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IODP EXPEDITION 311: CASCADIA MARGIN GAS HYDRATES
SITE U1328 SUMMARY

Site U1328 (Scientific Prospectus Site CAS-06A) is located within a seafloor cold-vent field, with dimensions 2 km by 4 km, consisting of at least four vents associated with near-surface faults. The cold vents are characterized by near-vertical seismic blank (or wipe-out) zones that are between 80 and several 100 m wide, and show a clear E-W trend as identified from 3D seismic imaging. The most prominent vent in the field, referred to as Bullseye vent, is the target of this site and has been the subject of intensive geophysical and geochemical studies since 1999. Site U1328 is different than all of the other sites visited during this expedition in that it represents an area of active, focused fluid flow. A number of seismic surveys cross this site, including two single channel seismic (SCS) 3D surveys and a regional multichannel seismic (MCS) data set.

Several different mechanisms have been proposed for the origin of the seismic blanking observed in the Bullseye vent area and for the implications concerning the nature of the fluid venting. The objectives of coring and logging at this location are to test the different models for the cold-vent structure and associated causes of seismic blanking, the rate of methane advection and potential loss of methane into the water column. It is important to obtain a high-resolution temperature profile for this area to assess any evidence of active fluid flow. Pressure coring using the PCS system will help assess the occurrence of free gas within the gas hydrate stability zone below Bullseye vent and possibly ascertain the cause of the observed seismic blanking. Additional pressure coring using the HRC and FPC systems will be used to recover high-quality gas-hydrate-bearing core for shore-based analyses.

Five holes were occupied at Site U1328. Hole U1328A was dedicated to LWD/MWD measurements to a total depth of 300 mbsf. Hole U1328B was continuously cored (6 APC, 2 XCB, 2 PCS cores; 72.8 % recovery) to a depth of only 56.6 mbsf, and was terminated after strong winds and severe ship heave conditions required us to pull out of the hole. Two APC temperature measurements were made (APCT and APC3). As a calibration experiment, the DVTPP was also deployed at the bottom of Hole U1328B. After waiting on weather for 16 hours, conditions had improved to the point to allow drilling and coring operations to continue. Hole U1328C was drilled from the seafloor to the maximum depth of Hole U1328B (56.5 mbsf). Hole U1328C was then continuously cored (4 APC, 22 XCB, 1 PCS cores; 80.7 % recovery) to a total depth of 300 mbsf. In addition, three APCT and two DVTPP temperature measurements were made. Hole U1328C was wireline logged with the triple-combo and FMS-sonic tool strings. The triple-combo logged from a total depth of 294 mbsf, and two up-hole passes of the FMS-sonic tool also logged the same depth interval. The wireline logging program in Hole U1328C included a VSP survey, with the deepest clamping position at 286 mbsf. The VSP included 35 clamping positions with the upper most station at 106 mbsf. Hole U1328D was cored as a special high-resolution combined microbiology and geochemistry research hole with two XCB cores and a single FPC taken at the bottom of the hole. Hole U1328E was a special tool hole, which also included the deployment of six XCB cores within the upper 46.0 mbsf to recover additional samples of gas hydrate. Seven pressure cores were taken (3 PCS, 2 HRC, and 2 FPC) separated by XCB cores and drilled intervals. Hole U1328E also included two DVTPP deployments for temperature data.

Site U1328 recovered a 300-m-thick sequence of Quaternary (0-1.6 Ma) slope and slope basin sediments. The biostratigraphy determined for Site U1328 was based on the examination of diatoms from Holes U1328B and U1328C. The stratigraphic section cored and logged at Site U1328 was divided into three lithostratigraphic units. Lithostratigraphic Unit I (0-56.50 mbsf in Hole U1328B, 56.50-132.60 mbsf in Hole U1328C, 0-15.00 mbsf in Hole U1328D, 0-92.26 mbsf in Hole U1328E) is characterized by fine grained detrital sediments (dark greenish gray clay and silty clay), with abundant coarse grained layers, up to 6 cm-thick, indicative of turbidite deposits. The boundary between lithostratigraphic Units I and II is marked by a sharp decrease of sand and silt layers and by the onset of diatom-bearing sediments. Lithostratigraphic Unit II (132.60-197.10 mbsf in Hole U1328C; 197.00-198.00 mbsf in Hole U1328E) is characterized by fine grained (clay to silty clay) detrital sediments with some silty interlayers from turbiditic deposits and siliceous fossils. Abundant marine diatoms along with resting spores within lithostratigraphic Unit II suggest the diatoms bloomed in a shallow water shelf environment associated with coastal upwelling, and then the diatoms were reworked. The boundary between lithostratigraphic Units II and Unit III is distinguished by the sudden absence of diatoms. Lithostratigraphic Unit III (197.10-300.00 mbsf in Hole U1328C) is characterized by fine grained (clay to silty clay) detrital sediments with very few silty interlayers from turbidite deposits likely deposited in an abyssal plain environment. The presence of authigenic carbonate cements show that diagenetic processes are active in lithostratigraphic Unit III. Because of the large input of turbidite deposits, in lithostratigraphic Unit I, we see a significant increase in sedimentation rate from 24.6 cm/k.y. in lithostratigraphic Unit II to 37.5 cm/k.y. in lithostratigraphic Unit I.

At Site U1328, gas hydrate was sampled and evidence of gas hydrate was found in the recovered cores in the form of soupy and mousse-like textures. At this site, soupy texture is only present within lithostratigraphic Unit I. At Site U1328 mousse-like textures are present occasionally within lithostratigraphic Units I to III.

The LWD/MWD and wireline logged section in Holes U1328A and U1328C was divided into three “Logging Units,” based on obvious changes in the downhole measured gamma ray, density, electrical resistivity, and acoustic measurements; for the most part these three logging units correspond closely to the lithostratigraphic Units I, II, and III. Logging Unit 1 (0-128 mbsf in Hole U1328A) is characterized by a well-defined increase in density with depth. The most striking feature in this unit is seen in the LWD/MWD logs between the seafloor and 46 mbsf, where high resistivities (more than 25 ohm-m) alternate with intervals of much lower resistivity (1-2 ohm-m). The high resistivities likely indicate the presence of gas hydrate, which were sampled during coring. Logging Unit 2 (128-200 mbsf in Hole U1328A) is marked at the top by a clear decrease in density log values. Unit 2 is also characterized by a constant relatively low background resistivity value just above 1 ohm-m and only one significant high resistivity log inferred gas hydrate occurrence at a depth of 160 mbsf. Logging Unit 3 (200-300 mbsf in Hole U1328A) is characterized by small increases in background resistivity and notably more variability resistivity and P-wave velocity log values.

Physical properties were measured in cores recovered from four of the holes at this site, with the core derived MAD data comparing favorably to both the LWD/MWD and downhole wireline data. Numerous low porosity outliers, however, were interpreted to represent sand-rich samples.

It has been shown that resistivity-at-bit images (RAB) as derived from the LWD/MWD GeoVISION tool can be use to image gas hydrate in sediment. High concentrations of gas hydrate are evident in the interval 0-46 mbsf of Hole U1328A, where resistivities are high. The RAB images from Hole U1328A also reveal numerous high resistivity sinusoidal features in the upper 46 mbsf in UHole 1328A, and again at a depth of 90–100 mbsf, which can be interpreted as dipping fractures containing gas hydrate or maybe free gas. These near-vertical fractures may act as gas migration conduits that feed the gas hydrate accumulation observed near the seafloor.

To estimate the amount of gas hydrate at Site U1328, the GeoVISION derived resistivity log data was used as input to the Archie relation to estimate pore volume water saturations. Gas hydrate saturation is the percentage of pore space in sediment occupied by gas hydrate, which is the complement of the water saturation. These calculations have shown highly variable gas hydrate saturations in the upper 46 mbsf, with values as high as 95% in several intervals up to 10 m thick. These layers of high gas hydrate concentrations alternate with layers of much higher water saturations.

The combined analysis of acoustic velocities and waveform amplitudes can also help identify the occurrence of gas hydrate and/or free gas. In the interval between 210 and 220 mbsf, near the seismically inferred depth of the BSR at ~219 mbsf, the P-wave velocity drops slightly while the S-wave velocity increases. This could be due to the coexistence of free gas and gas hydrate in the vicinity of the BSR, which has been observed on the Blake Ridge and Hydrate Ridge. Additional evidence for the occurrence of free gas below the BSR was noted in the analysis of the LWD/MWD acoustic coherence data, borehole fluid pressure response during drilling, and from the wireline P-wave, resistivity, density and neutron logs. The PCS degassing experiments of a single core in Hole U1328E also suggests the presence of a free-gas phase below the BSR at this site (see below). However, it is important to note that the VSP survey obtained in Hole U1328C yielded a very uniform velocity profile with depth and no clear velocity contrast around the expected depth of the BSR.

Although we deployed the APCT, APC3, DVTP, and DVTPP temperature tools a total of nine times we recorded only three reliable data points, which was mostly the result of severe ship heave conditions. The in-situ temperatures determined for Site U1328 are generally similar to those at Site U1327 and slightly higher than those determined at similar depths during Leg 146. For Site U1328 we observed a seafloor temperature of ~3.5°C and a geothermal gradient of ~5.4°C/100 m; which corresponds to a predicted depth to the base of the methane hydrate stability zone ranging from 222-247 mbsf given the uncertainty in the data.

All cores from this site were systematically scanned upon arrival on the catwalk to detect infrared (IR) anomalies indicative of gas hydrate dissociation during core recovery. Strong cold anomalies were detected in the shallowest cores from this site. A large amount of gas hydrate had been anticipated in the upper 30 mbsf based on LWD/MWD resistivity measurements and previous piston coring at this site, and a considerable amount was found. However, the LWD/MWD high resistivity inferred gas hydrate occurrence at 90-100 mbsf in Hole U1328A was not seen on either the IR images or the wireline logs, both taken in Hole U1328C. The IR data may have missed this interval due to poor core recovery, but the lack of a high-resistivity layer in the wireline log points to horizontal inhomogeneity. This is not unexpected, in that the high-resistivity layer in the LWD/MWD image contains a steeply dipping fracture that is unlikely to be intersected at the same depth even in two closely spaced holes. The strongest anomalies were detected just above the seismically inferred BSR (210-222 mbsf), and a few small but distinct cold anomalies were observed below it, one of which exhibited pore water freshening, indicative of the presence of gas hydrate (Core U1328C-22X at a depth of ~249 mbsf). The possibility of gas hydrate beneath the BSR may indicate the presence of Structure II gas hydrate, which is stable below the base of the pure methane Structure I gas hydrate stability zone. However, it should be noted that there remains a substantial uncertainty in the exact depth of the base of the gas hydrate stability field at this site and the depth of the BSR. All available data suggests that the gas hydrate stability zone could be deeper than the initially inferred depth of the BSR, which may result in shifting the observed IR anomalies to depths well within the gas hydrate stability field.

At Site U1328 we attempted 11 deployments of the three different pressure coring tools. The PCS was deployed six times at Site U1328 (twice in Hole U1328B, once in Hole U1328C, and three times in Hole U1328E), five of which recovered sediment under pressure. In addition to the PCS deployment, the HRC was used two times and the FPC was used three times, but none of these cores were recovered under pressure. The degassing of the five successful PCS cores from this site showed variable gas concentrations with depth. Two PCS cores were taken within the near-surface gas-hydrate-bearing section from 0 to 46 mbsf (Core U1328B-4P at 14.5 and Core U1328B-7P at 26 mbsf), which yielded 24.2 L and 4.5 L of methane, respectively, equivalent to a pore volume gas hydrate saturation of ~ 15% and ~2%. The X-ray images of Core U1328B-4P under pressure show 2-6-mm-thick low-density structures that disappeared after degassing and are interpreted as gas hydrate veins. This core showed large amounts of gas expansion and sediment extrusion during depressurization, as did Cores U1328B-7P and U1328E-10P to a lesser extent. The two PCS cores taken in the Holes U1328C and U1328E at 92.0 mbsf (Cores U1328C-5P, U1328E-10P) yielded each quite different amounts of methane gas and would equate to the occurrence of 22% (Core U1328C-5P) and 0.7% of gas hydrate (Cores U1328E-10P). One PCS core was taken from a depth of 233 mbsf, very close to the seismically inferred BSR depth. This core yielded 60 L of methane gas, the largest recovery of gas during this expedition. However, X-ray scans of this PCS core under pressure showed a gas bubble in the PCS outer core barrel. Gamma density scans during degassing and X-ray scans after depressurization showed almost no evidence of gas-expansion cracks or large voids in the core, which would be expected from a core that gave off 60 L of gas. It is speculated that most of the gas released during the degassing of this core came from the space between the inner and outer barrel, thus the apparent extra gas in the PCS during this core run must have been swabbed into the core barrel during the coring process.

A total of 91 interstitial water geochemistry samples were processed from four of the holes cored at Site U1328. The composite chlorinity profile for this site shows four distinct zones. In the upper ~30 mbsf, we see a striking increase in chlorinity, with maximum values exceeding 850 mM. The observed excess solutes are believed to be the result from salt exclusion from the water lattice structure during in situ gas hydrate formation, and have not been removed by advective or diffusive processes. The second zone from ~30 to ~150 mbsf, is characterized by relatively constant chlorinity values ranging from 538 to 570 to mM. A third zone, extending from ~150 to 250 mbsf, across the BSR, shows discrete excursions to fresher chlorinity values (as low as 348 mM), suggesting that gas hydrate was present in the cores and dissociated prior to processing the samples. The chlorinity anomalies are consistent with observations of distinct negative thermal excursions in IR scans. Our observations further indicate that most of the gas hydrates occupy relatively thin sand layers. In the deepest zone, below 250 mbsf, the chlorinity remains nearly constant at 493 ± 3 mM, suggesting communication with a fluid at greater depth that is notably different in composition from the deep-seated fluid sampled at Sites U1327 and 889/890.

To form and maintain shallow gas hydrate deposits near the seafloor, methane has to be supplied continuously. Furthermore, the shallow elevated chlorinity values would dissipate rapidly if they were not continuously maintained by ongoing gas hydrate formation. However, the chlorinity profile with depth at Site U1328 indicates a diffusion-controlled system. These observations indicate that the methane needed to sustain the shallow gas hydrate formation is likely supplied along faults or fracture zones, probably the ones imaged by the RAB tool within the gas-hydrate-bearing section immediately below the seafloor.

The shipboard organic geochemistry program for Site U1328 included analysis of hydrocarbons and nonhydrocarbon gases from headspace (HS) gas samples, void gas samples gas samples recovered during PCS degassing experiments, and gases from gas hydrate samples. Methane was the most prominent hydrocarbon gas in all of the samples analyzed; however, ethane was also present in almost all of the HS samples. Most of the gas hydrate samples and gas-hydrate-bearing sediments collected within the upper 46 mbsf under the vent site exhibited elevated ethane concentrations. These near-surface samples also contained slightly more air contamination and elevated H_2S concentrations. It is also notable that the concentration of ethane and other gas-hydrate-forming gases, including propane and isobutane, increase within the gas samples collected from the cores crossing the depth of the seismically inferred BSR where the chlorinity and IR temperature anomalies both indicate evidence for gas hydrate. The occurrence of propane and elevated isobutane to normal-butane (i-C_4/n-C_4) ratio support the hypothesis that the gas hydrates near the depth of the BSR may contain a mixture of Structure I and Structure II gas hydrate. It is also interesting that the ethane concentrations remain elevated below the depth of the BSR. Structure-II gas hydrate is stable to greater depths with increasing temperature than Structure I gas hydrate; however, the observed IR and chlorinity anomalies are not necessarily below the base of the Structure I methane hydrate stability field and therefore not automatically related to Structure II gas hydrate given the uncertainty in the temperature measurements. However, the gas geochemistry does strongly suggest the presence of some mixture of Structure I and Structure II gas hydrate near the depth of the seismically inferred BSR.

Microbiological subsampling was routinely conducted on cores recovered from Holes U1328B and U1328C. On each core run, perfluorocarbon tracers (PFT) were continuously metered into the drilling fluid and fluorescent microspheres were deployed on all cores in the continuously cored holes to investigate potential drilling fluid contamination of the core. These analyses confirmed that the center of each whole-round sample remains undisturbed for microbiological subsampling. Additional IR images were taken on the cut-ends of each microbiological core section to document the thermal warming process of the core before subsampling.

The main objectives at this site were to document the depth distribution of gas hydrates and their relationship to fluid and gas chemistry, lithology, and faulting; and to determine the fluid advection rate feeding the surface vents. Apparently, however, only the very shallowest (<40 mbsf) and deepest (250-300 mbsf) portion of the sedimentary section cored at Site U1328 is dominated by fluid advection. It appears that diffusion transport controls the chemical depth profiles from about 40 to 250 mbsf at this site. This apparent contradiction can be explained with the vent model brought forward by Riedel et al. (2006). The model, based on various geophysical and geochemical observations, predicted that the shallow gas hydrate accumulations to be the result of isolated feeder-channels or fractures. Along these fractures, seen as blanked zones on the seismic data from this area, the bulk of the methane gas is transported upward and results in the near-seafloor concentrated gas hydrate accumulation. Evidence of the existence of these fractures comes from the LWD/MWD downhole logging data showing at several depths steeply dipping resistivity anomalies typical of fractures filled with gas hydrate or possibly free gas. These potential gas migration conduits may be connected to the seafloor chemosynthetic cold vent communities observed by bottom video surveys.

The growth of gas hydrate near the seafloor has also resulted in solute exclusion and the development of high pore water salinities. This brine cannot be maintained in situ over a long period of time, unless gas hydrate is constantly formed at relatively high rates, thus showing the cold vent must be supplied with fluids and gas from greater depths. This is also indicated by the detection of a methane plume in the water column just above an active vent outlet. However, venting is most likely episodic since the methane plume is not always detectable. There is further evidence for the presence of Structure II gas hydrate at this site as seen by the presence of unusual amounts of propane and isobutane, which is unique when compared to the other sites cored during this expedition.

Various geophysical and geochemical data support the presence of a BSR at this site; however, the BSR at this site is difficult to identify with the available seismic data. The lack of good 3D seismic velocity control could potentially result in misinterpretation of the existing 2D seismic data, in that the observed BSR may actually be a side-diffraction and may not be exactly located beneath the active part of the cold vent and seismic blanking. In the LWD/MWD data a sharp decrease in electrical resistivity was observed at a depth of ~ 220 mbsf although it is coincident with a high density interval potentially related to the presence of carbonates. Acoustic wireline logging, however, shows a sharp discontinuity in P-wave and S-wave velocity at a depth of ~215 mbsf, close to the seismically inferred BSR depth of 219 ± 5 mbsf. The downhole temperature measurements from this site yielded a temperature gradient of ~54ºC/km, which predicts the base of gas hydrate stability at ~230 ± 10 mbsf for the observed pore water and gas geochemistries.

There is evidence for the occurrence of free gas at depths below the seismically inferred BSR; as demonstrated from pressure coring, LWD/MWD pressure monitoring, and elevated LWD/MWD electrical resistivity values. There are also seismic indicators for the occurrence of free gas below the BSR in the form of strong amplitude anomalies. However, the VSP does not show any evidence of a velocity change over the entire logged interval from 105 to 285 mbsf, which will be further examined after the cruise.