UNLOCKING UNPRECEDENTED SEISMIC RESOLUTION WITH FWI IMAGING

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Summary

A high-resolution seismic image is of great importance to exploration and production in many ways, such as bypassing drilling hazards and identifying compartmentalized reservoirs. To achieve seismic resolution as high as possible, the conventional seismic imaging process takes more of a linear approach to deal with one or a few specific issues at a time, such as noise and multiple attenuation, source and receiver deghosting, velocity errors, illumination holes, and migration swings. Full-waveform inversion (FWI) Imaging models and uses the full-wavefield data, including primaries and multiples (ghost included) and reflection and transmission waves, to iteratively invert for the reflectivity together with velocity and thus is an elegant solution to resolve those issues in one (iterative) inversion. FWI Imaging has proven to be a superior method for providing seismic images of greatly improved illumination, S/N, focusing, and thus better resolution, over conventional imaging methods. We demonstrate with a towed-streamer data set and an OBN data set that FWI Imaging with a frequency close to the temporal resolution limit of seismic data (100 Hz or higher) can provide seismic images of unprecedented resolution from the recorded seismic data, which has been impossible to achieve with conventional imaging methods.

Unlocking unprecedented seismic resolution with FWI Imaging

Introduction

The resolution of a seismic image is determined by its effective bandwidth within which reasonable S/N is present. Therefore, seismic resolution is mostly dictated by three parts: 1) the low-wavenumber resolution that is determined by the lowest frequency component in the recorded data; 2) the high-wavenumber vertical and lateral resolution that is determined by the highest frequency component in the recorded data, as well as the spatial sampling of sources and receivers; and 3) an accurate velocity model with proper low- and high-wavenumbers to correctly map the full-bandwidth seismic data in the time domain to an image in the depth domain. In addition, illumination holes, residual noise and multiples, and migration artifacts can introduce noise to the migration image and degrade the S/N and resolution.

The conventional seismic imaging process takes more of a linear approach to this problem, with numerous steps designed in preprocessing, velocity model building (VMB), migration, and post-processing to solve one or a few specific issues at each step. For instance, to improve the low-frequency content in the data, deghosting that removes the source- and receiver-side ghosts can be performed to increase the low-frequency S/N of the input data, and thus improve the low-wavenumber resolution of migration images. However, the efficacy of deghosting is often limited by the spatial sampling and S/N of the input data. Another case in point is multiple attenuation, which is not only time consuming, but it is also very difficult to completely remove multiples without damaging primary signals. More importantly, valuable information contained in the multiple energy that is essential for both vertical and lateral resolution is discarded. Although migration of multiples has been proposed to use the reflection multiples as input to infill illumination holes of primary energy, it generally suffers from crosstalk noise among primaries and different orders of multiples. It also often uses a velocity model obtained by separate VMB approaches with different input data and objective functions, which is usually not optimal to collapse all the multiple energy used in the migration. In short, the limits of individual steps and the disconnects between them make it difficult for conventional imaging processes to deliver a high-resolution image with well-focused details as implied by the maximum migration frequency.

Maximizing seismic resolution with FWI Imaging

Full-waveform inversion (FWI) Imaging (Zhang et al., 2020), which models and uses the full-wavefield data, including primaries and multiples (ghost included) and reflection and transmission waves, to iteratively invert for the reflectivity together with velocity, is a systematic approach to the seismic imaging problem and provides an elegant solution to mitigate most of the previously discussed limits imposed on conventional imaging approaches. By its nature, FWI Imaging can extract the full benefit of seismic data for optimal low- and high-wavenumber resolution with superior S/N and focusing.

Conventional imaging approaches require noise attenuation to improve the S/N of input data, which often compromises the signals when the S/N of the data is poor to begin with. This is most evident at low frequencies. In contrast, FWI Imaging can use input data with minimal preprocessing so that low-frequency signals are properly retained. In addition, FWI Imaging works on the entire wavefield and can utilize low-wavenumber information contained in large-angle data (e.g., diving waves) that cannot be used in conventional imaging approaches. Lastly, FWI Imaging can accurately handle low-frequency ghost effects by directly simulating them in the modelling engine and hence can further improve the low-wavenumber resolution.

As for higher wavenumbers, there are two factors that enable FWI Imaging to provide increased vertical and lateral resolution. First, FWI models different orders of multiples, which offers additional small-angle illumination on top of primary energy and increases both the vertical and lateral resolution of images. Second, diving wave energy, which is treated as noise in conventional imaging methods, can be properly utilized in FWI Imaging. As the diving wave energy travels horizontally with large angles, it can better resolve the lateral velocity variations and subsequently improve the lateral resolution of FWI images.

Finally, FWI Imaging obtains velocity and reflectivity in the same inversion and therefore the velocity is automatically consistent with the image for optimal focusing of all the energy. By iteratively updating

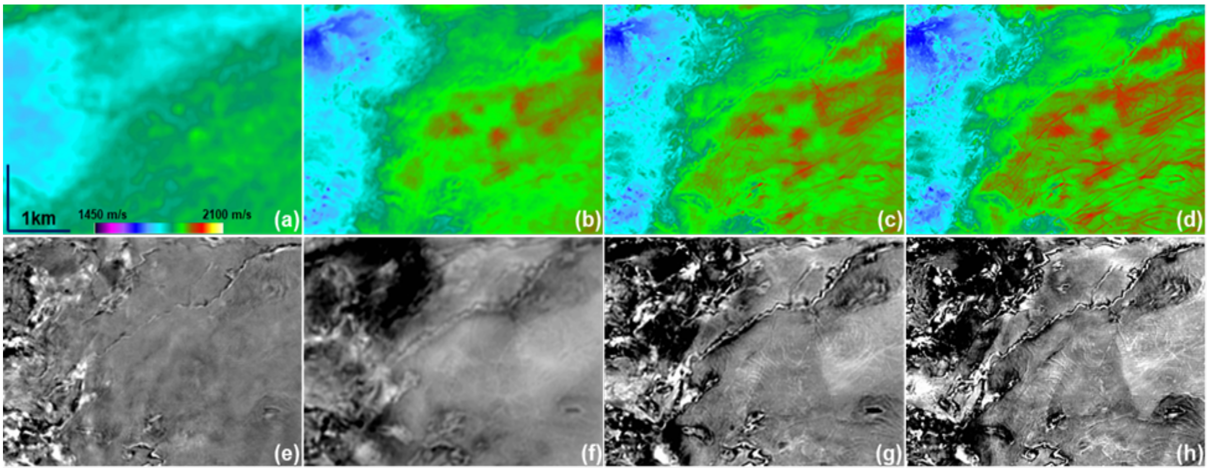

Figure 1: Depth slices at 600 m of a source-over-spread NATS data set in the Barents Sea. (a) 15 Hz TLFWI model, (b) 25 Hz TLFWI model, (c) 50 Hz TLFWI model, (d) 100 Hz TLFWI model. (e) 100 Hz Kirchhoff image with the 15 Hz TLFWI model in (a), and (f) – (h) are the FWI Images from the TLFWI models in (b) – (d), respectively. High-frequency FWI Images show improved structural details such as faults and channels.

velocity from low to high frequencies, FWI Imaging provides a proper low- and high-wavenumber velocity that can focus the full-bandwidth seismic data. With iterative least-squares fitting of the full-wavefield data, migration artifacts, noise in the input data, and illumination issues due to imperfect acquisitions, which often manifest in conventional migration images, are automatically minimized in FWI Images.

We performed FWI Imaging at 100 Hz or higher on both a streamer field data set and an ocean bottom node (OBN) field data set to demonstrate how FWI Imaging is able to effectively reveal subsurface geological details and even small man-made structures with unprecedented resolution that is impossible to achieve by other seismic imaging approaches.

Source-over-spread streamer data in the Barents Sea

To assess FWI Imaging's benefits, we examine its results on a streamer data set and compare it to conventional Kirchhoff. The data set comes from a source-over-spread narrow-azimuth towed-streamer (NATS) survey in the Greater Castberg area of the Barents Sea. This area features an iceberg-scoured, highly rugose water bottom with shallow gas anomalies, which poses challenges for imaging the faulted area in the deeper section. In this survey, a group of 5 sources with a horizontal span of 300 m and firing every 37.5 m along the inline direction are placed at the centre of 16 slant-towed streamers to acquire the near offsets for shallow imaging. Another front source is towed by the streamer vessel to provide long offsets up to 8.2 km for VMB (Vinje et al., 2017). The cable spacing is 60 m between streamers, and the receiver interval within each cable is 12.5 m.

With the acquired data right after deblending without any further processing, we ran Time-lag FWI (TLFWI) (Zhang et al., 2018) from the lowest usable frequency of the data at 3 Hz up to the imaging frequency at 100 Hz and compared the FWI Images to the Kirchhoff results. Figures 1a-1d show depth slices at 600 m of the TLFWI models from 15 Hz, 25 Hz, 50 Hz, and up to 100 Hz, which gradually reveal more details in the velocity models as the frequency increases. Correspondingly, the resolution of the FWI Images keeps improving when moving to higher frequencies, as shown in Figures 1f-1h.

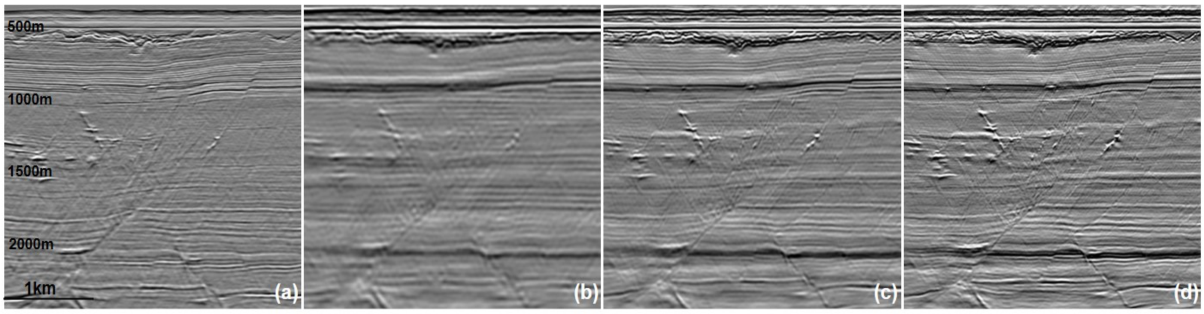

Figure 2: Section view of a source-over-spread NATS data set in the Barents Sea. (a) 100 Hz Kirchhoff image with the 15 Hz TLFWI model, (b) 25 Hz FWI Image, (c) 50 Hz FWI Image, (d) 100 Hz FWI Image. High-frequency FWI Imaging provides well-focused geological details, such as faults and diffractors.

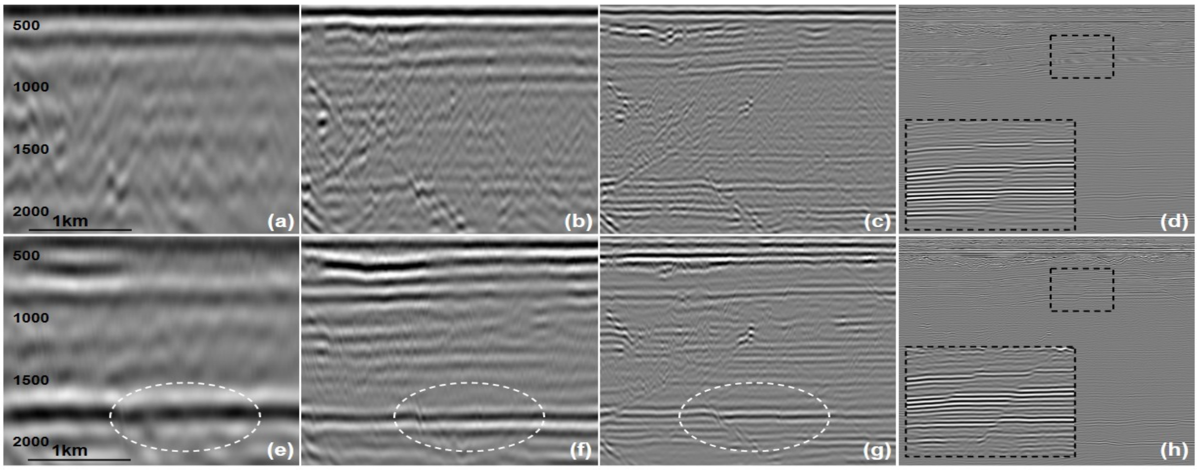

Figure 3. Section view of band-limited stack images from a source-over-spread NATS data set in the Barents Sea. (a) 0-4 Hz Kirchhoff stack, (b) 4-8 Hz Kirchhoff stack, (c) 8-16 Hz Kirchhoff stack, (d) 64-100 Hz Kirchhoff stack, (e) 0-4 Hz FWI Image, (f) 4-8 Hz FWI Image, (g) 8-16 Hz and (h) 64-100Hz.

Figure 1e is the Kirchhoff image with the 15 Hz TLFWI model using the input data that went through a conventional processing flow, including denoise, deghost, and demultiple. As we can see, the image quality of the 100 Hz FWI Image is much better than the 100 Hz Kirchhoff image, with more clearly defined fault planes and better imaged small channels and other geological details.

The improved vertical and lateral resolution of FWI Images can also be observed from the section views, as shown in Figure 2. Similar to the observations in depth slices, the resolution of the FWI Images from 25 Hz, 50 Hz, and up to 100 Hz progressively improves, and the 100 Hz FWI Image shows a much better resolution overall than the 100 Hz Kirchhoff image. It is also worth noting that the FWI Images have a broader bandwidth than the Kirchhoff images based on the band-limited images shown in Figure 3. From the images in different frequency bands, 0-4 Hz, 4-8 Hz, 8-16 Hz, and 64-100 Hz, we notice that the S/N of the FWI Images are overall better than the Kirchhoff images. Particularly, the FWI Image at the very low-frequency end (Figure 3e) shows coherent events that consistently appear in higher frequency images (Figures 3f-3g), while such events are missing in the Kirchhoff image (Figure 3a). This indicates that FWI can better compensate for the ghost effect through modelling and improve the low-frequency S/N. At the high-frequency end, the fault energy is better focused in the FWI Image (Figure 3h), while the Kirchhoff image (Figure 3d) suffers from contamination of migration swings that overshadow the subtle faults.

Shallow water, dense OBN data set

With the encouraging uplifts seen from FWI Imaging over Kirchhoff in the streamer data example, we moved to a dense OBN survey that was acquired specifically for shallow hazard imaging around existing platforms. The nodes were deployed underneath the platforms, while the sources were shot around the platforms. The nominal node spacing is 50x50 m and the nominal shot spacing is 6.25x12.5 m, though these parameters could have varied during acquisition due to factors such as obstructions and currents.

Starting from the raw field data, we performed TLFWI updates up to 150 Hz to derive the high-resolution FWI Image (Figures 4a and 4b). Another 150 Hz down-going RTM image using a legacy

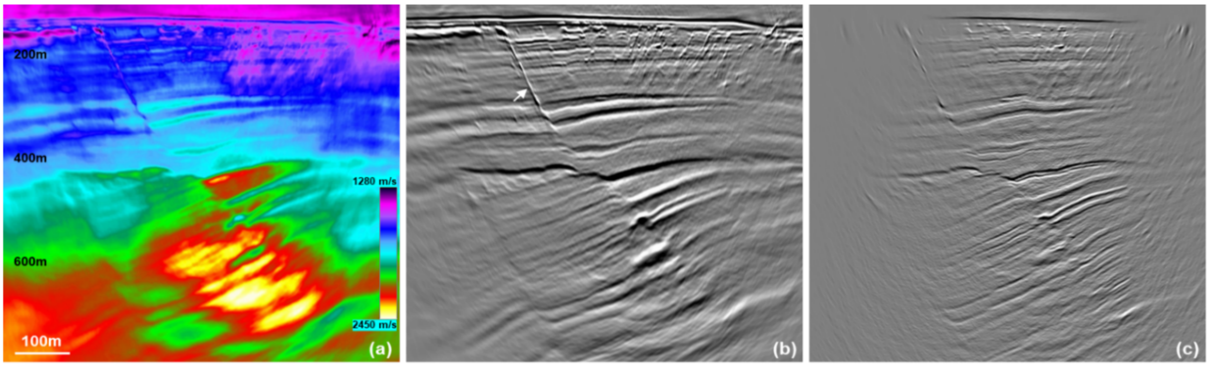

Figure 4. Section view of (a) 150 Hz TLFWI model, (b) 150 Hz FWI Image, and (c) 150 Hz RTM image from a shallow water, dense OBN data set. Faults, both large and small, and diffractors are better resolved in the FWI Image.

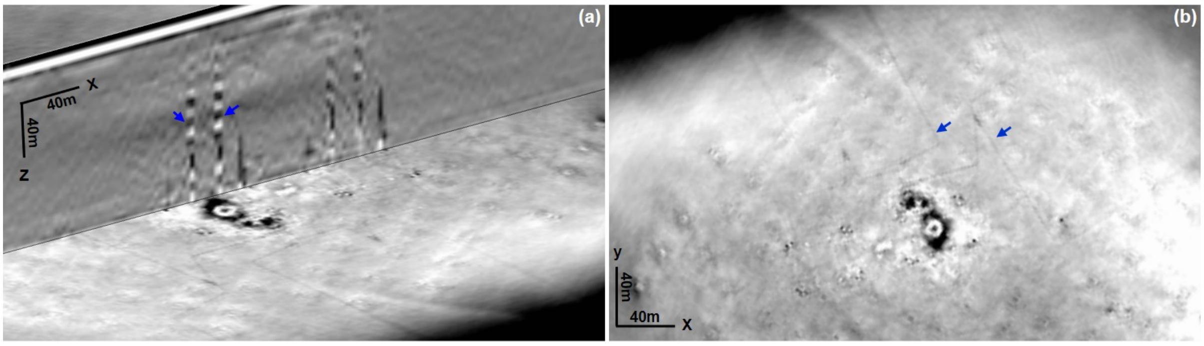

Figure 5. 150 Hz FWI Image from a shallow water, dense OBN data set: (a) section view and (b) depth slice at 120 m. Man-made structures, such as platform legs and subsea pipelines, are resolved in the 150 Hz FWI Image.

model was generated for reference (Figure 4c). Overall, the FWI Image provides improved structural information with more continuous events and better-defined faults, gas pockets, and diffractors. The FWI Image also extends the image beyond the node coverage and notably improves the image of a fault (white arrow in Figure 4b) that is barely observable in the RTM image using down-going primary data. This extra structural information is believed to be from the illumination of multiples and diving waves, which can be effectively utilized by TLFWI but are removed from the input for RTM.

The 150 Hz FWI Image not only better resolves the geological structures, but also provides extraordinary resolution to reveal small man-made features such as platform legs and subsea pipelines, which were rarely imaged previously with seismic data. A section view along two platforms is shown in Figure 5a, where we can see the platform legs in the water column as denoted by the blue arrows. A depth slice through the water bottom (Figure 5b) clearly reveals the subsea pipelines (indicated by the blue arrows). We believe that the imaging of these small man-made features is mostly attributed to the additional lateral illumination from diving waves and multiples, which helps resolve the lateral variations of the velocity model and therefore improves the lateral resolution of the FWI Image. Although the imaging of such features is not a major target, it gives us confidence that FWI Imaging can provide greater image resolution over other imaging approaches.

Discussion and conclusions

We demonstrated with streamer and OBN data examples that FWI Imaging can extract the full benefits of seismic data and yield unprecedented image resolution that has been impossible to achieve with other imaging approaches before. FWI Imaging can elegantly resolve issues such as velocity errors, migration artifacts, residual noise and multiples, and ghost effects in one (iterative) inversion. Additionally, proper handling of diving waves and multiple energy in the FWI inversion improves the vertical and horizontal resolution of images. Spatial aliasing is normally not the bottleneck for low-frequency FWI inversion for the purpose of velocity model building, but it could be an issue for high-frequency FWI Imaging. Additional illumination from diving waves and multiple energy have made FWI Imaging less sensitive to spatial aliasing issues than conventional imaging methods. However, if the spatial sampling of the input data is too sparse, the acquisition footprint could manifest in the high-frequency FWI Images. This suggests that acquiring denser data is still important for high-resolution FWI Images.

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