source and receiver locations as the loci. Based on the idea that reflection events should be stable but the migration responses of noises are variant as incidence angle changes, we perform geometrical incidence angle transform on the image cube. The geometrical incidence angle is defined as the angle between the incidence straight ray path linking an image point to the source and the vertical line through that image point. The dips of reflection events are invariant in different common incidence angle sections. The noise responses have roughly constant dip in a common incidence angle section. And the dip angle is 90 degrees minus the absolute value of the incidence angle. Lazaratos (1993) used incidence angle transform in the context of VSP-CDP mapping. We apply 2-D dip filters on the common incidence angle migration images to remove noises. Stacking of the noise filtered images gives high-quality subsurface impedance reflectivity images of multi-elastic wavemodes (P-P, P-S, S-P, and S-S). The detailed structure around a 100 ft reservoir has been successfully imaged, with resolution of a few feet. A good tie was achieved with sonic logs recorded at both wells. We propose a processing sequence of crosswell seismic data.

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