W003

Combination of Geomechanical Modelling and Tomography to Resolve Severe Velocity Variations Below Rugose Seafloor

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SUMMARY

Seismic imaging and depth-velocity modelling below a seafloor with complex topography are always challenging. The problems are caused by two types of lateral velocity variations: (1) contrast between the water and sediments and (2) velocity variations within shallow sediments created by the variable water depth.

Geomechanical effects contribute to velocity variations in shallow sediments. Variable water depth always creates some variations in overburden pressure and variable pressure changes seismic velocities.

We propose a new version of tomographic inversion that is focused (constrained) to recover these types of geomechanical (compaction driven) velocity anomalies associated with rugose seafloor. Applied together with geomechanical modelling and standard seismic tomography it helps to solve the strongest and most complicated water bottom related velocity anomalies. Synthetic and real data examples illustrate how this combination works.
Introduction

Seismic imaging and depth-velocity modelling below a seafloor with complex topography are always challenging. The problems are caused by two types of lateral velocity variations: (1) contrast between the water and sediments and (2) velocity variations within shallow sediments created by the variable water depth.

A few years ago geomechanical modelling (Birdus, 2009) was included into the depth-velocity modelling toolkit to solve velocity variations within shallow sediments caused by variable stress and differentiated compaction below a rugose seafloor. Since then, practical application on seismic data from different parts of the world confirmed its effectiveness and also revealed areas where additional research and software developments can provide further benefits, especially in cases of severe complexity of the water bottom (Figure 1).

In this paper, we propose a new version of tomographic inversion that is focused (constrained) to recover spatially variable velocity anomalies caused by geomechanical effects below rugose seafloor. Applied together with geomechanical modelling and standard seismic tomography it helps to solve the strongest and most complicated water bottom related velocity anomalies. Synthetic and real data examples illustrate how it works.

![Figure 1](image.png)

**Figure 1** 3D PSDM section migrated with the initial velocity model that includes only velocity contrast between the water layer and the sediments with smoothed velocity field. Interval velocity section is overlaid in colour. Rugose seafloor topography with up to 600m deep channels leads to strong image distortions. NW Australian shelf. Data courtesy CGGVeritas Multi-client Data Library.

**Geomechanical velocity anomalies below seafloor with complex topography.**

We know that a stress applied to given sediments changes seismic velocities. Variable water depth always creates some variations in overburden pressure and corresponding anomalies in interval velocities. These compaction driven velocity anomalies can extend far away from the seafloor and seriously affect seismic rays travel times and geometry. In case of severe variations in the water depth (seafloor channels, cliffs, prominent reefs, etc) these anomalies can be much stronger than typical velocity variations associated with lithological changes.

Standard seismic tomography often fails to correctly recover these velocity anomalies because (a) acquisition parameters may be selected for illumination of much deeper target intervals, so we do not have enough offsets to estimate moveout immediately below the seafloor and (b) the anomalies can have significant magnitudes (up to more than 20%) with complex 3D shapes and rapid variations. Luckily, the geomechanical anomalies obey laws of solid mechanics and petro-physical relationships between stress and interval velocities. We can calculate such anomalies using this knowledge.
Geomechanical velocity modelling consists of 3 major steps:
1. Determine the sources of anomalous geo-stress. If we know the seafloor topography and difference in density between the shallow sediments and the water, we can calculate variations in overburden pressure caused by the variable water depth.
2. Calculate how the stress propagates away from the sources in 3D geological media using principles of solid mechanics. These stress anomalies (Figure 2) extend far away from the seafloor. They become wider with depth and remain noticeable within a depth interval that many times exceeds the range of the water depth variations.
3. Transform anomalous geo-stress into interval velocity variations.

Figure 2 shows examples of real geomechanical interval velocity variations below simple structures on a seafloor: (A) a positive structure increases overburden pressure and interval velocities below and (B) a negative structure relieves some overburden pressure and thus reduces interval velocities.

The shapes of these velocity anomalies are important for the accurate ray tracing through the upper part of the model. In these examples, travel time distortions caused by the geomechanical velocity anomalies are stronger that the travel time variations corresponding to the water-sediments velocity contrast. Figure 2 can illustrate why simplified alternative methods (like replacement velocity statics, etc) cannot adequately solve the problem. In favorable shallow seismo-geological conditions, the standard seismic tomographic velocity modelling produces some approximations of compaction driven velocity anomalies but it cannot achieve the reliability and accuracy of straightforward geomechanical modelling.

Seismic reflection tomography constrained to geomechanical velocity anomalies.

The following equation describes how geomechanical modelling calculates interval velocity variations below rugose seafloor:

\[
\text{Vanomaly}(X,Y,Z) = \text{WB}(X,Y) \times \text{Propagate}(X,Y,Z) \times \text{SV}(X,Y,Z).
\]

The first term is the source of variable overburden pressure - the seafloor topography; in practice it is well known. The second term is a convolution operator that describes how variations in overburden stress propagate in 3D medium away from their source – rugose seafloor; this term is well determined by solid mechanics theory. The convolution of the first two terms is the variable overburden stress in sediments caused by the seafloor topography; it can be relatively easily calculated with sufficient accuracy. This convolution describes anomalies shown in colour on Figure 2 in units of pressure. The third term is the most challenging part of the equation; it sets relationships between variations in overburden stress and interval velocities. The third term is responsible for the absolute values of the anomalies shown on Figure 2 in units of velocity. In general, an increase in overburden stress leads to higher interval velocities but in practice we found it difficult to derive the necessary numerical functions with sufficient accuracy. In order to solve this uncertainty we use seismic topography approach. We build an initial interval velocity volume using geomechanical modelling with parameters based on our best a-priori estimation. Then we run PSDM, measure depth-residual moveout and set tomographic inversion to find velocity anomalies that would (a) minimize the measured residual moveout and (b) have 3D shape of stress anomalies corresponding to the given
water bottom topography. In this way, the tomography is constrained to estimate only the magnitude of anomalies with known shapes. It makes such hybrid tomography-geomechanical inversion robust and accurate even in the most difficult situations where the standard unconstrained tomography fails. This algorithm falls into a well known family of constrained tomographic inversions that includes layer constrained tomography, channel tomography, fault constrained tomography, dirty salt tomography, etc. They all benefit from focusing on certain types of velocity anomalies or certain intervals in the subsurface.

As soon as geomechanical modelling and geomechanical constrained tomography build an accurate velocity model for the shallow sediments affected by variable stress fields, we switch to standard tomographic sequence to recover other geologically determined velocity variations at all levels.

**Synthetic and real data examples.**

In reality, there is always have a combination of lithology dependent and compaction driven velocity variations, along with other types of velocity anomalies. In order to test different processing sequences and to provide some illustrations we created a synthetic dataset with geomechanical velocity anomalies corresponding to a fragment of a real seafloor with complex topography (Figure 3). The orange polygon on Figure 3.a shows the extent of the 3D synthetic dataset, the blue traverse is the location of the seismic section shown on Figures 1 and 4. The velocity volume for synthetic modelling consisted of three components: (a) water layer with sipican based vertical velocity profile (range from 1480m/s to 1530m/s), (b) smoothed compaction driven trend for the sediments and (c) geomechanical velocity anomalies caused by the given seafloor topography. All these contribute to the real velocity field, we just excluded lithology dependent variations from the model. The smoothed trend “b” can be seen in colour on Figure 1. The geomechanical velocity anomalies are displayed in colour on Figure 3.b, they have magnitude up to plus/minus 300m/s and extend down to approximately 1.5 km below the seafloor. PSDM section migrated with correct velocity can be seen on Figure 3.b. Figures 3.c and 3.d show PSDM gathers and stack migrated with the smoothed velocity model that excluded geomechanical anomalies. Colour overlay on Figure 3.d is the residual moveout (RMO) gamma section, it looks very similar to RMO measured on real data. The section on Figure 3.d is a synthetic equivalent of the real data section from Figure 1. The real seismic section (Figure 1) has been also affected by lithology dependent velocity variations but their impact seems to be much weaker than that of geomechanical anomalies. These results confirm that geomechanical velocity anomalies are responsible for the majority of imaging problems below rugose seafloor.

![Figure 3 Some results of synthetic modelling. See text for the details.](image-url)
All types of seismic tomography use PSDM gathers (Figure 3.c) to determine velocity variations (colour overlay on Figure 3.b). Geomechanical constrained tomography benefits from the a-priori knowledge of 3D shapes of geomechanical velocity anomalies. We used the synthetic data to compare (1) standard tomography, (2) geomechanical modelling followed by standard tomography and (3) geomechanical modelling followed by geomechanical constrained tomography. We saw noticeable increases in the quality of the results as we evaluated the workflows in this sequence. We started with a “perfect” synthetic dataset (Figure 3.c); then, to make the study more realistic, we excluded shallow events from the analysis and reduced number of valid RMO picks for deeper events, in these latter cases we observed an increased importance of geomechanical constraint as the standard tomography started to fail whereas the geomechanical constrained version was still producing reliable results. Figure 4 shows an example of PSDM section after geomechanical modelling and several iterations of tomography including geomechanical constrained inversion. This workflow removed all image distortions caused by the rugose seafloor.

**Figure 4** PSDM section after depth-velocity modelling including geomechanical constrained tomography. Interval velocities are overlaid in color. Depth scale. See Figure 1 for comparison.

**Conclusions**

Compaction driven velocity variations are important components of real velocity models. Geomechanical approach to building velocity models in areas with complex seafloor topography:

- enhances our understanding and representation of real velocity fields and seismic data;
- allows us to achieve distortion free seismic images below rugose seafloor.

Geomechanical constrained tomography:

- uses seismic data to estimate vital parameters of geomechanical velocity models;
- provides a robust and accurate solution even in cases of inadequate illumination, poor seismic data quality or structural complexity.

**Acknowledgement**

The authors thank CGGVeritas management and Multi-client Data Library for permission to present these results.

**References**

Birdus S. [2009]. Geomechanical modeling to resolve velocity anomalies and image distortions below seafloor with complex topography. 71st EAGE Conference & Exhibition, Extended Abstracts, U014.