Velocity model building challenges and solutions for seabed- and paleo-canyons: a case study in Campos Basin, Brazil

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Summary

The Campos Basin, offshore Brazil, features complex shallow geology in the forms of pronounced seabed canyons and paleo-canyons. The rapid variations in the velocity field due to these complex shallow geologic features can be difficult for ray-based tomography techniques to resolve, resulting in distorted images in deeper section. Full waveform inversion (FWI) is able to utilize the recorded diving–wave energy to resolve the high-resolution velocity model in these geologically complex areas. Additionally, dip-constrained non-linear slope tomography introduces dip constraints to ray-based residual move-out tomography and is able to capture small-scale velocity anomalies associated with these shallow heterogeneities. A combined workflow of FWI and dip-constrained tomography enabled Chevron to build accurate and detailed velocity models in the Campos Basin, resulting in fewer seismic image distortions. We demonstrate the method using a Campos Basin, Brazil narrow-azimuth streamer dataset.

Introduction

It has been long noticed that submarine canyons incised into the continental slope water bottom present significant challenges in seismic imaging and interpretation for oil and gas exploration. Such complex seafloor bathymetry can distort seismic wavefronts and amplitudes, making it difficult to estimate accurate velocity models and construct real geologic reflectivity images, and therefore negatively impacts the results of the derived interpretation. In time processing, it was suggested to use wave-equation datuming (Berryhill, 1986) or time-variant statics (Dent, 1983) to reduce the "pull up" or "push down" effects. Such approaches do not solve the velocity problem but instead provide horizons which are perceived as true geology. Debenham and Westlake (2013) compared pre-stack time migration (PSTM) and pre-stack depth migration (PSDM) workflows with a 2D line study and demonstrated that image distortions and amplitude dim zones cannot be fixed by a static-correction method, while PSDM image with careful depth model building workflow shows obvious uplift. The practice of 3D depth imaging in the Campos Basin has taught us a couple of things. First, initial velocity models that honor shallow geologic features are very helpful and sometimes critical for tomography to converge quickly to reasonable final models. Birdus (2009) proposed the use of geo-mechanical methods to build initial seabed-canyon models. Arnaud et. al. (2008) built an initial model with 1D inversion of a picked sub-channel horizon to a reference horizon. The second thing experience has taught us is that high-resolution (HR) model building techniques are important to capture the velocity variation associated with the narrow canyon widths – typically narrower than the acquisition streamer length. Thus far, techniques for implementing or improving ray-based tomography have dominated discussions of velocity model-building strategy for submarine canyons; analysis relies heavily on the quality and density of the residual moveout (RMO) picks to build accurate high-resolutions models (Fruehn et al., 2015). In addition, different techniques such as pick weighting and layer constraints (Sun et al., 2011; Chen and Shen, 2012; Chen and Hu, 2014), reference horizons and offset-consistent dip constraints (Graham and Richard, 2009, Guillaume et al., 2013, Chen and Hu 2014), have been explored to help invert good models.

However, ray-based analysis has been hindered not only by the lack of sufficient offsets for picking shallow events, but also by the complex ray paths generated by steep canyon walls. Deeks and Lumley (2015) pointed out that multiple paths of prism waves are usually generated by the canyons, even at short offsets. Prism wave energy becomes stronger in narrow and deep canyons and creates shadow events in stacked images and CDP gathers (Deeks and Lumley, 2015; Debenham and Westlake, 2014). Confidence in picking proper RMO and geological events is low in the presence of prism waves. Furthermore, multi-pathed energy cannot be properly handled by single-path residual curvature analysis (RCA) and migration algorithm like Kirchhoff migration, which are typically used in this case.

FWI provides a different way to tackle the problem. It uses the wave equation to produce high-resolution velocity models by directly comparing modeled data to the real seismic records. It handles complex ray paths naturally and doesn't rely on *a priori* geology assumptions or RMO picking. We applied FWI in this case study in Campos Basin, followed by a ray-based model building workflow with dip-constrained non-linear slope tomography (Guillaume et al., 2013). The result shows improvement in the sub-canyon image and satisfying quality in both the data and gather domains.

Study area and workflow

The study area is situated in the Campos Basin, offshore Brazil. Water depths range from 150m to 1,500m. The typical rugose seafloor in the area is presented in Figure 1, where canyons carved about 300m into the continental slope.

The first 3D narrow azimuth streamer data (NAZ) acquisition in this area was acquired and processed with conventional ray-based tomography model building workflow for PSDM in 2008. Imaging suffers from structure distortions below seabed-canyons down to the Cretaceous at around 3 km depth. In 2010, a new 3D NAZ streamer survey was acquired. This data was processed in 2011-2012 using a workflow of layer-constrained HR tomography with structurally-guided weighting. Details of the workflow can be found in Chen and Shen (2012). Compared to the original imaging, the 2012 workflow was able to greatly reduced sub-canyon image distortions. However, with this method, a lot of labor-intensive effort and attention was required during each of the tomography iteration to evaluate stack image in order to identify potential non-geologic artifacts in velocity model. Despite the good effort in 2011-2012 work, there were still residual image distortions in deeper part of section because we didn't fully resolve velocity anomalies in shallow overburdens, as proved by well data.

Due to FWI's ability to provide high resolution velocity model in shallow overburden, it is designed to be the main part of a 2015 re-imaging effort to update the velocity model using the 2010 NAZ dataset. We utilized an acoustic, finite difference time domain FWI for the study (Ratcliffe et. al, 2011). The velocity update is primarily driven by refraction energy. The smoothed 2012 model served as input model for the 2015 FWI. 48 iterations of FWI were run from 5 to 10Hz in order to minimize the misfit of phase between synthetic shot gathers and real shot gathers. After reaching a good match in the data domain, Kirchhoff PSDM (KPSDM) was run to evaluate the FWI updated model in the image and gather domains. As we'll show in the next section, most of the non-geological structural undulations were removed from the stack, but some small residuals remained. We then applied additional iterations of dip-constrained non-linear tomography. RMO and dip fields on near, middle, and far stacks were picked for dip-constrained tomography. A model was derived to flatten the gathers as well as minimize the difference between offset dependent dips and a reference dip. This final model healed all residual non-geological post-FWI structural undulations.

Results and analysis

Since FWI attempts to match modeled and recorded shots, we performed data domain QC first to validate the FWI update. Near/mid/far channels are evaluated in figure 2. The top panel is modeled data with the initial model; the middle panel is modeled data with the FWI updated model, and the bottom panel shows the recorded field data. The initial model provides good match for near water-bottom events, but poor match for deeper events. Better match with the real data is seen after the FWI update which indicates that it worked as expected.

KPSDM results with the initial model and the FWI updated model are shown in Figure 3 (a) and (b). The "pull-up" and "push-down" structure associated with the canyon shape is clearly observed in the initial model image from ~1,400m to ~3,000m. FWI model fixes the "pull-up" pointed out by the arrows however some short wavelength undulations still remain. Multiple reasons could explain why FWI could not fully resolve the canyon related velocity issues. First, the strong featherings of the NAZ acquisition without good uniformed source-receiver patterns could be an issue. Second, no usable signal could be extracted below 5Hz from the NAZ data while a lower frequency is usually important to for FWI to avoid cycle skipping. Third, the acquisition direction, which is parallel to the canyon direction (dip to structure), may also play a role in preventing FWI from resolving a perfect model. Besides the data limitations, the FWI algorithm can also suffer from possible anisotropy and density leakage. In order to completely fix the image distortions in deeper section, subsequent ray-based tomography is applied. Dip fields are picked on the stack and reference structural dips are created by smoothing out these small undulations. After dip-constrained tomography, we obtained the 2015 final model. Figure 3 (c) is KPSDM QC of the 2015 model. It shows smooth sediment layers in the entire section. For a fair comparison, we generated KPSDM stack using the 2012 final model, as shown in Figure 3 (d). The 2012 model also shows a good fix in the shallow depth. However, in the deeper section, a mild residual can be seen below 2,600m. From depth slice QC's, this observation is even more apparent. Figure 4 compares depth slice images at 1,500m and 2,100m for the initial, the 2012 and the 2015 final models. In the initial model image, jitters caused by the seafloor canyons exist everywhere and become milder at deeper depth. The 2012 image did a good job at reducing most of the distortions but some small residuals can still be seen on the 2,100m depth slice. In the 2015 image, all sediment contours are smooth without distortion.

Gather domain QC's provide additional support for the 2015 model. Figure 5 presents the three models overlaid on their corresponding KPSDM stack with CIG gathers on the right side. The initial model is a smoothed velocity field without any lateral changes. The gathers show quite large RMO. Far offsets (~2,000m) quickly stretch out or disappear in this area, which is not ideal for ray-base tomography. The speed up and slow down associated with canyon flanks and valleys are captured in the 2012 and

2015 final models. The latter puts a smoother velocity inside canyon flanks (black circle) and a stronger velocity variation around 1,500m. The oscillating velocities healed the imaging undulations and minimized gather RMO. The 2015 final image provided a higher level of confidence in the interpretation results. The image depthing accuracy was proved by a well drilled shortly after the processing. Other products based on the seismic, like seismic inversion, were also greatly benefited, showing better continuity and better match with wells data. By resolving the effects of seabed cannyons, we were able the reduce the uncertainty on the placement of horizontal wells in thin and low dip-angle reservoirs in the field.

Conclusions

We presented a model building workflow of combined FWI and ray-based dip-constrained tomography to solve for an accurate model in complex geology settings of seabed-canyons. FWI has an advantage over conventional ray-based tomography which can break down without good picks and cannot handle multi-pathing. Although with this NAZ data, FWI alone did not fully resolve the problem, it fixes large image distortions and provides a better starting point for ray-based tomographic update. Dip-constrained tomography further resolves the residual undulations using RMO and offset dependent dips. It has been shown that this workflow is effective at automatically resolving image distortions down to target level without manually pre-setting layers or regions for tomographic update. With the proposed workflow, we achieved a high-resolution model efficiently that is geology conformable and geo-mechanically meaningful.

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Figure 1 Campos Basin Location Map and water bottom map of the study area.

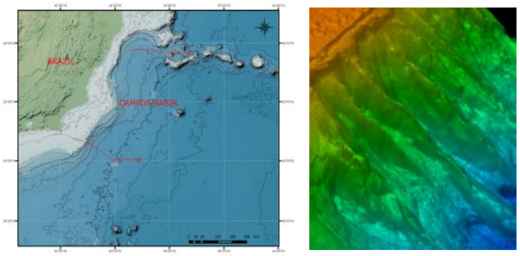


Figure 2 On the left, near/mid/far channels (a) modeled with initial smooth model (b) modeled with FWI update model and (c) recorded. On the right, recorded shot is presented with wiggles and modeled shot is overlaid with positive amplitude in red and negative amplitude in blue. Better blue to trough and red to peak alignment indicates better matching between the modeled and recorded shots. (d) Modeled shot with initial model is overlaid on recorded shot gather; (e) Modeled shot with FWI model is overlaid on recorded shot gather; (f) Recorded shot gather

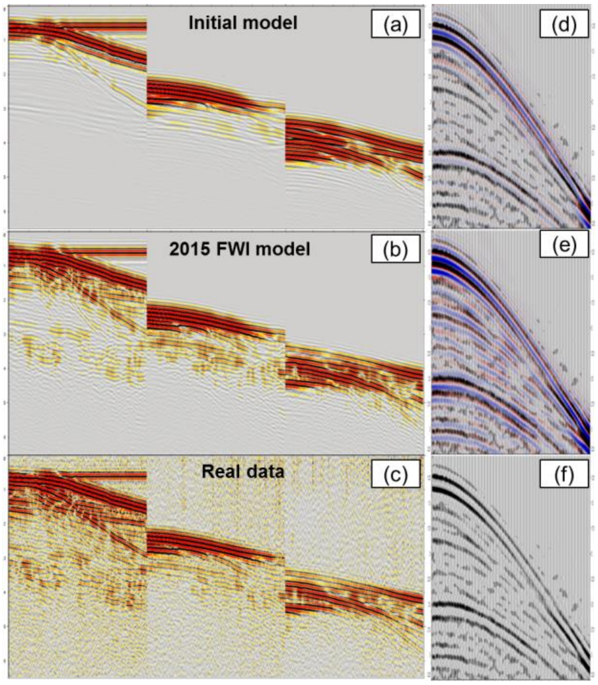


Figure 3 Kirchhoff PSDM stacks for (a) initial model (b) FWI update model (c) 2015 final model (d) 2012 final model.

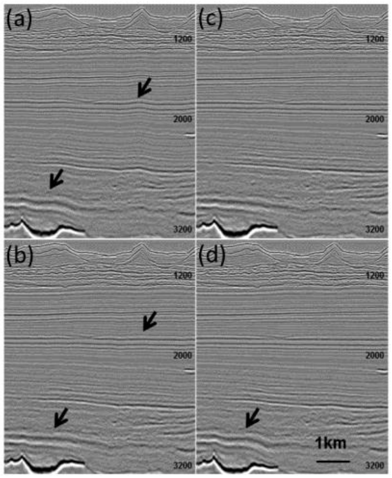


Figure 4 Depth slice at 1,500m (left) and 2,100m (right) for (a) initial model (b) 2012 final model and (c) 2015 final model

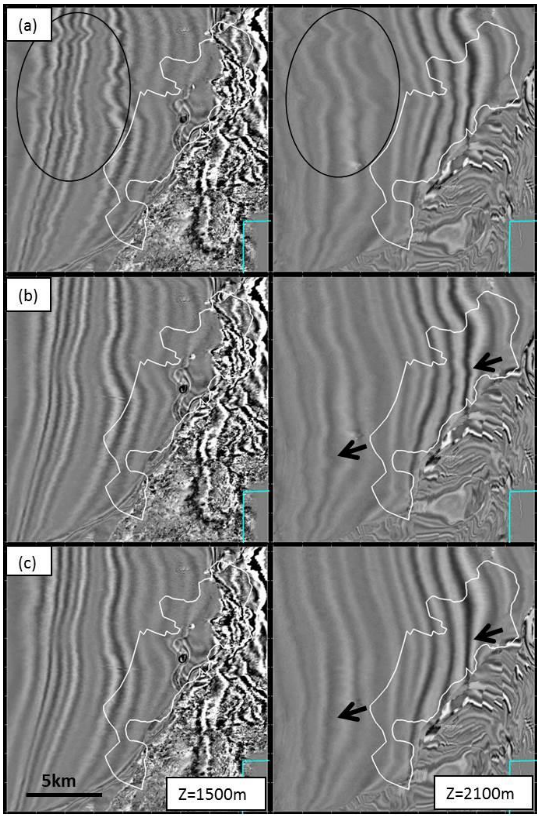
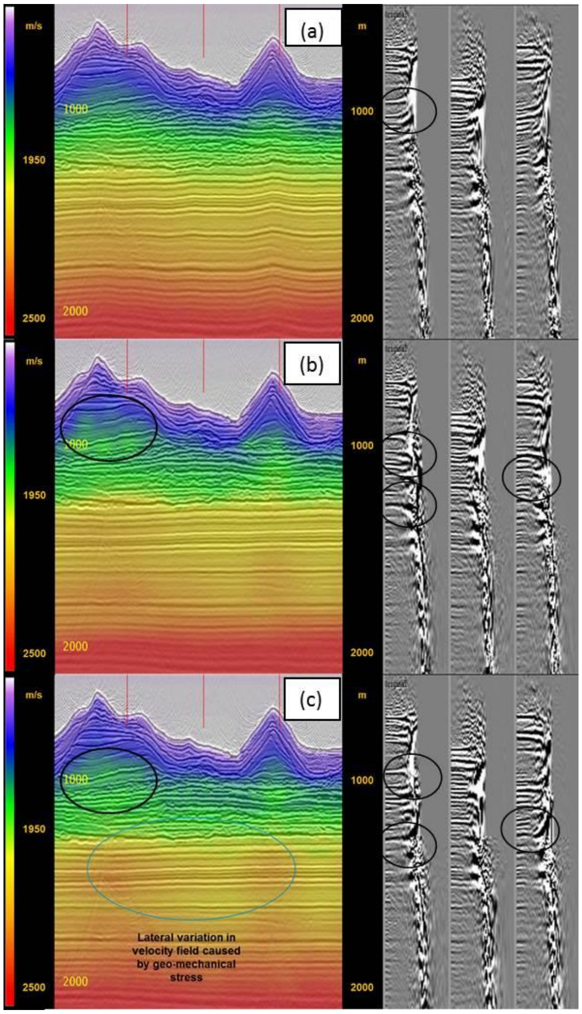


Figure 5 Model overlaid on PSDM stack for (a) initial model (b) 2012 final model and (c) 2015 final model. Gathers at the selected location are shown on the right side.



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