AVO Inversion in Marine Gas Hydrate Studies*

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Abstract

Seismic studies of marine gas hydrates include attempts to determine the gas hydrate concentration above, and free-gas concentration below, the base of the gas hydrate stability field, which is usually inferred by the observation of a bottom-simulating reflector (BSR) on low frequency seismic records. One of the methods that may provide constraint on the concentration of gas hydrate and free-gas from suitable multichannel seismic (MCS) data is the study of BSR amplitude variation with offset (AVO), a method commonly used for hydrocarbon detection in the oil and gas industry. Most gas hydrate AVO studies have used forward modelling to match theoretical AVO curves with measured AVO data. However, this approach does not address the range of solutions that can satisfy the AVO problem to within data uncertainties. In this study, a nonlinear Bayesian inversion is applied to estimate one- and two-dimensional marginal probability distributions (MPD's) of physical parameters (P- and S-wave velocity (Vp, Vs) and density (ρ) of both media) at a gas hydrate related BSR interface. The parameter MPD's are related to gas hydrate and free-gas concentration through a rock physics model.

BSR AVO Studies

To assess the reliability of AVO analysis in marine gas hydrate studies, synthetic cases representative of available AVO data are considered. The BSR is modelled as a planar interface between two half-spaces, with model parameters Vp, Vs, and ρ for both media. True parameter values are chosen based on a rock physics model for unconsolidated sediments with partial gas hydrate saturation in the upper media, and partial free-gas saturation in the lower media. Using Zoeppritz' equations, synthetic reflection coefficient vs. incidence angle data are generated for a case with 15% gas hydrate pore space saturation above the BSR, and 1% free-gas saturation below.

The nonlinear Bayesian inversion is applied to the synthetic AVO data to obtain MPD's of physical parameters. The inversion is tested several times, using a wide range of additional constraints. The most highly constrained parameter distributions are obtained when the following prior information is used:

- The density of both media is constrained by well log data,
- The Vp – Vs relationship in the upper media is constrained by the rock physics model, and
- Vp of both media is constrained by NMO velocity analysis of MCS data.

Parameter MPD's for this case are shown in Figure 1. Inversion results are further constrained when physical parameters are reorganized into the parameters of the Aki-Richards approximation of Zoeppritz' equations: P-reflectivity ($\Delta Vp/Vp$), S-reflectivity ($\Delta Vs/Vs$), fractional change in density ($\Delta\rho/\rho$), and squared S- to P-wave velocity ratio (Vs2/Vp2), where Δ represents the difference between the lower and upper media, and Vp, Vs, or ρ with no subscript indicates the average value of both media. This choice of parameterization is favorable, because it highlights relationships between parameters that are typically well resolved by reflection seismic data.

In the Aki-Richards formulation, the most highly constrained parameters are P- and S-reflectivity. A joint MPD of these parameters is shown in Figure 2 as a contour plot, and is overlain by a grid of gas hydrate and free-gas concentration scenarios. This quantitatively shows the range of scenarios that satisfy the synthetic AVO data, and gives an idea of the results to be expected for the inversion of MCS data.

The MCS data used in this study was acquired from a well-studied area offshore Vancouver Island. The survey provided BSR amplitude data as a function or source-receiver offset. For quantitative AVO analysis, BSR reflection coefficients as a function of BSR incidence angles are required, and a true amplitude data processing scheme was implemented. The AVO data used in the inversion is shown in Figure 3.

The inversion is applied to the MCS AVO data, using the same optimal set of prior constraints used to invert synthetic data, and the resulting physical parameter MPD's are again used to obtain a joint MPD of S- vs. P-reflectivity. This distribution is shown in Figure 4, overlain by a grid of gas hydrate and free-gas concentration scenarios. Results indicate, at a 90% credibility interval, that the observed AVO data could have been produced by scenarios ranging from 0% gas hydrate saturation above the BSR and 3% free-gas below, to 25% gas hydrate above and 0% free-gas below. Better S-reflectivity resolution is required in order to distinguish between these possibilities.

Ostrander Gas Sand AVO Studies

Our study is directed primarily at AVO for gas hydrate related BSR's, but may have important applicability in testing the degree of constraint in other AVO studies. The inversion is also applied to synthetic AVO data generated from Ostrander's gas sand model, for the top-of-sand reflection (Figure 5), using prior constraints on ρ of both media (from well log data), and on the Vp – Vs relationship in the overlying shale (from the mudrock relation). Joint MPD's of selected parameters are shown in Figure 6. The results provide good constraints on the relationship between Vs and Vp in the sand unit: plotted with a Vp – Vs mudrock line, the MPD shows the sand to be gas charged, as the distribution lies above the mudrock line (Figure 6d). For quantitative estimates of porosity, a suitable rock physics model is required.

Gas Hydrates vs. Gas Sands

The variable degree of model constraint obtained for the gas hydrate BSR and Ostrander gas sand cases show that the success of AVO is highly dependent on the nature of the AVO problem at hand. In the gas hydrate AVO study, the limited amount of constraint obtained for model parameters is attributed to the low P- and S-wave velocities expected in unconsolidated sediments, and to the small contrast in physical parameters across the BSR, related to a change in pore space content (gas hydrate vs. free-gas) rather than a change in lithology. In the gas sand AVO study, sediments are consolidated, and therefore have higher and more easily resolved P- and S-wave velocities. Furthermore, the AVO reflection studied corresponds to a change in lithology (shale vs. sandstone), so greater physical parameter contrasts are expected at the interface. Nonetheless, the variable degree of model constraint obtained from AVO inversion in this study highlights the need to include quantitative uncertainties in all AVO studies.

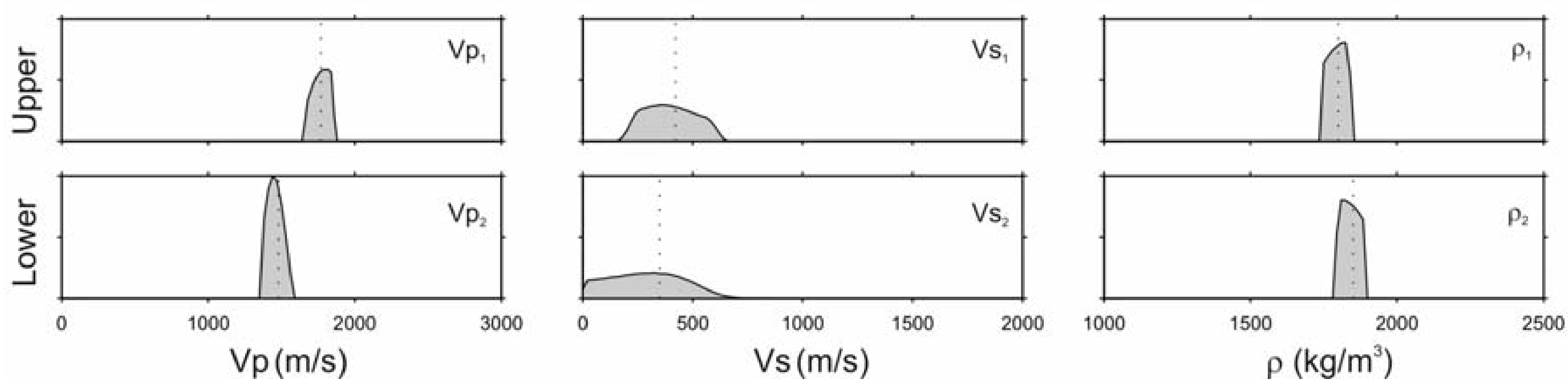

Figure 1. MPD's of model physical parameters obtained from the inversion of synthetic BSR AVO data. Dotted lines indicate the true model value.

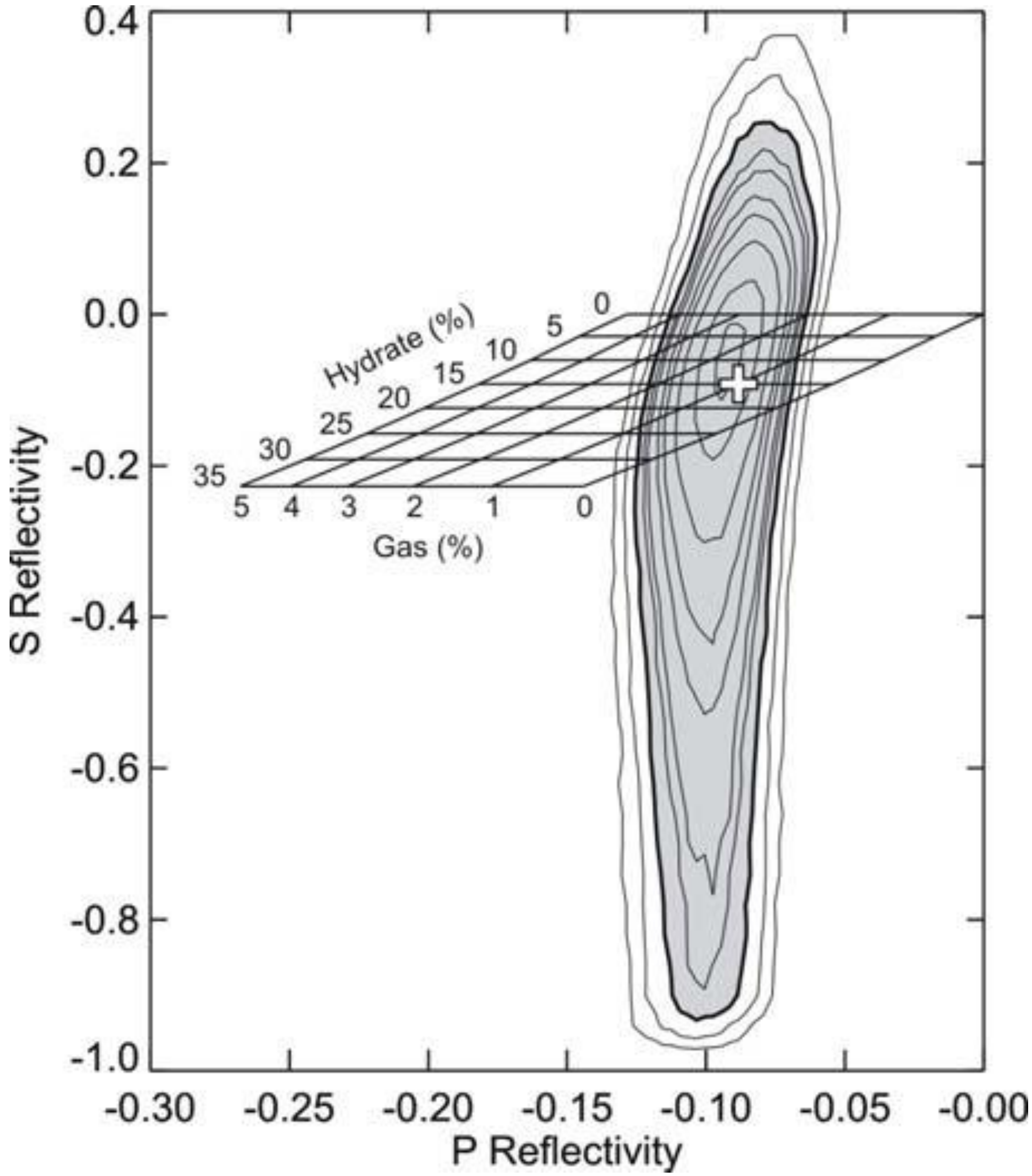

Figure 2. Contour plot of the joint MPD of S- vs. P-reflectivity for synthetic BSR AVO data. The 90% credibility interval is drawn in bold. The MPD is overlain with a grid showing where models with varying gas hydrate and free-gas concentration lie in S- vs. P-reflectivity space, while true model parameter values are indicated by the cross.

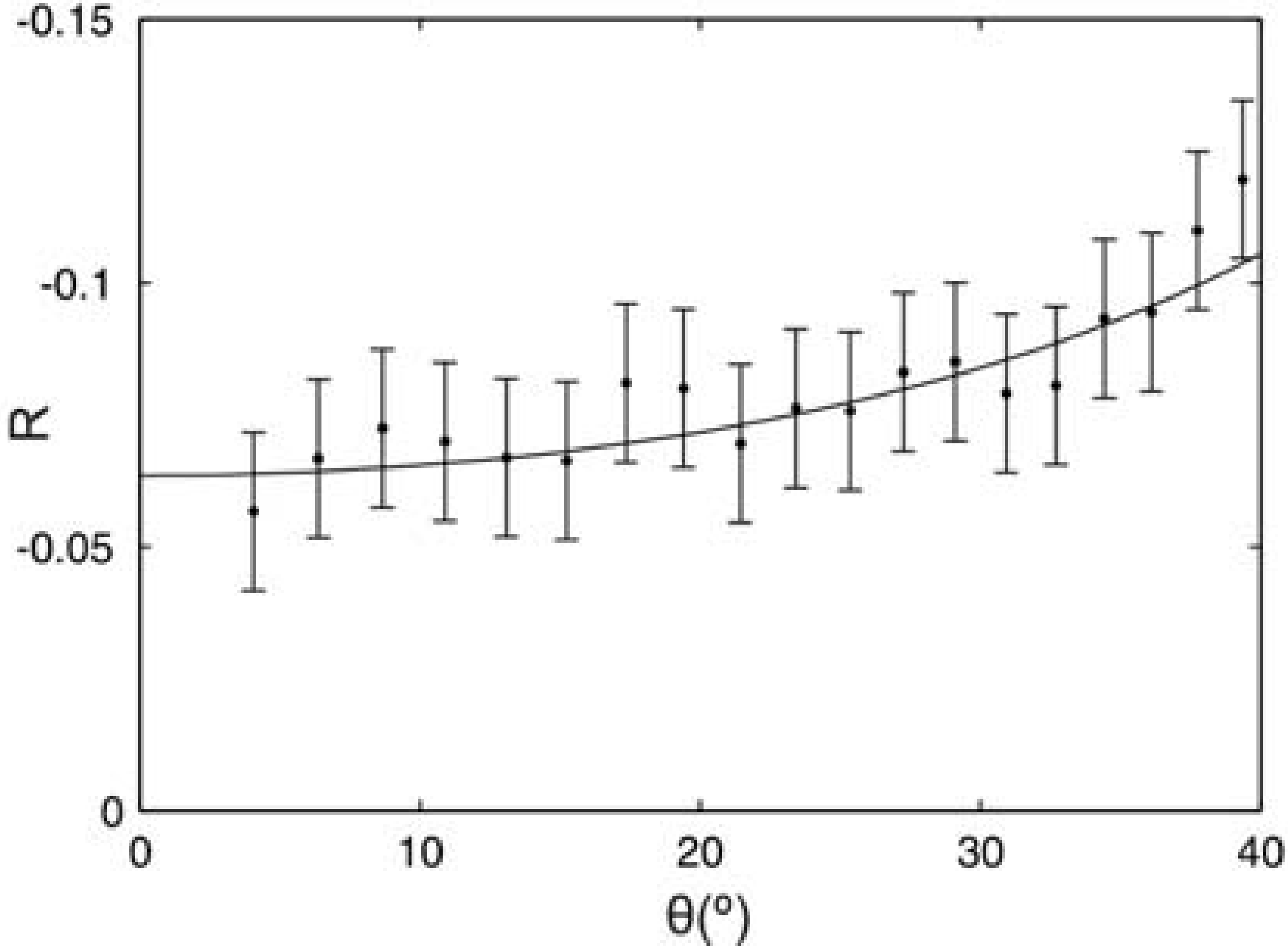

Figure 3. BSR Reflection coefficient R vs. incidence angle θ, obtained from a MCS survey offshore Vancouver Island, Canada. Two-standard-deviation error bars are shown, and the solid line indicates the predicted data for the best parameter estimates.

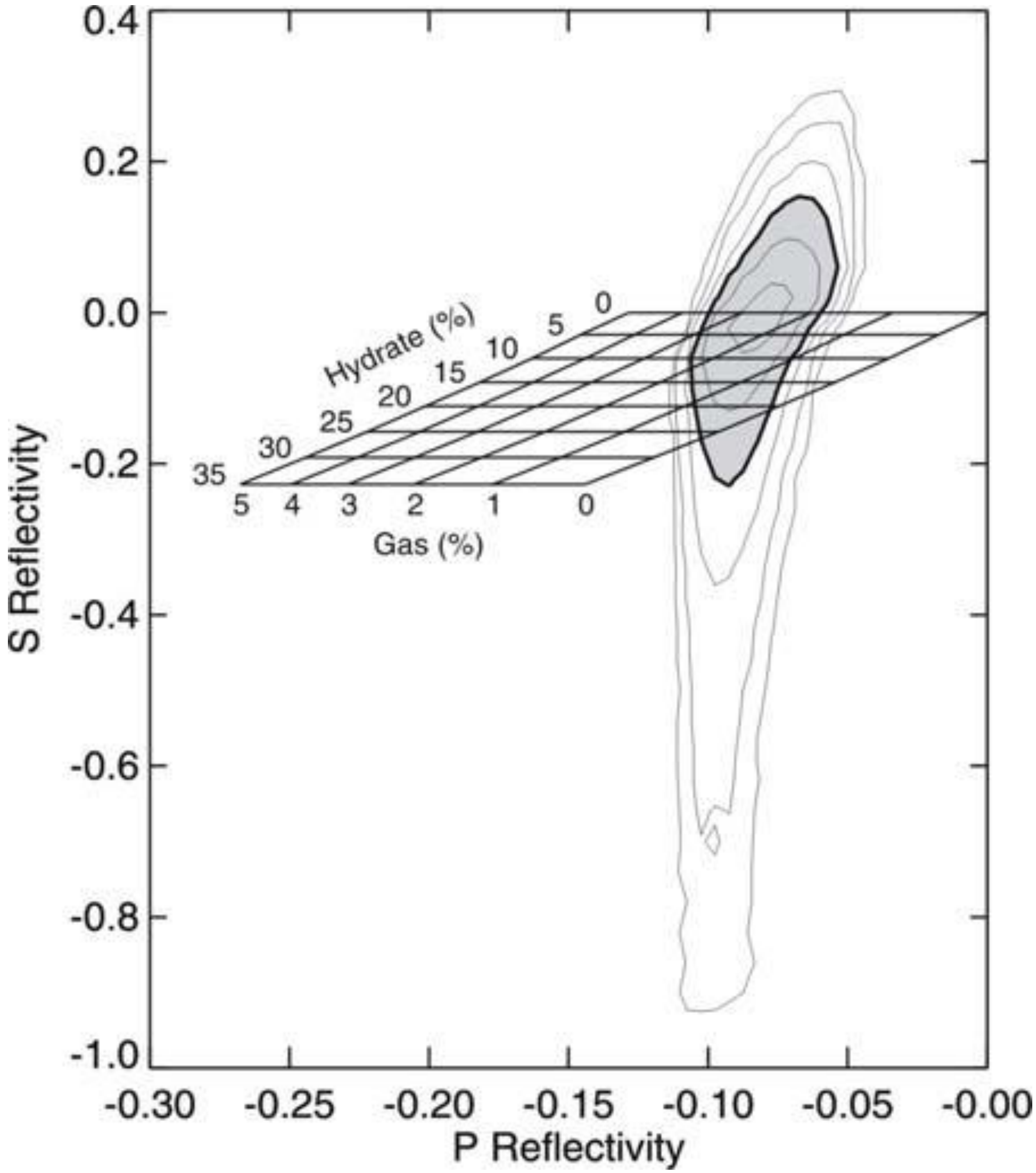

Figure 4. Contour plot of the joint MPD of S- vs. P-reflectivity for MCS-derived BSR AVO data. The 90% credibility interval is drawn in bold. The MPD is overlain with a grid showing where models with varying gas hydrate and free-gas concentration lie in S- vs. P-reflectivity space.

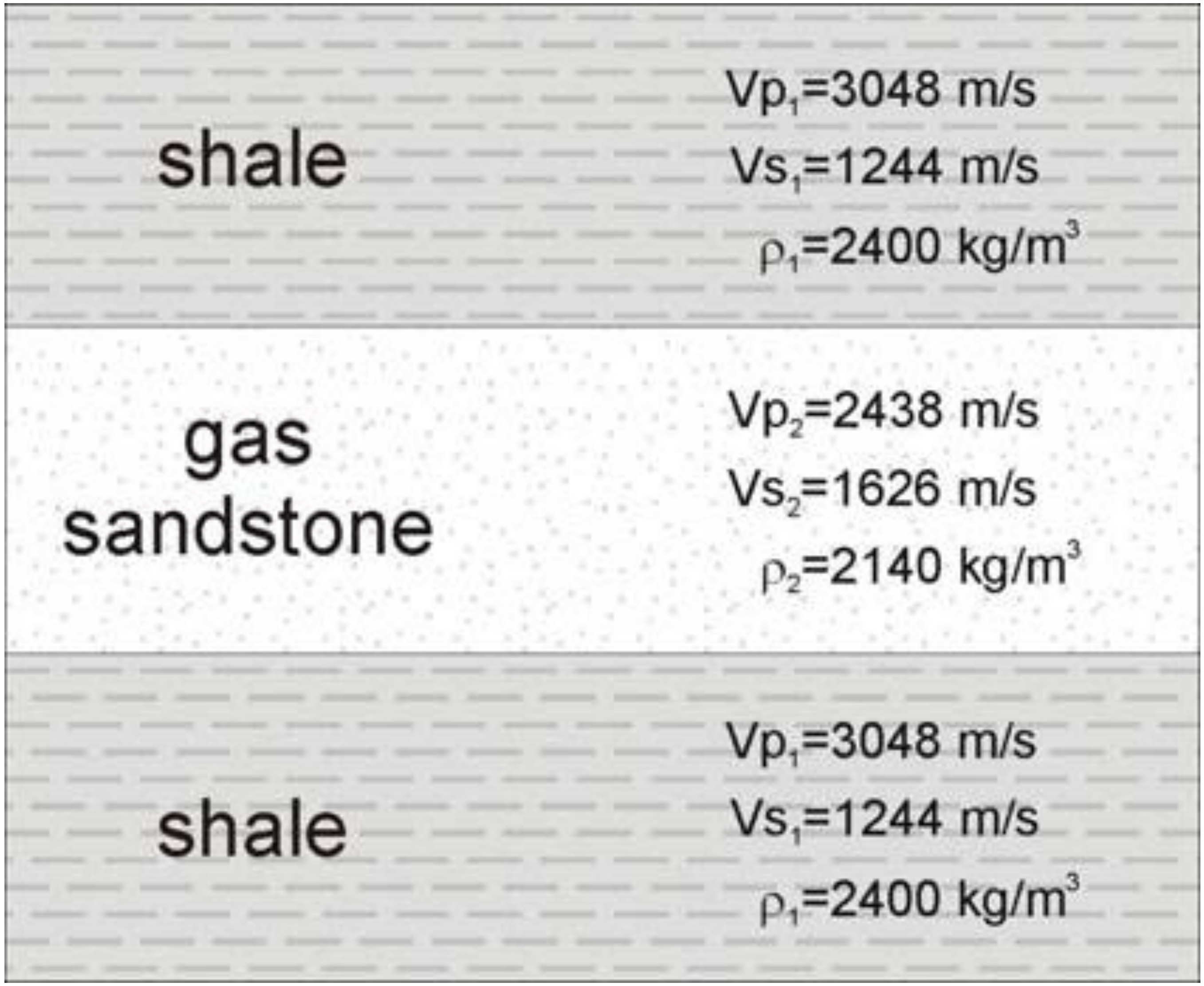

Figure 5. Schematic representation of the Ostrander gas sand model, consisting of a low-velocity sandstone, encased in high-velocity shales. In this study, the AVO reflection off the top of the sand is modelled.

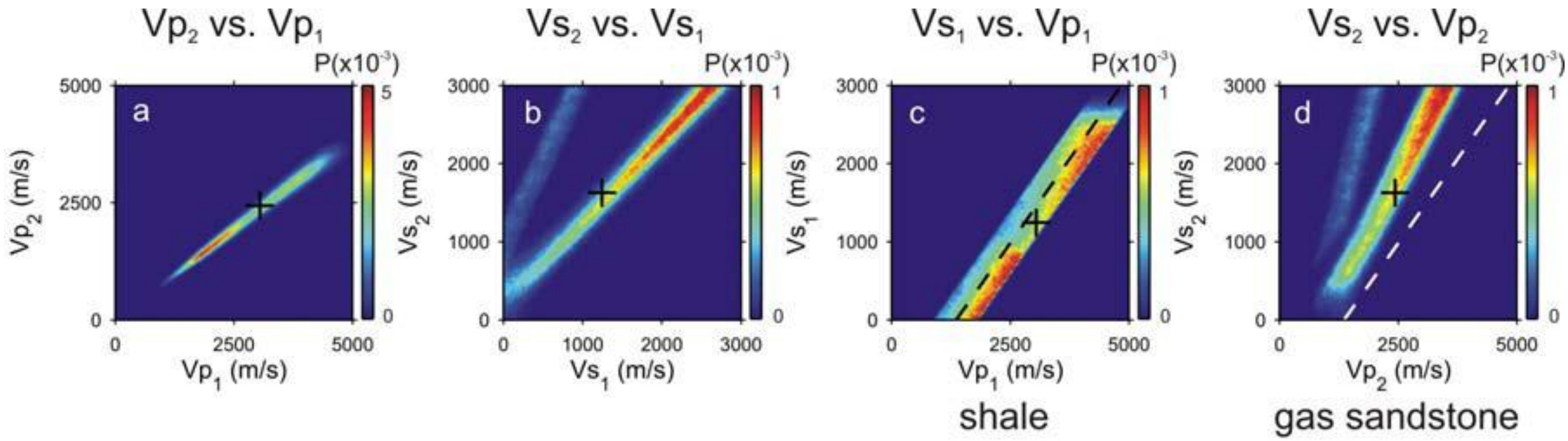

Figure 6. Joint MPD's of selected model parameters of the Ostrander gas sand synthetic case. Subscripts 1 and 2 on Vp and Vs indicate the upper and lower media (shale and gas sandstone, respectively). In (c) and (d), the dashed line is the mudrock line for water saturated clastic rocks. The crosses indicate true parameter values.