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A Full-waveform Inversion Case Study from Offshore Gabon

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SUMMARY

We applied full waveform inversion to a seismic dataset from offshore Gabon. This dataset features complex geology such as diapirism, shallow gas pockets and dewatering faults. We show the results on a large production-size swath using an advanced full waveform inversion method based on a specialized quasi-Newton optimization algorithm. The updated velocity model highlights an uplift in resolution and a consistency with the geological features observed in the depth migrated stack. The benefits include identifying features and faults in the overburden, and improved top-salt characterization. This results in better imaging in both the post- and pre-salt regions, as well as a velocity model that aids the geological interpretation.

Introduction

Full waveform inversion (FWI) continues to be an active research area in industry and academia. It plays an increasingly relevant role in oil and gas exploration to determine high-resolution velocity models for improved seismic imaging and interpretation, especially in regions of the Earth that are well probed by diving waves. Most production FWI algorithms are based on a local, linearized, iterative, least squares inversion process. Due to cost restrictions these generally use a steepest descent, or gradient only, based optimization. More advanced optimization algorithms, falling under the general class of Newton methods are based on including Hessian information (the second order derivative of the cost function) in the optimization. For example, see Virieux and Operto (2009) and references therein. In this paper we describe a FWI case study from offshore Gabon that was inverted with a quasi-Newton scheme (L-BFGS) to highlight the complex geological history of the region in both the seismic and FWI velocity model.

L-BFGS optimization scheme in FWI

The benefit of using inverse Hessian information to invert a large non-linear problem is well known to the general optimisation community. There are a number of ways this information can be obtained, with various levels of approximation involved: we refer the interested reader to Virieux and Operto (2009) for a good review of typical methods. In this work we employ the limited memory version of the well-known quasi-Newton BFGS algorithm, L-BFGS (Nocedal and Wright, 1999), which effectively estimates the action of the inverse Hessian by using a limited update history of gradient and model differences. The use of this method has been promoted in FWI before by various authors: for example, Brossier *et al*. (2009), Deng *et al*. (2012) or Kamath *et al*. (2015). It is also often used as a benchmark in comparison with more computationally demanding algorithms: for example, in Métivier *et al*. (2015). When dealing with large field datasets in a production setting we have found L-BFGS to be effective in estimating the inverse Hessian contribution and we use this technique here.

Case study setting: Offshore Gabon geology

The geological setting of the offshore Gabon case study area is shown in Figure 1. The South Gabon Basin started to form in Early Cretaceous times when the opening of the South Atlantic rift initiated. At that time, fluvial and lacustrine type continental sediments were deposited to form today's main hydrocarbon source and reservoirs rocks. Later on, in Aptian times, a layer of salt was deposited as sea waters progressively made their way through the area and arid climate conditions prevailed with high evaporation rates. This now heavily deformed salt, indicated in purple on Figure 1, forms a major top seal across the South Gabon Basin to stop and trap hydrocarbons below. At the basin scale the salt acted as a regional detachment layer and, helped by the ocean-ward tilt of the West Africa margin, overlying sediments slid down-slope to form a large scale gravity sliding complex over tens of thousands of square kilometres. This resulted in the formation of very complex salt structures with

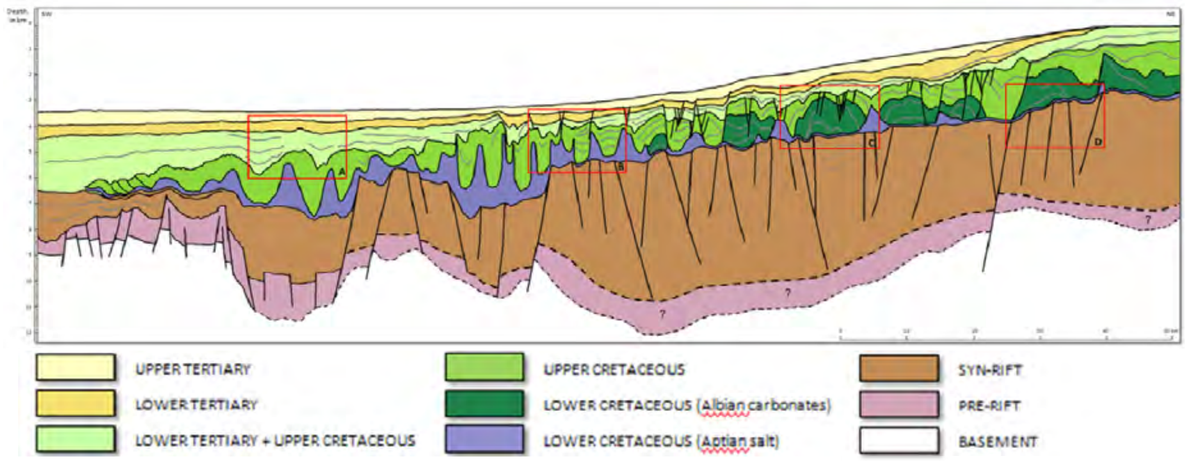

***Figure 1** Geology of the South Gabon Basin.*

diapirs, thrusts and canopies making seismic imaging of sub-salt targets and velocity modelling very challenging. Another source of complexity is the presence of the so-called ‘carbonate rafts’ (dark green area on Figure 1), which are simply the remaining pieces of the broken-up Albian carbonate shelf now sliding on the salt. These also generate prominent velocity anomalies in the seismic data.

Data acquisition and pre-processing

The offshore Gabon dataset was acquired between 2014 and 2015 (Duval and Firth, 2015) with a 10 km maximum offset. A variable-depth streamer configuration allowed acquisition of high quality low-frequency data that is beneficial in FWI (Jupp *et al*., 2012). The full size of the survey is 25,000 km^2 and we show here results from a large test swath covering an area 98 km × 16 km = 1568 km^2. The pre-processing for FWI involved basic trace edits, swell noise attenuation and an advanced de-noise process to specifically enhance the low frequencies (Yu *et al*., 2015). The source wavelet for FWI was estimated using an inversion of near field hydrophone measurements (Ni *et al*., 2014).

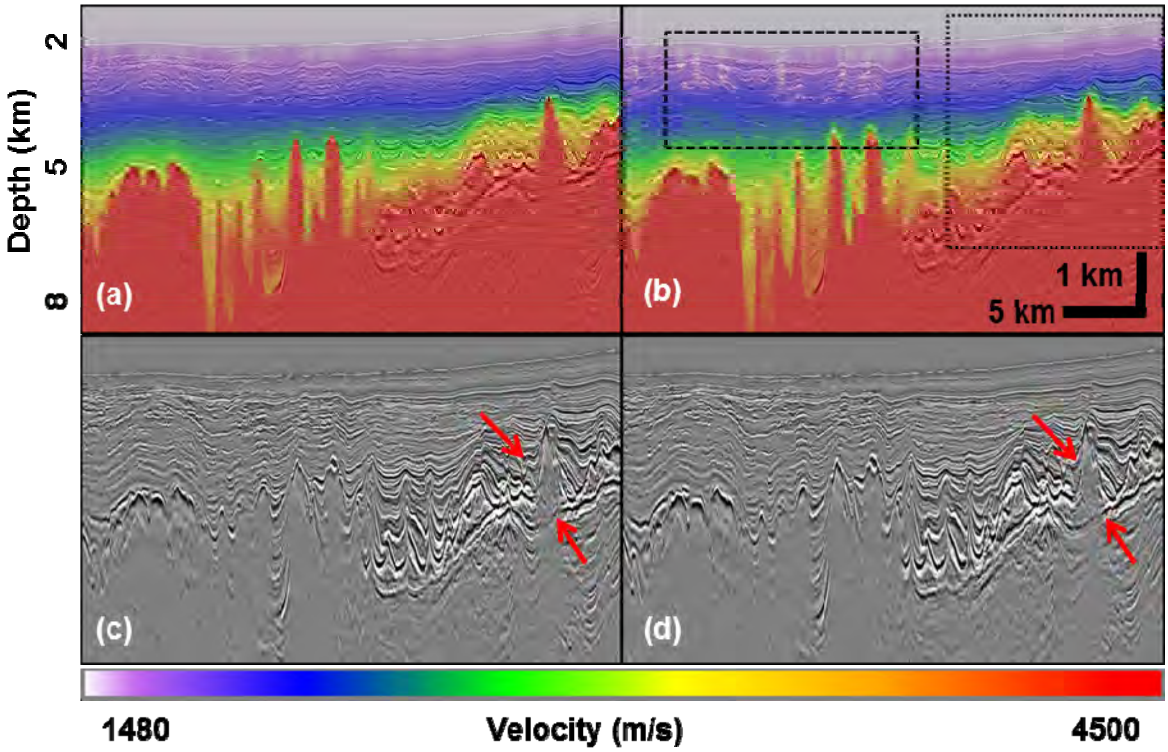

Figure 2 *Velocity models: (a) before, and (b) after 10 Hz FWI overlaid with the corresponding migrated stacks (shown in (c) and (d), respectively). A post-FWI salt flood has been applied to both models. The dashed and dotted boxes in panel (b) correspond to the zoomed areas in Figures 3 and 4.*

FWI results and velocity model interpretation

Figure 2 shows overlays of the migrated stacks with the corresponding velocity models: (a) before, and (b) after 10 Hz FWI, while panels (c) and (d) show the corresponding images alone. Below the top salt the velocity models are not well probed by diving waves and have been flooded with a salt velocity in those regions. For clarity, Figure 3 shows zooms of the dashed and dotted boxes on Figure 2b of the migrations with the velocity models before and after FWI. The imaging benefits from the FWI velocity model are evident: (i) in the shallower section, indicated by the red arrows on panel 3b, where we see a correction of pull-up/push-down image distortions, and (ii) in the salt body on the right, indicated by the red ellipses on panel 3d, where, mainly due to a better overburden description, the subsalt reflector in particular shows improved focus and continuity, along with some uplift in the salt flanks. Overall the FWI velocity model shows uplift in resolution, especially at shallow-to-medium depths, with a number of geological features consistent with the migrated stack.

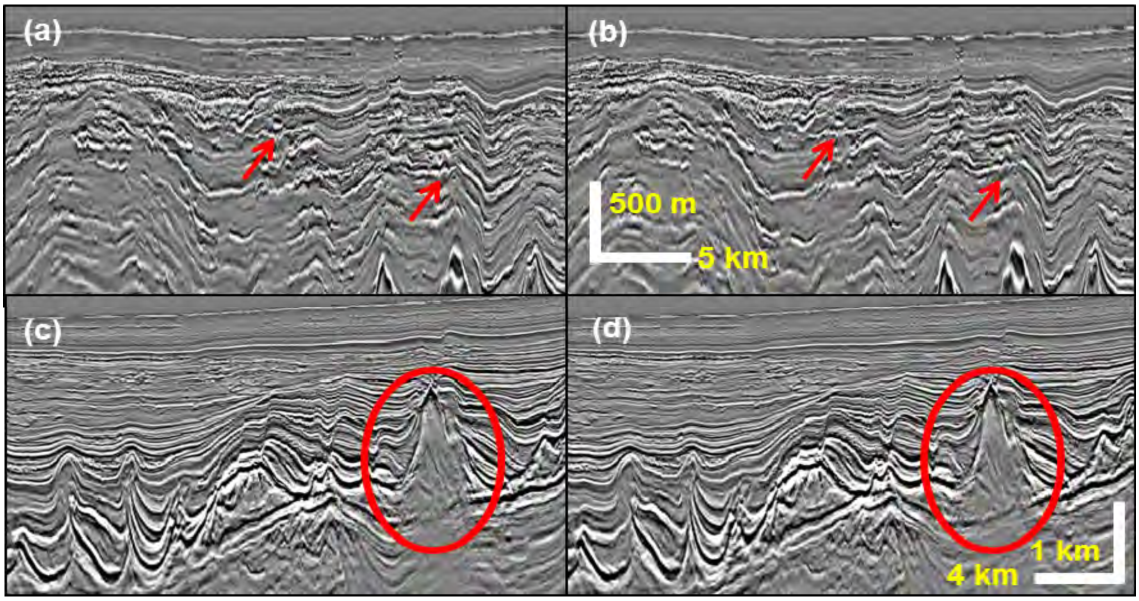

Figure 3 *Zoomed displays of the images migrated with the velocity model before, (a) and (c), and after FWI, (b) and (d), corresponding to the two boxes in Figure 2.*

To highlight the interpretation of the FWI velocity model, in Figure 4 we show the two different zooms of the FWI velocity model before the salt flood process. Focussing on the shallow section first, by comparing the stack (panel 4a) with the velocity model overlay (panel 4b), it is possible to identify the shallow bright amplitude packets in the image (white ellipse in panel 4a) as slow velocity gas pockets in the velocity model (black ellipse in panel 4b). These pockets are usually located directly above the crest of the salt diapirs (indicated by the arrows in panels 4a and 4b). These sharp, localised, low velocity anomalies are typically associated with high absorption in the seismic data and a push-down effect on the image due to the anomalous velocity. FWI finds the low velocity, allowing the subsequent image to improve in both shallow and deep. The near surface is also affected by polygonal faulting throughout the first few hundred metres (the Pliocene-Pleistocene section), meaning that the sediments are still dewatering at present. This is consistent with what is observed in panel 4b, where a very low interval velocity (close to water velocity) is visible in the very shallow because the sediments are very unconsolidated and still contain large volumes of water. We also see evidence for a gas escape conduit in both the seismic image and inverted velocity model (indicated in panels 4a and 4b). Considering now the deeper section, we see that the location of the top salt reflectors is well captured by FWI (see, for example, the salt diapirs in panel 4b). This is particularly clear when looking at panel 4d where the deeper sand channels are visible with higher velocity (black arrow on the left) and the carbonates floating above the top salt show a consistent velocity increase (black arrow at the bottom).

Conclusions

We have used an advanced FWI inversion algorithm to address the geological complexity in an offshore Gabon dataset to obtain: 1) an improvement in the velocity model resolution, 2) a better seismic depth image coming from migration with the FWI velocity model, and 3) an increased consistency between this image and the features observed in the velocity model. The consistency between the geological features in the migrated image and the velocity features in the velocity model gives the exciting prospect of using this high-resolution velocity model as an interpretation tool.

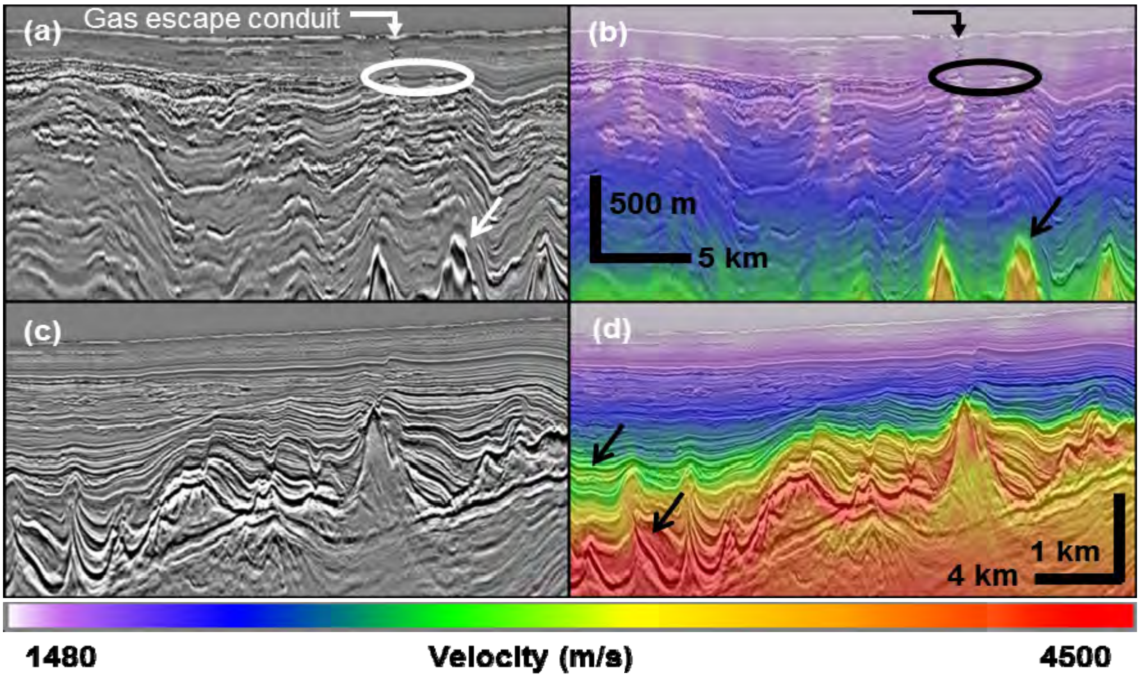

Figure 4 *Zoom displays of the migrated images, (a) and (c), and FWI velocity model overlays, (b) and (d), corresponding to the boxes in Figure 2. For clarity, the FWI model is shown before the salt flood.*

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