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Dual-vergence structure from multiple migration of widely spaced OBSs

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ABSTRACT

The detailed structure of the northern Cascadia basin and frontal ridge region was obtained using data from several widely spaced ocean bottom seismometers (OBSs). Mirror imaging was used in which the downgoing multiples (mirror signal) are migrated as they provide information about a much larger area than imaging with primary signal alone. Specifically, Kirchhoff time migration was applied to hydrophone and vertical geophone data. Our results indicate remarkable structures that were not observed on the northern Cascadia margin in previous single-channel or multi-channel seismic (MCS) data. Results show that, in these water depths (2.0–2.5 km), an OBS can image up to 5 km on either side of its position on the seafloor and hence an OBS spacing of 5 km is sufficient to provide a two-fold migration stack. Results also show the top of the igneous oceanic crust at 5–6 km beneath the seafloor using only a small airgun source (120 in.^{3}). Specifically, OBS migration results clearly show the continuity of reflectors which enabled the identification of frontal thrusts and a main thrust fault. These faults indicate, for the first time on this margin, the presence of a dual-vergence structure. These kinds of structures have so far been observed in $< 0.5\%$ of modern convergent margins and could be related to horizontal compression associated with subduction and low basal shear stress resulting from over-pressure. Reanalysis of previous MCS data from this region augmented the OBS migration results and further suggests that the vergence switches from seaward to landward around central Vancouver Island. Furthermore, fault geometry analyses indicate that the total amount of shortening accommodated due to faulting and folding is about 3 km, which suggest that thrusting would have started at least ~65 ky ago.

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1. Introduction

Ocean bottom multiple imaging techniques have become popular in recent times. Previously, multiples were treated as noise and were separated from the seismic data during the data processing stage. But recent studies (for example, Reiter et al., 1991; Godfrey et al., 1998; Ronen et al., 2005; Grion et al., 2007; Dash et al., 2009; Wong et al., 2012a, 2011) show that multiples contain abundant information about the structure beneath the seafloor.

Data from an ocean bottom seismometer (OBS) have several advantages for seafloor imaging compared to conventional ship-towed hydrophone streamer data. OBS data provide wide-azimuth illumination and shear wave recording, and in addition the fixed OBS position on the seafloor provides a quiet recording environment and better repeatability for time-lapse seismic surveys (4D) (Grion et al., 2007). OBS nodes record four-component seismic data, with one hydrophone component recording pressure and three geophone components recording ground velocity in three perpendicular directions. The pressure and velocity components can be decomposed to form upgoing (primaries) and downgoing (multiples) waves. This helps to attenuate water column reverberations and improves first-break analysis (Barr and Sanders, 1989). As well, Ronen et al. (2005) presented a method of imaging the downgoing waves recorded on the seafloor and showed that the illumination is better particularly for shallow targets when compared to images produced using conventional migration of upgoing waves. The main advantage of OBS multiple imaging is that it provides information about a much larger area than imaging with the primary signal alone. Furthermore, it can be easily adapted to existing migration algorithms by simply changing the receiver depth. OBS node geometry is sometimes sparse due to large costs associated with OBS deployment. Therefore, shallow reflectors are often poorly imaged, particularly when the reflector depth is smaller than the node separation. This problem is handled efficiently by using downgoing multiples for imaging, which bounce

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from the same reflectors as the primary waves, but the subsurface reflection points for the multiple are much farther away from the OBS than for the primary, because of the additional sea-surface reflection point.

The method of seismic multiple migration can be applied to non-OBS data types as well. For example, Reiter et al. (1991) used deep water receiver multiples from an ocean bottom hydrophone for imaging and showed that the final image contains higher signal to noise and greater lateral extent. Godfrey et al. (1998) applied a multiple imaging method to ocean bottom cable data, but without wavefield decomposition. Yu and Schuster (2004) developed a crosscorrelogram migration method to image the ghost reflections recorded on VSP data and showed better illumination coverage than standard migration routines.

Processing and imaging of OBS data are complex. For example, standard processing routines are inadequate when applied to OBS data acquired from the deep ocean with large separation between nodes (Pacal, 2012). Downward continuation is sometimes used to remove the contribution of the large water column by bringing the shot and receiver positions to a common datum such as the seafloor. However, this method is uncertain because it assumes continuity of the wavefield and potentially fails when there are anomalies present above the common datum (e.g., near surface anomalous velocity structures). In this scenario, the mirror migration technique is quite useful. In a recent study, Wong et al. (2010) showed that joint least-squares inversion of upgoing and downgoing signals from OBS data provides better subsurface illumination with enhanced resolution and more balanced amplitude information. In a later study, Wong et al. (2012b) also showed that joint inversion of OBS and streamer data in a linearized inversion scheme provides a better subsurface image with fewer migration artifacts and is useful in correctly imaging dipping reflectors.

On the Cascadia margin, Dash et al. (2009) applied a multiple imaging technique using down-going waves to image the shallow subsurface structures, at depths of 300–400 m below the seafloor (mbsf), with the gas hydrate bottom simulating reflector being the main target. In the present study, with a large trace length (~12 s) and a large receiver separation (up to 5 km), we used a similar multiple migration technique to image the deep structure beneath the north Cascadia margin and adjacent ocean basin. Our results indicate for the first time that a multiple imaging technique provides an image of deep subsurface structure that is significantly better

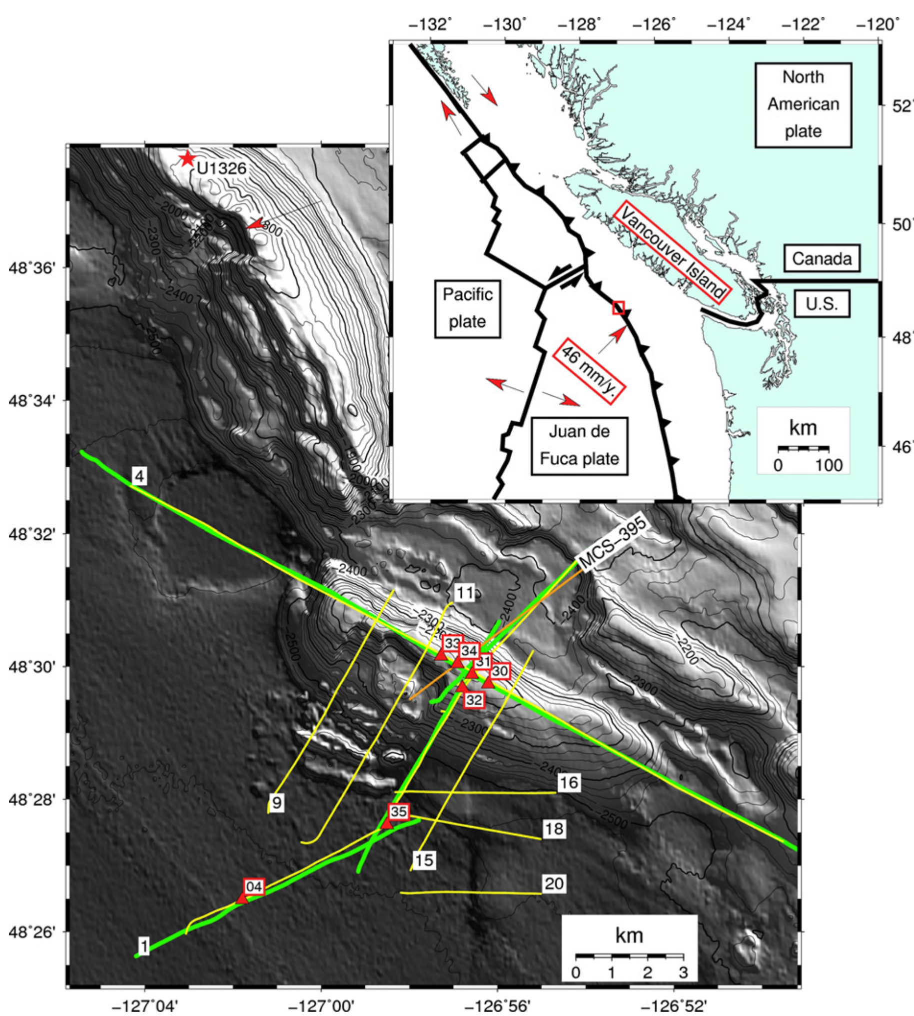

Fig. 1. Bathymetry map showing the location of all OBSs (red triangles). OBSs 33, 34, 31, 30 and 32 were deployed on the frontal ridge adjacent to slipstream slide. OBSs 04 and 35 were deployed in the deep basin where water depths are around 2500m. Green lines represent refraction lines. Yellow lines correspond to single channel reflection lines; line-4a and line-1a are mostly coincident with refraction line-4 and line-1, respectively. Orange line corresponds to approximate location of MCS line 395 collected by University of Bremen, Germany. Red star corresponds to Site U1326 from IODP X311. Arrow indicates Orca slide discussed in the text. Inset shows tectonic setting with convergence at 46mm/year. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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