# Accurate velocity-depth estimation in a complex deep-water setting using refracted arrivals from wide-angle seismic datasets

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## Keywords

Downward continuation, Tomography, Pre-stack depth migration

## Summary

Accurate velocity-depth modeling in a complex geologic setting especially in a deep-water environment, using towed streamer marine seismic data, is very challenging. Interval velocities derived using normal move-out (NMO) analysis of the reflected seismic signals for shallow reflectors (<1 km below the seafloor) is significantly compromised by the combination of a long wave path in the water column and the complex ray paths due to topography, leading to small move-out differences between reflectors. Additionally, refraction arrivals associated with the low sediment velocities and deep water only appear at far offsets, containing information about deeper structures. In this study, we present an innovative method where a 12 km long towed streamer seismic data are downward continued to the seafloor leading to the collapse of the seafloor reflection and the emergence of refraction events as first arrivals close to zero offset, which are used to determine a high-resolution near surface velocity-depth model using an efficient tomographic method. These velocities are then used to perform pre-stack depth migration using a coincident 5.5 km long, shallow streamer data. Our findings infer that the velocity-depth model derived from tomography of downward continued towed streamer data provides a far superior pre-stack depth migrated image than those produced from velocity-depth models derived from conventional velocity estimation techniques.

## Introduction

Imaging of subsurface details, using NMO based traditional seismic data processing technique, is very challenging in a complex geological settings in deep water environments, like the salt diapirs of Gulf of Mexico (Galloway, 2008), or in subduction settings, such as Cascadia (Yelisetti *et al*., 2014), Sumatra (Singh *et al*., 2012) where the seafloor could be very rough and water depth could vary drastically from a couple of meters to several kilometers across the subduction front. To get rid of such difficulties, we present a novel technique, in which we have carried out downward continuation of the surface seismic data to the seafloor followed by a travel time tomography of first arrivals.

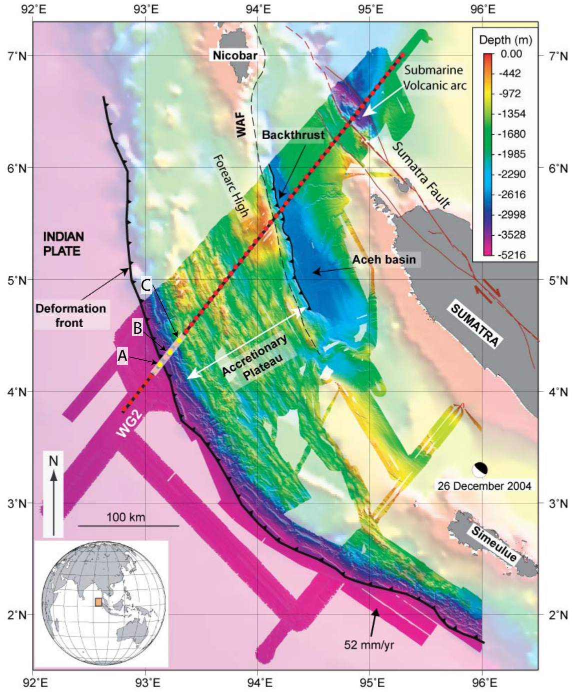

Figure 1: Location of seismic reflection profile WG2 superimposed on bathymetric data. Red dots: OBS locations; Solid Black line indicates the WG2 profile. Study area is marked by the whitened segment of the profile.

To do so, we have used a coincident deep seismic refraction and reflection profiles acquired in July–August 2006 using the French R/V Marion Dufresne and the Western Geco M/V *Geco Searcher* vessels carrying 8260 cu in. and 10170 cu in airgun array sources, respectively in. The 520-km-long WG2 profile (Figure 1) is oriented ~20◦ anticlockwise from the trench normal on which 56 ocean-bottom seismometers (OBS) spaced at 8.1 km were deployed and shots were fired at 150 m intervals. A 12-km-long streamer towed at 15 m was used for the reflection survey at 50 m shot interval, to image the deeper structure of the megathrust (Singh *et al.*, 2008). Another 5.5-km-long streamer was towed at 7.5 m water depth to acquire high-resolution data to better image the near surface features. In this study, the 5.5 km towed streamer data are used to produce the pre-stack depth migrated images; the three velocity-depth models are derived from the 5.5 km towed streamer data, the OBS data and the longer 12.0 km towed streamer data.

## Theory and/or Method

### (i) Downward continuation of streamer data

Towed marine seismic data recorded over deep water often leads to a superposition of reflection and refraction events from near-surface structure on the recorded shot records. Downward continuation (DC) (Berryhill 1979; Arnulf *et al.* 2011; Ghosal *et al.*, 2012, 2014) extrapolates the water-surface recorded wavefield to an arbitrary surface e.g. seafloor, so that refraction events become the first arrivals across the shot record's offset range and reflections arrive after their associated refractions. The seafloor reflection is also removed from the downward continued seismic shot record, leading a survey geometry similar to land seismic survey without any ground roll (Arnulf *et al.*, 2011; Ghosal *et al.*, 2012, 2014).

The improvement gained in reflection and refraction event discrimination by DC of the source and receiver positions to the seafloor is illustrated in figure 2. Figure 2c shows the impact of downward continuation on the 12.0 km long streamer shot record located on the frontal slope in which the source and receiver positions are extrapolated to the seafloor (Figure 2d). The refracted phases, which are observed at very far offset between 9 and 12 km (Figure 2a), are now visible at the near offset extending until the end of the streamer. The direct arrivals and the effect of the seafloor reflections are thus superseded. The downward continued shot records are, therefore, easier to interpret and make velocity-depth model building through first arrival tomography more accurate.

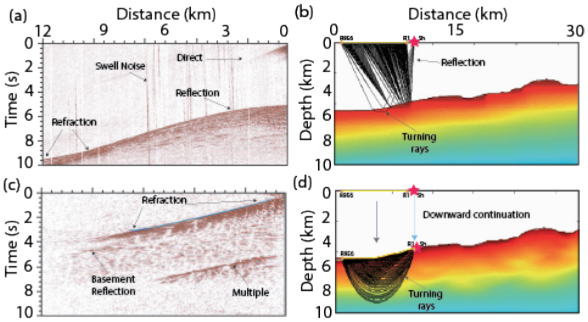

**Figure 2:**(a) Raw 12.0 km towed marine shot record and (b) associated ray diagram and (c) the same shot record after downward continuation (DC) to place the source and receiver positions on the sea-floor. Downward continuation separates the superposition of refraction and reflection events and ensures that the refractions are the first arrivals on the shot record. Black curves are reflections from the seafloor and turning rays in sediments.

### (ii) Travel time tomography of downward continued data:

Travel time tomography, which provides a smooth velocity-depth model, was carried out by inverting refracted arrivals from every fourth downward continued shot gather using the algorithm developed by Van Avendonk et al., (2004). The ray tracing of this downward continued shot gather (Figure 2c) is described in figure 2d. The shot and receivers are located on the seafloor after downward continuation and the rayfans mapped the subsurface until a depth of ~8.5 km (Figure 2d).

### (iii) Pre-stack depth migration of 5.5 km streamer data:

The interval velocity, which is required as the input for pre-stack depth migration, was obtained from NMO velocity analyses of 5.5 km streamer data, and the travel time tomography of OBS and downward continued 12 km long streamer data. We have used the same short streamer (5.5 km) data as used in the conventional processing, for pre-stack depth migration wherein sampling interval was kept as 2 ms, in order to obtain high-resolution image. Additionally, preprocessing steps were applied to remove swell noise and multiples. Apart from this, we have also applied inner trace mute on these data to effectively suppress the existing residual multiples from the near offset. Effect of side scattering is reduced by applying dip filtering. Moreover, a mild triangular anti-aliased filter was used by setting aperture length to 3.5 km during migration.

## Examples (Optional)

Figure 3 (left panels) shows three velocity models that were determined from the data recorded over 30 km segment of WG2 profile along the slope: (1) interval velocities calculated from the 5.5 km towed streamer data using conventional NMO approach (Figure 3a), (2) tomographic inversion of the sparse OBS data using travel time tomographic study (Figure 3c), and (3) the travel time tomographic inversion of the downward continued 12.0 km towed streamer data obtained from this study (Figure 3e). The interval velocity based on 12 km streamer data was similar to that of 5.5 km streamer data owing to higher slope. In each instance, the velocity-depth model was interpolated to a 500 m grid and was used for pre-stack depth migration of the 5.5 km long towed streamer data and are shown in the Figures 3b, 3d and 3f.

The velocity-depth model from the tomographic inversion of the OBS data produced poor migrated image (Figure 3d), simply because the OBS's were too far apart and their data could not accurately characterise the velocities in the topographically complex near surface. The interval velocities calculated from the 5.5 km streamer data are inaccurate and produce a poorly focused depth migrated image (Figure 3b). Tomographic inversion of the 12.0 km long offset streamer data produces the most accurate velocity-depth model. The resulting migrated image is sharp with clear definition of reflection events and faults (Figure 3f).

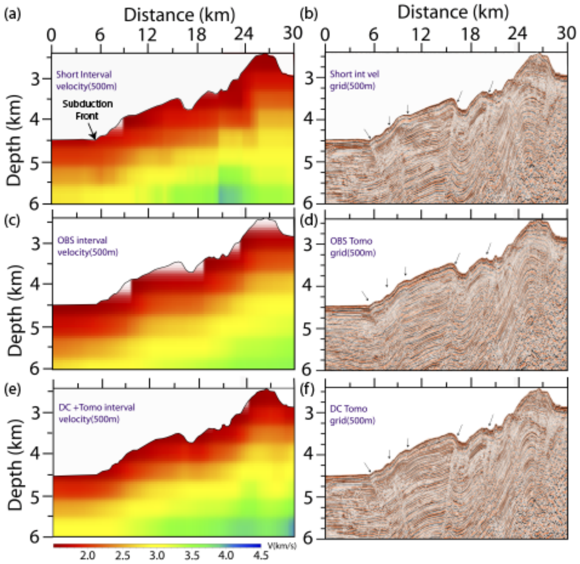

**Figure 3:** Velocity models on a 500 m grid and associated pre-stack depth migrations of the 5.5 km towed streamer data for: (a) interval velocities from the 5.5 km towed streamer data, (b) pre-stack depth migrated section using interval velocity derived from NMO picking velocity, (c) tomographic inversion of sparse OBS data recorded at the sea-floor, (d) pre-stack depth migrated section using interval velocity derived from inverted OBS tomography velocity, (e) tomographic inversion of downward continued 12.0 km towed streamer data, and (f) pre-stack depth migrated section using the interval velocity derived from high resolution tomography of downward continued data.

## Conclusions

Present study focuses on the effect of interval velocity-depth model derived from three different modeling techniques on a complicated geologic setting: northern offshore Sumatra. Since the conventional NMO analysis is based on the approximation of flat or shallow dipping reflectors only, the sudden changes of dip along the frontal slope cause severe complicacies in carrying out velocity modeling using this method and ends up with an erroneous velocity-depth model, which eventually leads to inaccurate imaging of the subsurface folded and faulted beddings.

The OBS tomography could be a great alternative to this NMO based technique, but due to limited number of OBSs with sparse spacing between two consecutive OBSs, the spatial and temporal resolution remained in the kilometer scale and was not efficient to model the finer details of the shallow subsurface structures and eventually lead to the poor depth migrated image.

The best image of the accreted sediments below the frontal slope is obtained using the downward continued streamer datasets. Relatively fine shot and group intervals (50m and 12.5m, respectively) associated with a very long streamer (12 km) accurately imaged the sedimentary column until a depth of 3 km below the frontal slope. As the refracted arrivals are very sensitive to the fluctuations of the fine layers, the inversion results from the downward continued data ultimately became very useful for pre-stack depth migration providing the best quality of subsurface image.

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