

Estimating movement of reflectors in the water column using seismic oceanography

D. Klaeschen,¹ R. W. Hobbs,² G. Krahmann,¹ C. Papenberg,¹ and E. Vsemirnova²

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[1] The observation of spatial and temporal dynamics of the ocean is fundamental to understand global and regional aspects of water mixing. Physical oceanography has traditionally observed ocean structures with in situ measurements, often limited in temporal and/or spatial resolution. In exploration seismology a set of techniques has been developed over the last decades to image and characterize the physical properties of sub-seafloor structures by inversion methods at high horizontal resolution. The two different fields have made contact in seismic oceanography where the well developed methods of marine reflection seismology have been applied to the dynamic ocean. However, one aspect, so far ignored in seismic oceanography, is the dynamical, temporally varying nature of water structures. Here we show that it is possible to estimate temporal variations of reflectors in water structures as an inversion parameter. The new dynamic property reflector movement velocity gives an additional parameter to characterize ocean water dynamics. **Citation:** Klaeschen, D., R. W. Hobbs, G. Krahmann, C. Papenberg, and E. Vsemirnova (2009), Estimating movement of reflectors in the water column using seismic oceanography, *Geophys. Res. Lett.*, 36, L00D03, doi:10.1029/2009GL038973.

1. Introduction

[2] The new field of seismic oceanography used in its early stage existing seismic methods developed mainly for sub-seafloor characterization in hydrocarbon industry [Holbrook *et al.*, 2003]. Limitation and resolution originated from the physical parameters of the ocean were analyzed methodically and compared to oceanographic in situ measurements [Nakamura *et al.*, 2006]. It has been shown that seismic oceanography is able to map a physical contrast as a seismic reflector with lateral resolution of less than 10 meters and with frequency dependent reflection amplitude corresponding to the expected acoustic impedance contrast [Páramo and Holbrook, 2005]. Additionally, the multi-channel seismic (MCS) acquisition traditionally offers to the possibility to invert for sound speed [Klaeschen *et al.*, 2006; Wood *et al.*, 2008]. Seismic inversion methods using the complete wave field, amplitude and phase information were able to resolve the sound speed to a few meter/second. New inversion methods are continuously developed to directly address unresolved questions in seismic oceanography [Krahmann *et al.*, 2008].

[3] During the interdisciplinary GO (Geophysical Oceanography) project observations were located in the Gulf of Cadiz, a region with a strong subsurface boundary current of the Mediterranean outflow water (MOW) and known as a source of eddy-generation. Both oceanographic features show significant temporal and spatial variability with currents up to 0.5 m/s [e.g., Ambar *et al.*, 2008]. During the campaign a number of seismic repeat surveys (time lapse seismic) with repeat times from 30 min to 12 hours showed substantial changes of the seismic reflection patterns as well as lateral shifts of a Meddy's (eddy of Mediterranean water) frontal zone. During one particular repeat survey with 3 seismic lines and with a 12 hour repeat time the translation speed of a well defined Meddy front was estimated to be about 0.1 m/s in mostly westerly direction. A second and unexpected observation was apparent wave length changes of reflections depending on the orientation of the seismic profile. These changes appeared to vary in strength with the orientation of the seismic profile relative to the actual flow direction as measured simultaneously by oceanographic methods. This finding raised the idea of an effect somewhat similar to the Doppler-effect. As traditional seismology has always taken proper care of the ship's movement, it appeared that it was the reflecting boundary that was moving, a condition rarely, if ever, seen in sub-seafloor media.

[4] To study the underlying principles we first simulated a simple synthetic reflector boundary in form of a moving cosine with different movement directions relative to the ship. In a second step we applied the newly developed method on a more realistic oceanographic model simulating a gravity flow over sill, and finally we derived reflector movements for two real example sections from the GO project.

2. Method

[5] The presented seismic imaging approach is described and applied to 2D but the method in general can be extended and applied in 3D. The basic principles and terminology used in the following and in seismic oceanography in general are summarized and illustrated for both communities by Ruddick *et al.* [2009]. The fundamental processing step in the presented seismic imaging method is the migration, which increases the lateral and temporal resolution by reducing the Fresnel zone and correctly images the subsurface structures in space and depth with amplitudes corresponding to the impedance contrast in the subsurface. Depending on the complexity of the sound speeds, in general 3D-elastic media, an adequate algorithm is needed. In seismic oceanography the media possesses acoustically smooth lateral and spatial sound speed changes

¹Leibniz Institute of Marine Sciences at University of Kiel (IFM-GEOMAR), Kiel, Germany.

²Earth Sciences Department, Durham University, Durham, UK.

(only up to 40 m/s in the whole water column) and small reflector dips ($0-3^\circ$). Here a true amplitude pre-stack time migration is the most efficient approach with the advantage of analytically calculated travel time and weight functions to recover the amplitude information. However, migration algorithms are very sensitive to acquisition geometry errors. In the case of unknown movement of the subsurface structure the absolute geometry cannot be determined from the shot and receiver positions on surface alone. To overcome this computational problem we make two basic assumptions: (1) the correct sound speed is known for non-moving reflectors. (2) the reflectors do not move during the shot and the recording of the reflected signals, called 'stick-slip' model assumption. The first assumption is critical if there was no independent sound speed measurement acquired simultaneously with the seismic data. Assuming, for the second assumption the listening time does not exceed 2 s two-way travel time, a reflector speed of 1 m/s or 0.1 m/s will result in a lateral geometry error of 4 m or 0.4 m, respectively. With expected reflector speeds to be significantly less than 1 m/s and with the spatial CMP (common midpoint) distance for the GO survey of 6.25 m the 'stick-slip' assumption is adequate. Taken together these two assumptions simplify the computational problem and has a major impact for the efficiency of the migration because a single shot-gather migration image appears free of internal movement distortion, except a possible unknown lateral shift.

[6] To scan a seismic line for different hypothetical reflector movement velocities, migrated common image point (CIP) shot-gathers must be shifted laterally to each other (CMP renumbering). With additional knowledge of the acquisition time difference between the individual CIP shot-gathers a movement velocity can be assigned from the quotient of the spatial shift and temporal delay. With this procedure a series of images are constructed for a range of likely constant movement velocities. An issue here is that the variation of water movement velocities results in a change of the total seismic profile length because each seismic profile correspond to a restored image for an assumed constant movement velocity. To quantify the stacking efficiency for a given movement velocity, a phase coherency value between 0 and 1 is estimated for each data sample [Schimmel and Paulssen, 1997]. To compare the coherency values of the individual movement stacks, a lateral reference coordinate system must be defined to compensate for the differing profile lengths. We used the reference system for non-moving structures to preserve the

lateral extend of non-moving seafloor and sub-seafloor structures. The compensation results in lateral stretching of images with movement velocities in the direction of vessel movement and squeezing for movement velocities against the vessel movement direction, respectively. For each CMP location an automatic maximum amplitude picking algorithm is used to define the movement velocity with best coherency stacking values for each time slice. It must be noted that horizontal reflectors theoretically are not sensitive to movement velocities, due to nearly equal coherency values for different moving velocities. To avoid artifact picking, a coherency threshold is introduced. This assures that movement velocities are only assigned to realistic and physically meaningful velocities.

3. Results

[7] To demonstrate the method we analyzed a synthetic dataset with a non-moving and a moving cosine boundary. The vessel velocity is 2 m/s and the moving reflector speed is -1 m/s (vessel and boundary are moving in opposite directions), 0 m/s (the static case), and $+1$ m/s (vessel and boundary are moving in the same direction). The reflector images and the estimated property movement velocity (Figure 1) show different apparent horizontal wavelength of the cosine boundary depending on the relative movement to the direction of the vessel. The estimated movement velocity of events shows the expected movement velocities of 0 m/s for the static case (Figure 1a). In case of a moving boundary of $+1$ m/s or -1 m/s only the dipping parts of the boundary shows the expected values (Figure 1b). A non-moving model (static case) with an assumed lower sound speed results in apparent movement velocity against the vessel direction for up-dip structures and with the vessel direction for down-dip structures, and reversed for an assumed higher sound speed (Figure 1c). To quantify the errors of the first basic assumption that during the shot-gather migration a correct non-moving sound speed must be known, theoretically expected errors following this assumption are calculated for the given travel time and a maximum CIP aperture length of 1200 m (2400 m streamer length). The uncertainty of movement velocities for an incorrect migration sound speed depends on the sound speed error, image dip and the relation of movement velocity to ship speed (Figure 1d). The smaller the dipping boundary is, the higher the error of inverted movement velocities for a constant move-out error. Comparing a Levitus sound speed to actual measured sound speeds by densely sampled XBT profiling in the area of the Gulf of Cadiz gives a maximum

Figure 1. Theoretical and inverted movement velocities estimated from 2D synthetics of a cosine boundary with maximum absolute dip of 1.7 degree. (a) Seismic image and inverted movement velocity for a static boundary: Inverted movement velocity (red curve) coincides with the theoretical value of 0 m/s (black line). (b) Inverted movement velocities if the vessel and boundary are moving in the same direction or opposite directions: Inverted movement velocity (red curve) coincides with the theoretical value of $+1$ m/s and -1 m/s (black line) except for small dip angle where no movement could be estimated. (c) Inverted movement velocity for a static boundary with an assumed wrong migration velocity of 1495 m/s or 1505 m/s (velocity error of -5 m/s or $+5$ m/s): Inverted movement velocity (red curve) will result in a dip dependent apparent reflector movement. The theoretical values for the dip angles of $+1.7$ and -1.7 degree (black lines) coincides with inverted movement velocity for this angle. (d) Theoretical uncertainty of movement velocity to vessel speed relation. All calculations are based on a reflector depth of 1.33 s TWT, CIP offset of 1200 m (2400 m source receiver offset), and a correct migration velocity of 1500 m. For a dip angle of $+1.7$ degree, vessel speed 2 m/s, and an assumed velocity of 1505 m/s or 1495 m/s, the apparent movement velocity is -0.19 m/s or $+0.16$ m/s, respectively.

root mean square velocity error of approximately 4 m/s inside a Meddy core.

[8] To determine movement velocities in a more realistic simulation a oceanographic model “gravity flow over sill”

(simulating an overflow of the Mediterranean water from the Alboran Sea into the Gulf of Cadiz across the Strait of Gibraltar) was inverted. The determination of movement velocities in this model is restricted due to the low frequen-

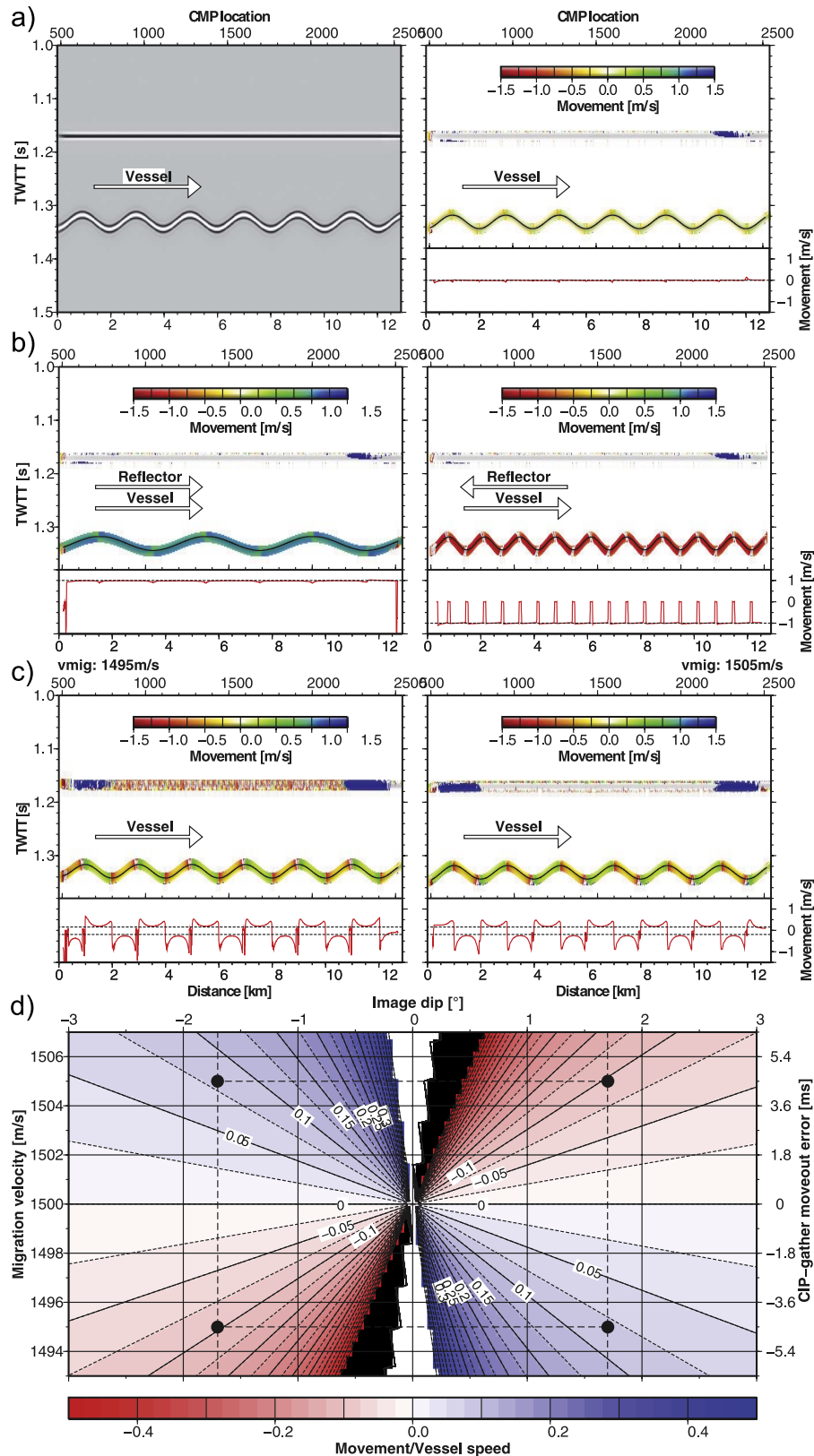


Figure 1

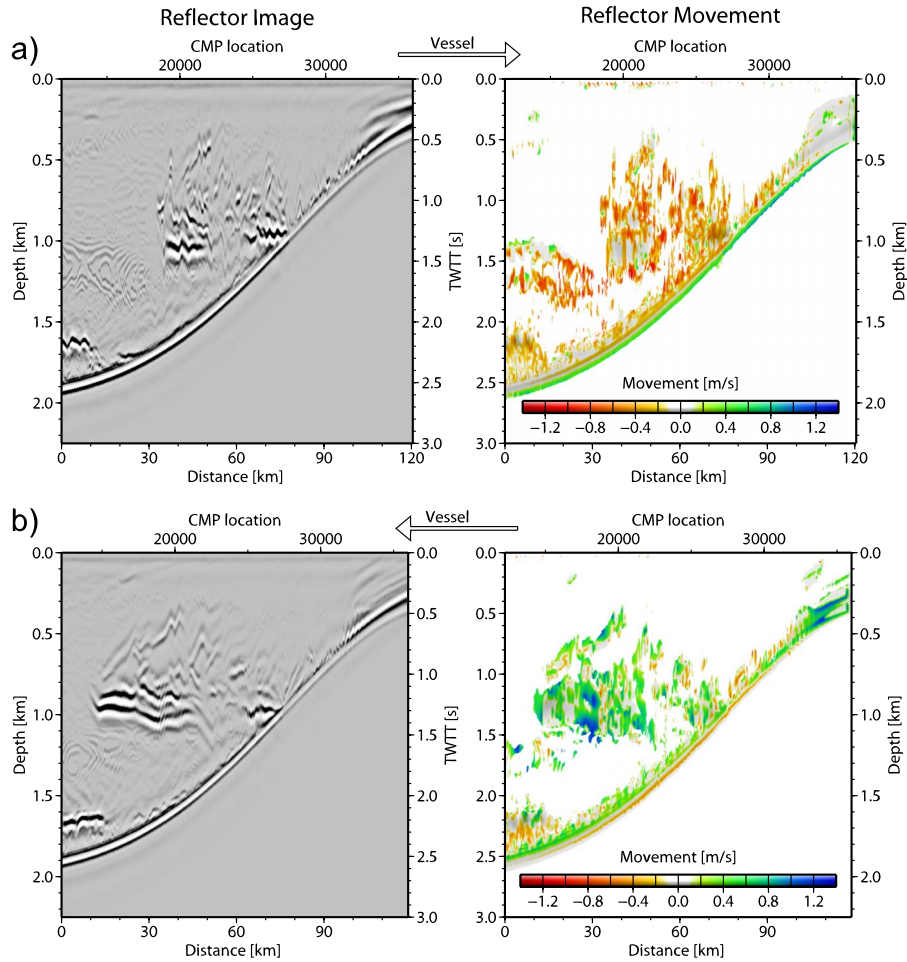


Figure 2. Inverted movement velocities estimated from a synthetic model “gravity flow over sill”. (a) Vessel is moving upslope and estimated reflector movement velocity is opposite to the vessel direction. (b) Vessel is moving down slope and estimated reflector movement velocity is same as the vessel direction.

cy content of the seismic data (10 Hz), normal move out stretching effects, and the resulting minimum reflector dip, which can be resolved (Figure 2). Independent of these strong limitations and knowing the non-moving sound speed, a general movement velocity can be detected for the modeled down flow water. Both seismic simulation against and with the out flow direction show mean values of -0.6 m/s and $+0.6$ m/s, respectively. The horizontal wavelength changes for both images of the seismic lines already indicate a reflector movement and hence suggest water flow. However, with the information of a single seismic line this observation would not be available, but using the above analyses the movement velocity and especially the direction of movement will be detected.

[9] During the seismic GO experiment a second vessel simultaneously measured the water flow velocities with a lowered acoustic Doppler current profiler (LADCP). Even if a direct relation between water flow velocities based on particle movements in the water column itself and reflector movement in general does not exist explicitly, the MOW may have an effect on the reflector movements as shown by the synthetic oceanographic model. The seismic reflector image of GO-LR-05 (Figure 3) located in the Gulf of Cadiz shows two distinct reflectivity patterns located around CMP 9000 between 700 m and 900 m depth and around CMP

12000 between 1200 m and 1400 m depth. Comparing the horizontal (wavelength) extent of the reflector patterns it self suggests longer wavelengths around CMP 9000 than around CMP 12000. Confirmation of this intuitive interpretation is estimated by the velocity of the reflector movement. Both locations have a mean movement velocity of 0.1 m/s but with opposite directions. The estimated inline components to the seismic line from the LADCP water flow velocities confirm the results of this inversion.

4. Discussion

[10] A basic lower dip limitation of reflectors in estimating moving reflector velocities is given by a quarter of a wavelength. To increase the sensitivity of our method higher signal frequencies are needed. The impact of high frequency signals on water structures and consequently on reflector dips are discussed by *Ruddick et al.* [2009] and *Nakamura et al.* [2006]. The uncertainty of our method is coupled to reflector dip and signal frequency, as the error increases with decreasing dip angles if a velocity error is assumed (Figure 1d). Highest confidence will be reached for dipping structures of more than 1 degree. A restoration of movement free reflector images will consequently only be applicable

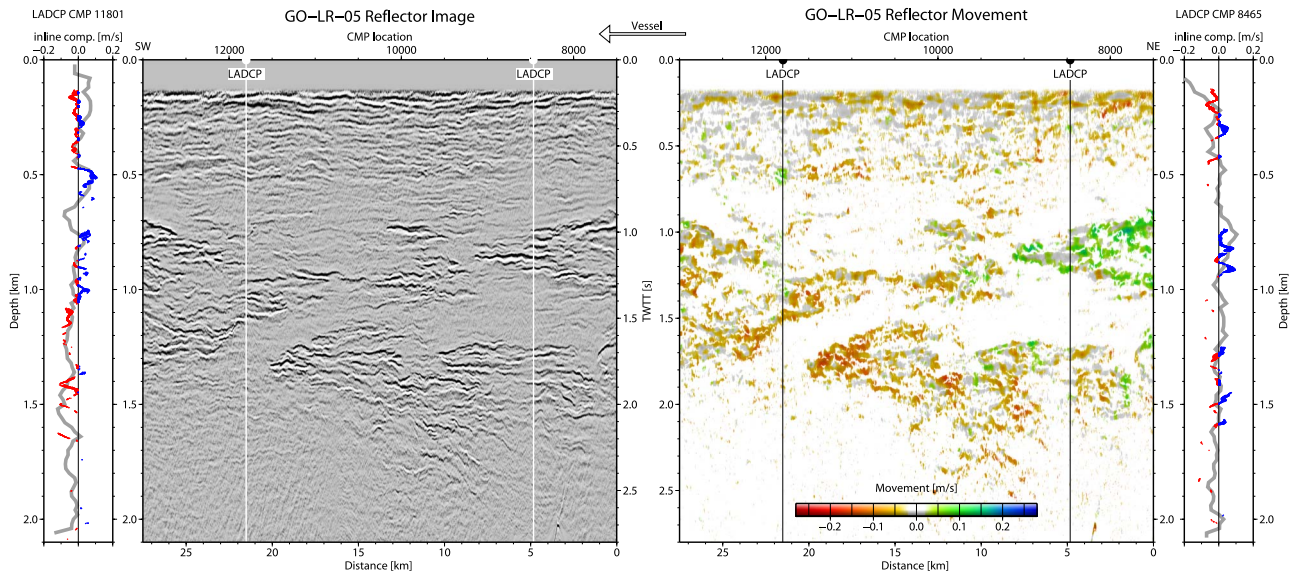


Figure 3. GO-LR-05: Migrated reflector image of a MOW structure, inverted movement velocities, and LADCP profiler data at two different CMP locations. The inverted reflector movement velocities (red and blue curves) from the two CMP locations follow the in-line component trend (grey curve) of the in situ measured water flow velocity.

for dipping structures. How to include near horizontal reflectors for a restoration is still an open question.

[11] The basic assumption that the true non-moving sound speed must be known is a severe limitation of the method. If no external sound speed measurement is available, a sound speed inversion of structures with dips below a quarter of a wavelength could lead into a dip and

frequency dependent inversion procedure [Sirgue and Pratt, 2004]. Here further studies are needed. The computational efficiency of the developed method comes from one single shot-gather migration and hypothetical CIP CMP renumbering. As shot-gather migrations have strong edge effects due to the limited streamer aperture, common offset migrations would be preferable but with an extreme additional com-

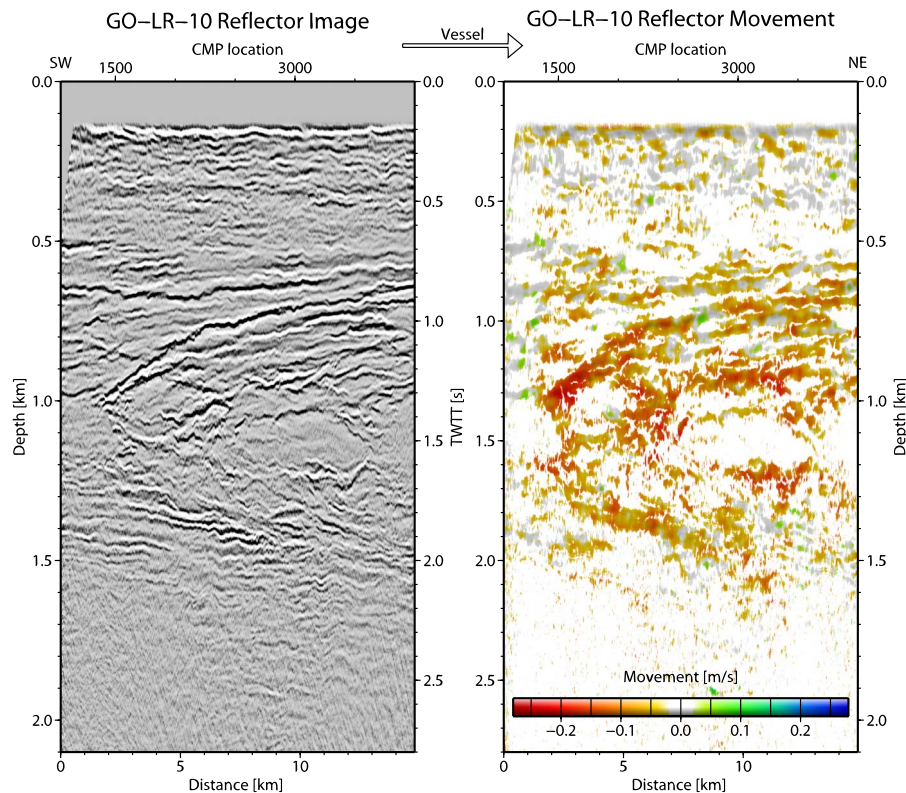


Figure 4. GO-LR-10: Migrated reflector image and inverted movement velocities at a Meddy front. The inverted reflector movement velocities may be biased because of the 3D nature of a Meddy.

putational cost of common offset migrations for all hypothetical movement velocities.

[12] Estimated reflector movement velocities derived for a 2D seismic line can only give one inline component of a 3D reflector movement velocity field. A maximum apparent reflector movement velocity of -0.2 m/s is estimated at the Meddy front (Figure 4), but the currents at this location are composed of two main features, the Meddy's circular currents peaking at about 0.3 m/s some 22 km from its center and the background translation of 0.1 m/s in westerly direction with which the Meddy and the surrounding water masses are moving. To estimate the 3D reflector movement velocity of a rotating Meddy with dynamic filaments an estimate of a second cross line component of the movement velocity is required. To calculate the vector property reflector movement in 3D multiple streamer acquisitions will be needed in the future.

5. Conclusion

[13] For migration of seismic data over the solid Earth we know the geometry and need to find the optimum sound speed model, here we reverse this procedure, given the sound speed model we can compute the optimum geometry for a dynamic fluid and hence its motion. Based on this space sound speed relation we have shown that it is possible to estimate reflector movement velocities as an additional property from seismic reflection data. The movement velocity gives a dynamic property to the instant seismic reflector image and may have great potential to study the temporal dynamics of the water structure. Further it may be used for correcting spatial wavelength spectra estimated from seismic data, especially when turbulence and mixing processes are studied. Regional oceanographic dynamic modeling studies would be able to verify their results in a horizontal scale of several of tens of meters over horizontal distances of the acquisition of an existing seismic line.

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- R. W. Hobbs and E. Vsemirnova, Earth Sciences Department, Durham University, Durham DH1 3LE, UK.
- D. Klaeschen, G. Krahmann, and C. Papenberg, IFM-GEOMAR, Kiel D-24148, Germany. (dklaeschen@ifm-geomar.de)