SEISMIC IMAGING OF THE DYNAMIC WATER COLUMN

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ABSTRACT

The reflection seismic method is the primary tool to investigate detailed subsurface structures. It assumes that subsurface changes occur on much larger time scales than the actual acquisition time of the seismic data. In seismic experiments in the dynamic ocean this condition is often not satisfied. To investigate the effects of the dynamic ocean on seismic images we conducted a 2D synthetic modeling study using an ocean model of the Mediterranean outflow through the Strait of Gibraltar. The model simulates mesoscale structures of the interaction between Atlantic and Mediterranean water masses. The salinity, temperature and density distributions were used to set up an acoustic model of the ocean for this area. Significant temporal velocity variations for the seismic acquisition were identified to be in the order of about 100 s. Therefore the acoustic ocean model was updated every 100 s during the synthetic seismic acquisition. For the seismic modeling a wave equation technique using a pseudo-spectral approach was used. Double precision arithmetic was required to avoid numerical artifacts because of the small acoustic impedance contrast in the ocean model. Among others two seismic experiments were simulated for the dynamic ocean. In the first experiment the acquisition direction was with the flow of the water masses whereas in the second experiment the data were acquired against the flow direction. The data set was processed using the conventional CMP approach to generate stacked images. The comparison of these images revealed a dependence of the reflections on the acquisition direction. Despite similarities in the reflection events of dominant structures significant differences are observed. Some imaged events are found only in one of the sections but not in the other one. All events imaged against the flow appear shorter in their lateral extent. Moreover, the surface roughness of the imaged structures displays a shorter spatial wavelength than for the events imaged for the data acquired with the flow. These differences in spatial extent and surface roughness are unlikely to lead to the same oceanographic interpretation. Conclusions on the lateral extent and surface roughness of structures in the ocean need to be considered with great care if no appropriate correction for the dynamics is applied. These corrections are, however, not yet available. The conventional CMP approach does not appear to be the appropriate method to process ocean seismic data since it averages over the whole acquisition time in the stacked image. Even on the time scale for the acquisition of a single CMP dynamic effects may already influence the seismic gather particularly for high fold long-offset data. Since single shot data are acquired within a few seconds they are free of effects of the dynamic ocean. Single shot processing, however, does not provide the advantages of the CMP reflection seismic method.

INTRODUCTION

Reflection seismic techniques are usually applied to analyze the solid earth. These methods also allow to image acoustic boundaries within the ocean and are called seismic oceanography (SO). This phrase was introduced by Holbrook et al. (2003) who linked reflections of the water column to the thermohaline structure in the ocean. Since then, a great variety of acoustic ocean structures were imaged using reflection seismic data. These structures were, e.g. intrusions, internal waves, fronts (Holbrook et al., 2003), water mass

boundaries (Nandi et al., 2004), top and base of the thermocline (Géli et al., 2005), meddies and cyclones (Biescas et al., 2008; Ménesguen et al., 2012), as well as several features of the Mediterranean Undercurrent (Buffett et al., 2009) and thermohaline staircases (Fer et al., 2010). Furthermore, seismic data were used to infer physical properties of the water, like temperature and salinity (e.g., Páramo and Holbrook, 2005; Wood et al., 2008; Papenberg et al., 2010) or to estimate the energy of internal waves (Holbrook and Fer, 2005) and diapycnal mixing rates (Sheen et al., 2009). So far, an important characteristic of the ocean, its dynamic behavior, was neglected in most SO studies although the dynamics of the ocean can cause relevant reflector movement during the seismic data acquisition. For example, with water flow velocities between 0.1 - 0.5 m/s and a ship velocity of about 2 m/s the water body would move between 1 - 5 km during the seismic acquisition for a 20 km long profile.
It was already shown by, e.g., Vsemirnova et al. (2009) and Klaeschen et al. (2009) that the dynamics in the water column can considerably affect the seismic image. They observed different reflector undulations in two seismic profiles recorded at the same location but acquired in opposite directions. They related these and similar observations in synthetic data experiments to the direction of ship movement relative to the direction of reflector movement. The difference in reflector undulation is a result of the well-known Doppler-effect. Vsemirnova et al. (2009) demonstrated that internal wave spectra derived from seismic data (see, e.g., Holbrook and Fer, 2005; Fer et al., 2010) are erroneous if the reflector movement is not correctly considered. In addition, Klaeschen et al. (2009) developed a method to estimate the velocity and direction of reflector movement from seismic data, but under the assumption of a known correct seismic velocity for spatially stationary reflectors, which limits the method (Klaeschen et al., 2009). Also others (e.g., Géli et al., 2009; Carniel et al., 2012) observed short-term variability of the reflectivity of the water column by repeatedly recording seismic profiles within a few hours.
So far only a few studies on the influence of ocean dynamics on seismic data were performed and at present no solutions exist to take reflector movement into account during data processing. Prior to quantifying reflector movement and incorporating it in data processing it is interesting to investigate its actual influence on the seismic images obtained with conventional data processing work flows currently applied in SO. A comprehensive modeling study using different acquisitions for an existing ocean model can quantify the influence of water movement on the resulting seismic images. This provides the motivation of our work.
In this paper we present a 2-D synthetic seismic modeling study based on a dynamic ocean model of the Mediterranean outflow through the Strait of Gibraltar into the Gulf of Cádiz. We display reflection images for various acquisition geometries and model situations. In the next section the synthetic seismic experiment is described, then we present the dynamic ocean model and finally imaging results obtained from the synthetic data using conventional processing work flows. Discussion and conclusions finalize the study.

SYNTHETIC SEISMIC EXPERIMENT

To evaluate the influence of the dynamics in the ocean on the seismic image we computed four synthetic data sets using the same dynamic ocean model. The model used in this work is a 2D dynamic ocean model of the Mediterranean outflow through the Strait of Gibraltar into the Gulf of Cádiz kindly provided to us by Nuno Serra. For the computation of each data set we used exactly the same model geometry. Two data sets were computed for the dynamic model, i.e., the acoustic properties change with time. The velocities are a function of position and acquisition time. We consider two acquisition geometries, i.e., with the flow and against the flow of the water masses. Additionally, two data sets for static models were computed for comparison with the images of the dynamic model. The static models represent two velocity snapshots of the dynamic model, i.e., two velocity sections for two fixed times. For these models the velocities are only dependent on position. The first static model represents a velocity snapshot of the dynamic model at the beginning of the acquisition, the second static model corresponds to a velocity snapshot of the dynamic model at the end of the acquisition. The static models are not realistic scenarios for ocean seismic data but are shown here as a reference result for comparison with the data from the dynamic model. For these data the fundamental assumption of CMP processing that reflectors are stationary is fulfilled. For easier identification of the different data sets we named them according to Table 1.

For the modeling of each data set 625 shots were computed with a maximum offset of 2000 m and a total of 101 receivers. The shot and receiver spacing was 40 and 20 m, respectively. For DYN-right

Table 1: Names and description of the data sets presented in this paper.

Name of data set	Description of data set
DYN-right	Dynamic model. The ship movement is to the right. First shot was at the left side of the model (at kilometer 2) and the last shot of the data set is at the right side (at kilometer 27).
DYN-left	Dynamic model. The ship movement is to the left. The first shot was at the right side of the model (at kilometer 25) and the last shot of the whole data set is at the left side (at kilometer 0).
STAT-beg	Static model representing the velocity snapshot of the dynamic model at the beginning of the acquisition. The acquisition geometry is the same as for DYN-right.
STAT-end	Static model representing the velocity snapshot of the dynamic model at the end of the acquisition. The acquisition geometry is the same as for DYN-right.

and the static models the acquisition is designed such that the ship moves to the right for the synthetic data modeling , i.e., the first shot is at 2 km and the last shot is at 27 km. Data set DYN-left is computed with the ship moving to the left, i.e., the first shot is at 25 km and the last shot is at 0 km. The acquisition geometry is sketched in Figure 1(f). Please note that the CMP locations of DYN-left do not cover the same area as the other acquisitions. This should be kept in mind, because it could lead to confusions when comparing the different seismic images of the model. In total, 2597 CMPs were acquired covering an area of 25.96 km with a CMP spacing of 10 m. Assuming a ship velocity of 2 m/s the recording time of the seismic line is 208 min. for continuous shooting with a firing interval of 20 s. The fold is 25 and it takes more than 8.5 minutes to complete a CMP. In the next subsection we present the dynamic model and discuss the variability of the velocity model during the recording time of a seismic line.

Model description

The model used in this work is a 2D dynamic ocean model of the Mediterranean outflow through the Strait of Gibraltar into the Gulf of Cádiz. The time sampling is 100 s so that for every 5th shot an updated velocity model is used for the computation of the data sets for the dynamic models. On a time scale of less than 100 s the temporal variations for this model are too small to influence the seismic image. Since the acquisition time to complete a CMP is more than 8 minutes changes in the dynamic model even affect a single CMP gather. This model was already used by Vsemirnova et al. (2009) and Klaeschen et al. (2009), but with a temporal sampling interval of 900 s. The model simulates mesoscale structures of the interaction between Atlantic and Mediterranean water masses (see Figure 1(d)). The Mediterranean water is situated in a basin on the right side of a Gaussian-shaped sill that represents the Strait of Gibraltar. The water flows to the left over the sill, following the continental slope into the stratified water body representation of the Gulf of Cádiz where it reaches a depth of neutral buoyancy between approximately 500 and 1500 m. On the top of the Mediterranean water a flow of fresher, less dense water counter flows to the right, entering the basin with the Mediterranean water on the right side of the sill. This setting realistically resembles large scale mixing and entrainment processes with respect to the entrainment rate, rate of descent and level of neutral buoyancy (Vsemirnova et al., 2009). However, there are some limitations in this model. The resolution and 2D nature of the model do not allow to describe some specific mixing and fine scale processes in the Gulf of Cádiz. Nevertheless, the model is sufficient for studying the influence of the dynamic ocean on the seismic image, since the influence of the dynamics in the water can be seen already on large scale structures.

The oceanographic model provides the spatially and time dependent temperature, density and salinity. This information is used to compute the acoustic properties, i.e., sound speed of the water column using the EOS80 equation (CSIRO, 2010). The variation of the sound speed in the whole model is less than two percent with a minimum velocity of 1497 m/s and a maximum of 1526 m/s. The resulting impedance contrasts (product of velocity and density) are rather small and require special consideration in the seismic modeling as described below. Figure 1(d) shows the acoustic velocity snapshot of the model taken at the time of the first shot. Two black lines mark the part of the model which was actually used for the generation of the synthetic seismic data sets. The acoustic velocity snapshots for three different times are presented

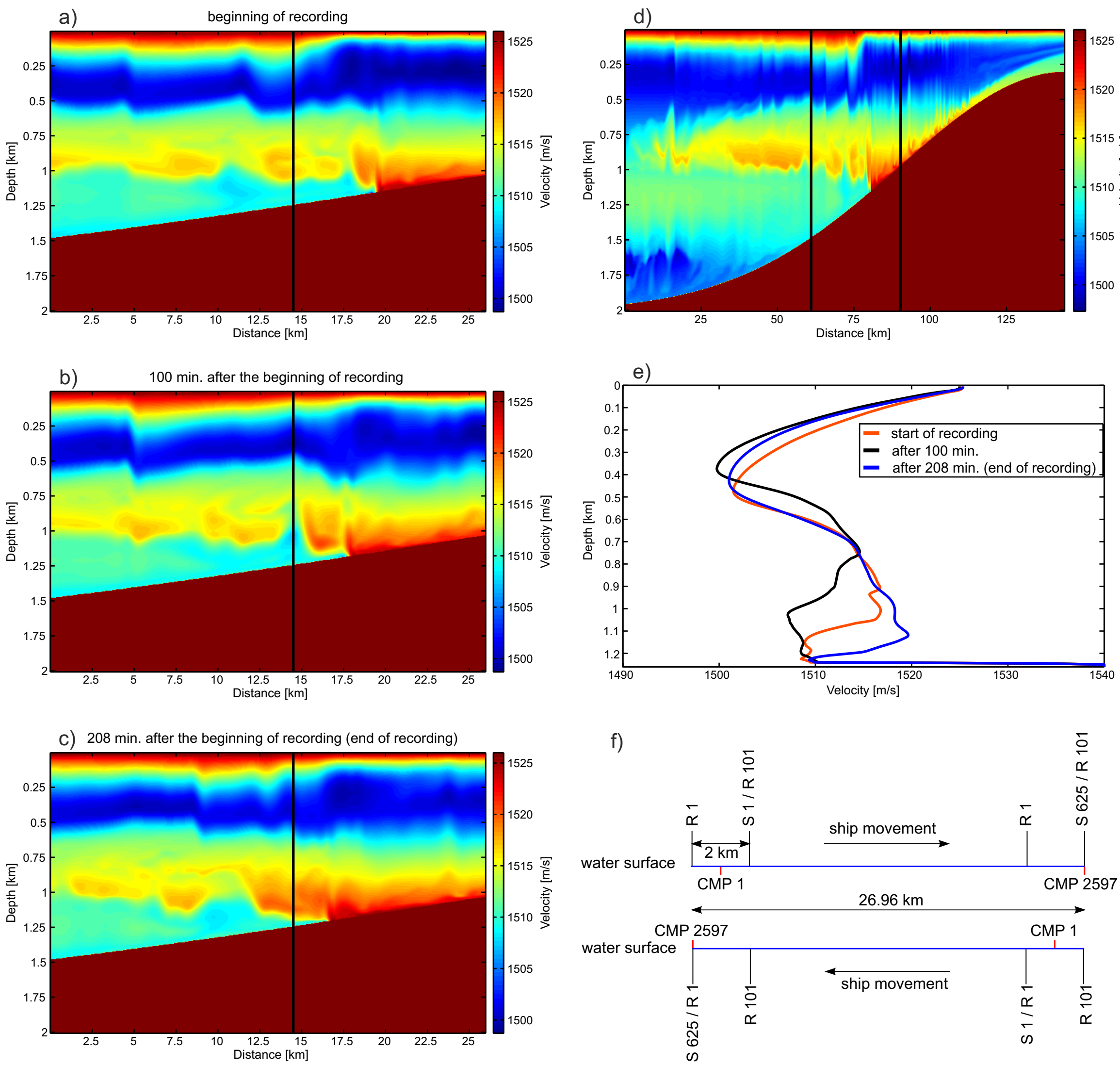

Figure 1: In (d) a snapshot of the acoustic velocities of the oceanographic model is shown. The velocities were taken at the time the first shot is recorded. Two black lines mark the model excerpt which was used for the synthetic data experiment. (a), (b) and (c) show snapshots of the model excerpt at the time of the first shot, 100 min. later and at the time of the last shot, respectively. For a better visualization the color scale is clipped. The sub-seabed velocity is 1540 m/s. The vertical lines in (a), (b) and (c) mark the position where the 1D velocity depth profiles were extracted. The 1D velocity depth profiles for the different times are jointly plotted in (e). The acquisition geometry used for DYN-right, STAT-beg and STAT-end is sketched in the upper part of (f) and for DYN-left in the lower part. R1, R101, S1 and S625 mark the positions of receiver 1 and 101 and shot number 1 and 625, respectively. In total 2597 CMPs are acquired.

in Figures 1(a), 1(b) and 1(c). The higher acoustic velocities (red to yellow colors) of up to 1526 m/s mark the Mediterranean water body which is surrounded by Atlantic water with lower acoustic velocities with a minimum of 1497 m/s. To prevent the sea bottom reflection from dominating the seismic image the sub-seabed velocity was set to 1540 m/s, which is close to the seismic velocity in the water. When comparing the three different velocity snapshots, it can be observed that boundaries between Atlantic and Mediterranean water move horizontally and vertically throughout the recording time. The most significant water movement in the model is the migration of the Mediterranean water "front" to the left observed at a depth between 800 and 1200 m. At the beginning of the recording (Figure 1(a)) this front appears at a distance of approximately 18 km. During the recording it advances about 6 km to the left to approximately 12 km at the end of the recording (Figure 1(c)). For the position marked by a black line in Figures 1(a-c) velocity variations during the recording are compared to each other by overlaying the vertical velocity depth profile of the snapshots (Figure 1(e)). Vertical shifts of the boundary between the Atlantic water and the Mediterranean water layer as well as changes of layer thickness in the order of several 100 m can be observed. With a typical horizontal and vertical resolution of marine seismic measurements of less than 10 m, these reflector movements can be easily resolved. Hence, they might cause distortions in the seismic image. Another important observation is the velocity variation at one and the same position in the 1D profiles. In the depicted example the maximum velocity change of 12 m/s or about 0.8 % occurs at a depth of 1120 m.

Velocity changes and reflector movements during the acquisition of a seismic line are not included in the theory of the conventional reflection seismic CMP method, which assumes a static subsurface during the acquisition. With this modeling case study we want to quantify the effect of the dynamic ocean on the seismic image for a particular ocean model and discuss possible consequences for the oceanographic interpretation of the images. In the next section we describe the numerical seismic modeling and the processing of the data to obtain stacked sections.

Computation of synthetic seismic data and processing

For the computation of the synthetic seismic data we used a 2D isotropic seismic modeling program that solves the wave equations directly where the spatial partial derivatives are computed by a pseudo-spectral method. Time integration is performed by the rapid expansion method (see description of the method e.g. in Kosloff et al. (1989)). For the modeling of the synthetic seismic data a sample interval of 1 ms and a Ricker wavelet with a maximum frequency of 120 Hz (peak frequency of 60 Hz) were used. The minimum seismic wave length is about 12.5 m when an average velocity of 1500 m/s is assumed. To satisfy Shannon's sampling theorem for the pseudo-spectral approach the horizontal and vertical resolution of the model was chosen as 5 m in both, vertical and horizontal direction. The grid was resampled from the original oceanographic model with a sampling of 160 m in the horizontal direction and 2 m in the vertical direction. Numerical experiments revealed that a time step of 100 s for the oceanographic model is sufficient. Changes in the model for shorter time intervals were negligible for seismic modeling. With a temporal shot interval of 20 s the model had to be updated for every fifth shot of the numerical seismic experiment.

In the modeling process we encountered problems previously unknown from computing seismic data for conventional solid earth subsurface models. The impedance contrasts in the ocean are significantly smaller than typical impedance contrasts of rocks, which leads to very small reflection coefficients in the water column in the order of 10^{-4}. When performing the computation of the data with a computational accuracy of single precision, the amplitudes of the water column reflections are only one order of magnitude larger than the amplitudes of the numerical noise. A computational accuracy of single precision usually is sufficient for the modeling of conventional seismic data. For synthetic SO data the seismograms are affected by numerical noise due to the weak amplitudes of water column reflections. Computational accuracy of double precision led to satisfactory results. This conclusion applies not only to the pseudo-spectral but also to the Finite-Difference approach. We performed tests for Finite-Differences that showed similar noise features and structures in single precision arithmetic as the pseudo-spectral approach.

Since the strong amplitudes of the direct wave mask shallow weak water column reflections direct wave removal is a standard procedure in ocean seismics. In 2D synthetic ocean seismic modeling additional care is necessary with respect to the 2D Green's function due to a line source. The 2D Green's function is not a spike as for point sources in 3D media (Aki and Richards, 1980) but a time signal with an impulsive rise and a long tail where the amplitudes never reach zero. In solid earth modeling reflection amplitudes are considerably higher than the amplitudes of the tail of previously arrived events. However, the weak ocean seismic reflection amplitudes might be hidden in the tail of earlier arriving events which requires special processing next to the direct wave removal (see Raub (2011) for further details).

MODELING RESULTS

To evaluate how strongly seismic images of the water column are influenced by the dynamics of the water column we compare stacked sections of the dynamic model (Figures 2 and 3 with stacked sections of static models displayed in Figures 4 and 5. Only few similarities between these images are discernible at first sight. Particularly the two images of the dynamic model but with opposite acquisition direction reveal substantial differences. This includes the structural features as well as the position and lateral extent of imaged events. It is unlikely that any interpreter would attribute these images to the same dynamic ocean model. The two static models also display more differences than similarities. This first analysis shows that the dynamics of the water column have a strong influence on the images generated from reflection seismic data using conventional reflection seismic processing.

Usually, in conventional field operations, only one of the two data sets of the dynamic model is acquired and in some cases the flow direction in the area of interest might not a priori be known. In a synthetic data experiment as considered in this study it is possible to additionally look at snapshots of the dynamic model. Some similarities between the stacks of the dynamic model and the static models are visible but only in areas where the acquisition times coincide as discussed in the folling paragraph.

The acquisition of DYN-right started at the left side of the model and progressed to the right side. Thus, the stack of DYN-right and the stack of the static model that represents the beginning of the recording (STAT-beg) are most similar at the very left side of the stacks. Following the same principle, similarities can also be observed between the stacks of DYN-right and STAT-end (Figure 5). Since the acquisition of DYN-right ended at the right side of the model the stacks of DYN-right and STAT-end match the most at the right side of the stacks. In the stack of DYN-left (Figure 2) the area that is most similar to the stack of STAT-beg is at the right side of the stack, since the acquisition of DYN-left started there.

The comparison is shown here just for illustration purposes since it is not realizable in field work. One obvious difference between the stacks is the lateral position where strong water column reflections touch the sea bottom reflection. This position varies between a distance of 19 km in the stack of STAT-beg and 12.5 km in the stack of STAT-end, whereas the stack of DYN-right shows it only at 15.5 km and the stack of DYN-left at 17 km. Evidently, the stacks of the dynamic model represent local vertical snapshots, i.e., small stripes, representing the dynamic model around this particular lateral position at the corresponding recording time, instead of showing a snapshot of the whole subsurface like it is the case for a crustal image with static subsurface features. This explains the good comparison of the two stacked sections of the dynamic model in Figures 3 and 2 at the position indicated by a vertical line representing the same recording time for both acquisitions, i.e., both acquisitions were "seeing" the same velocity distribution at this time and location. Please note, that the comparison in two-way-time is almost perfect along the vertical line. However, the lateral extent of the events differs significantly due to the different acquisition directions. The interpretation of lateral extensions of events appears to be very involved if acquisition direction with respect to flow direction and flow speed are unknown. Evaluations of wave spectra and surface roughness of internal ocean features derived from reflection seismic data have to be performed with greatest care to say the least.

In the stack of DYN-right strong reflections can be observed at a distance from 1 to 8.7 km between 0.1 and 0.95 s. One of these reflections is marked by a black arrow. These events are not visible at all in the stack of DYN-left. Another difference can be seen from a distance of 20 km and extending to the right side of the stacks at times between 1 and 1.4 s. In both stacks the area with the mentioned events is marked by red arrows. In the stack of DYN-left these reflections are almost parallel to the sea bottom reflection. In contrast to that, in the stack of DYN-right, the reflections undulate and appear discontinuous, which may indicate a turbulent environment. Both images would most likely lead to different interpretations of oceanographic features.

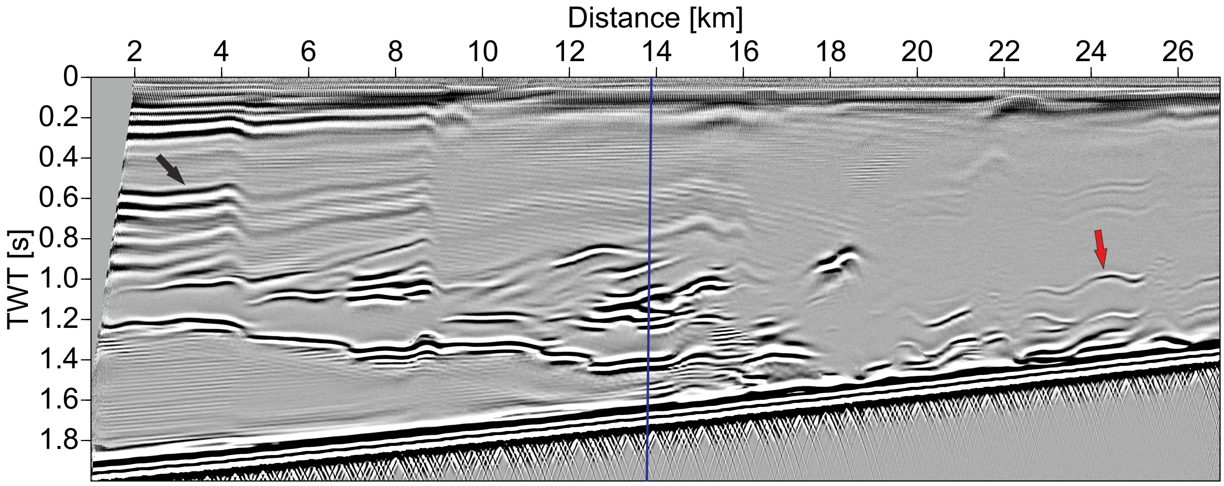

Figure 2: Stacked section of DYN-right. The vertical line marks the location where the velocity distributions in DYN-left and DYN-right are identical. The arrows point out areas that differ significantly in both stacks.

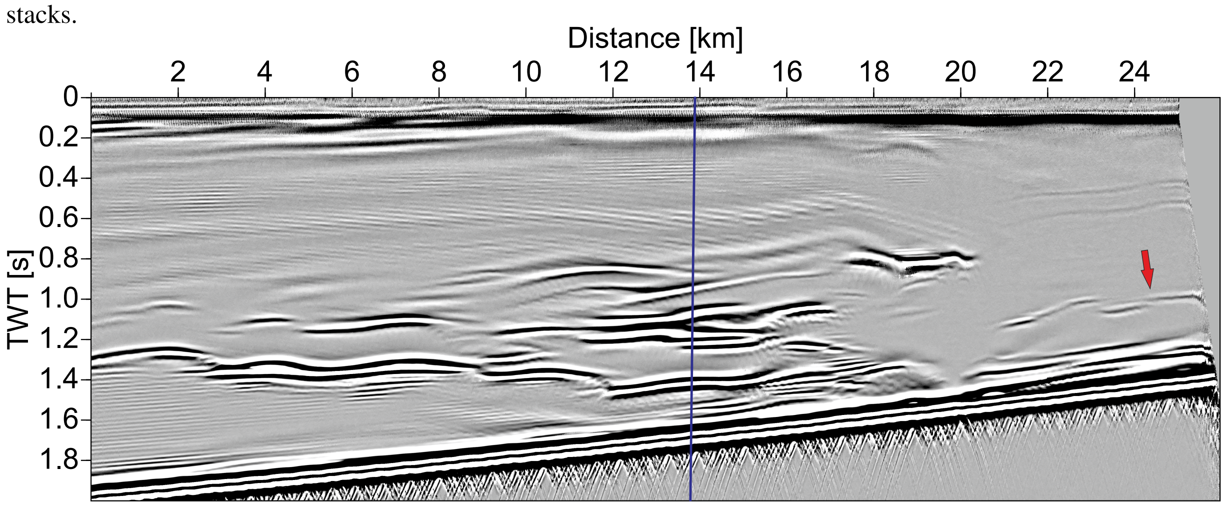

Figure 3: Stacked section of DYN-left. The vertical line marks the location where the velocity distributions in DYN-left and DYN-right are identical. The arrow marks one area which appears different in the stack of DYN-right.

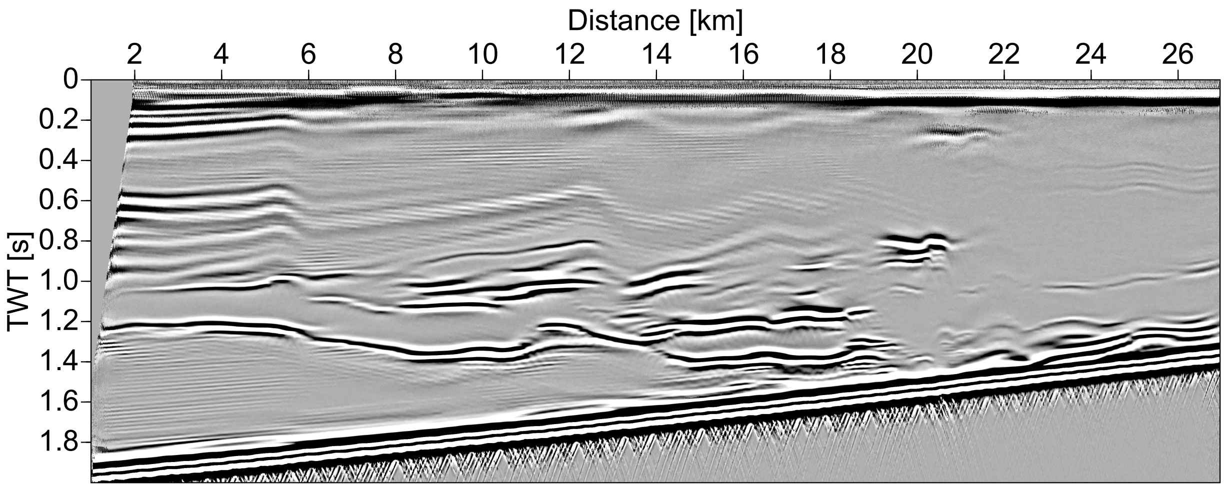

Figure 4: Stacked section of STAT-beg.

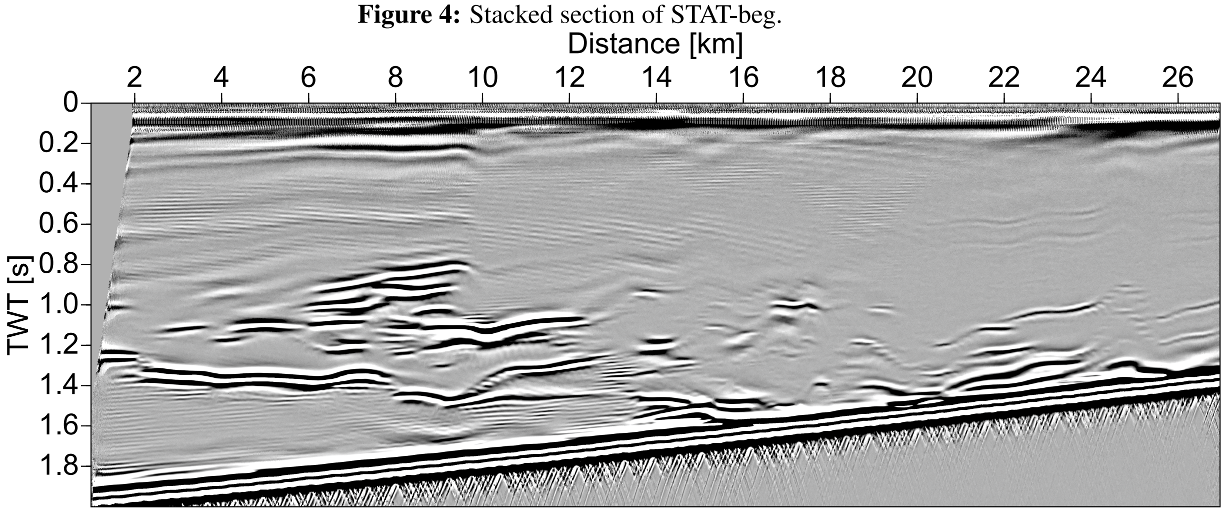

Figure 5: Stacked section of STAT-end.

The difference in lateral extent of the imaged features is a result of the Doppler effect. In the stack of DYN-right we observe a reflection terminating at the left side of the stack at approximately 1.22 s and extending to a distance of approximately 14.5 km. This event is disrupted into six smaller reflection segments with lengths between 1 and 2.4 km. A similar reflection is also seen in the stack of DYN-left at approximately 1.3 s. But here it appears stretched and consists of only four reflection segments with lengths from 2.3 to 6.2 km. In general it can be said that reflections in the stacked section of the data from the dynamic model with the ship moving in the opposite direction of the reflector movement are shortened while in the stacked section of the dynamic model with the ship moving in the same direction as the reflector movement they appear stretched. Similar observations on synthetic data and field data have been made by Vsemirnova et al. (2009) and Klaeschen et al. (2009).
As the last processing step we performed a depth conversion using a constant velocity of 1520 m/s in order to shift the reflections from the time section to the correct reflector positions in a depth section. Usually this step is performed by pre-stack depth migration after velocity model building. Due to small velocity changes and small reflector dips in the water column, we may not expect to see significant differences between sections obtained after depth migration and after simple depth conversion. Therefore, we chose the simple transformation of the vertical axis from time to depth with a constant medium velocity.
In the digital supplementary material to this paper two movies labeled ModelWithDYN-right.avi and ModelWithDYN-left.avi can be found. They compare the respective seismic images of the dynamic model to the velocity model by overlaying the seismic images of DYN-right and DYN-left with the sound speed. The snapshots of the movie at the recording time of the first and the last shot are shown in Figures 6a and 6b for the data set DYN-right and in Figures 7a and 7b for the data set DYN-left. The reflectors with the strongest amplitudes in the water column are observed around the Mediterranean water body and are caused by the transition of the Mediterranean water to the lower and upper Atlantic water layers. The Mediterranean water can be recognized by yellow to red colors at a depth between 700 to 1100 m. Throughout the recording the depth level of the Mediterranean water changes only slightly. Thus, in this synthetic data experiment the seismic images of the dynamic model are able to resemble roughly the mean buoyancy depth of the Mediterranean water body. The lateral position of structures in the model and their horizontal extension cannot be interpreted quantitatively without further information (e.g., flow speed of water masses, acquisition with respect to flow direction). For example the position where the Mediterranean water body detaches from the sea bottom propagates from right to left in the dynamic model. In the seismic images of the dynamic model this appears at different positions for the data sets with opposite acquisition direction, which would lead to different interpretations of the images.

Short reflector segments in the images of the dynamic model match the position in the snapshot of the dynamic model representing the time when this reflector segment was recorded. The lateral extension of this reflector segment cannot be interpreted like data acquired over a static subsurface. The reflector extension appears stretched or shortened, depending on the direction of acquisition. None of the two stacks of the dynamic model matches the dynamic model throughout the whole recording time and the images show quite different characteristics despite the same dynamic ocean model. DYN-right appears more choppy with numerous shorter undulating reflector segments compared to the image of DYN-left, which seems to represent a calmer water column. The feature both images have in common is the depth level at which the strongest reflectors of the water column are located.

DISCUSSION

In this seismic modeling study we conducted a reflection seismic experiment using a time-dependent dynamic ocean model. Salinity, temperature and density of this model were used to determine the acoustic properties, i.e., the sound speed distribution of the ocean. The time step of the ocean model was 100 s. With a shot interval of 20 s the acoustic ocean model was replaced by the updated one after every 5th shot of the acquisition. Seismic reflection coefficients in the water column are rather small compared to seismic modeling in the solid earth. To avoid numerical artifacts in the resulting seismograms double precision arithmetic was required. Some of these artifacts even display hyperbolic moveout and can be easily confused with ocean seismic reflections (Raub, 2011). This applies to Finite Difference modeling codes as well as to pseudo-spectral approaches. The latter was used for generating the synthetic seismic data in this

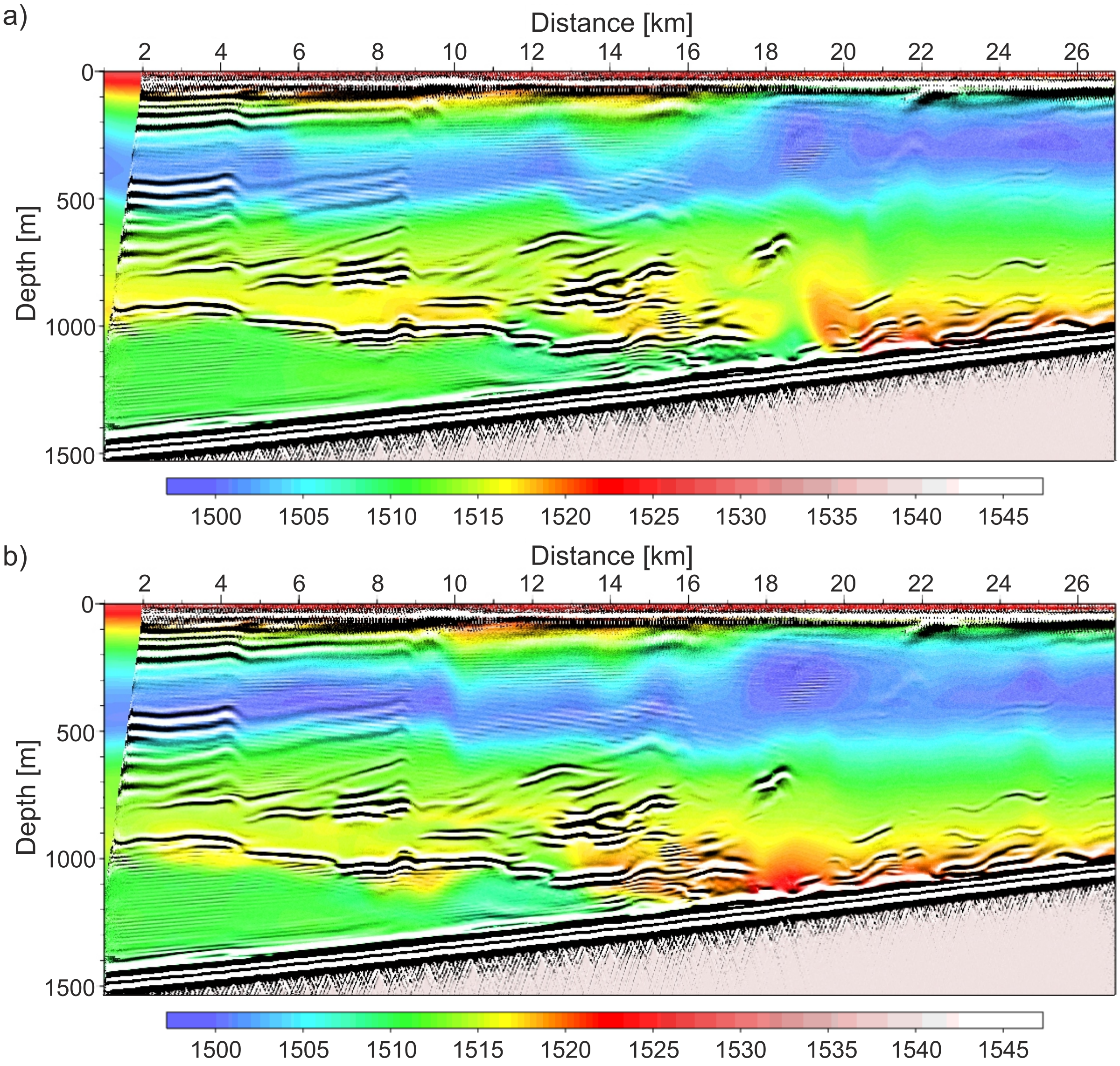

Figure 6: Seismic image of DYN-right on top of snapshots of the sound speed for the dynamic model at the beginning (a) and the end (b) of the recording. The color bars show the acoustic velocity in m/s.

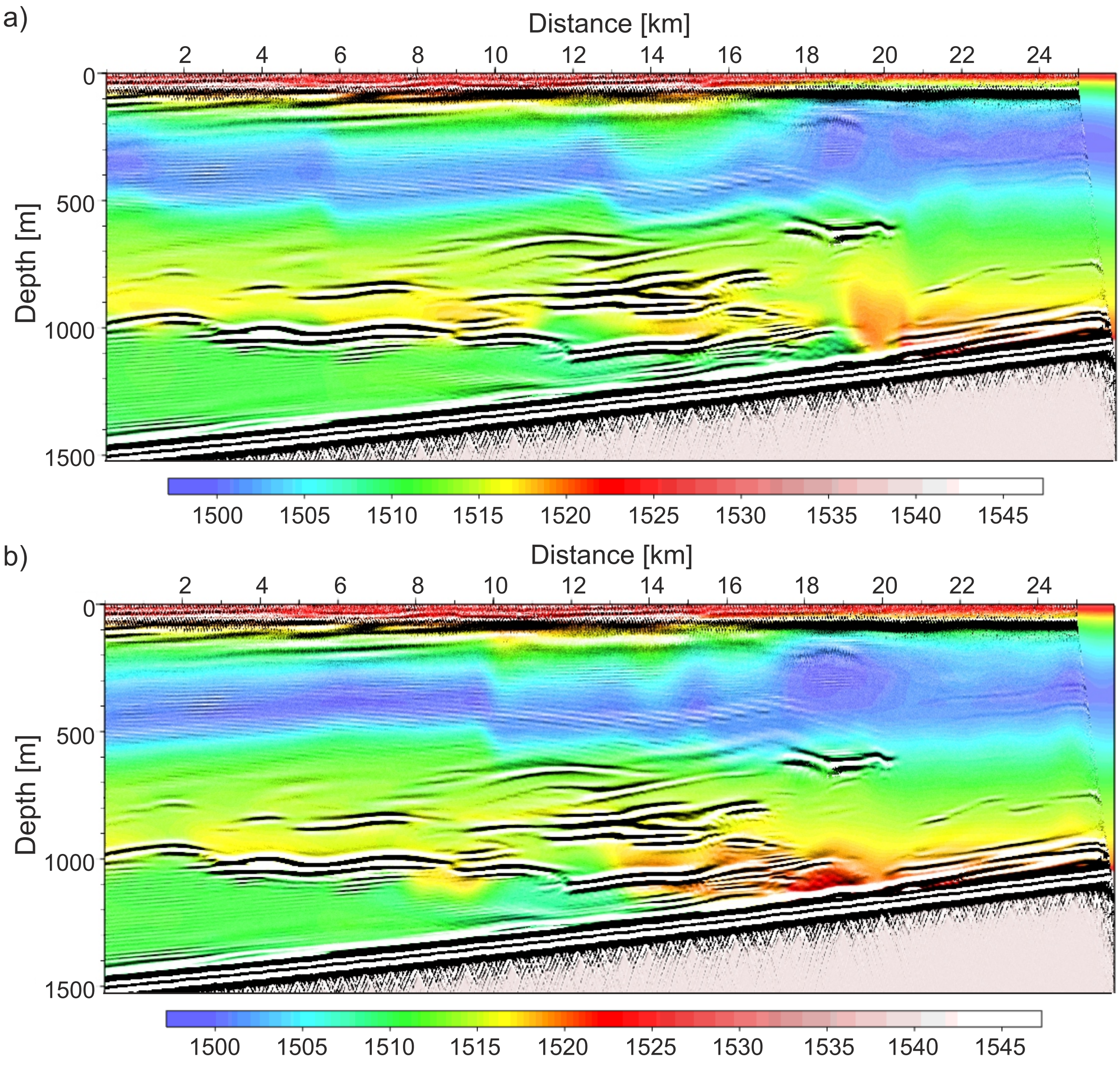

Figure 7: Seismic image of DYN-left on top of snapshots of the sound speed for the dynamic model at the beginning (a) and the end (b) of the recording. The color bars show the acoustic velocity in m/s.

paper.
We have shown that conventional CMP processing of seismic data of a dynamic ocean reveals strong dependence of the resulting seismic images on acquisition direction and acquisition time. These effects are unknown for solid earth seismic imaging and processing since the subsurface changes on time scales much larger than the acquisition time. Although several structures in the images can be attributed to certain features of the oceanographic model we should keep in mind that we made these correlations based on a precise knowledge of the ocean model at any time of the acquisition. In field experiments this is usually the other way around since we want to determine ocean features from the seismic image. A blind test with the images obtained with different acquisition directions would most likely identify the region with most structural features, e.g., dynamics. These regions are between 11-18 km in the seismic sections and right above the sea bottom in the right part of the section. The characteristics of the events, however, are very different. Whereas the events for DYN-left appear elongated with a long spatial wavelength in the undulation or roughness we observe considerably shorter elements with undulations of shorter spatial wavelength for DYN-right. It appears unlikely that one would draw the same conclusion with respect to the ocean dynamics from the two images.

CONCLUSIONS

We conducted a synthetic seismic data experiment to evaluate the influence of the dynamics in the ocean on conventionally processed seismic images. As the comparison between the stacks of DYN-right and DYN-left clearly demonstrates, the interpretation of seismic images of the ocean has to be handled with care due to the displacement and shortening or stretching of reflections caused by dynamics. For example, the analysis of reflector lengths, e.g., Biescas et al. (2008), who analyzed reflection lengths in seismic images from three different meddies, is challenging. The same applies to investigations on the spatial wavelength of reflection undulations or reflector surface roughness, e.g., Holbrook and Fer (2005), who estimated internal wave energy and Sheen et al. (2009) who determined spatial variances of diapycnal mixing rates by extending the approach of spectral analysis. Similar approaches based on the use of quantitative interpretations of the lateral extension of reflectors have to be regarded with great caution. The merging of seismic profiles recorded at different days or seasons is also considered to be critical since they may image different features. E.g., Pinheiro et al. (2010) merged two seismic lines that were acquired in opposite directions and with a time break of three days. Depending on the strength of the dynamics in the ocean, distortions in the image are present, which need to be considered during the analysis. If neglected, the oceanographic interpretation of the images may lead to erroneous conclusions.
The reflection seismic method still is a helpful and unprecedented tool for remote investigations of the ocean, considering that conventional oceanographic measurements cannot compete with the lateral resolution of seismic data. But the processing techniques and interpretation of the data should be revised. For example, the recording time to complete a CMP may be short enough not to be influenced by the dynamics of the ocean. The time to complete a CMP depends on the total fold and the shot interval. For data with high fold over a dynamic ocean even a single CMP gather may be affected and interpretation techniques like, e.g., amplitude versus offset (AVO) studies may be prone to errors. Low fold CMP gathers (e.g., by skipping larger offsets) may be suitable for AVO analysis though. Another possible approach is to process shot gathers since they are completed within a few seconds, whereas the completion of a 100 fold CMP gather requires about half an hour provided a 20 s shot intervall is maintained throughout the acquisition. The analysis of stacking velocities revealed that even in a single CMP gather the influence of the dynamics in the water is detectable.
Further investigations are required to assess which information can be actually derived from an image of the dynamic ocean. For field data it would be helpful to perform simultaneous acquisitions with two ships recording the same seismic line with opposite directions. Unfortunately, the high acquisition costs may prevent such an experiment. One may argue that the ocean model chosen in this paper is an example with particularly strong dynamics and that in many other situations the dynamics may have a small impact on the seismic images. However, it is just these areas of strong dynamics that are of particular interest to oceanographers and it is not by chance that this region was already investigated in several other studies. An already common procedure in SO experiments is the simultaneous recording of oceanographic measurements during the acquisition of seismic data. Most typical are measurements of temperature and salinity

depth profiles, but also flow velocities of the water can be directly obtained. They could be used to estimate the influence of the dynamics in the water on the seismic images. A synthetic experiment under controlled conditions that combines data from oceanographic measurements with synthetic data from a dynamic ocean model would yield an improved understanding and further insights into the subject.
Due to the high variability of the seismic images of the dynamic ocean the commonly used expression seismic oceanography appears to be misleading. Ocean seismics or water seismics provides images that depend on acquisition direction and time. The careful interpretation of these images including the effects of the dynamics of the ocean may still lead to conclusions valuable to oceanographers. These methods, however, are not yet quantified and routinely applied. Whether there are alternative techniques besides the conventional CMP approach for processing ocean seismic data to properly account for effects of the dynamic ocean needs further investigation. Processing and imaging on a shot basis could be an option since it is free of time dependent effects of the ocean. Stacking provides a first subsurface image and increases the S/N ratio compared to the CMP data. These advantages we would lose when considering single shots only. Shot gather migration could lead to results suitable to estimate reflector movement. However, since we should not stack more than a few shots, the image may display migration artifacts because of poor illumination of reflecting structures. Moreover, the S/N ratio of these images may be too poor for quantitative interpretation because of the weak ocean reflections. The power of the reflection seismic method has its foundation in the multifold principle by imaging the very same part of the subsurface from different angles. In a dynamic ocean, this part of the subsurface, i.e., the ocean, is moving. The study in this paper has shown that the effects are not negligible if a realistic ocean model is considered. For 4-D studies in the solid subsurfaces the dynamics of the ocean may mimic or even cover the processes in the reservoir.

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