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On the development of elastic three dimensional full waveform inversion in exploration geophysics

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Full waveform inversion (FWI) is a classical inverse method that tries to estimate subsurface models of parameters that affects wave propagation. The key requirement for the method is the numerical solution of the wave equation that is used to iteratively update the subsurface model through a optimization procedure of the dissimilarities between the synthetic and measured seismic data. Due to the computational cost to use FWI in practice, the standard procedure for applications of FWI in exploration geophysics has been to assume that the subsurface is a two-dimensional acoustic medium.

One of the goals for FWI is to estimate the subsurface parameters using a three-dimensional elastic description of the medium. By incorporating more real world physics into the FWI method, the inversion results are more likely to be close to the true solution. The challenges towards this goal from a computational point of view is the extreme cost related to the numerical solution of the elastic wave equation, in addition to the required storage needs for performing one iteration of the optimization method. From a theoretical point of view, multi-parameter inversion (i.e. inversion of the density, P- and S-wave velocities) using surface seismic data is challenging because the inverse problem is ill-posed (in the Hadamard sense) and non-linear. In addition, the sensitivity in the data with respect to the elastic parameters is dependent on how the data are acquired. Hence, three-dimensional elastic FWI is challenging from both a theoretical and a computational point of view.

In the recent years we have developed a three dimensional elastic FWI method where we are able to invert for the density, P-wave and S-wave velocities. To reduce the required storage needs for computing the model gradients through the adjoint state method, we have developed an efficient wave field reconstruction method that uses values on the domain boundaries to reconstruct the wave field inside the domain. To minimize the dissimilarities between the synthetic data and the measured data, we use methods like the conjugate-gradient method or the L-BFGS method. During our development, we have studied which parameters that we are most likely to have a successful recovery of using elastic FWI using surface seismic data.

We have used the three dimensional elastic FWI method on both synthetic and field data examples. In addition, the FWI method have been used to estimate time-lapse changes directly in the elastic parameters. The synthetic examples showed that we are able to estimate changes in the elastic parameters using an approach where we focused on explaining the data-differences in the time-lapse seismic data. By combining the elastic FWI method in a conventional seismic imaging procedure, the field data example from the CO_2 injection project at Sleipner outside Norway showed that FWI is able to improve the parameter models as well as the seismic images both prior and during injection of the gas.