The Low-Frequency, Densely Sampled Wavefield in Exploration Seismology: Applications of Full-Waveform Inversion and Passive Seismic Interferometry

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When exploration seismologists acquire controlled source seismic data, both the source and receiver spacing are usually on the order of tens of meters. In marine seismic acquisition with ocean bottom receivers (cables or nodes), we acquire data with hundreds of receivers and thousands of sources. Though wavefield sampling is still not spatially dense with respect to the targets of interest (meter scale), if data with low temporal frequencies are recorded, the dense sampling of the low wavenumber portion of the wavefield allows a number of advanced processing techniques to be used in the estimation of the subsurface velocity model. Two of these techniques, full-waveform inversion and passive seismic interferometry, have been previously discussed in detail by Sirgue et al. (2008, 2009), Mika et al. (2012), Dellinger et al. (2009, 2010, 2013), and de Ridder and Dellinger (2011), respectively, and are summarized below.

Full-waveform inversion (FWI) is a relatively automated method for updating velocity models via iteratively matching forward modeled, synthetic seismic data with field data (e.g., Pratt, 1999; Plessix, 2006). The technique recovers seismic imaging velocities with a resolution proportional to the wavelength of the recorded seismic wavefield, and has become more viable in recent years due to advancements in both seismic modeling and inversion algorithms (Sirgue et al., 2008; Virieux and Operto, 2009). A significant increase in the amount of affordable compute power available to industry has enabled fairly routine application of FWI to large, 3-D seismic surveys, albeit for temporal frequencies to approximately 10 Hz.

As implemented within BP, FWI is fairly robust in terms of its ability to use many data types, including narrow-, multi- and wide-azimuth towed-streamer acquisitions, as well as ocean bottom cable and node acquisitions. The simultaneous inversion of multiple datasets, including different acquisition types, is both possible and beneficial, as our inversion results improve with both longer offset and wider azimuth datasets (Mika et al., 2012).

FWI has been applied in a variety of geologic settings worldwide, and has proven particularly well suited to resolving shallow, low-velocity anomalies, such as the mud volcanoes common to the Caspian Sea, or due to accumulations of shallow gas, as at the Valhall field in the North Sea, or offshore Trinidad (Mika et. al., 2012).

The Valhall field, in particular, has proven to be an exemplary "proving ground" for investigating the low-frequency, densely sampled wavefield in exploration seismology (Sirgue et al., 2009; Barkved et al., 2010). A "full field," permanent, ocean-bottom cable seismic monitoring system (the "Life of Field Seismic" system, or LoFS) has been in place since 2003. Though intended as a tool for reservoir surveillance, the LoFS array has also proven to be useful for guiding the drilling of new wells through the overburden and providing essential information about 4-D, production-induced effects outside the reservoir.

A recent pilot study has shown that passive ambient noise recorded by the LoFS array can be used to image features in the shallow subsurface, using only the low-frequency surface waves generated by the wave action of the ocean (Dellinger and Yu, 2009). Over a frequency band of approximately 0.18 – 1.75 Hz, virtual sources at every ocean-bottom receiver location can be created from the noise background using seismic interferometry. As surface waves, these Scholte and Love waves lack the depth of penetration of body waves, but at such low frequencies they can be used to image velocity anomalies within approximately the top 200 meters below mudline (BML). These same features appear in the P-wave FWI velocity models at depths of 60 to 100 meters BML (Barkved et al., 2010; de Ridder and Dellinger, 2011; Dellinger et al, 2013).

BP has used full-waveform inversion of active source, low-frequency seismic data to solve a variety of complex overburden challenges around the world. Passive seismic interferometric imaging using surface waves shows promise as a possible real-time monitoring system for shallow subsurface features. Whether surface waves are sufficiently sensitive to the kinds of 4-D subsurface changes that would be significant remains an unanswered question, but may be mitigated by the processing of multiple passive datasets in real time (Dellinger et al., 2013). By continuing to densely acquire repeat, controlled source seismic datasets, we can also compute FWI velocity models for analysis in a 4-D sense, examining the results from both active and passive seismic data for correlative features in the subsurface. In each of the above examples, the dense spatial sampling and long-offset recording geometry of the acquisition designs used have proven essential to the success of the both full-waveform inversion and passive seismic interferometry.

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