SEISMIC STRUCTURE, GAS-HYDRATE CONCENTRATIONS, AND SLUMPING ALONG THE IODP X311 TRANSECT ON THE N. CASCADIA MARGIN

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ABSTRACT

On the lower continental slope off Vancouver Island near scientific ocean drilling IODP Site U1326, traveltime modeling along several ocean bottom seismograph (OBS) profiles shows anomalous high velocities of about 2.0 km/s at 70 - 100 m depth (compared to a no-hydrate reference of about 1.6 km/s). These velocities are consistent with the Site U1326 downhole sonic logs that show velocities up to 2.8 km/s near these depths. The drillhole high velocities are interpreted as caused by nearly massive hydrate with concentrations as large as 60-80% of the pore space. The OBS seismic velocities show that high hydrate concentrations of at least 20-30% are laterally extensive out to distances of at least 6 km on either side of the drillhole. A grid of migrated single-channel data shows a sequence of 15- to 75-m-high seafloor scarps, cutting across the ridge perpendicular to the deformation front. These are interpreted as normal faults. Two of the largest fault scarps bound a prominent ~2.5-km-wide slump feature on the steep seaward slope of the frontal ridge. This provides strong evidence that the slump is fault-controlled, and the base of the slump is near the base of hydrate stability suggesting that the slumping is also related to the presence of gas hydrate.

At IODP drill Site U1327 on the mid-continental slope, seismic data were recorded along a 1-km-long profile of 10 OBSs. Traveltimes from wide-angle and vertical-incidence arrivals were inverted simultaneously for velocity structure. Corresponding hydrate concentrations increase with depth with an average of about 15% in the 100-m-thick layer above the base of hydrate stability. The seismic structure shows that this local hydrate distribution extends on the kilometer-scale away from the drillhole, as also suggested by multichannel interval velocities in the region.

At Site U1328 (Bullseye Vent), seismic images derived from the very high resolution deep-towed DTAGS reflection data show that the top of a zone of high reflectivity, 10-25 m in thickness, extends from the seafloor to a depth of ~30 m. This zone likely corresponds to the shallow region of massive methane hydrate detected in the upper 40 m in the drillhole, and may represent a system of fractures through which fluids and gas pass from the main vent to the seafloor.

Keywords: gas hydrates, seismic reflection, seismic refraction, hydrate concentrations, slumping

INTRODUCTION

Sediments of the accretionary prism of the Northern Cascadia accretionary margin contain widespread gas hydrates down to depths of several hundred metres below the seafloor. To assess the long-term energy potential of gas hydrate and the role it plays in global climate change and in slope stability, the Integrated Ocean Drilling Program (IODP) Expedition 311 in September 2005 sought to derive a detailed geological model to understand the formation and dissociation of hydrate and its association with fluid flow across the continental margin.
Prior to the expedition, seismic experiments were carried out over the continental slope to provide geophysical information in support of drilling. In this paper we report on seismic results near three sites from the IODP expedition (Fig. 1) – Site U1326 on the frontal ridge, Site U1327 on the mid-slope, and Site U1328 at a prominent vent site where massive hydrate had previously been found [2]. Our results illuminate how sedimentary structures and hydrate-bearing layers extend beyond the drillholes at the kilometer-scale laterally. At U1326 and U1327, wide-angle seismic experiments using ocean bottom seismometers (OBSs) constrain the seismic velocity structure down to depths of about 400 m below the seafloor (mbsf) at a vertical resolution of 10-20 m. The velocities provide the quantitative means to estimate the concentration of hydrate. At U1326, vertical-incidence reflection data image a series of normal faults that cut across the ridge normal to the margin and, in association with gas hydrate, likely control the location of large blocks that have slumped on the seaward side of the frontal ridge. At U1328, high-resolution deep-towed seismic reflection data show details of a dipping fracture zone, hosting massive gas hydrate, that extends from the seafloor to the main vent.

**GAS HYDRATE AND SLUMPING NEAR SITE U1326**

**Velocity structure and hydrate concentrations**

In August 2005, eight OBSs were deployed in a grid-pattern at a nominal separation of 650 m on the frontal ridge, just landward of the deformation front (Fig. 1). The seismic source was a GI-gun configured with a 105 cu. in. generator and a 105 cu. in. injector. Eight seismic lines were recorded on the OBSs out to shot-receiver offsets of about 10 km. An approximate 3D velocity structure on the frontal ridge was estimated by determining 2D velocity models along 3 profiles [3]. Velocities on each profile were modeled using traveltimes from wide-angle reflections and refractions recorded on the OBSs, and from vertical-incidence reflections recorded on coincident single-channel seismic lines. Velocity model construction was an interactive process that combined forward and inverse modeling, using the traveltime inversion routine of Zelt & Smith [4].

At the location of Site U1326, the most prominent feature of the velocity model is a high velocity layer of 1.95 (±0.05) km/s at a depth of 80-110 mbsf (layer L2 in Fig. 2). This layer extends laterally throughout the frontal ridge region, out to distances of at least 4 km from the drillhole along the ridge.

![Fig. 1. In 2005, seismic lines using a single GI-gun source were recorded on two grids of OBSs (triangles), one centred on IODP Site U1326 and the other on Site U1327. Inset shows plate tectonic setting off Vancouver Island.](image-url)
the ridge and 1-2 km normal to the ridge. The sonic velocity data at U1326 indicate even higher velocities (up to 2.8 km/s; Fig. 2) at depths of 60-95 mbsf, while the resistivity log shows a layer from ~75-105 mbsf with resistivities that are 3-fold higher than other depths [1].

Layer L3 is located just above the bottom-simulating-reflector (BSR), assumed to mark the base of gas hydrate stability. Compared to velocities recorded with a downhole sonic tool at the drillhole [1], the optimal inverted seismic velocity is higher by about 100 m/s, although the values agree within the estimated errors and OBS velocities at ~600 m to the northeast agree very well with the sonic velocities. The depth of the BSR at the drill site from the velocity modeling is 240-260 mbsf, in good agreement with the estimate from the sonic log. However, the BSR depth based on traveltimes from multichannel seismic data and the sonic velocities yield a value of 235 m. Possible explanations for this discrepancy are a) the slightly lower sonic velocities are just a local effect around the drillhole, and b) cold drilling fluids (seawater) lower the sediment temperature below the BSR back into the stability field of gas hydrate.

Gas hydrates increase the sediment P-wave velocity, and so velocity information can be used to estimate gas hydrate concentrations. A reference velocity-depth profile for sediments with no hydrate was based on analyses of multichannel seismic data near Site U1326 [5]. To convert velocity increase to hydrate concentration, a simple porosity-reduction model was used [6,7]. Gas hydrate saturation is largest in layer L2, with values of 30-38% of the pore space. From the sonic log, both a rock-physics model and the porosity-reduction method had previously been used to estimate saturations of ~60% of the pore space in the high-velocity layer [5]. For layer L3, saturations calculated from the OBS data increased from 15-20% at a depth of 120 mbsf to 25-30% at a depth of 260 mbsf.

**Fig. 2.** Velocity-depth profiles at IODP Site U1326. Layer numbers (L1, L2, etc.) represent layers of the OBS velocity model (thick solid line).
Slumps, faults, and gas hydrates

On the frontal ridge near Site U1326, a large slump is observed in newly-acquired multi-beam bathymetry data (Fig. 3a) (D. Kelley, pers.comm. 2005) and on a grid of single-channel seismic data collected in 2004. The slope failure is located on the western side of the frontal ridge in the middle part of the local ridge structure. The headwall of the slide is ~250 m high and the slump has eroded the ridge over a length of ~2.5 km.

On the migrated single-channel seismic data (Fig. 3b), a series of 13 seafloor scarps, 15- to 75-m in height, are observed on nearly all lines [3]. The scarps appear to be seafloor expressions of faults that cut through the accreted sediments of the frontal ridge. The faults strike NE-SW, perpendicular to the margin and parallel to the direction of convergence. The faults are interpreted as normal, with extensional motion oriented NW-SE.

The primary faults (A, B, C, D) indicate that the lateral extent of the slumping is fault-controlled (Fig. 3a). This observation is strongly supported by the seismic and bathymetry data: faults A and D align closely with the outer sidewalls of the slump feature, while faults B and C may bound sub-blocks within the slump.

At the frontal ridge, gas hydrate is widely distributed based on the presence of strong BSRs in the area surrounding the slump feature (Fig. 3b). Within the slumped sediments, there is only a weak indication for the presence of a BSR, indicating that there has been insufficient time for the BSR to re-establish itself. The original seafloor surface before the slide was estimated from the detailed bathymetry data, by interpolating depth contours from either side of the slump. The depth of the glide plane below the seafloor could thus be determined – in mid-slump, the amount of material removed is about 255 m. This depth corresponds closely to the depth of the BSR on the ridge, which is well-constrained based on both reflection data and wide-angle refraction data recorded on OBSs. The coincidence of the glide plane and the BSR strongly suggests that the slumping is related to the presence of gas hydrate. The basis of this hypothesis is that the sediments above the BSR are cemented by the gas hydrate and thus strengthened. In contrast, the sediments below the BSR contain free gas and are weak since no hydrate cements them.

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Fig. 3. (a) Multi-beam bathymetry data from the frontal ridge. The blue line identifies the top of the slump headwall, which has a slope of ~45º compared to a slope of ~12º for the frontal ridge north of the slump. Red dashed lines correspond to the peaks of the seafloor scarps as identified on single-channel seismic data. (b) Migrated single-channel seismic line CAS3B-15, at the top edge of the slump headwall.
GAS HYDRATE CONCENTRATIONS NEAR SITE U1327
In September 2005, ten OBSs were deployed in a linear array at a nominal spacing of 100 m, near IODP Site U1327 and ODP Site 889 (Fig. 1). The seismic source was a single GI-gun configured with a 45 cu. in. generator and a 45 cu. in. injector and fired at a shot interval of ~16 m. The survey included 5 parallel lines normal to the margin, at a spacing of ~500 m, and 3 shorter cross lines. The source was recorded on both the OBSs and on a surface single-channel seismic (SCS) streamer.

Wide-angle arrivals from all OBSs were modeled simultaneously with vertical-incidence reflections from the SCS dataset [8]. A 2D velocity model (Fig. 4) was obtained using a combination of forward and inverse traveltime modeling [4]. The model is constrained up to 2 km on either side of the OBS positions.

The final P-wave velocity model includes 3 layers above the BSR. The first layer has very low velocities (1.50-1.52 km/s) representing very unconsolidated marine sediments. Velocities increase slightly in the second layer, also containing slope sediments. The bottom layer constitutes consolidated sediments of the accretionary prism, with much higher velocities varying from 1.62 km/s at the top to 1.88 km/s at the BSR. The BSR depth of 230 m, which is well-constrained with an uncertainty of less than 5 m, agrees well with the BSR depth inferred from sonic data at Site U1327 [1] and from Vertical Seismic Profile (VSP) data at ODP Site 889 [9]. However, the VSP data at U1327 (Fig. 4b) implies a BSR depth of ~250 m; the disagreement may be due to an error in baseline reference for the VSP.

Gas hydrate concentrations were calculated from the wide-angle velocity data at Site U1327 using the simple porosity-reduction method [6,7] and assuming a reference velocity trend from MCS velocity analyses [5]. For the bottom layer, an average concentration of ~15% was estimated, matching well the estimates from the average sonic velocity data [5].

In the velocity model, velocities increase uniformly with depth over a 4-km-long profile centred on the U1327 drillholes. No evidence was found for layers with high hydrate concentrations at depths between 120-138 mbsf as detected at Hole U1327A [1]. This occurrence must be very localized – it was also not detected in nearby Hole U1327E at 70 m distance.

Fig. 4. (a) Time-migrated single-channel seismic data plotted with the final velocity model. Velocities were determined by simultaneous traveltime modeling of OBS wide-angle arrivals and reflections from the SCS data; dotted red lines indicate the 3 sediment reflections used in the modeling. (b) The velocity-depth profile at the location of U1327 (green lines) compares well with the drillhole sonic velocities (red line); Vertical Seismic Profile (VSP) data indicate a BSR that is anomalously deep. Also shown are velocities from a previous study [10].
SEISMIC STRUCTURE OF BULLSEYE VENT NEAR SITE U1328

In 2002, deep-towed multichannel seismic lines were collected on the Cascadia margin using the high-resolution Deep-Towed Acoustics and Geophysics System (DTAGS) of the US Naval Research Laboratory. The primary target was the region of Bullseye vent, later drilled at Site U1328 [1]. The vent field including Bullseye vent was first detected in 1998 during an initial DTAGS survey; the vents were identified by significant seismic blanking, or reduction in amplitude, over regions up to 500 m in diameter [11,12]. At Bullseye vent, piston cores had sampled massive hydrate at sediment depths of 0.5 to 8 m [2]. In the region where hydrate was recovered, a grid of single-channel seismic lines showed a prominent mushroom-shaped reflector, interpreted as the top of a hydrate cap [2]. The hydrate cap was drilled at 5 holes of U1328; massive hydrate was recovered in the upper 40 m, and downhole logs showed very high resistivity in the upper 40 m consistent with hydrate saturations of 60-80% (Fig. 5b) [1].

The deep-towed DTAGS images the shallow structure below the seafloor at much higher resolution than surface-towed multichannel systems – the high-frequency source (220-650 Hz) increases the vertical resolution, while the nearness of the source and receivers to the seafloor (200-300 m) improves the horizontal resolution. However, the source position and the cable geometry are poorly controlled during the survey. To achieve optimal resolution, relative source positions are determined by using the high degree of recording-array overlap from shot-to-shot; as well, the cable geometry is determined by inversion of traveltimes for the direct arrivals and reflections from the sea surface [13].

At Bullseye vent, the DTAGS data image a ~10-m-thick high reflectivity zone, extending from the seafloor to a depth of ~25 m and dipping seaward at a small angle of ~7º (Fig. 5a) [13]. This likely corresponds to the upper portion of the massive hydrate layer that was encountered at IODP Site U1328 [1]. The high reflectivity zone is interpreted as a complex near-surface hydraulic fracture system filled with hydrate and associated with steeply-dipping faults below it.

Fig. 5. (a) DTAGS seismic section crossing Bullseye vent. A zone of high reflectivity interpreted as a fracture zone extends from a seafloor pockmark to a depth of ~25 mbsf, dipping SW at a shallow angle of ~7º. (b) The fracture zone corresponds to the top of a zone of high resistivity detected at IODP Site 1328, interpreted as massive gas hydrate.
REFERENCES


