

# Seismic Imaging of Gas Hydrate Distribution - A Case Study\*

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## Abstract

Natural gas hydrates, a type of inclusion compound or clathrate, are composed of gas molecules trapped within a cage of water molecules. The pressure and temperature conditions for gas hydrate stability zone are found in permafrost areas and deep water basins around the world (Kvenvolden, 1993). The presence of gas hydrates in permafrost regions has been confirmed by core samples recovered from the Mallik gas hydrate research wells located within the Mackenzie Delta in Northwest Territories of Canada (Dallimore et al., 1999 and Dallimore et al., 2005). Strong vertical variations of sonic logs and seismic expressions of gas hydrates indicate that lithological heterogeneities control the lateral distribution of gas hydrates. Seismic scattering studies predict that typical horizontal scales and strong velocity contrasts due to gas hydrate concentration will generate strong forward scattering, leaving only weak energy to be captured by surface receivers. Vertical Seismic Profile (VSP) techniques can be used to calibrate seismic imaging of gas hydrate distribution through surface seismograms.

## Seismic Scattering due to Gas Hydrate

The effects of heterogeneities on seismic waves can be classified in terms of the primary wave number  $k$  and heterogeneity scale  $a$  (Wu, 1989). If  $ka \gg 1$ , i.e., scatters' scale is much larger than the wave length, small-angle scattering or foreshattering is much stronger than backward scattering, leaving weak information about heterogeneities captured by surface receivers. Sonic logs from gas hydrate research well Mallik 2L-38 present strong vertical velocity variation ([Figure 1](#)), ( $\Delta v_p > 30\%$ ) (Milkereit et al., 2005). A high resolution 3-D seismic survey estimates the correlation length of gas hydrate is around 50 m (Schmitt et al., 2005). High gas hydrate concentration will enhance forward scattering.

## Methodology and Case Studies

In order to solve the scattered wave field, parallel 3-D viscoelastic Finite Difference modeling (Bohlen, 2002), a most accurate and expensive method so far, is selected to simulate wave propagation in the presence of gas hydrate zones with different lateral lengths. Parallelization based on clusters significantly reduces the calculation time of 2-D and 3-D modeling. A rheological model called Generalized Standard Linear Solid (GSLs) containing springs and dashpots is used to model the viscoelastic behavior of wave propagation ([Figure 2](#)). P- and S-wave energy can

be separated to study P-wave velocity contrasts and S-wave velocity contrasts as well as P-to-S or S-to-P conversion caused by gas hydrates. Seismic wave propagation and scattering procedure can be visualized through snapshots from this program.

Since 1998, the JAPEX/JNOC/GSC Mallik 2L, 3L, 4L, and 5L-38 gas hydrate research wells have been drilled to about 1150 m depth at the northeastern edge of the Mackenzie Delta, Northwest Territories of Canada. Mallik 5L-38 well logs indicate three gas hydrate bearing zones: 896 m – 928 m, 950 m – 1030 m, and 1074 m – 1112 m (Dallimore et al., 2005). In order to amplify heterogeneity influence, certain correlation lengths are assigned to the second gas hydrate layer and 2-D elastic models are constructed ([Figure 3a](#)). Receivers to capture transmitted energy are located horizontally at depth of 1400 m and above the added reference reflector at depth of 1600 m.

The gas hydrate bearing sediments are treated as patches (Bellefleur et al., 2006). High velocity patches represent high gas hydrate concentration zones (80% of pore space), while low velocity zones play the role of low gas hydrate concentration zones (40% of pore space). They are connected by short transition zones (e.g., 50 m) with constant thickness. The relationship between hydrates concentration and velocities can be found by using rock physics, e.g., weighted equations or effective medium theory (Lee, 2002).

The presence of forward scattering is observed in the snapshots of seismic wave propagation ([Figure 3b](#)). The backward scattering is weaker than the reflection occurring on other layers. For the convenience of visualization, three types of seismograms (reflection, VSP, and transmission) are merged in [Figure 4](#) to easily trace the down-going and up-going waves. Seismic expression from heterogeneous zones can be identified in the reflection seismogram by knowing the arrival time from zero offset VSP. Horizontal discontinuities on the surface seismic profile are observed but are disturbed by scattered lateral propagating waves at large offsets. Lateral variations of transmitted P-wave amplitude are due to discontinuous gas hydrates.

### **Conclusion and Outlook**

Due to pronounced forward scattering, information about heterogeneity scales extracted from surface waves is weak and signals at large offsets are contaminated. Transmitted P-wave energy is favored for extracting information about heterogeneity scales. As horizontal receiver arrays at depths are difficult to implement, multi-offset VSPs operated in vertical boreholes provide a suitable acquisition geometry for capturing forward scattered waves ([Figure 5](#)). However, different source locations and large offsets are required to cover large targets. More effective acquisition geometries are required to capture foreshattered energy propagating through large target areas. For example, offset VSP operated in lateral wells is predicted to be a cost effective acquisition geometry. Data from optimum acquisition geometries can be used to image the lateral distribution of targets in 3D and provide accurate locations for further drilling activities.

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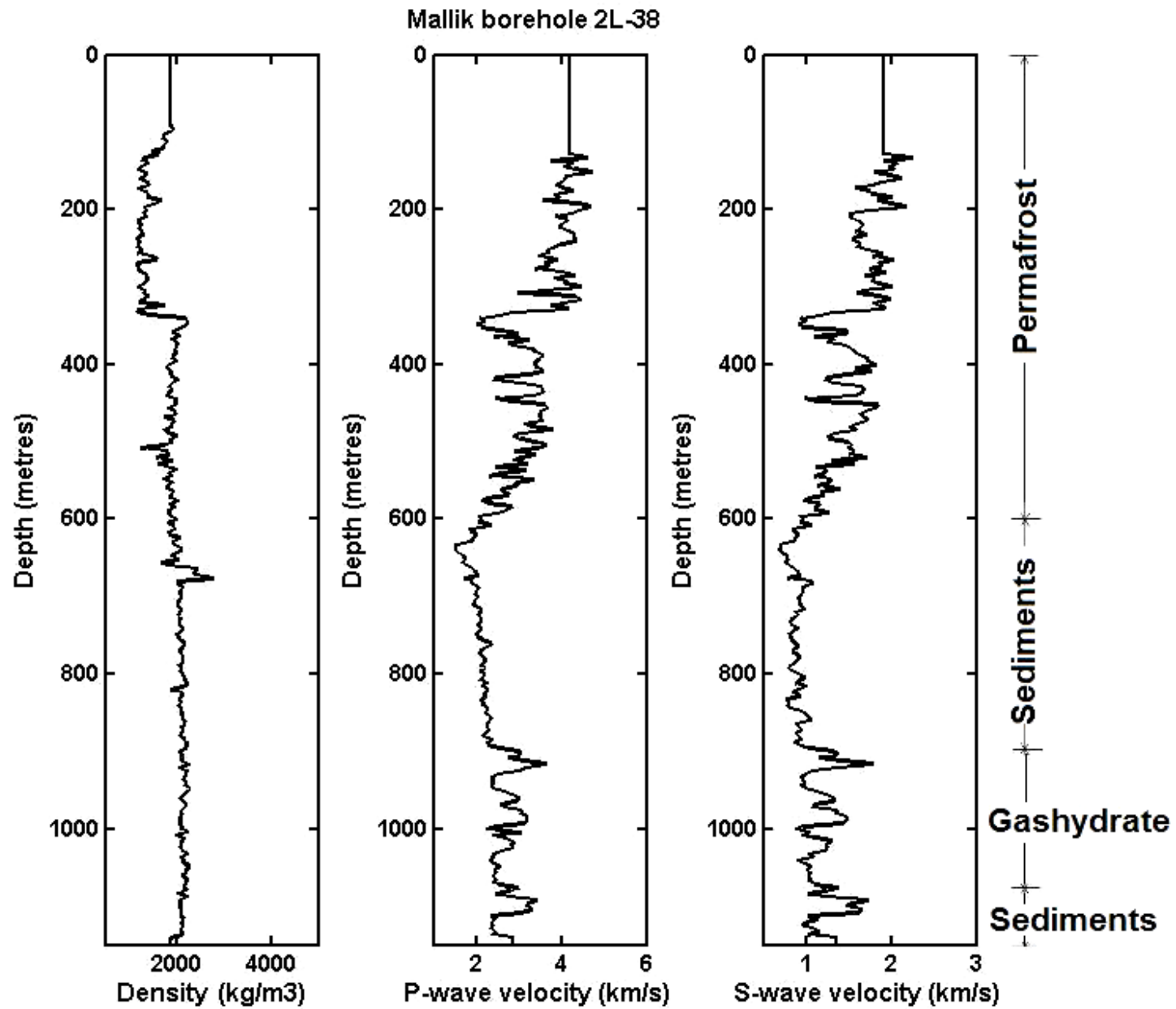


Figure 1. Processed logs from the JAPEx/JNOC/GSC Mallik 2L-38 well are the basis of models constructed in this work. Stratigraphic sequences are marked on the right. Velocity contrasts are over 30% (from Milkereit et al., 2005).

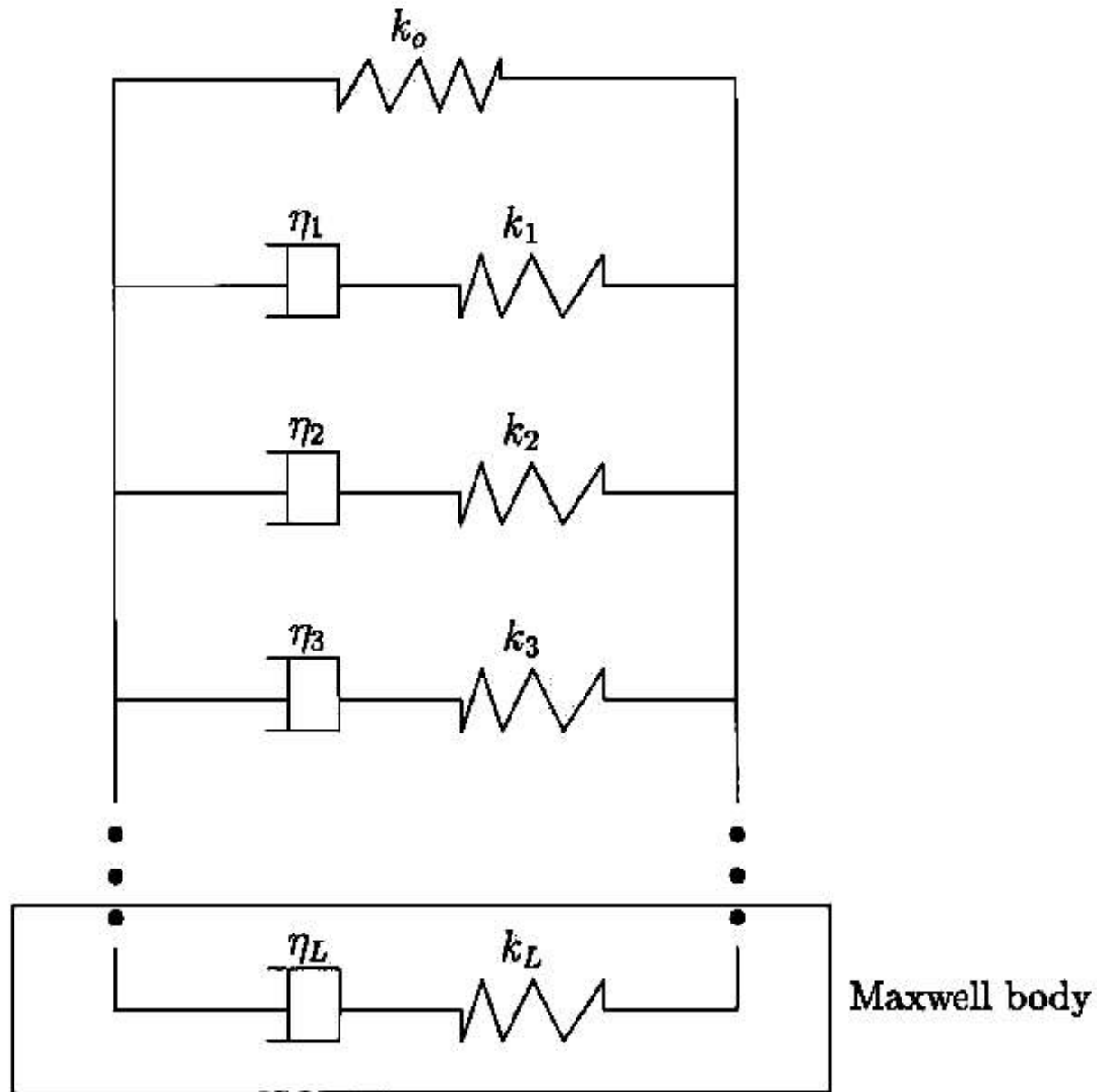


Figure 2. Schematic diagram of a generalized standard linear solid (GSL) composed of  $L$  so-called relaxation mechanisms or Maxwell bodies.  $k_i$  and  $\eta_i$  are the moduli of the  $i^{\text{th}}$  spring and Newtonian viscosity of the  $i^{\text{th}}$  dashpot (from Bohlen, 2002).

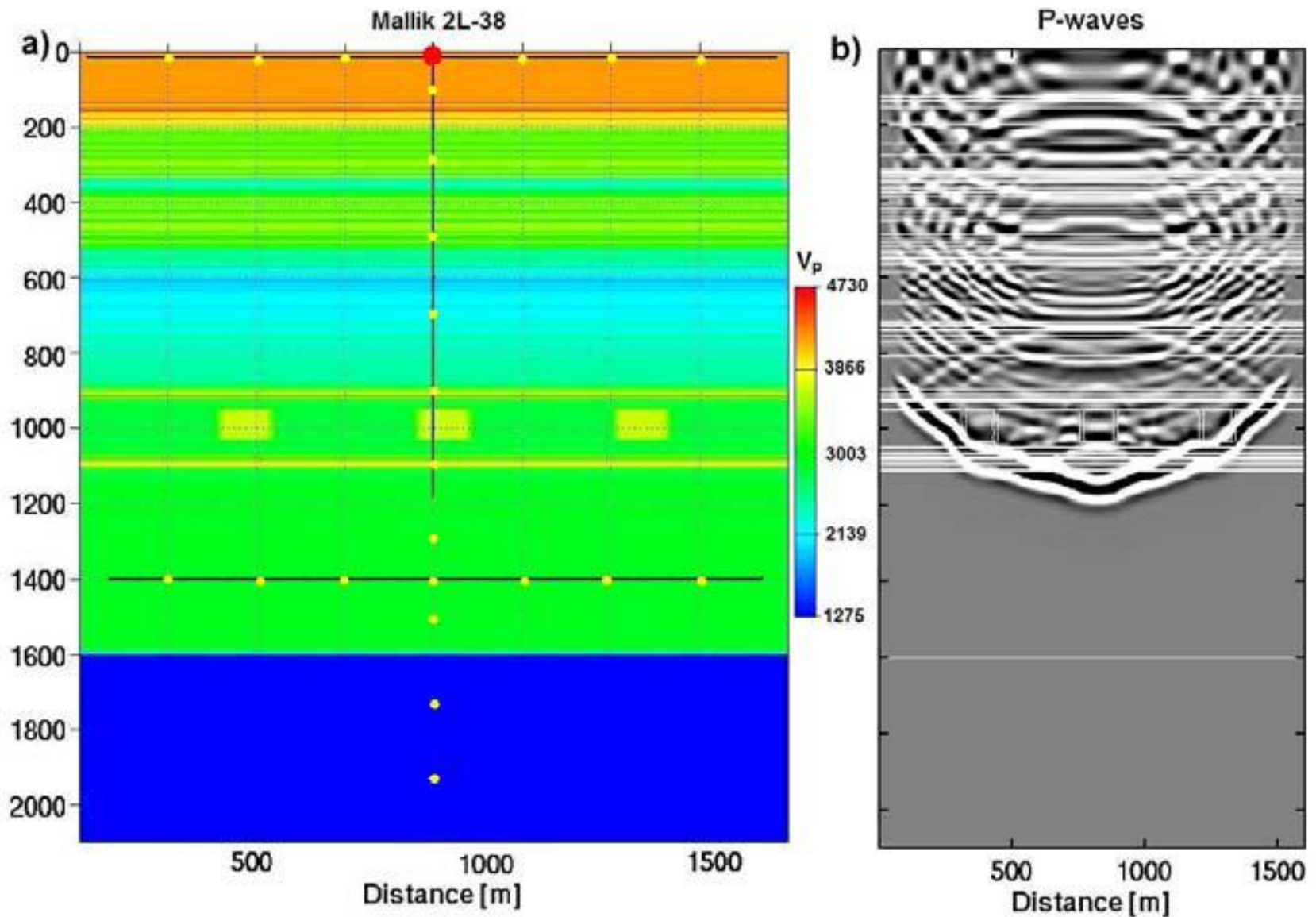


Figure 3. (a) Conceptual layered P-wave velocity model of 2D, 1500 m wide and 2100 m deep, has one patchy gas hydrate distribution between 950 m and 1030 m. Deep reference reflector is at 1600 m. Acquisition geometries are represented by dots and lines. Red dot denotes the source location, yellow solid dots represent the receivers. (b) One snapshot with surface source. Up-going waves carrying heterogeneity information are weaker than reflections from the above layers.

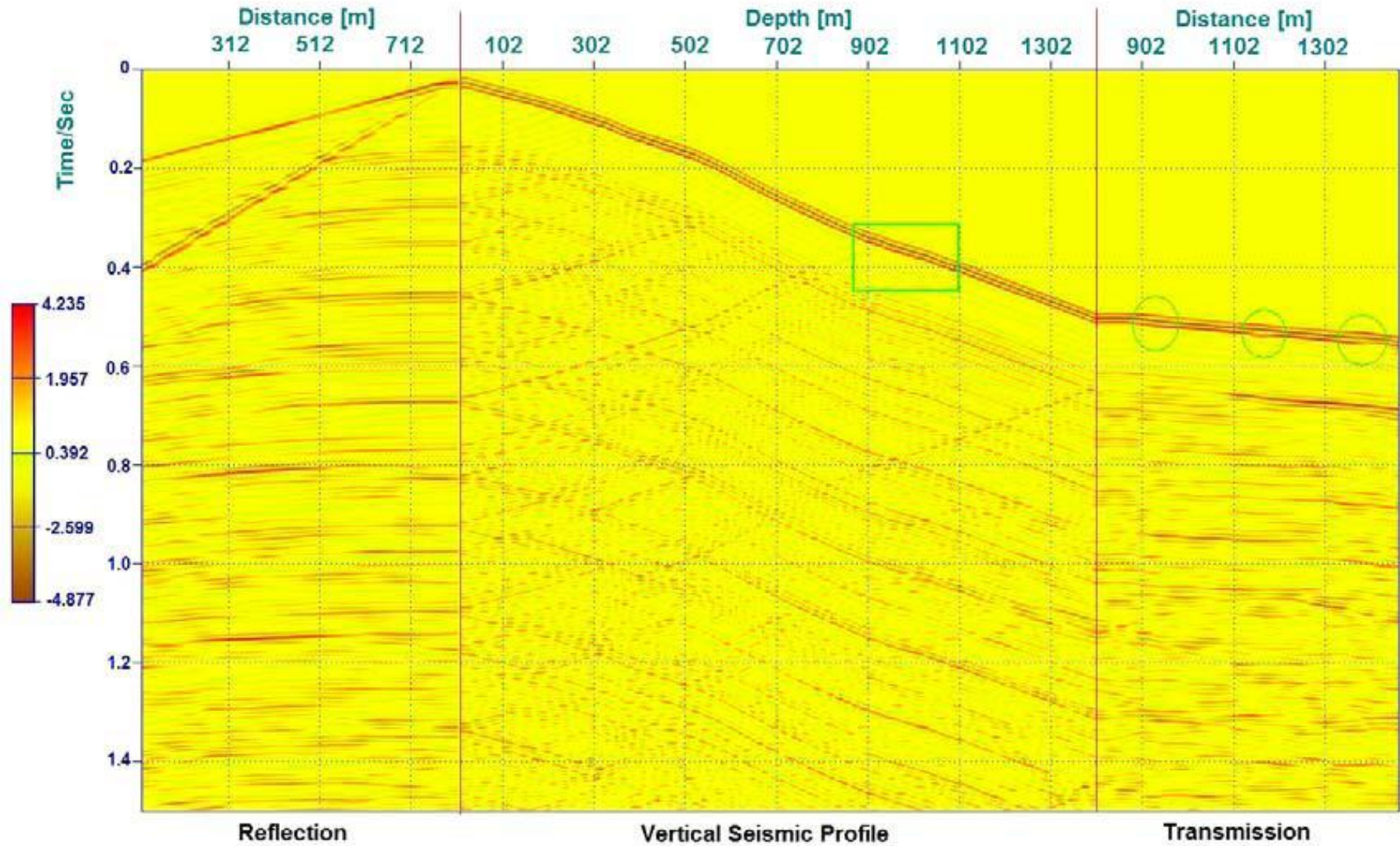


Figure 4. Merged reflection seismogram with Vertical Seismic Profile and transmission seismogram, P-wave component only. The box marks the gas hydrate depth and the circles show the lateral variations of amplitude due to heterogeneity. The arrival times of up-going waves from gas hydrate layers can be observed between 0.65 s and 0.80 s. Automatic gain control was applied.

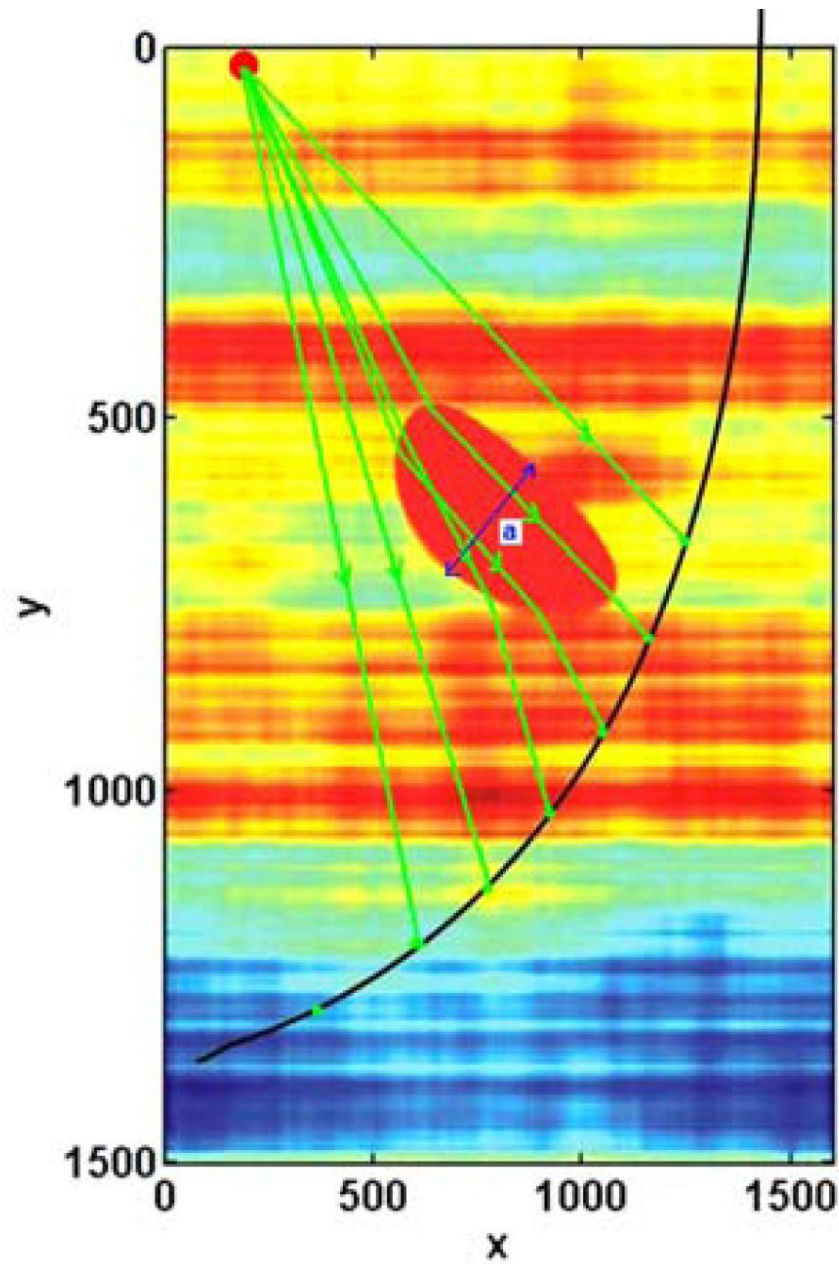
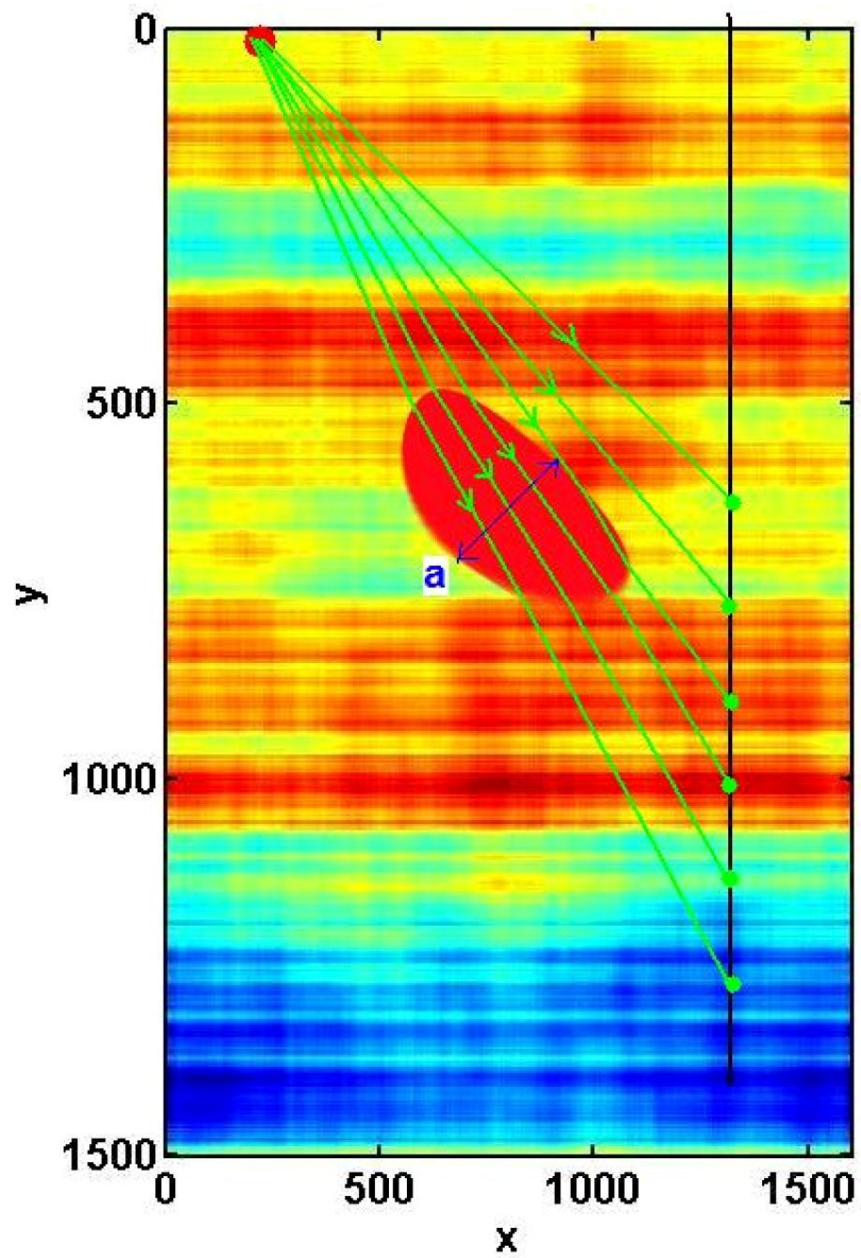


Figure 5. Large offset VSP acquisition geometry and VSP operated in lateral wells capture the down-going waves which maintain strong information of lateral heterogeneities of target, e.g., gas hydrate.