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The seismic response of a thin basalt layer – relevance to full waveform inversion

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Introduction

Full waveform inversion is an attractive approach in vulcanised regions where conventional imaging fails. Typically, data from such areas contain strong and pervasive multiple energy, often with move-out velocities around and above those of sub-basalt primary arrivals, and the ability of full waveform inversion methods to manage such arrivals correctly is valuable when multiple suppression methods are insufficient.

It is well known that the high impedance contrasts at interfaces between sediments and volcanics lead to significant back-scattering of the wavefield, and typically the majority of energy recorded in a surface experiment has not sampled the region beneath the volcanics. The residuals in waveform inversion are similarly affected, with slight errors in the upper model dominating any signals from the imaging targets. Therefore, most successful approaches have required careful data selection strategies, for example using time-offset data windows (Shipp, 2000) or discrete temporal frequencies (Pratt *et al.*, 1996; Sirgue & Pratt, 2001).

Many of the high-impedance screens encountered on the North Atlantic margin take the form of thin basaltic sills or lava flows (hereafter referred to as 'sills' for convenience). A combination of tuning effects and high velocities cause the seismic reflectivity and transmissivity of thin sills to be highly variable with temporal frequency and propagation angle (or, equivalently, horizontal slowness component). This paper describes the calculation of these frequency-slowness domain amplitude spectra, and their application in designing data windowing and filtering strategies for deeper targets in waveform inversion. The term 'thin' applies to layers whose thicknesses are small compared to a seismic wavelength, by at least a factor of four.

The sill response calculation

Although the following method may be applied to an arbitrary succession of layers, this example is for a single sill set in a background material with the same properties above and below. The 1-D model is described by 7 parameters: the P- and S-wave velocities and density of both the background medium and the sill, and the sill thickness.

The reflectivity modelling method (Kennett & Kerry, 1979) is a well-known and efficient technique for stratified (1-D) earth models. For a plane wave, incident on a single interface, the Zoeppritz equations give complex reflection and transmission coefficients for each of the four generated modes (both P- and S-wave in each medium). These coefficients are independent of frequency. The frequency dependence of the spectrum comes from interference between the wavefields scattered by spatially separated interfaces.

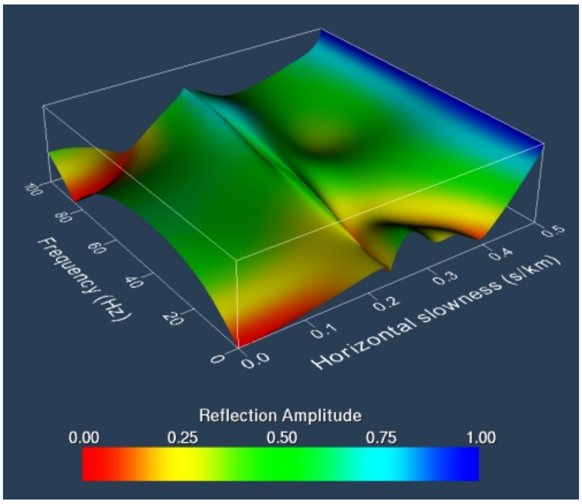

Figure 1: The P-wave reflectivity amplitude of a 25m basaltic sill in sediments. This dimensionless spectrum must be convolved with a source spectrum to give a true response.

Taking each frequency-slowness pair in turn, a reverberation matrix is constructed to represent a complete 'cycle' of the wavepath within the sill, incorporating coefficients of internal reflections and conversions, along with phase shift operators representing the propagation of the wavefield through the sill.

The infinite series of internal reverberations may then be written in terms of the reverberation matrix, and this series takes the form of a Taylor series expansion, which is contracted to give an exact and finite expression for the reflectivity and transmissivity of the sill. For the purposes of this work, only the amplitude of the complete spectrum is considered.

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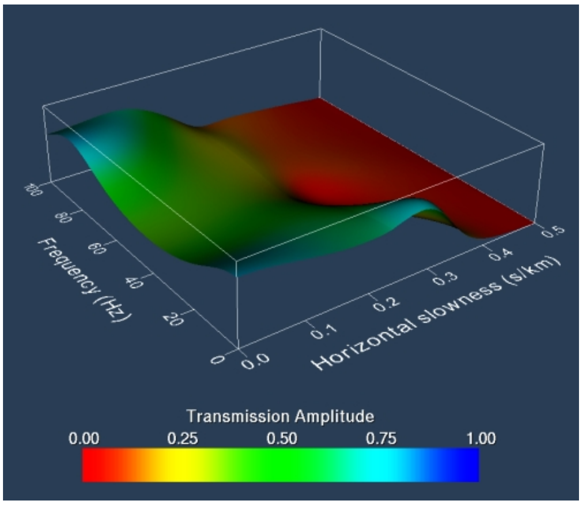

Figure 2: The equivalent two-way transmission amplitude response of the same sill as used to calculate Figure 1. Note the efficient tunnelling of low frequencies in the post-critical slowness range.

Thin bed equivalence

Waveform inversion schemes for laterally heterogeneous models make use of discretely gridded models, the resolution of which is often larger than individual basalt layers. As observed by Widess (1973), the expected near-offset reflection response of the sill is a wavelet shaped as the time derivative of the incident wavelet, with an amplitude proportional to the product of acoustic impedance contrast and sill thickness. This is due to the interference of the reflections from the top and bottom of the bed, the latter having opposite polarity.

Although the basalt velocity is well-constrained by the critical angle reflection (figure 1), a gridded scheme can exploit the trade-off between density and thickness to match the near-offset reflection behaviour well. However, the high wavespeeds in igneous material, combined with the generally accepted requirement of long-offset recording, lead to significant portions of data containing the critical-angle and post-critical response of the sill. At these further offsets, the vertical wavenumber in the sill becomes imaginary, and thus the tuned amplitude between top and bottom interfaces relies upon the negative exponent of the thickness, rather than a linear relationship. Therefore, the amplitude equivalence does not hold around and beyond the critical angle.

Any such unmatchable amplitude behaviour must be removed from the waveform residuals if it is not to dominate the inversion at the expense of deeper targets.

Enhancement of the transmitted wavefield

The transmission spectrum of the sill (figure 2) can be convolved with the source spectrum to determine which wavefield components penetrate the sill, and it is possible to design a filter to focus on these components while removing energy we are sure cannot have reached beneath, thus enhancing the signal-to-noise ratio. This filtered dataset can then be used for targeted waveform inversions, and indeed for conventional imaging techniques where there may be strong coherent noise across the whole spectrum.

Discussion

In order to target waveform inversion schemes on the model beneath basalt sills, it is first necessary to account for the strong arrivals from above, which would otherwise dominate the objective function. This suggests a ‘layer-stripping’ approach, using knowledge of the overburden to design model and data windowing strategies to proceed downwards.

In some circumstances, it may be impossible to model critical reflections from the sill, and the removal of these from the residuals by, for example, frequency-slowness filtering is essential.

Filters designed on the transmission behaviour of the overburden enhance the sub-basalt signal, improving the performance of the inversion.

Larger-scale volcanic sequences often take the form of thinly-interbedded layers of lavas, tuffs and clastic sediments, and the analysis of such sequences is a straightforward extension of the method for a single sill.

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