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Special Section

Broadband seismology in oil and gas exploration and production — Introduction

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The last decade has seen considerable success toward solving long-standing exploration and reservoir characterization challenges, such as subsalt reservoir imaging. These advances have been enabled through new acquisition techniques in combination with advances in methods for processing, imaging and inversion of seismic data that is rich in low frequencies. In particular, methods such as reverse-time migration rely on highly accurate velocity models. Deriving such velocity models in turn fundamentally requires the acquisition of low-frequency seismic data. In addition, as is nicely demonstrated in one of the papers in this special section, low frequencies also benefit higher resolution images and enables deeper penetration in the subsurface (ten Kroode et al., 2013). The need for extending the temporal bandwidth of seismic data has therefore become increasingly evident and is a key area for research and development both in industry and academia.

In this special section we have included papers both describing marine and land applications. We have included papers that

- demonstrate the benefit of data rich in low frequencies,
- describe new methods for imaging and inversion enabled by data richer in low frequencies,
- describe advances in methodologies for providing low-frequency data.

The techniques for providing broadband frequency data in turn follow three different directions. First, seeking to widen the data bandwidth by filling in the notches caused by ghost arrivals, several papers in the special section present techniques for deghosting conventional marine seismic data. Second, aiming to push data acquisition toward lower frequencies, other papers describe methods based on advances in acquisition technology such as multicomponent streamers, ambient noise recordings or vibroseis sweep technology. In particular, methods relying on multicomponent streamers achieve separation of up- and downgoing wavefields through the combination of complementary measurements sometimes is referred to as wavefield decomposition as opposed to deghosting (the latter relying on pressure data only). Third, papers have been included that suggest new ways of acquiring and processing data that naturally ensure data with temporal and spatial bandwidth fit for imaging and inversion.

Many of the new developments of acquisition systems and practices as well as the techniques for imaging and inversion are quite new and some are still in development. We therefore expect the acquisition, processing and imaging of broadband seismic data to remain in the focus of the exploration seismic industry for many years to come.

ten Kroode et al. demonstrate the importance of low frequencies in seismic reflection data for enhanced resolution, better penetration and waveform and impedance inversion. Various theoretical arguments are reviewed underlining why adding low frequencies may be beneficial and provide experimental evidence for the improvements by a number of case studies with recently acquired broadband data.

Amundsen and Zhou propose a solution to seismic deghosting that deghosts the low-frequency components of the seismic pressure data, up to a frequency that is typically half of the second notch frequency. The deghosted pressure is computed trace-by-trace as the sum of the pressure and its scaled temporally integrated and temporally differentiated fields.

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Ferber et al. present a novel technique estimating the vertical component of particle motion from marine single-component pressure data. The estimated particle motion data is then used in a conventional 2C technique for receiver ghost attenuation by combination with the original pressure-wave data.

Soubaras and Lafet describe a marine streamer acquisition method based on a variable streamer depth profile as well as a receiver deghosting algorithm called joint deconvolution allowing post and prestack receiver deghosting of such acquisitions. Synthetic and real data are used to assess the capability of this acquisition and processing method to obtain imaging with a very large bandwidth, as well as reliable elastic inversion results.

van Borselen et al. use Rayleigh's reciprocity theorem to derive the relevant equations for wavefield decomposition for multi-sensor and single sensor data, both for depth-varying and depth-independent recordings from marine seismic experiments using a single source or dual source configuration. A comparison is made between the results obtained for a 2D synthetic example designed to highlight the strengths and weaknesses of the various acquisition configurations.

Day et al. discuss the robustness of deghosting methods for dual-sensor towed streamer data to noise, to limitations of practical field acquisition geometries such as limited aperture and coarse sampling as well as to uncertainties in the parameters describing the various deghosting operators such as receiver depth, wave propagation velocity, and water density. They show that dual-sensor wavefield separation is less sensitive to these errors than deghosting methods requiring knowledge of the correct ghost operators and demonstrate methods to overcome the most significant error sources, which are imposed by the acquisition geometry.

Yarman and Ramirez present an alternative point of view for up- and downgoing wavefield decomposition by using the relationship between the integral representation of the upgoing wavefield, given by Green's theorem, and the analytic part of the pressure wavefield. This relationship is used to formulate directional decomposition with respect to any given source and receiver directions.

Mayhan and Weglein explain that the freedom of choosing a convenient reference medium (and associated Green's function) means Green's theorem offers a flexible framework for deriving a number of useful algorithms including deghosting. The authors present the theory of Green's theorem-derived deghosting and its first application on deep-water Gulf of Mexico synthetic (SEAM) and field data.

Wei and Phillips provide very useful information on extending the Vibroseis data acquisition toward low frequencies. Insightful analysis on the vibrator limitations at low frequencies is offered.

Mordret et al. demonstrate the potential of ambient noise Helmholtz tomography on a very dense seismic network. The paper opens a wide application field in exploration geophysics, such as continuous monitoring or high-resolution imaging of the subsurface.

Baird et al. discuss frequency dependent shear-wave splitting in microseismic data, comparing scattering and poroelastic squirt-flow effects. Both mechanisms show a sensitivity to mean fracture size and compliance, making them useful for fracture characterization; however, the authors find that at microseismic frequencies squirt-flow will likely be the dominant effect.

Vasconcelos presents a framework for wave-equation-based, reverse-time imaging of dual source, 4C seismic data that is based on exact integral source-receiver reciprocity. The method accounts naturally for all in- and outgoing waves at both source and receivers surfaces, implicitly handles amplitude effects related to finite-frequency directivity, and its nonlinear version retrieves images with resolution beyond the Born-Fresnel limits by making use of nonlinear, multiple scattering effects.

Vasconcelos and Rickett discuss a method for estimating depth-domain, broadband extended images gathers that simultaneously relies on multiple wavefield experiments (e.g., from different types of data) that are jointly imaged by means of a multidimensional deconvolution (MDD) scheme. The MDD imaging conditions use the so-called joint point-spread functions, which allow properly accounting for blended/simultaneous-source data implicitly without the need for data deblending or for explicit estimates of the inverse of encoding operators.

Fleury and Vasconcelos discuss an approach for imaging acoustic data with multicomponent (4C) sources and receivers using the adjoint-state method with a specific source and receiver weighting scheme that is custom-designed to use wavefield directional information contained in gradient data. This results in a finite-frequency, reverse-time method for depth imaging, capable of handling both source and receiver ghost fields, and that sets a framework for full-waveform inversion of gradient seismic data.

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