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IODP EXPEDITION 311: CASCADIA MARGIN GAS HYDRATES
SITE U1327 SUMMARY

Site U1327 (Scientific Prospectus Site CAS-01B) is located near ODP Site 889/890 approximately at the mid-slope of the accretionary prism over a clearly defined BSR, estimated to be at a depth of 223 mbsf. The primary research objectives for this site are linked to the transect-concept of this expedition. Site 889/890 has provided critical baseline data for the development of the objectives of this research expedition. Historical work with data from Site 889/890 has shown that the concentration of gas hydrate in sediments has been estimated by using (a) deviations in interstitial water chlorinities from measured baseline conditions, (b) electrical resistivity measurements by applying Archie's relation, and (c) using both seismic and downhole log-derived P- and S-wave velocities. But results from Leg 146 have left many questions unanswered (Riedel et al., 2005), such as:

(a) What is the geochemical reference profile for chlorinity and other geochemical gas hydrate proxies?
(b) What is the electrical resistivity baseline for the sediments drilled at this site and what are the appropriate empirical Archie coefficients?
(c) What is the reference profile for acoustic P- and S-wave velocities?

Answers to these questions are needed to calibrate remote sensing techniques, such as reflection seismic and controlled-source electromagnetic surveys (CSEM), which can be obtained through research coring and downhole logging.

Five holes were occupied at Site U1327. Hole U1327A was dedicated to LWD/MWD measurements to a total depth of 300 mbsf. Initially we had planned to drill to a depth of 350 mbsf, but tight time constraints during the LWD/MWD operations made it necessary to reduce the depth of the planned deepest penetrations at this site. The first APC in Hole U1327B missed mudline with a full core, the core was curated and a new hole was spudded without offsetting the ship. Hole U1327C was then cored (10 APC, 22 XCB, 3 PCS cores; 88.3% recovery) to 300.0 mbsf. The PCS was deployed three times in Hole U1327C and four APCT temperature measurements were made (Cores 311-U1327C-3H, 5H, 7H, 9H). Three additional deployments using the DVTP and DVTPP tools were attempted, but data quality is marginal due to strong heave conditions and instrument failures. In Hole U1327D, which was drilled and cored as a special tools hole, two APC cores were also taken from the surface to a depth of 16.4 mbsf for a high resolution microbiological and geochemical study of the sulfate/methane interface (SMI). In this hole, the PCS was deployed three times, together with four deployments of the HRC and two deployments of the FPC pressure coring system. The last pressure core was taken at a depth of 246.5 mbsf and the hole was advanced to a TD of 300 mbsf for the logging program. The first tool deployed was the triple-combo, which reached a depth of 295.4 mbsf and the hole was logged to near the top of the log run without incident. A combination of a ship heave event (>3 m) and the oversized borehole apparently caught and tore off the density tool caliper arm. The damaged tool string was returned to the ship without further incident. The VSP logging program in Hole U1327D was started the following morning with the one hour long pre-shooting marine-mammal observation period and a 30 minute pressure-ramp up time for the GI gun. The VSP program was successfully carried out with 16 clamping stations covering the depth range from 181 to 276 mbsf before the arm on the WST tool apparently broke. The WST was returned with some difficulties to the ship. Due to the critical nature of the acoustic wireline logging program to the expedition, it was decided to drill a new hole and acquire additional pressure cores and a wireline acoustic log survey.

Hole U1327E was advanced to 3 mbsf and a single 9.5 m long APC core was taken for high resolution microbiological and geochemical sampling of the SMI, which was partially missed during an earlier attempt. Two additional PCS pressure cores and one HRC core were taken, out of which only the second PCS at ~80 mbsf recovered sediment under pressure. Excessive heave over 3.5 m forced the termination of pressure coring operations and the hole was advanced by drilling to a completion depth of 300 mbsf to prepare the second wireline logging run. Due to the excessive heave conditions it was decided to run a non-standard tool string composed of the HNGS-DIT-DSI, which allows measurement of natural gamma, resistivity and acoustic data (Vp, Vs). Two successful runs of this tool string were completed recovering high quality downhole logging data.

Site U1327 is located near two prominent topographic highs, composed almost entirely of accreted sediments that rise more than 200 m above the surrounding seafloor . The ridges of accreted sediment lack any coherent seismic reflections and are associated with underlying thrust faults that contributed to the overall uplift of the area between the two ridges (Westbrook et al., 1994; Riedel, 2001). Site U1327 is situated near the NW flank of the eastern-most ridge and is characterized by a ~90-m-thick cover of slope-basin sediments, underlain by a thick section of accreted sediments. The stratigraphy at Site U1327 was divided into three lithostratigraphic units. Unit I (0–90.1 mbsf in Hole U1327C, age: Holocene–Pleistocene, < 0.3 Ma) is composed of dark greenish gray and dark gray clay and silty clay, often interbedded with silt, clayey silt, sandy silt, sand and gravel layers. Lithostratigraphic Unit I is characterized by fine grained detrital sediments (clay and silty clay), with abundant coarse grained layers up to 6 cm-thick indicating turbiditic deposits with a sedimentation rate of 22 cm/k.y. Authigenic carbonate cement is present in Unit I, but no evidence for dolomite precipitation is found, which is inferred from interstitial water analyses. A unique characteristic of Unit I is the anomalous occurrence of lithified carbonate nodules and rocks of various lithologies, such as granite, which probably are dropstones from rafting icebergs. The lithostratigraphic boundary between Unit I and II is marked by a sharp decrease in sand and silt layers and the onset of diatom-rich sediments. It is also the seismically inferred boundary between slope-basin type and accreted sediments.

Lithostratigraphic Unit II (90.1–170.4 mbsf in Hole U1327C, age: Pleistocene, > 0.3–1.0 Ma) is composed of dark greenish gray and dark gray clay, clay with diatoms, and silty clay, silty clay with diatoms and diatom silty clay locally interbedded with sandy silt and sand layers and lenses. Very few carbonate cements are present in Unit II, but lithified carbonate nodules and exotic rocks (some up to 8 cm in diameter) as described in Unit I are very abundant. Within Unit II soupy and mousse-like sediment textures related to the presence of observed gas hydrate can be correlated to IR imaged cold-spot anomalies detected on the catwalk. The sedimentation rate of Unit II is estimated at ~16 cm/k.y. and the intervals with a high ratio of non-marine versus marine diatoms indicate the increasing contribution of terrigeneous detrital sediments from land sources via turbidites. The great abundance of marine diatoms along with resting spores within lithostratigraphic Unit II suggests blooming in shallow water shelf environment and coastal upwelling, then reworking by turbidity currents.

Lithostratigraphic Unit III (170.4–TD in Hole U1327C, age: Pleistocene > 1 Ma) is composed of dark greenish gray and dark gray silty clay in the upper part of the unit, whereas the lower part (below 248 mbsf) is dark greenish gray silty clay with diatoms. Lithostratigraphic Unit III is distinguished from lithostratigraphic Unit II by the sudden absence of diatoms, as well as the degree of induration of the sediments. Diatoms reappear at the bottom of Unit III. Few carbonate cements are present and lithified carbonate nodules and exotic rock clasts were found, especially within Core 311-U1327C-24P taken at a depth of 197.3 mbsf.

The depositional environment for Unit III was interpreted as an abyssal plain, with sediment transport and deposition dominated by low-energy turbidity currents. The sedimentation rate in this section, as determined from biostratigraphic analyses of diatoms, is low for this site at ~12 cm/k.y., which is consistent with a basin-plain setting.

Pre-coring LWD/MWD logging was conducted at all sites occupied on Expedition 311 to direct special tool deployments, such as the PCS, HRC, and FPC pressure core systems. The downhole logged section at Site U1327 was divided into three “Logging Units” based on obvious changes in the LWD/MWD and wireline gamma ray, density, electrical resistivity, and acoustic measurements. There is no apparent correlation between the logging units and the lithostratigraphic units at this site. Logging Unit 1 (0-120 mbsf) is characterized by a resistivity trend that steadily increases from around 1 ohm-m near the seafloor to about 2 ohm-m at the bottom of the unit. The P-wave velocities in this unit average about 1550 m/s. Logging Unit 2 (120-240 mbsf) is characterized by a constant background resistivity value around 2 ohm-m and relatively high P-wave velocities that average about 1750 m/s over most of the interval. This unit shows a number of thin (0.5 to 1.0 m thick) high resistivity sections that may be attributed to gas hydrates, and the occurrence of relatively high downhole measured P-wave velocities in these same intervals also indicates the presence of gas hydrate. A thick section of continuous high electrical resistivities and P-wave velocities combined with low density measurements were observed in the LWD/MWD data at a depth of 120–138 mbsf in Hole U1327A, which was the target of several pressure coring deployments (see below for details). However, it was later determined that this high resistivity zone was laterally discontinuous and was penetrated in the adjacent Holes U1327C and U1327D at a much greater depth (ranging from 20 to 35 m deeper) and was not intersected in Hole U1327E. The top of Logging Unit 3 (240-300 mbsf) is defined by a sharp decrease in P-wave velocity. Below 240 mbsf, P-wave velocities drop to very low values near fluid velocities (~1500 m/s), suggesting the presence of small amounts of free gas. Logging Unit 3 also displays a small drop in resistivity compared to logging Unit 2. Although resistivity tends to be just above 2 ohm-m in Unit 2, it is just below 2 ohm-m in Unit 3.

Variations in the core-derived physical properties apparently do not correlate well with the identified lithostratigraphic and logging units, with the exception of the boundary between lithostratigraphic Unit I and II, marked by a sharp increase in magnetic susceptibility. Sediment density and porosity determined from MAD analyses show a typical trend with depth suggesting normal compaction. Slight deviations from this trend reflect small-scale lithologic variability and generally match the porosity and density trend determined from the LWD/MWD data.

Infrared (IR) imaging of the recovered cores was routinely carried out on the catwalk to detect and characterize the nature of gas hydrates in the cores. A large number of IR identified cold spots were detected in the cores from Holes U1327C and U1327D; however, an apparent depth mismatch in the occurrence of major cold core sections between the holes indicated significant intra-site geologic variability. Apparent mismatches between the IR inferred gas hydrate occurrences in Hole U1327C with the LWD/MWD resistivity inferred gas hydrate occurrences in Hole U1327A further documents the lack of lateral continuity at this site. In situ temperature measurements with the APCT (four measurements), DVTP (one deployment, instrument failure) and DVTPP3 (two deployments, poor quality due to heave and instrument calibration problems) tools were conducted. The data suggests a geothermal gradient of ~ 61ºC/km, which is considerably higher than what was estimated for Site 889 (~54ºC/km).

The PCS was deployed eight times at Site U1327 (three in Hole U1327C, three in Hole U1327D, two in Hole U1327E), five of which recovered sediment under pressure. In addition to the PCS deployment, the HRC was used four times (with three core recoveries under pressure) and the FPC was used twice, but only one of the FPC cores was recovered under pressure. The degassing of the five PCS cores from this site that were recovered under pressure showed variable gas concentrations with depth. The deepest PCS core was taken at a depth of 246.5 mbsf, which is ~25 m deeper than the seismically inferred BSR depth. This pressure core (U1327D-17P) had a pore space methane concentraton of 220 mM, which is equivalent to a free-gas concentration in the pore space of the sediment of 1.1%. The other four PCS cores were taken from within the predicted depth interval of the methane hydrate stability zone. Core 311-U1327E-3P is the shallowest PCS core taken at this site, which was from a depth of ~80 mbsf. It yielded 0.9L of methane (93 mM) or equivalently 0.4% gas hydrate concentration. The remaining three PCS Cores 311-U1327C-15P (yielded 1.07 L of methane gas, 106 mM methane), 311-U1327D-10P (yielded 9.4 L of methane, 685 mM methane), and 311-U1327C-24P (yielded 4.2 L of methane, 263 mM methane) were taken at 122.3, 155.6, and 197.8 mbsf, respectively. Out of these three cores, only Core 311-U1327D-10P yielded enough gas to infer the occurrence of a significant amount of gas hydrate; with an estimated gas hydrate pore-space concentration of ~8%. The other two PCS cores yielded gas hydrate pore-space concentrations of less than 1%.

Three HRC cores (311-U1327D-4E from 125.3 mbsf, 311-U1327D-12E from 170.5 mbsf, 311-U1327D-14E from 217.7 mbsf) and one FPC core (311-U1327D-13Y from 203.6 mbsf) were successfully recovered and transferred under pressure to storage chambers for shore-based analyses. All of these cores were X-ray imaged, P-wave velocity and density logged within their storage vessels. Some of the recovered pressure cores exhibited evidence of gas hydrate, including high P-wave velocities and anomalous low density readings.

High resolution interstitial water sampling was carried out to characterize the sulfate/methane interface (SMI), which was determined to be located between 9 and 10 mbsf. An overall smooth decreasing trend in pore water chlorinity and salinity is observed similar to results from Site 889/890 (Westbrook et al,. 1994). At a depth of ~120 mbsf the chlorinity and salinity profiles exhibit distinct anomalies that likely indicate freshening as a result of the dissociation of gas hydrate during the core recovery process. Chloride values as low as 70 mM (equivalent salinity 3.7) were measured in two samples, correlated to sand layers (up to 3 cm thick), that also showed clear IR cold spot anomalies. Such a low pore water chlorinity is equivalent to a pore space gas hydrate concentration of ~80%. No chlorinity anomalies occur below the depth of ~225 mbsf, which is close to the seismically inferred depth of the BSR. However, the strongly decreasing chlorinity profile from the surface to below the BSR at Site U1327 suggests the mixing of standard marine pore water with a deep-sourced, relatively fresh fluid. Interestingly, interstitial water chlorinity and salinity remain almost constant beneath the BSR.

Organic geochemical studies at Site U1327 included analysis of the composition of volatile hydrocarbons (C_1-C_5) and non-hydrocarbon gases (i.e., O_2 and N_2) from headspace gas samples, void gas samples, and gas samples recovered during PCS degassing experiments The predominant hydrocarbon gas found in the cores from Site U1327 was methane; however, we did see an increase in ethane concentrations in the void and headspace gases collected from stratigraphic section overlying the projected depth of the BSR. This increase in ethane concentrations near the BSR can also be seen in the C_1/C_2 void gas ratios, which decrease with depth toward the BSR. Other studies have shown that void gas ratios can decrease in a gas hydrate with the preferential selection of ethane into the gas hydrate structure. But the observed increase in the C_1/C_2 ratio below the projected depth of the BSR may indicate a methane enriched free-gas accumulation. In general, the C_1/C_2 ratios were generally high (above 1000), indicating a predominant microbial origin for the observed methane.

Microbiological subsampling was routinely conducted on cores recovered from Hole U1327C. On each core run, perfluorocarbon tracers (PFT) were continuously metered into the drilling fluid and fluorescent microspheres were deployed on selected cores 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 primary research objectives of this site are linked to the results from Site 889/890 of ODP Leg 146 to delineate critical geochemical, geophysical and microbiological data for gas hydrate proxy analyses. Site U1327, along with Site 889/890, is the near the center of a research study area that since 1992 has been the focus of many interdisciplinary gas hydrate studies.

Geochemical analysis of core recovered gas samples and interstitial fluids have documented a relatively complex fluid regime for this site, similar to what was observed at Sites 889/890 and U1329. The rapid Cl concentration decrease with depth strongly suggests fluid communication with a deep-seated, fresher fluid source. Earlier interpretations of the chlorinity profile measured at Site 889/890 have attributed the pore water freshening entirely to gas hydrate dissociation upon core recovery (Hyndman at al,. 1999). However, the new IW data collected at Site U1327, in combination with other gas hydrate proxy data (such as IR images and downhole log measurements) strongly supports the development of a new undisturbed baseline for interstitial water chlorinity along the Cascadia margin that progressively decreases with depth, similar to what was suggested by Ussler and Paull (2001). In other words, gas hydrate related pore-water freshening at Site U1327 is believed to be limited to only the interval from ~120 mbsf to a depth of ~220 mbsf, which is near the depth of the seismically identified BSR. The geochemical analyses of hydrocarbon gases from this site reveal a similar story as the analysis of the interstitial fluids with the gas chemistry in the inferred gas-hydrate-bearing section dominated by gas hydrate formation processes with an apparent increase in the more stable gas hydrate natural gas components.

Identifying gas hydrates and constraining their relative abundance in combination with providing physical models for the BSR are critical geophysical objectives at this site. A suite of geophysical experiments were conducted including pre-coring LWD/MWD logging, conventional wireline logging and vertical seismic profiling (VSP) to characterize the physical properties of gas-hydrate-bearing sediments. The presence of gas hydrate is generally characterized by increases in measured electrical resistivity and acoustic velocity. However, the LWD/MWD data from Hole U1327A showed an 18 m thick zone of increased resistivity and acoustic velocity values combined with a decrease in density, which was interpreted to contain large amount of gas hydrate, with concentrations exceeding 50% of the pore volume. However, the same interval was penetrated in the adjacent core holes, Hole U1327C and Hole U1327D, at much greater depths and with lower estimated gas hydrate concentrations inferred from the wireline electrical and acoustic logs. In the repeat wireline logging in Hole U1327E, no evidence of this interval was found. This shows large intra-site variability in gas hydrate content that is probably controlled by lithostratigraphic changes or structural complexities. This observation has dramatic implications on the calibration of geophysical surveying techniques such as seismic methods or controlled-source electromagnetic surveys that are commonly used to detect and quantify gas hydrates.

The combined use of IR imaging, interstitial pore water analyses and void/head-space gas sampling revealed that many IR cold-spots identified on the catwalk occur in relatively thin, but coarser grained intervals of sand and/or silty sand (interpreted to represent turbidite deposits) with gas hydrate concentrations in several cases exceeding 80% of the pore space. The gas hydrate forms preferentially in these coarser grained sections. Therefore, it is likely that the 18-m thick LWD/MWD measured high resistivity and acoustic velocity interval (120-138 mbsf) in Hole U1327A is a localized feature made up of discontinuous thinly bedded gas hydrate saturated turbidite sand lenses; that when surveyed with a logging tool with relatively lower vertical resolution the gas-hydrate-bearing section appears more massive in nature as a single unit on the downhole log.

The results of the VSP seismic experiment taken in combination with the downhole acoustic log from Hole U1327E also shows a relatively thick zone below the depth of the BSR that probably contains a considerable amount of free gas. The acoustic velocity decrease at the BSR is not abrupt, it is more transitional across a ~25-m-thick interval from >1800 m/s in the gas hydrate stability zone to as low as 1280 m/s in the underlying section. This confirms earlier interpretations of the frequency dependent reflection behavior of the BSR from vertical incidence seismic data. The BSR was thought to be a gradient zone in which velocity decreases over several meters (Chapman et al., 2002).

This site was intended to characterize the gas hydrate occurrence on the Northern Cascadia Margin to establish an understanding of the geologic, geophysical and geochemical controls on the occurrence and abundance of gas hydrates along the five site transect established during this expedition. All of the objectives set for Site U1327 are considered fulfilled.