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RESEARCH NOTE

The problem of water-column multiples for processing converted *S* waves in marine VSP data

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SUMMARY

Seismic data from marine VSPs contain converted *S* waves which can be used to provide information on the internal structure of the subsurface rocks. To make the best analysis of these waves it is necessary to choose a suitable offset to maximize the converted energy. Numerical modelling with a hard sea-bottom shows that even for the moderate offsets which provide the best conversions at the sea-bed in a shallow-water environment, it is not possible to jointly compensate the *P* and *S* waves for their effective seismic signatures using a single common scalar function. This is due to a difference in the periodicity of the water-column multiples associated with the two wavetypes. The difference becomes more pronounced for a large Poisson's ratio in the sea-bed sediments. Standard processing on the three-component recordings cannot be adequately performed except for subvertical incidence. Consequently, *P* and *S* waves must be separated before signature deconvolution, or else a more sophisticated multicomponent operator must be deployed. In the process of acquisition design, the detailed modelling required to understand the multicomponent response must be weighed up against the offset desired for optimal conversion.

Key words: converted shear waves, marine VSP, water-column multiples.

1 INTRODUCTION

Multicomponent seismic data are used increasingly to provide what were previously inaccessible properties of reservoir rocks, through the analysis of differential changes in various components of the multicomponent (compressional and shear) wavefield. Examples of these are bright spots in the ratio of P and *S* wave velocities (Tatham & McCormack 1991), shear-wave birefringence (Crampin & Love11 1991), or dimming between split shear-wave amplitudes (Mueller 1991). One, or preferably a combination, of these may be indicative of ***in situ*** porosity, fracturing, fluid content (lithology), and stress direction. Even with these potential benefits, there still appears to be little interest in examining such data from offshore VSP surveys in the North Sea. For marine surveys, one major hurdle in processing is that direct shear-wave generation is not possible. Although three-component downhole tools can record vector wave data in a VSP, shear waves must be generated by mode conversion of the P waves at appropiate interfaces along the ray paths from source to receiver. The survey consequently lacks control in the excitation mechanism. The nature of this generating mechanism must be further investigated before adequate knowledge is available to process the shear waves.

For most purposes it is usual to use offset VSPs to generate high-amplitude converted waves, as the more oblique ray direction produces a greater conversion coefficient. This exploits the well-known properties of the plane-wave P-P and *P–SV* transmission coefficients (Ergin 1952) shown in Fig. 1, in which we also show the P-P reflection coefficient to aid interpretation. We consider interface coefficients at the sea-bottom, as this *P–SV* wave is the most straightforward converted wave to analyse as it is the one which is least contaminated by P-wave interference (Ahmed 1989). The seismic velocities for this example are higher than those expected in typical sea-bed sediments, and are chosen to give a clear illustration of the offset dependency of the water-column multiples in our later synthetic seismogram example. The hard bottom allows us to focus on this particular aspect of the wave propagation without considering other interfering arrivals that are likely in realistic soft sediments with velocity gradients (Stephen & Bolmer 1985).

In Fig. 1 there is an abrupt peak in the reflection coefficient at the P-wave critical angle, θ_P, of 32"

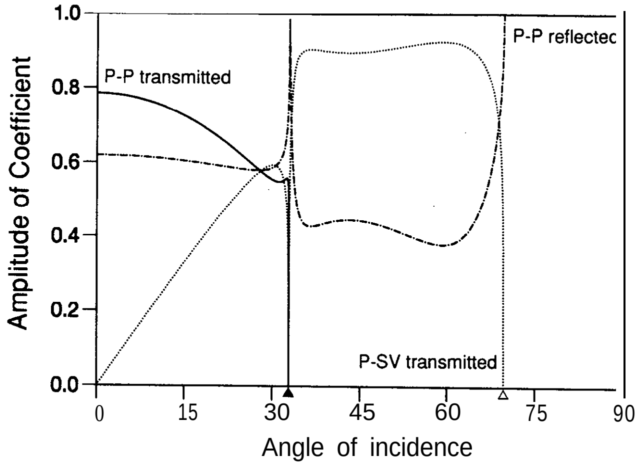

Figure 1. Downgoing plane-wave reflection and transmission coefficients for ***P*** waves incident from above a water-solid interface. The solid medium has α = 2.77 km s^{-1}, β = 1.60 km s^{-1} and a density of 2.3 g cm^{-3}. Solid and open triangles mark the critical angles for ***P*** waves and ***S*** waves in the lower medium respectively.

($\theta_P = \sin^{-1}(\alpha_1/\alpha_2)$, where α_1 = 1.5 km s^{-1} and α_2 = 2.77 km s^{-1} are the P-wave velocities in the water and solid respectively). This sharp rise is expected from ray theory as this is the direction at which total internal reflection of the ***P*** wave takes place. There is a sharp decline as critical angle is exceeded, where ***SV*** waves that had abruptly vanished, reappear with a change in phase and stronger than before. Beyond the critical angle, the downward-propagating ***P*** waves in the solid are absent and exist as evanescent waves at the interface, but there is a strong converted shear wave which accounts for the decline in the ***P-wave*** reflection coefficient. The converted ***SV*** amplitude falls rapidly at a second critical angle, θ_S, of 70° ($\theta_S = \sin^{-1}(\alpha_1/\beta_2)$, where β_2 = 1.60 km s^{-1}), at which the ***SV*** energy becomes evanescent and there can be no further rays propagating into the solid medium. The first critical point determines the offset beyond which optimal conversion should be achieved. If ***SV*** waves can be observed beyond this angle, they are minimally contaminated by the P-wave coda and are likely to be large in amplitude. At vertical incidence there is no ***SV*** wave conversion for a plane horizontal interface.

This behaviour appears well understood for a variety of sea-bottom conditions, the optimal conversion point varying between 30" and 50" for the softer marine sediments in the North Sea, which can be readily accommodated in the design of VSP studies. However, a complete optimal acquisition design must also take into account the ease of processing the recordings, and hence other undesirable wave behaviour which serves to complicate the seismic records. One of these complications is the reflection of the acoustic radiation emitted by the airguns at the water surface and the sea-bed. The effective seismic signature is thus composed of a primary wavelet, ghost reflection, and ensuing multiple bounces in the water column. This signature is a sensitive function of ray direction and frequency (Parkes & Hatton 1986), and is likely to be particularly important for shallow-water regions such as the North Sea. Thankfully standard procedures are available for deconvolving the effective seismic signature in most cases, as either a deterministically or a statistically derived function, with a consequent reduction of the water-column multiples and simplication of the P-wave data. Although the effects of these water-column multiples have been extensively studied, their influence on converted waves has not been fully documented. This is particularly crucial as split shear waves (carrying anisotropic information) have polarizations and time-delays which may be easily distorted by interfering multiples from different events. Although it is of considerable benefit to processing if a single common source function could be applied to the entire wavefield, is this justified for converted waves? To answer this more fully we must obtain an understanding of the nature and generation of the converted ***SV*** waves through numerical modelling.

2 SYNTHETIC SEISMOGRAM MODELLING

Converted shear waves are examined by constructing full-wave synthetic seismograms using the reflectivity method (Kennett 1983; Taylor 1991), which is similar to earlier algorithms used to compute synthetic seismograms for offset VSPs by Stephen (1977). These computations allow us to examine the medium's response to a point explosive source in a shallow-water layer, and how it relates to the ideal plane wave reflection and transmission coefficients of Fig. 1. Fig. 2 shows the geometry of the numerical model, where we have attempted to simulate typical physical parameters encountered in the North Sea. The explosive source is positioned 3 m below the surface of a 50 m thick water layer. The underlying solid medium is isotropic with seismic velocities and density representing an average of those properties from a range of sea-bed materials, being identical to those used in Fig. 1 (density is 2.3 g cm-"). Three-component geophones are positioned 800 m below the sea-bed, and varied in horizontal offset between 25 m and 2 km to simulate various offset VSPs. The range of P-wave ray directions from these offsets is from 4" to 67" for the ***P–SV*** path, providing good coverage of the conversion behaviour in Fig. 1. In marine VSP experiments it is usual to employ an airgun, or an array of airguns, generating acoustic radiation which covers a wide bandwidth with a roughly flat amplitude spectrum from several hertz to several hundred hertz. However, due to attenuation in the shallow sediments and underlying layers, the final recorded peak frequency of the ***S*** waves is usually around 20 Hz, with the ***P*** waves having a maximum at 40 Hz. Consequently, wavelets with peak frequencies of 10, 20 and 40 Hz are chosen for the modelling.

Figure 3 shows the resultant radial and vertical component recordings. Fig. 4 is for the same model parameters, but with the water-column multiples inhibited so that the move-out of the individual arrivals in the seismic response may be used as a reference for Fig. 3. The gross characteristics of the waves in Figs 3 and 4 are in agreement with the expected behaviour from the plane-wave interface coefficients in Fig. 1. At normal incidence the shear conversion is zero, increasing with offset in tandem with the decrease in the transmitted P-wave energy. The amplitude variations for the transmitted ***P-P*** wave do not mirror the variations in Fig. 1 exactly, as the ray path subtends a set of near-vertical ray angles in the water layer. . A small proportion of P-wave energy is still visible on both components as the critical angle for the ***P-P*** ray path is not

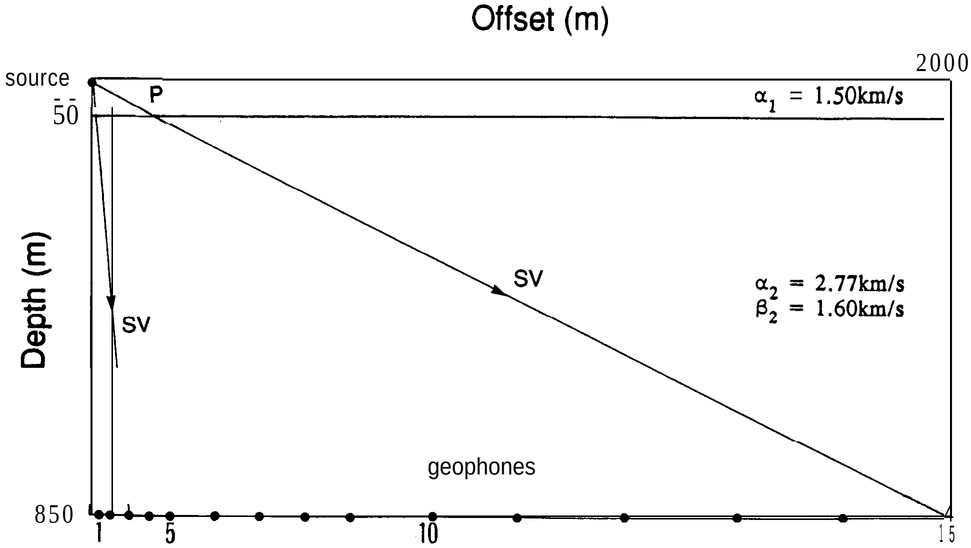

Figure 2. Acquisition geometry used in the numerical modelling to simulate a range of converted wave behaviour. An explosive source is positioned 3 m from the free surface of a water layer 50 m thick. Fifteen geophones are positioned at offsets of 25, 50, 100, 1.50, 200, 300, 400, 500,600, 800, 1000, 1250, 1500, 1750 and 2000 m, along a common depth of 850 m.

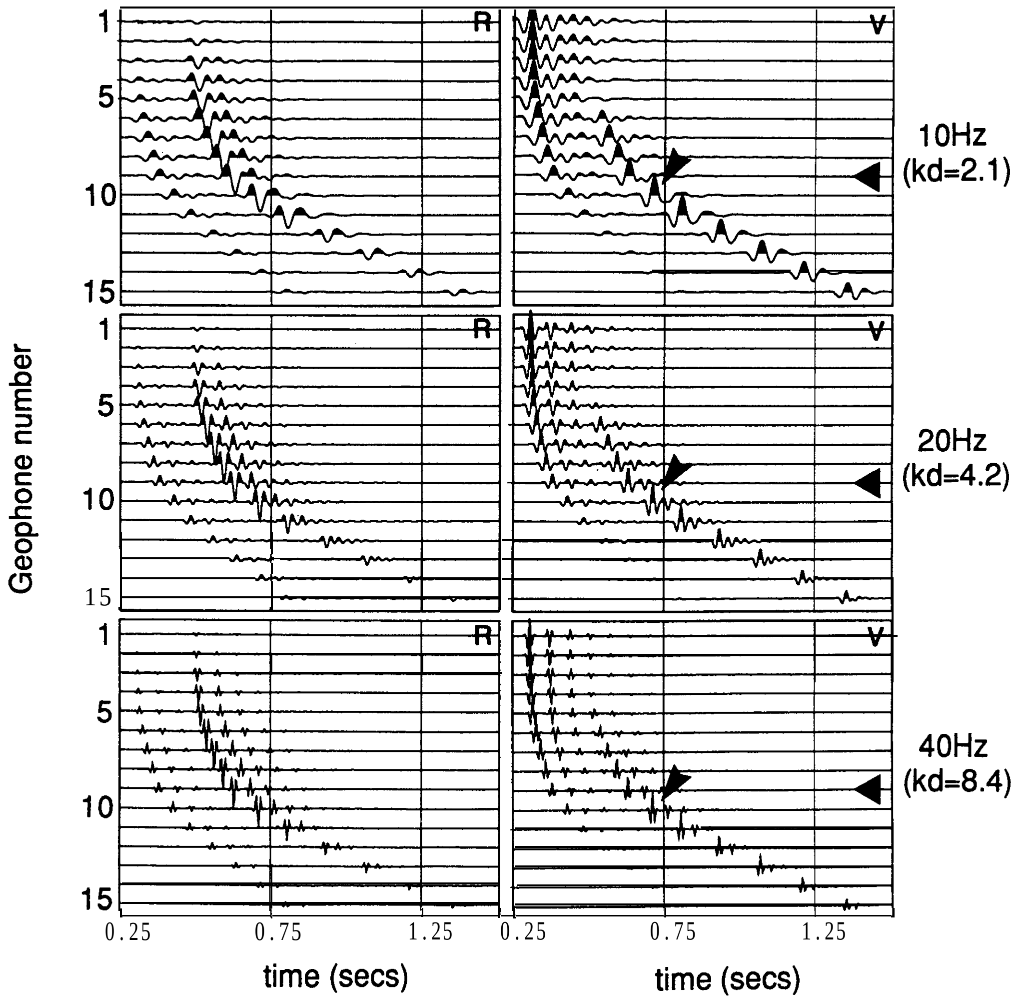

Figure 3. Radial- and vertical-component synthetic seismograms from numerical calculations based on the reflectivity method, for three different wavelet peak frequencies of 10, 20 and 40 Hz. Traces show true relative amplitudes, being normalized by the maximum vector amplitude for the entire trace set. Solid arrowhead marks the *S* wavelet which is optimally converted. Solid triangle marks the offset at which ***P*** waves in the converted ***P-SV*** path exceed the first critical angle of incidence sin-' (α_1/α_2). The frequencies correspond to a wavenumber (k) × layer thickness (d) of 2.1, 4.2 and 8.4.

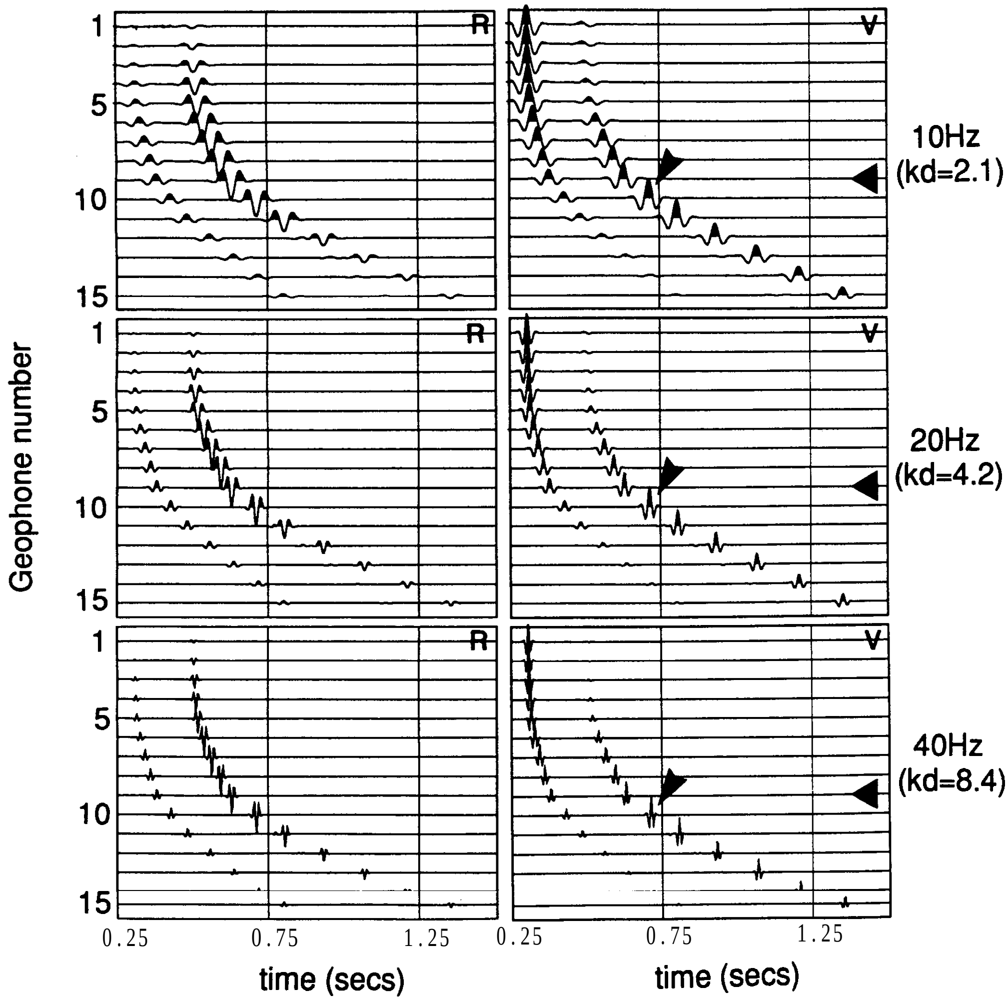

Figure 4. Radial- and vertical-component synthetic seismograms from numerical calculations based on the reflectivity method. The model is identical to that used for Fig. 3, except that the multiples in the water layer have been mathematically suppressed by setting the downgoing P-wave reflection to zero. Notation and normalization as in Fig. 3.

exceeded, even at 2 km offset (several degrees difference). The converted S-wave amplitude reaches a maximum close to the first critical angle, and then falls gradually due to geometric spreading. The P-waves in the water layer for this P-S ray path exceed the first critical angle after an offset of 600 m (geophone 9). The periodicity of the converted S waves generated by the multiply reflected P waves in the water column decreases for larger offsets, and for the 10 and 20 Hz waves actually become short coda. In contrast, the P-wave multiples remain fairly consistent in periodicity as the ***P-P*** ray path subtends a smaller range of angles closer to normal incidence. Fig. 5 illustrates this behaviour, showing that for converted S waves the water layer segment is more oblique, so that there is a reduction in the multiple spacing (Parkes & Hatton 1986). This effect is strongly dependent upon V_P/V_S in the solid, which determines the ray directions and the overall behaviour of the interface coefficients. Fig. 6 shows calculated periodicity for the water-column multiples for the ***P-P*** and ***P-SV*** waves as a function of offset, and the exacerbating effect of a larger V_P/V_S. Although these curves are model dependent, the behaviour is expected to be similar for other seismic velocities.

An interesting effect occurs at the lowest frequency. Multiples are visible for the ***P*** waves only near normal incidence, where the S-wave amplitude is low. Beyond a critical offset of 600 m (geophone 9) there is little sign of the multiple arrivals, and the wavelets appear simple, being comparable with those in Fig. 4. The reason for this is that the multiples have a period much smaller than the seismic period and cannot be distinguished by the broad seismic pulse. As the frequency of the waves increases, the multiples become more evident. This is a direct consequence of the lower frequency and the reduced multiple period due to the increasing offset. The amplitude and width of the pulses may, however, increase due to this overlap. It should be noted that the seismograms in Fig. 4 are generated from the model of Fig. 2 with the downgoing reflection suppressed, but the free-surface reflection present, so that similar vertical dipole wavelets are used for comparing both cases. As the sea-bottom is considered to be isotropic in this particular study, the resultant particle motions for ***P*** and S waves are linear. The phase shifts in the transmission coefficients do not affect the motion in the sagittal plane, only the shape of the wavelets. This would not be true for an anisotropic sea-bottom, where there would be a phase

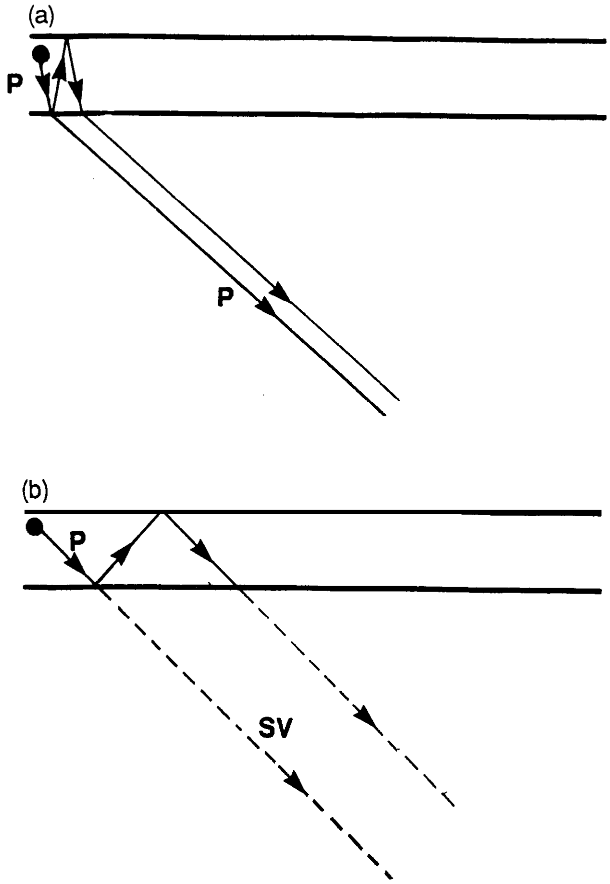

Figure 5. Illustration of different ray paths for: (a) transmitted ***P*** waves and (b) converted ***SV*** waves, which account for the observed change in the effective source signature of these two wavetypes.

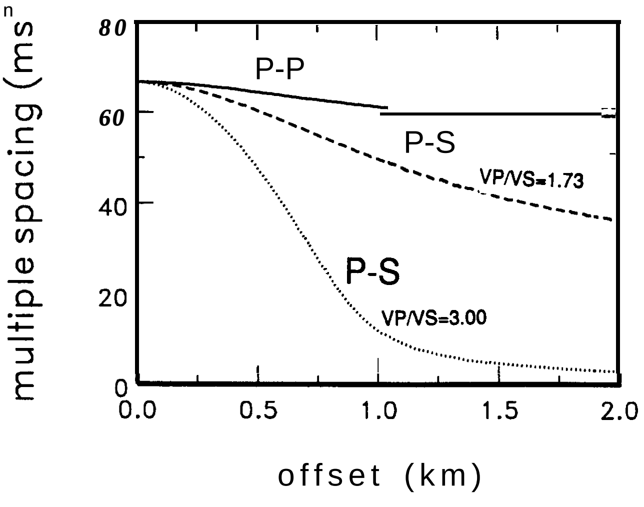

Figure 6. Periodicity of water-column multiples for direct ***P*** wave (solid line) and converted SV-wave arrivals (dashed line for V_P/V_S of 1.73 and dotted line for V_P/V_S of 3.0).

difference between the conversion coefficients for the different split shear waves.

3 IMPLICATIONS OF RESULTS

Converted S waves are difficult to analyse as they are masked by the presence of P-wave multiples and an effective source signature which is sensitive to the peak frequency of the source, the acquisition geometry and the velocity model. These unfortunate conditions challenge analysis procedures designed to estimate wavefield parameters sensitive to anisotropy of the sub-bottom layers. To improve the converted waves to ensure accurate analysis of polarizations and time-delays between split shear waves, it is desirable to increase the signal-to-noise ratio in these waves by optimal acquisition design and to eliminate the inevitable multiples which appear in their effective signature by suitable processing. Unfortunately, optimal conversion, which occurs at ray directions beyond the first critical angle in Fig. 1, also marks the direction for which there are dramatic changes in the periodicity of the water-column multiples associated with the S waves due to refraction. This variation is understandably more pronounced than that commonly observed for ***P*** waves, and therefore presents problems for a common signature deconvolution. The disparity is more pronounced for a larger ratio between ***P***- and S-wave velocities (1.73 is assumed in this work). Although the behaviour of the converted waves is governed by the ratios of the ***P*** and S velocities in the media on each side of the interface, we expect this conclusion to be applicable to a wide range of models.

For the offsets shown in our synthetic example, multiple reduction schemes based on a vertically incident ***P*** wave would be satisfactory for the ***P-P*** transmission. However, even at relatively near offsets of less than 600 m it is not possible to use a common source function to compensate ***P*** and S waves for the VSPs of interest to shear-wave analysis. This means that conventional processing may be incorrectly applied to three-component VSP recordings, and can contaminate S waves by imposing a different effective source signature, complicating the waveforms and rendering them uninterpretable. The safest procedure for preserving the multicomponent response is therefore to separate the wavetypes before deconvolution. However, decomposition into ***P*** and S waves is a major processing step as these waves do not appear as distinct linearly polarized signals for anisotropic media, and special filters must be employed to separate without distortion. An alternative strategy is to use more sophisticated techniques which model the complete multicomponent operator, accommodating both ***P*** and S waves by accurate numerical modelling, from which a suitable inverse operator can be designed. This scheme would rely upon a detailed knowledge of the source function and elastic properties of the near-surface, and this is already a requirement of many standard schemes for deconvolution. Another approach is suggested, if energy at sufficiently low frequencies is recorded, for which it appears unnecessary to deconvolve the S waves, as the reduced period multiples combine with the broad direct wavelet to form a single simple wavelet. This may provide a way of obtaining effective and directly interpretable shear-wave measurements at offset.

DISCUSSION AND CONCLUSIONS

Multiples in shallow-water environments such as the North Sea produce well-known intrinsic complications in the effective seismic signature, dependent upon the reflection coefficients at the sea-surface and sea-bed, the water thickness, and depth and offset of the source. It is standard practice to correct for this by using a normal incidence model, or more occasionally, if desired, by oblique offset modelling of the angular dependent signature (Parkes & Hatton 1986). These procedures are widely accepted practice. Converted waves cannot be treated by the same algorithms, and must be considered separately as the effective source signature changes dramatically at the optimal conversion point. This effect has not been identified before as studies have mainly concentrated on high-frequency P-wave data. These results highlight the necessity in converted wave studies, not only for accurate modelling of the source conditions (Ziolkowski 1991) but also for the near-surface conditions, to correctly account for the refraction and conversion processes. This forms a natural progression of current advances which drive the processing sequence towards model-based processing and acquisition design using actual wave-propagation schemes, rather than the traditional philosophy of developing handy analytic approximations.

This study forms part of an investigation on optimal conversion in marine environments, with the objective of developing multicomponent processing schemes which extend existing land-based processing flows making efficient and consistent use of conditioning, processing and interpretation (Wild *et al.* 1993). In these procedures, multicomponent processing steps must be performed in strict accordance with the properties of the matrix quantities which define an allowable direction and order for the sequence of operators (Kennett 1983). It is important to apply them at the correct point in the sequence to make data comparisons between similar trains of sequences. If these are correctly taken into account, processing and interpreting multicomponent data may in fact be easier than for scalar data.

Future work will concentrate on further difficulties associated with more realistic, softer sediment structures, and a possible processing solution.

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