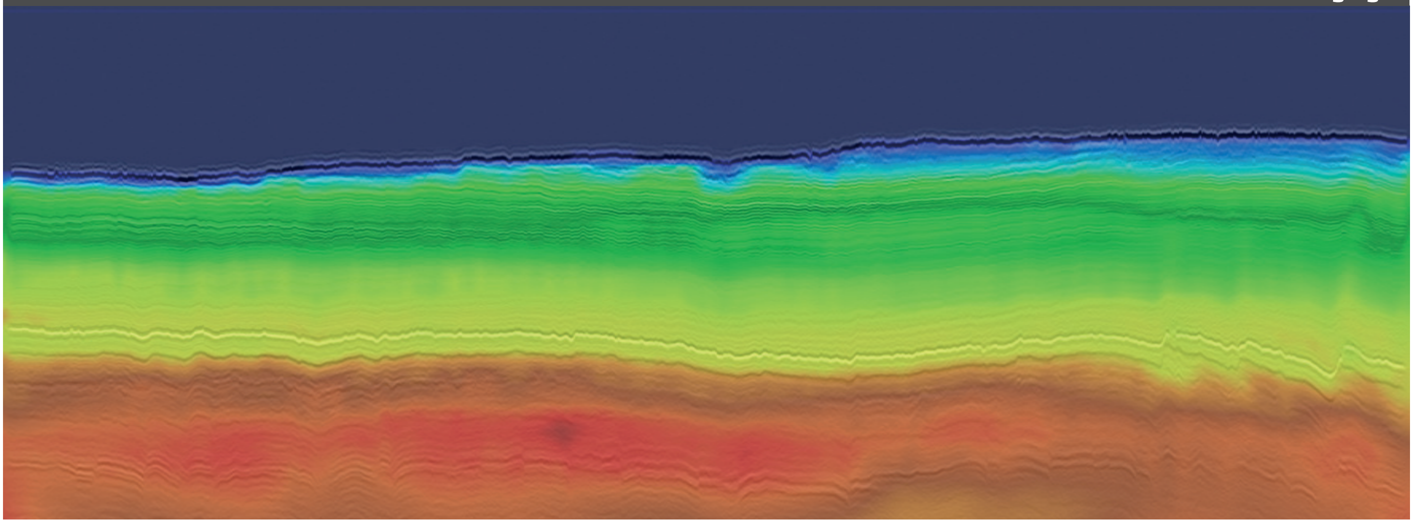


Full Waveform Inversion

Full Waveform Inversion (FWI) is a methodology that seeks to find high-resolution, high-fidelity velocity models of the subsurface capable of matching individual synthetic seismic waveforms with an original raw field dataset. This is achieved iteratively by determining and minimizing a residual; the difference between modeled and recorded data.

PGS FWI utilizes the full wavefield, so both diving waves (wavefronts continuously refracted upwards through the earth due to the presence of a vertical velocity gradient) and reflections. FWI is successful in resolving small scale features; in particular, in shallow-water environments where reflection based tomographic inversion methods are limited.

Efficient Model Building

As FWI operates directly on shot gathers, it can be deployed early in the model building process and it is an efficient velocity model building tool. FWI can be used as part of any Prestack Depth Migration (PSDM) velocity model building flow with virtually no time impact, as the input data requires minimum pre-processing and any free-surface effects can be left in the data.

The method begins from an initial starting model which is then iteratively improved using a sequence of linearized inversions, to solve the full non-linear 3D FWI problem.

FWI and the Inverse Scattering Imaging Condition

In conventional Reverse Time Migration (RTM), there is a forward and reverse time propagation of the source and receiver wavefield. In FWI, the back projection step basically constitutes a RTM run where the receiver wavefield is replaced by the residual between the modeled and recorded data. To rely less on refractions and to better utilize reflections in the

KEY BENEFITS

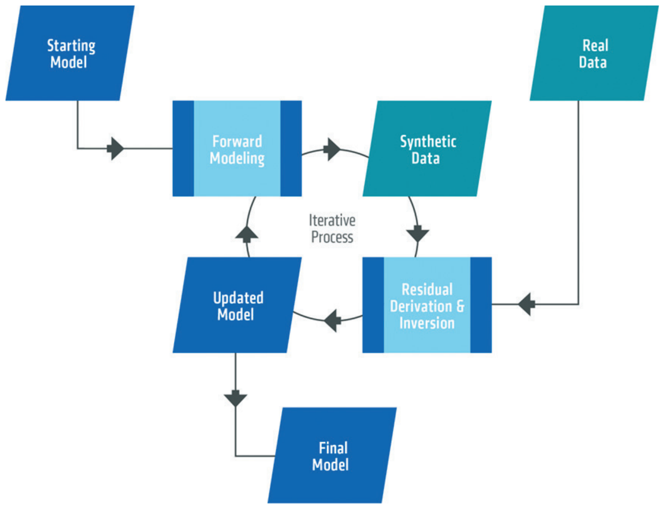
- Uses diving waves, refractions and reflections together to reduce dependence on very long offsets and provide high-fidelity velocity models
- Avoids cycle-skipping artifacts and delivers models with correct long wavelength information
- Removes migration isochron artifacts resulting in accurate deep velocity models
- High-resolution deep velocity updates translate to improved subsurface images and robust reservoir characterization

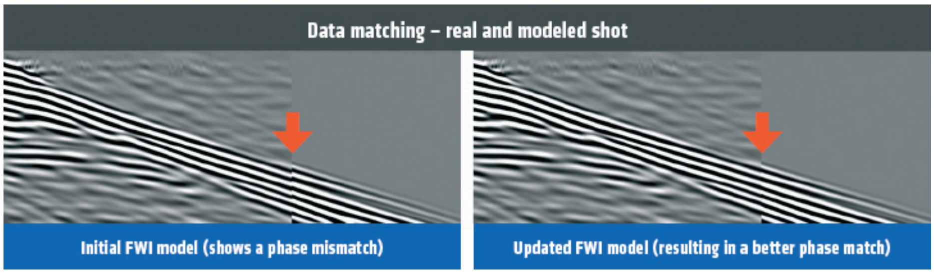
FWI updates, the PGS implementation of FWI uses a variation of the Inverse Scattering Imaging Condition (ISIC) found in PGS RTM.

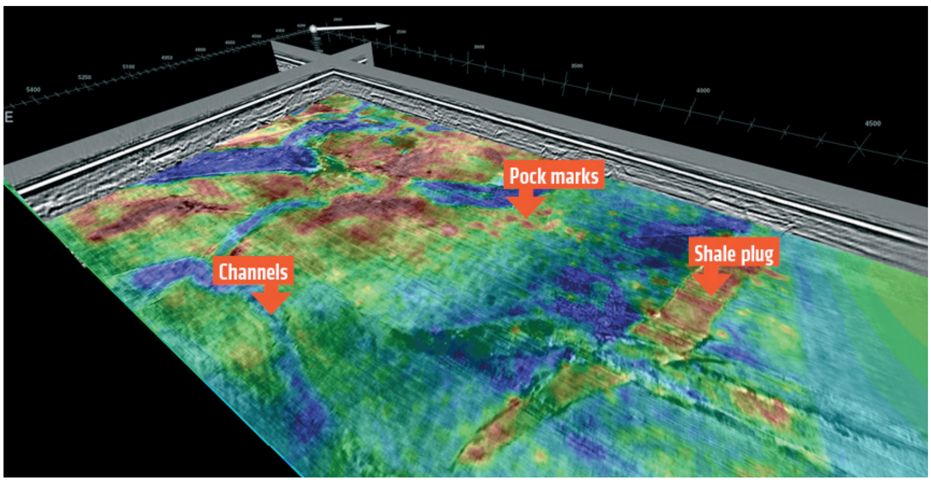
While in RTM, ISIC is used to remove backscattered and diving wave energy to produce a clean migration operator, the opposite is the case for FWI; we want only the backscattered and the diving wave energy. The ISIC formulation for RTM is based on a sum of two imaging kernels (to remove the low wavenumbers), whereas for FWI it is based on the difference of the same two kernels, to remove the high wavenumbers.

Transmission FWI requires long offsets to provide a deeper update, and lower frequencies will increase the width of the kernel, allowing for the update of larger areas in the model. In contrast, using the ISIC gradient of PGS' FWI, we can suppress the migration operator artifact, and hence reveal the underlying backscattered energy. This can then be used to provide model updates much deeper in the section than with conventional FWI.

The resulting FWI models are often used as input to ray-trace based migration methods such as Kirchhoff or Beam migrations to improve the underlying reservoir image. However to retain the structural detail of the velocity field achieved with this FWI update the use of high-fidelity migration algorithms such as RTM or WEM is recommended. Unlike conventional reflection tomography, FWI typically uses wide-angle refracted arrivals and reflections to build its model.







3D View of a depth image at 250 m depth with FWI velocity model overlaid.

Avoiding Cycle Skipping

Low frequencies in the field data are essential for robust and effective inversion without cycle skipping issues. GeoStreamer® dual-sensor acquisition provides these crucial low frequencies from the deep tow of the streamer. To ensure convergence of the model and avoid cycle skipping, FWI starts with the lowest frequencies in the data which contain coherent energy. The frequency content may subsequently be increased to add spatial resolution to the updates.

Additionally, to overcome cycle skipping limitations associated with simplistic starting models, PGS FWI uses sophisticated regularization schemes like the L1 norm of total variation (TV) of the model to stabilize the inversion space.

An accurate convergence of an FWI model phase is measured at each iterative stage using an integrated quality control procedure. Metrics demonstrating an improvement in the correlation of modeled and field data are used alongside data observations in both data and image space.

Conclusions

By towing GeoStreamer deep we preserve the low frequencies that are important for the success of FWI without sacrificing a broadband signal that is vital for producing high-resolution reflection images of both the shallow overburden and deep reservoir sections.

FWI utilizes reflections and refractions and eliminates the restrictions posed by conventional reflection tomography. This leads to highly accurate high-resolution velocity models.

Recording the full wavefield enables the model builder to progressively add the detail required to resolve complex velocity issues.