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Wide-area imaging from OBS multiples

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ABSTRACT

The subseafloor structure offshore western Canada was imaged using first-order water-layer multiples from ocean-bottom seismometer (OBS) data and the results were compared to conventional imaging using primary reflections. This multiple-migration (mirror-imaging) method uses the downgoing pressure wavefield just above the seafloor, which is devoid of any primary reflections but consists of receiver-side ghosts of these primary reflections. The mirror-imaging method employs a primaries-only Kirchhoff prestack depth migration algorithm to image the receiver ghosts. The additional travel path of the multiples through the water layer is accounted for by a simple manipulation of the velocity model and processing datum: the receivers lie not on the seabed but on a sea surface twice as high as the true water column. Migration results show that the multiple-migrated image provides a much broader illumination of the subsurface than is possible for conventional imaging using the primaries, especially for the very shallow reflections and sparse OBS spacing. The resulting image from mirror imaging has illumination comparable to the vertical incidence surface streamer (single-channel) reflection data.

INTRODUCTION

Recording of ocean-bottom seismometer (OBS) data has several advantages over conventional near-surface recording. Because of their deployment on the ocean floor, OBS are less vulnerable to noise and disturbances in the water column and thus have a relatively higher signal-to-noise ratio. OBS also offer wide-azimuth geometry, which is important for imaging under complex overburden such as salt domes and for the analysis of angle-dependent reflectivity.

Although it is impossible to record shear waves in conventional surface streamer surveys, multicomponent marine data from OBS hold much information about shear velocities and reflectivity because converted shear waves are recorded primarily by horizontal geophone components. However, OBS data acquisition and processing have their share of difficulties. For example, inadequate coupling of OBS sensors with the ocean bottom can cause signal distortion. Secondly, because of the high cost of acquisition, OBS are deployed at large intervals. Conventional migration from sparse OBS distributions often produces poor images with narrow illumination, especially for shallow reflectors whose depth below the seafloor is less than the OBS spacing.

Another well-known problem with both streamer and ocean-bottom data is that measurements are contaminated by water-layer reverberations, caused by energy trapped in the water layer after downward reflection from the sea surface. Several techniques exist in the literature to suppress water-layer multiples (see, for example, Weglein, 1999). Most demultiple techniques are based on the assumption that multiples are noise and need to be removed before further interpretation of the primaries. However, multiples are formed by the same source signal as primaries but travel along different paths in the medium. Hence, they might provide additional information under certain circumstances. For example, water-layer multiples have reflection points located at greater distances from a receiver station than the primaries. With careful processing, they can provide information on parts of the subsurface where primaries fail to propagate.

Here we exploit this feature of water-layer multiples by treating them as signal. Several authors have used water-layer multiples in migration of OBS data (Godfrey et al., 1998; Ronen et al., 2005; Pica et al., 2006; Grion et al., 2007; Muijs et al., 2007), either in combination with primaries or separately. We follow the method of Ronen et al. (2005) to image the primaries and multiples separately. This

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method is also discussed in Grion et al. (2007). We utilize downgoing, first-order, receiver-side water-layer multiples from OBS to image the shallow structure beneath the seafloor. Sometimes these events are referred to as receiver ghosts.

Our objective is to compare the results from primaries and multiples and to demonstrate how water-column multiples can be utilized to image the shallow subsurface structure where OBS spacing is sparse. In the following sections, we describe the general procedure of seismic wavefield separation into primaries and multiples followed by the migration procedure. Then we present imaging results from a real data set off the west coast of Canada.

WAVEFIELD SEPARATION

The most common practice for OBS primary-multiple separation is to decompose the wavefield into upgoing and downgoing wavefield potentials by combining the pressure and the vertical geophone (velocity) components. This idea was first envisaged by White (1965), who recognized that a proper combination of ocean-bottom pressure and ground velocity can attenuate receiver-side water-layer multiples. This is because pressure is a scalar quantity and upgoing and downgoing pressure wavefields show the same polarity on hydrophone recordings. However, ground velocity is a vector quantity and upgoing and downgoing pressure wavefields show opposite polarities on vertical geophone recordings. Therefore, by combining the hydrophone and vertical geophone data (dual-sensor or *PZ* summation; Barr and Sanders, 1989), upgoing and downgoing wavefields can be separated as:

$$U = (P + \rho c Z)/2$$

and

$$D = (P - \rho c Z)/2, \qquad (1)$$

where U is the upgoing wavefield, D is the downgoing wavefield, P is pressure as recorded on the hydrophone, Z is particle velocity recorded on the vertical geophone, ρ is the density of water, and c is the acoustic velocity. The above equations assume that the pressure and geophone sensitivities are the same and that coupling is ideal. In addition, it should be noted that the above equations are valid for vertical arrivals only but can be modified easily to take into account any propagation angle (see, for example, Bale, 1998). In practice, *PZ* summation processing also must account for the instrument response differences, as well as the phase and spectral differences that can be caused by poor coupling (Soubaras, 1996; Schalkwijk et al., 1999). For the case study that follows, we use a 2D *f-k* implementation of the wavefield separation method as described in Schalkwijk et al. (1999).

The ocean-bottom seismometers lie at the boundary separating two different media (acoustic to elastic) and hence a distinction must be made between wavefields just above and below the seafloor (Amundsen and Reitan, 1995; Osen et al., 1999; Schalkwijk et al., 1999). The initial source signal that travels directly through the water column gets partially reflected at the water-sediment interface and partially transmitted into the seabed. For example, the direct wave and the wave reflected at the seafloor arrive almost at the same time at the receiver just above the seafloor. Therefore, the direct event contains both upgoing and downgoing components just above the seafloor but only downgoing just below. The receiver-side (water-layer) multiples are also both upgoing and downgoing above the seafloor but only downgoing below the seafloor.

Similarly, when an upward-propagating signal (reflection event) encounters the water-sediment interface, it gets partially transmitted into the water column and partially reflected back into the seabed. Therefore, the reflected signal (primary) is both upgoing and downgoing just below the seafloor but only upgoing just above the seafloor. In our work, we apply mirror imaging to the downgoing pressure wavefield just above the seafloor, and apply conventional imaging to the upgoing pressure wavefield just below the seafloor.

MIGRATION

Usually, seismic migration from OBS data is performed using upgoing primary reflections. The upgoing wavefield below the seafloor is preferred over the upgoing wavefield above the seafloor because the latter is contaminated with water-layer reverberations. However, migration of the upgoing primary wavefield is not the best option for sparse receiver geometries. In such cases, OBS multiples can provide a better structural image of the subsurface from a wider angle and thus can be used for migration (Godfrey et al., 1998; Ebrom et al., 2000; Ronen et al., 2005; Grion et al., 2007). This is because downgoing receiver ghosts bounce from the same reflectors as the primary waves but farther away from the receiver station (Figure 1). Similar ideas also have been implemented on VSP data (e.g., Verm et al., 1987; Jiang et al., 2005, and Lou et al., 2008).

Migration using the multiples, or the downgoing receiver ghosts for the case of OBS, is called mirror imaging because the sea surface acts as a mirror reflecting the image of subsurface structure. As noted in Grion et al. (2007), mirror imaging increases illumination width at the expense of illumination fold. In general, this fold decrease is found to be insignificant because of the quiet recording environment for OBS data, especially in deepwater. Kinematics of the extra travel path of the receiver ghosts are accounted for by assuming the signal is not recorded on the seabed but on a sea surface twice as high as the water column. The propagation path of the receiver ghost is unwrapped by placing the receiver at a virtual position as if it is mirrored by the water surface (Figure 1c). The source is kept at the original level. These simple modifications of the processing datum and the velocity model allow mirror imaging to be performed using a conventional prestack depth migration (PSDM) algorithm designed for primaries only.

CASE STUDY

Next we present results of OBS migration from a survey on the northern Cascadia continental margin offshore western Canada. The area is known to contain gas hydrates, which are solid, ice-like crystalline substances formed from water molecules containing methane. Methane hydrates are stable under low temperature and high pressure and are detected on seismic data by identifying the characteristic bottom-simulating reflector (BSR), representing the base of the hydrate stability zone. To investigate the shallow sediment structure above the BSR, seismic single-channel (SCS) and ocean-bottom seismometer (OBS) data were collected along five parallel lines normal to the margin, with a line length of about 12 km, and three shorter cross lines with a line length of 6 km (Figure 2). Line spacing was kept at 500 m. Ten OBS were deployed at 100-m spacing in water depth of about 1300 m along the central line perpendicular to the margin to record shots from a $45/45\text{-in}^3$ GI gun fired at intervals of 6 s (approximately 16 m).

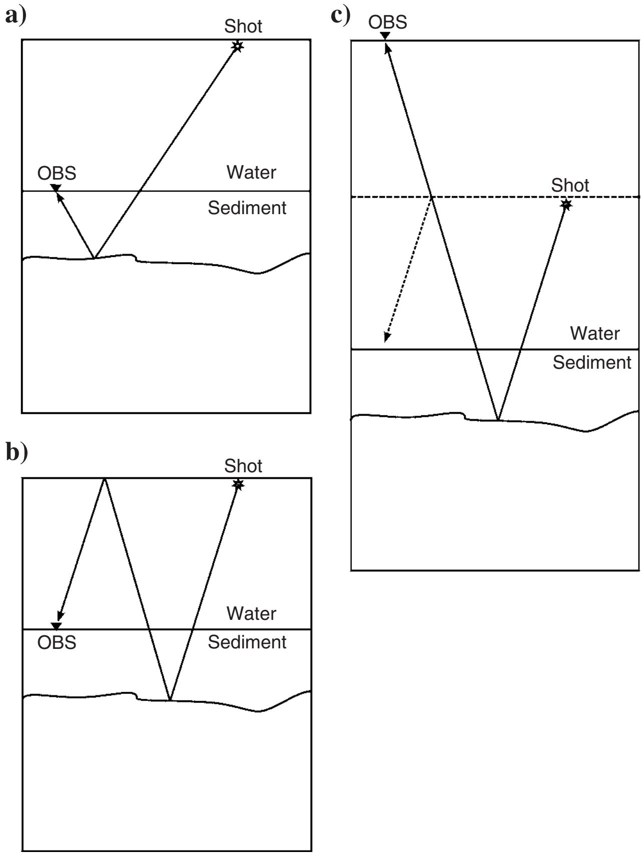


Figure 1. Raypaths of (a) upgoing primaries, and (b) downgoing multiples. The downgoing receiver ghost in (b) can be treated as an upgoing primary reflected downward from the sea surface. For migration, multiples can be treated as primaries assuming that the data is not recorded on the seafloor but above a layer with twice the thickness of the water column (c).

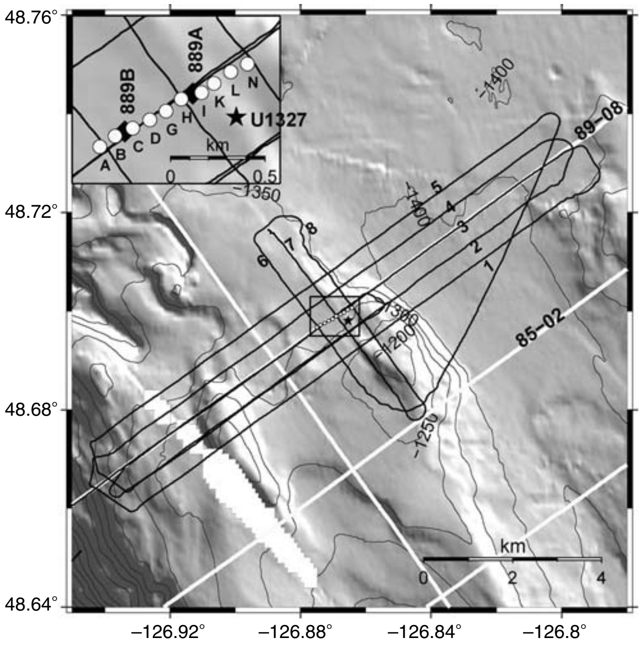


Figure 2. Wide-angle and normal-incidence seismic experiment in the mid-continental slope off Vancouver Island near IODP Site U1327. Ten OBS were deployed at 100-m spacing in water depth of about 1300 m along the central line. The shot line spacing was 500 m. Shots were fired from a 45/45-in^3 GI gun (dominant frequency of about 120 Hz) every 6 s (about a 16-m interval).

Preprocessing

At vertical incidence, the main target reflectors (including the BSR) lie within about 300-ms two-way time below the seafloor (Figure 3). To suppress the source bubble pulse, gapped deconvolution with a 12-ms gap length and 300-ms filter length was applied to the hydrophone and vertical component data. Amplitude calibration of the pressure components was applied to compensate for sensitivity variations across the receivers.

Because OBS multicomponent recording involves vector measurements of the seismic wavefield, faithful recording of vector components is necessary to image elastic properties of the subsurface properly. However, this is rarely achieved in practice, because OBS deployment often is accomplished by allowing the OBS to free-fall from the ocean surface. This also makes the position of the OBS on the seafloor uncertain. Therefore, two major processing steps for OBS data included OBS relocation and correction for orientation effects.

OBS positions on the seafloor were relocated by following the source-receiver localization procedure of Zykov (2006). Direct-arrival traveltimes through the water column were inverted using a regularized inversion approach to correct for both source and receiver coordinates and for GPS clock drift.

The ocean-bottom seismometers landed on the seabed at random orientations. Therefore, the instrument X, Y, and Z components had to be rotated to horizontal-radial, horizontal-transverse, and vertical directions before data processing could commence. The first arrivals are radial if there are no scattering and velocity variations, which is an adequate approximation for our deepwater study area. The horizontal orientation (HOR) angle was estimated by fitting a line to the hodogram from the first arrivals of each shot. For a perfectly vertically deployed OBS (with zero tilt), all the shots would agree on the HOR angle with little error. However, the HOR angle estimate from each shot would be different for a tilted OBS. To estimate the deviation of the Z component from vertical and the horizontal orientation of this deviation from north, we searched for the angles that minimize the standard deviation of the HOR angles (Li et al., 2004; Li and Ronen, 2005).

Out of ten receivers, only seven had tilts of less than 10°. The other three receivers were not included in further analysis. We excluded the highly tilted receivers because the geophones and sensor packages we used are designed to record and couple to the seabed at small tilt angles only.

Our acoustic wavefield-separation approach above the seafloor is based on the adaptive decomposition method of Schalkwijk et al. (1999). In particular, we determined the calibration filter between the pressure and the vertical velocity component by imposing that there should be no primary reflections present in the decomposed downgoing wavefield above the seafloor. The filter was obtained by minimizing the primary energy within a window between the direct arrival and the first-order water-layer multiple. This method is suitable and effective for our deepwater scenario, where the temporal separation between direct arrival and first-order water-layer multiple is large. Wavefield separation into upgoing and downgoing components just below the seafloor was achieved using the gapped deconvolution approach described in Soubaras (1996). Figure 4 shows the upgoing and downgoing wavefields just above and below the seafloor.

Comparison of migrations

Kirchhoff prestack depth migration was applied to the upgoing primary wavefield just below the seafloor and the downgoing first-order multiples just above the seafloor. The input velocity model for the traveltime computation was obtained from 2D traveltime tomography of the OBS and single-channel reflection data in the area (Dash, 2007). The input velocity model for the mirror migration of downgoing multiples was designed such that the receivers were placed effectively at the sea surface (not on the seafloor) of a water column twice as thick as the original water layer.

First, the upgoing wavefield below the seafloor was migrated. Illumination is very poor (Figure 5): the seafloor and the shallow reflectors immediately below the seafloor are not imaged. Only reflectors near the BSR are well imaged. However, migration of the downgoing wavefield just above the seafloor (using the same 45° migration aperture angle as for Figure 5, produces a much better image (Figure 6a). Lateral illumination is much enhanced and shallow layers are imaged clearly. Ronen et al. (2005) argue that upgoing waves are more susceptible to inhomogeneities near the seabed than downgoing waves. Mirror imaging using a larger migration aperture angle of 70° produces an image with much wider lateral illumination (Figure 6b). Pica et al. (2006) state that illumination of the seafloor is de-

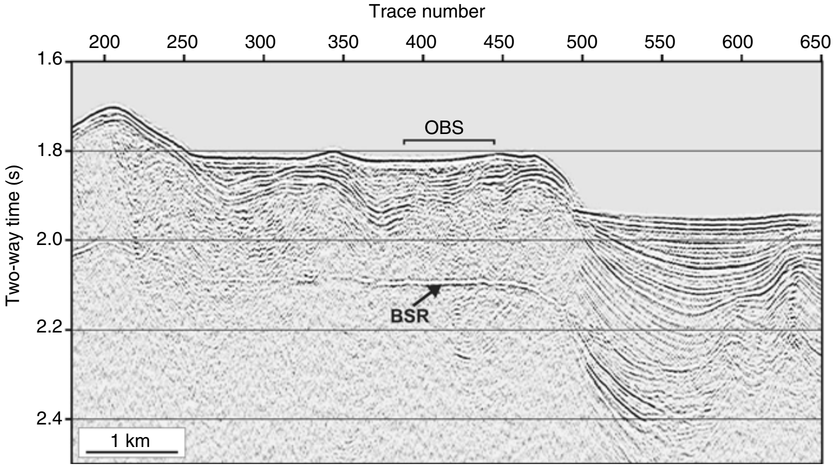
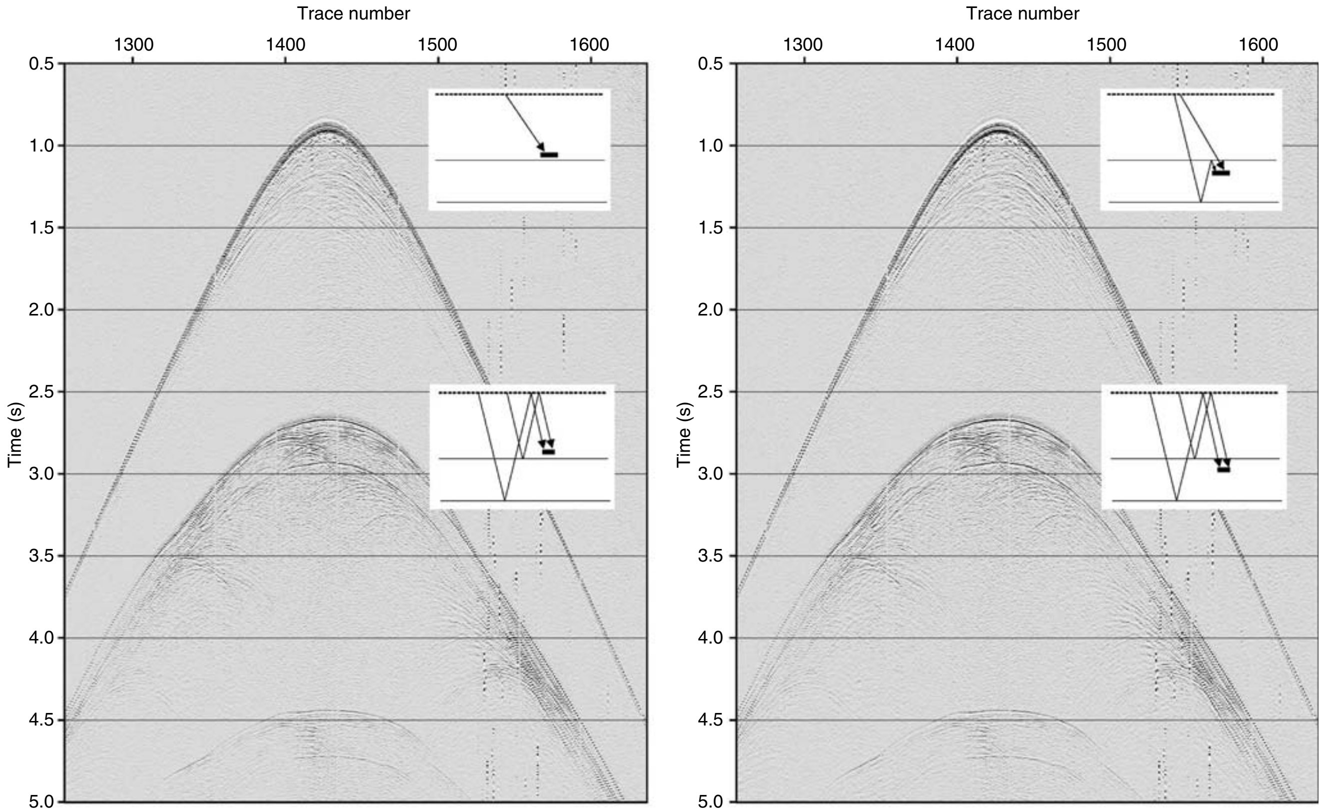
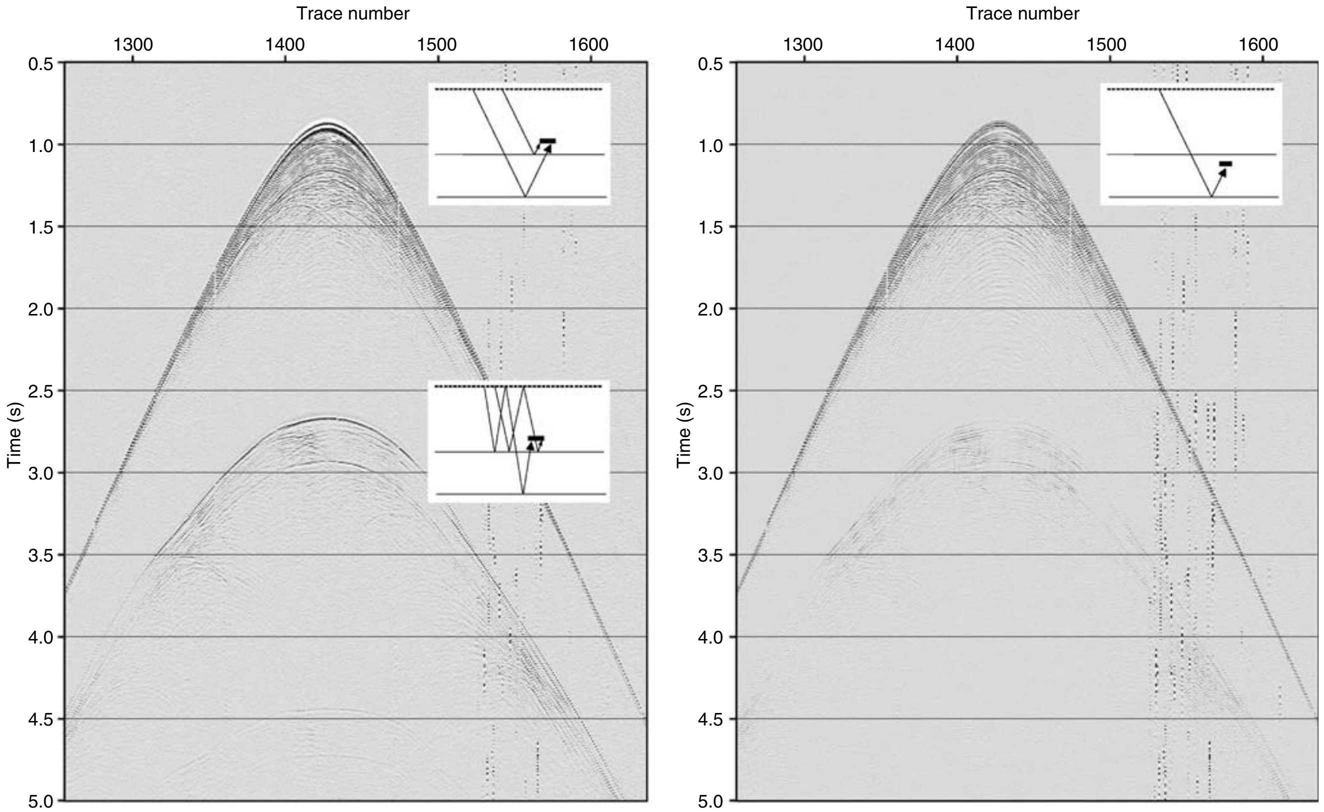


Figure 3. Single-channel seismic data along the central line (line 3 in Figure 2). The bottom-simulating reflector (BSR) is seen at about 2.1-s two-way time.



Downgoing above seafloor

Downgoing below seafloor



Upgoing above seafloor

Upgoing below seafloor

Figure 4. Upgoing and downgoing wavefields above and below the seafloor. Only the downgoing wavefield below seafloor and upgoing wavefield above seafloor are migrated.

pendent on receiver depth, and with no dip limitation, the maximum extent of illumination is two-thirds of the source profile. However, the maximum extent of the seafloor illumination will depend upon the migration aperture angle. In our case, the 70° aperture angle produced the best image. The mirror-migrated image is seen to be comparable or better than the image obtained from single-channel streamer data (Figure 3).

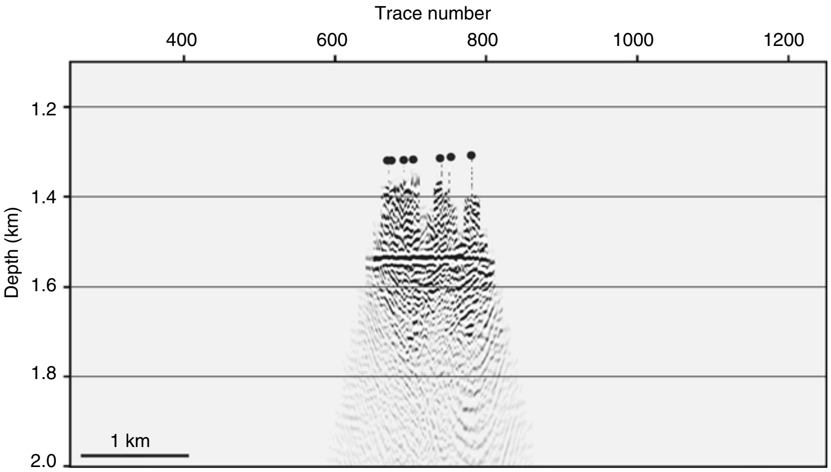


Figure 5. Migrated image of the upgoing wavefield below the seafloor. Black dots indicate the location of the OBS nodes.

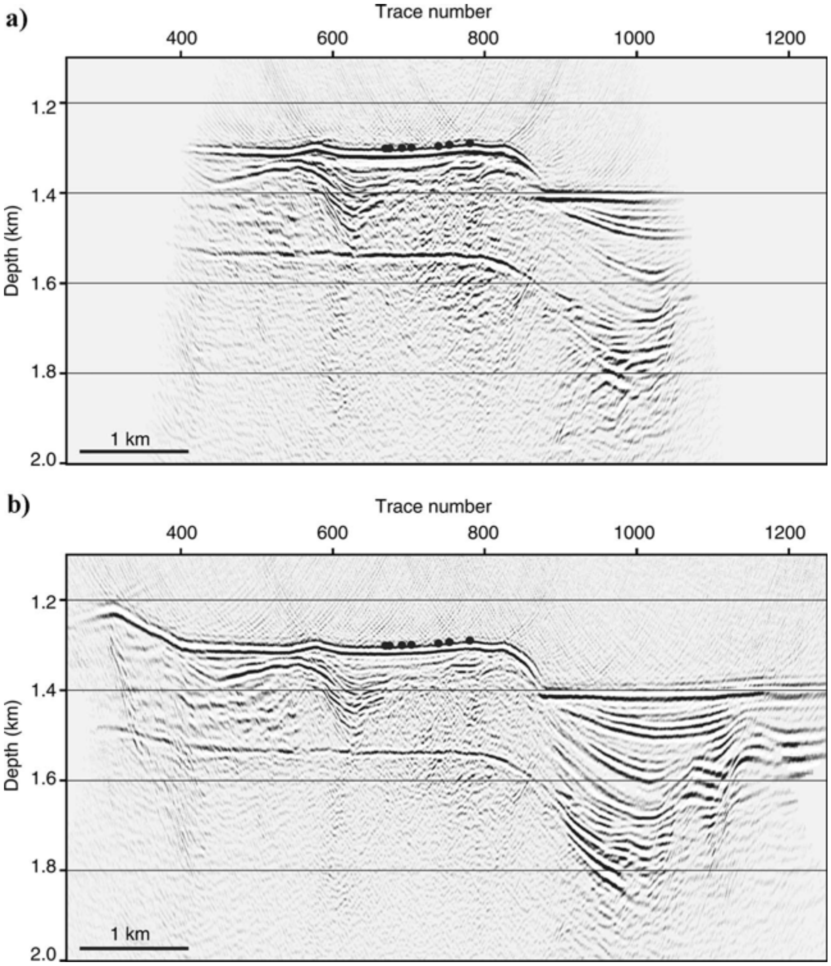


Figure 6. Migrated image of the downgoing wavefield above the seafloor with (a) the same migration aperture in Figure 5 and (b) a wider migration aperture. Notice the wider illumination of the shallow layers in (b).

CONCLUSIONS

Although multiples are often discarded as noise, they might contain additional information about the subsurface. When properly imaged, they can provide complementary information on parts of the subsurface not illuminated by primary reflections. Ocean-bottom receiver ghosts can be imaged using existing migration algorithms by allowing different elevation for the receivers. In our study, the image produced from migration of receiver ghosts alone is comparable to the near-vertical reflection image obtained from single-channel surface-towed streamers. It is much better than the image produced from migration of the upgoing primary wavefield just below the seafloor. The improvement, especially for shallow near-seafloor targets, is mainly because of wider illumination and reduced exposure to shallow inhomogeneous anomalies under the seabed.

Although lateral illumination from mirror imaging depends primarily on the extent of the source patch, it is much better in deepwater environments where primaries and first-order, water-layer multiples are clearly distinguishable. For the OBS data presented here, illumination from multiples is particularly wide because the shooting area is significantly larger than the receiver area and the primaries and multiples are separated completely. In the shallow-water case, however, migration-angle limitations have more impact (Grion et al., 2007) and the mirror-migrated image might not provide much additional information.

Mirror imaging has significant implications for processing and acquisition of OBS data, especially in deepwater. In particular, mirror imaging is well suited to a dense-shot and sparse-receiver geometry because it enables greater tolerance to large intervals between the receivers.

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