

Resonance Scattering - A New VSP Technique to Assess Lateral Continuity

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ABSTRACT

In layered and heterogeneous media, the angular and frequency dependent seismic response is affected by the statistical distributions of physical properties. Investigations of the statistical nature of velocity and density perturbations may provide insights into mechanisms governing wave propagation as there may exist a strong correlation between the spatial properties of the velocity field of a reflective target and the lateral correlation length of the resulting seismic wave field. Reservoir zones are often characterized by strong perturbations in elastic parameters, in particular compressional wave velocities. Lateral variations of compressional and shear wave velocities are best determined in the forward scattering (transmission) direction provided by 3-component VSP data acquisition geometry. Analysis of the transmitted seismic wavefield helps to assess how well log data relate to the surrounding reservoir zone.

Methodology

The need to develop efficient and robust seismic techniques for the assessment of lateral continuity (scale parameters) in boreholes has long been recognized. Figure 1 illustrates the problem of lateral continuity in the immediate vicinity of an exploration well (Halderson and Golf-Racht, 1992). The different subsurface models match core sampling and borehole logs (vertical scale) but differ significantly as far as lateral continuity of lithological units are concerned (horizontal scale length). The effects of heterogeneities on seismic wave propagation can be described in terms of different propagation regimes (Wu, 1989): quasi-homogeneous for heterogeneities too small to be seen by seismic waves, Rayleigh scattering, Mie scattering and small-angle scattering. These scattering regimes cause characteristic amplitude, phase and travel time fluctuation, which can be used to obtain estimates of scale length and thereby assess lateral continuity of lithological units and structure in the immediate vicinity of boreholes.

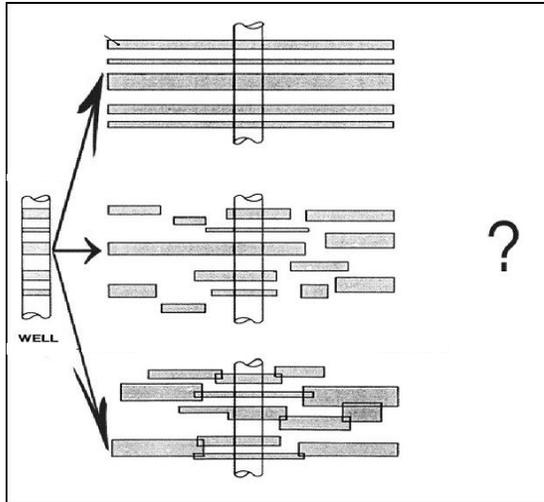


Fig. 1: How to assess lateral continuity in the vicinity of an exploration borehole. Modified after Halderson and Golf-Racht, 1992.

The Link Between Petrophysical Scale Parameters And 3d Seismic Wave Propagation

In layered and heterogeneous media, the angular and frequency dependent seismic response point towards unique statistical distributions of physical properties. Investigations of the statistical nature of velocity and density perturbations provided useful insights into mechanisms governing wave propagation as there exist a strong correlation between the spatial properties of the velocity field of a reflective target and the lateral correlation length of the resulting seismic wave field. Here we present results from an integrated seismic modeling and borehole seismic acquisition project.

Multi-offset vertical seismic profiling (VSP) techniques can be employed to image a target zone in a complex geological setting. The integration of borehole geophysical logs, offset VSPs, and 3D elastic modeling studies provide new insights in the scale dependent petrophysical parameters and the internal structure of the target zone. Scale-dependent elastic parameters are best determined in forward scattering (transmission) direction such as offset VSP and walkaway VSP experiments. Results from the 3-D modeling study were used for refine survey design and processing strategies of the VSP experiments. In our 3D modeling study, the target is characterized by strong variations in elastic parameters. Within the model, the Poisson's ratio varies from 0.15 to 0.48. Direct solutions of the elastic wave equation by finite differences (FD) must be obtained for complex fine-scale 3D subsurface models to better assess systematic variations of angular (amplitude-versus-offset) and other frequency dependent seismic attributes (Bohlen and Milkereit, 2001). Figure 2 shows petrophysical models for a heterogeneous reservoir model. The vertical scale length for all models is 50 m and the models can be tied to an

existing borehole log; the horizontal scale of the reservoir model has a correlation length of 2000m (Fig. 2A), 500m (Fig. 2B) and 50m (Fig. 2C).

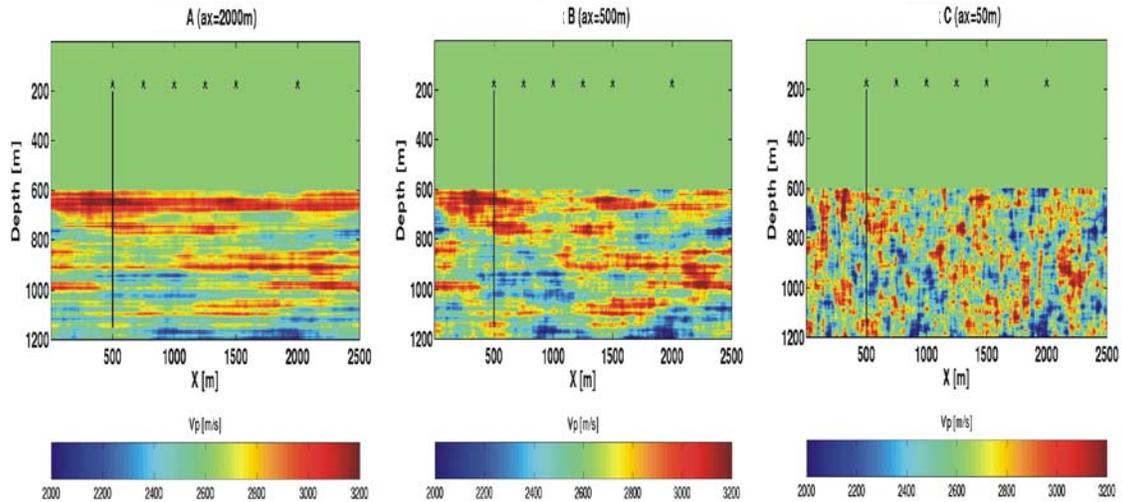


Fig. 2: Petrophysical reservoir models for different lateral correlation length. Note the 1:2 vertical exaggeration. Vertical line indicates location of borehole for offset VSP modeling.

Modeling Results

A full suite of multi-component, multi-offset VSP data are computed to analyze travel time fluctuation, amplitude fluctuations and frequency-wavenumber spectra of the transmitted and reflected wavefields. Fig.3 shows the vertical component, zero-offset data for the three synthetic reservoir models. Systematic travel time and amplitude fluctuations are observed (most pronounced for large offset recordings). Travel time fluctuations of large offset recordings reveal bulk anisotropy in the target zone if a large lateral correlation length is assumed. Amplitude fluctuations at large offsets correlate well with the vertical scale length of the media. Amplitude fluctuations are best explained by transmission losses (caused by layering) and converted S-waves (both in reflection and transmission). In practice, amplitude and travel time fluctuations must be obtained from raw VSP data before any amplitude scaling, deconvolution or alignment of direct (down going) energy.

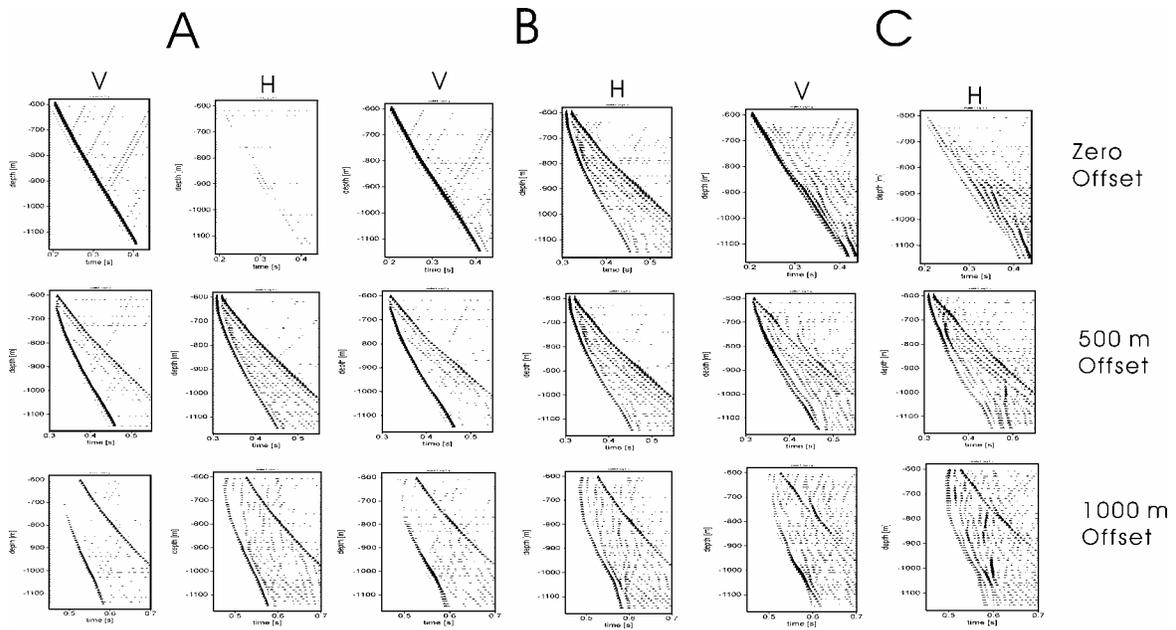


Fig. 3: VSP recording for petrophysical models (A, B, C) shown in Fig. 2.

Resonance Scattering

Information about short wavelength horizontal scale parameters are contained in the transmitted (forward scattered) elastic wavefield. Most promising results are obtained from full waveform resonance spectra. Fig. 4 shows the resonance spectra for the three synthetic reservoir models. The spectra are computed for seismic frequencies from 20 to 120 Hz. As expected, seismic waveform data for models with large horizontal scale length show no evidence of resonance scattering (Fig. 4A, 4B). For short wavelength horizontal scales lengths, prominent resonance peaks are observed in the resonance spectra (Fig. 4C).

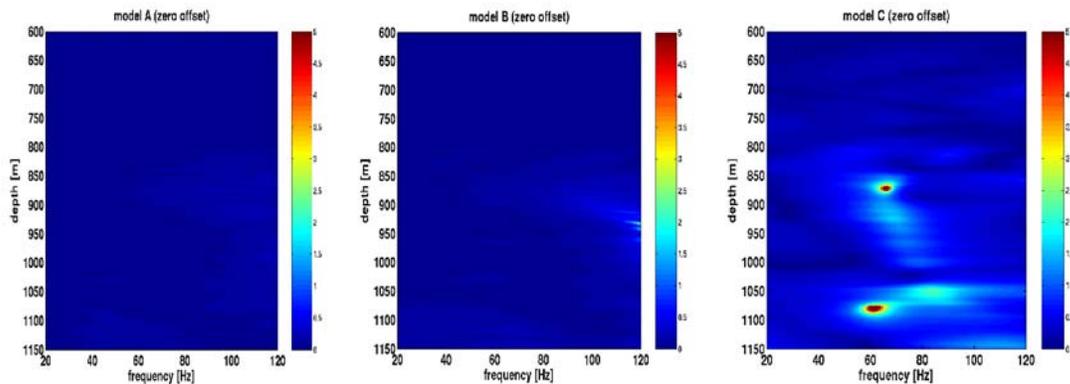


Fig. 4: Resonance spectra amplitude for reservoir models with different lateral scale length. Seismic frequencies range from 20 – 120 Hz corresponding to wavelength 120 – 20 m.

Horizontal resolution of exploration seismic data is often discussed in terms of Fresnel zone. For surface and VSP data, the Fresnel radius increases with increasing depth of investigation. The lateral resolution scale obtained from resonance scattering, however, is limited only by the effective frequency content of the seismic signal. Figure 5 shows the lateral resolution for resonance scattering (obtained from forward scattered wavefield data) and radius of Fresnel zone for surface sources.

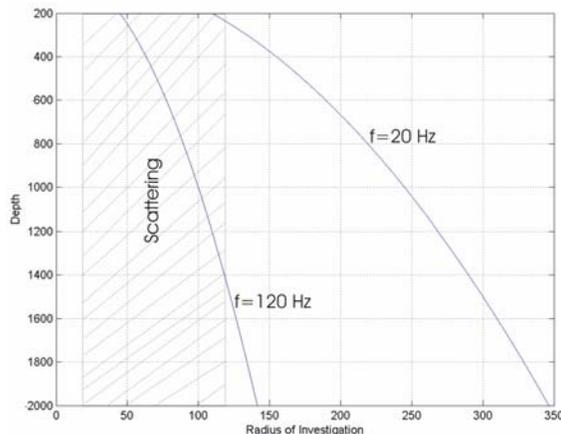


Fig. 5: Lateral resolution as defined by Fresnel radius for surface source and resonance scattering as observed by receivers in VSP geometry (model parameters: $V = 2400$ m/s, $f_{min} = 20$ Hz and $f_{max} = 120$ Hz).

Outlook

Broadband seismic source signals up to 120 Hz provide the basis for resonance scattering analysis of 3 component seismic profile. The resonance scattering analysis reveals the presence scale dependent petrophysical parameters in the target zone. Information about short wavelength horizontal scale parameters is contained in the resonance spectra of the forward scattered wavefield recorded in VSP geometry. The peak frequency may provide information about scale, composition and shape of the scattering structure. The analysis of so-called resonance spectra may become a new tool which helps to assess how well log data relate to the surrounding reservoir zone.

References

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