Proceedings of the 6th International Conference on Gas Hydrates (ICGH 2008), Vancouver, British Columbia, CANADA, July 6-10, 2008.

VELOCITY ANALYSIS OF LWD AND WIRELINE SONIC DATA IN HYDRATE-BEARING SEDIMENTS ON THE CASCADIA MARGIN

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ABSTRACT

Downhole acoustic data were acquired in very low-velocity, hydrate-bearing formations at five sites drilled on the Cascadia Margin during the Integrated Ocean Drilling Program (IODP) Expedition 311. P-wave velocity in marine sediments typically increases with depth as porosity decreases because of compaction. In general, Vp increases from ~1.6 at the seafloor to ~2.0 km/s ~300 m below seafloor at these sites. Gas hydrate-bearing intervals appear as high-velocity anomalies over this trend because solid hydrates stiffen the sediment. Logging-while-drilling (LWD) sonic technology, however, is challenged to recover accurate P-wave velocity in shallow sediments where velocities are low and approach the fluid velocity. Low formation Vp make the analysis of LWD sonic data difficult because of the strong effects of leaky-P wave modes, which typically have high amplitudes and are dispersive. We examine the frequency dispersion of borehole leaky-P modes and establish a minimum depth (approx 50-100 m) below the seafloor at each site where Vp can be accurately estimated using LWD data. Below this depth, Vp estimates from LWD sonic data compare well with wireline sonic logs and VSP interval velocities in nearby holes, but differ in detail due to local heterogeneity. We derive hydrate saturation using published models and the best estimate of Vp at these sites and compare results with independent resistivity-derived saturations.

Keywords: sonic logging, LWD, marine sediments, CH_4 hydrate saturation

INTRODUCTION

Sonic velocity logs provide one of the best means to investigate the physical properties and porosity of drilled sequences and to tie logging data with seismic and core measurements. Increasingly, these measurements are required for geotechnical and shallow seismic exploration in shallow marine sediments where P-wave velocity is extremely low, often close to the fluid velocity. Such low velocity values make the analysis of sonic logs from logging-while-drilling (LWD) measurements challenging because of the strong effects of wave modes linked to the presence of a logging tool in the borehole, such as leaky-P modes [1]. Leaky-P (Airy) modes are excited when trapped fluid arrivals from a large-amplitude source in a borehole interfere with the compressional head wave propagating along the formation. The resulting leaky-P modes are dispersive: their phase velocity is near the formation velocity at low frequencies and tends to the fluid velocity as frequency increases. These dispersion effects must be accurately analyzed to measure formation velocity from leaky-P waveform data.

In this paper, we present results from LWD and wireline sonic tools deployed in shallow gas-hydrate bearing hemipelagic muds on the Cascadia margin [2]. Five sites were drilled

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through a relatively heterogeneous section of hemipelagic sediments with generally high core recovery (Fig. 1).

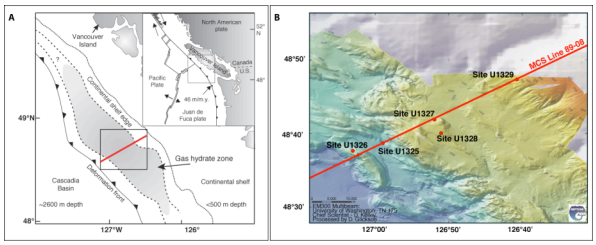

Figure 1 Location map and bathymetry for the sites drilled during IODP Expedition 311 [2]

The Schlumberger SonicVision LWD tool was deployed at all five sites during IODP Expedition 311, penetrating from the seafloor through the BSR at 200-300 m depth below seafloor (mbsf) at Sites U1325–U1329. (Fig. 2). More than 1400 m of LWD sonic waveform data were successfully recorded. Reidel et al. [2] describe preliminary compressional velocity (Vp) logs computed from the leaky-P wave mode in these data. We produce new Vp estimates from the LWD sonic waveforms using high-resolution dispersion analysis and compare the results with both wireline logs and core and VSP data acquired at these sites. Throughout this paper we refer to the P-wave slowness, the inverse of Vp, in typical units of microseconds per foot (μs/ft).

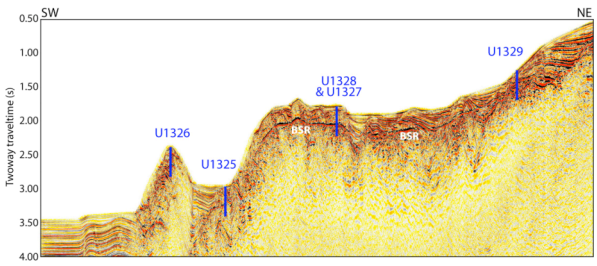

Figure 2 Multichannel seismic cross-section with site locations and approximate penetration [2]

DATA

LWD sonic waveforms

The LWD sonic tool is 17 cm (6.75 in) in diameter, and the hole was drilled with a 25-cm (9.875 in) bit. The tool records four waveforms over an array of receivers spanning a distance of 3.0-4.2 m from the source at 20-cm intervals [3]. The tool was configured with a wide-band source function, generating P-wave energy over frequencies from ~1-10 kHz. Drilling rates were generally maintained between 25-35 m/hr in each hole, and waveform data were recorded within ~20 min of bit penetration [2]. A waveform data set consisting of eight stacked waveforms was measured over every 0.15-m interval. Differential caliper logs measuring the distance from the tool to the borehole wall show these holes are in gauge for the most part, and the quality of the waveforms is not significantly degraded by borehole conditions. The recorded waveforms have relatively high signal amplitude because drilling noise is strongly attenuated in these high-porosity sediments.

The LWD waveform data recorded in low-velocity sediment contain dispersive energy from leaky-P, fluid, and tool modes [1]. We illustrate the dispersion curves for the recorded waveform using Prony's method, which computes the phase velocity for each mode at every frequency step [4]. For example, Figure 3 shows the computed slowness dispersion from multiple leaky-P wave modes for representative depth points *a* to *f* at Site U1326.

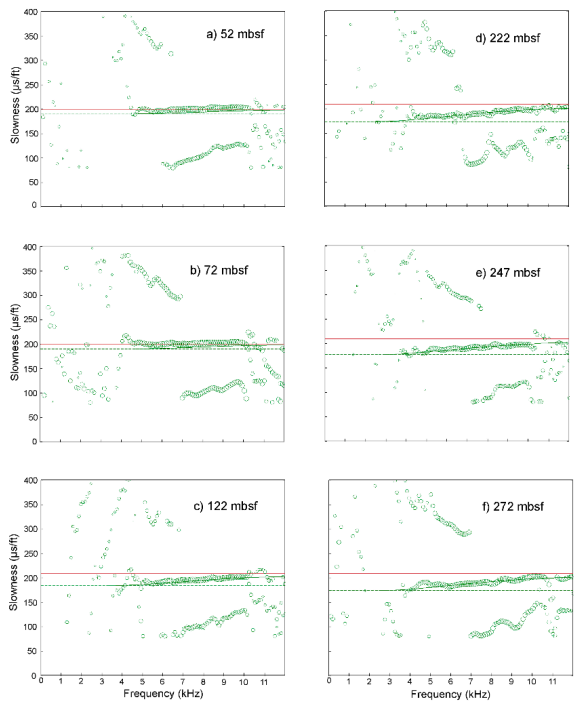

Figure 3, *a–f*. Slowness dispersion plots of LWD sonic data at representative depths at Site U1326

These plots clearly illustrate that dispersion is present in the leaky-P modes throughout the hole, illustrated by an overall increase in slowness with increasing frequency, and that slowness tends to

the borehole fluid slowness (red line) at higher frequency. Dispersion appears reduced at shallower depths (e.g., Fig. 3*a-b*) with small differences between leaky-P (green line) and borehole fluid slowness at low frequency. Higher and lower order modes are indicated by points far above and below these lines. The depth at which the fluid can no longer be distinguished from the leaky-P slowness at low frequency – where the red and green lines converge to within the resolution of the estimate point – determines the depth at which Vp can be reliably estimated using these data. Above this minimum depth, the leaky-P and fluid modes cannot be separated reliably.

Velocity logs

Figure 4 shows Vp logs computed from LWD sonic data collected at 5 sites during IODP Expedition 311 [2]. Fluid velocity estimated from LWD data (black curve) and an estimate of the base of the gas hydrate stability zone (GHSZ) is shown at each site (black lines). Slowness values were estimated from full dispersive analysis of the waveforms in post processing [5, 6].

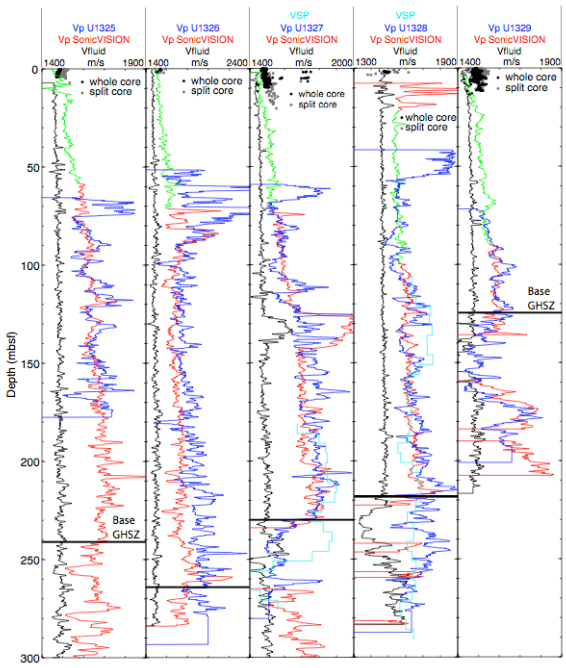

Figure 4 LWD and wireline Vp logs, core and VSP velocity estimates at sites U1325-U1329

LWD estimates of formation Vp from dispersion analysis are shown; reliable values (red curve) and unreliable values (green curve) based on the stepwise slowness dispersion analysis. Vp estimates from wireline logs (blue curve) and data from laboratory measurements on core samples (points) are also shown for comparison. Table 1 gives the depths below which LWD estimates are reliable for each site. Below these depths, wireline Vp logs follow closely with the LWD estimates, with some small-scale and local geological differences. Hole locations at each site are offset by ~10 m, on average, which introduces lateral variability over even these short distances between the LWD and wireline holes. LWD and wireline logs may therefore differ significantly in holes where methane hydrate or free gas occurs (e.g., Site U1327, 130-150 mbsf).

Site	Depth (m bsf)
U1325	57
U1326	71
U1327	71
U1328	100
U1329	90

Table 1 Minimum depth for reliable Vp estimation from LWD data at IODP Expedition 311 sites

Comparison with VSP

In Figure 4, comparison of the LWD and wireline logs and the VSP estimates of Vp (light blue curve) indicate that all follow similar trends with depth, but of course the VSP results have lower vertical resolution. Considering the lower frequency and greater investigation volume of the measurement, differences between the logs remain within the accuracy of the VSP estimate (+/- 0.2 km/s) at each site and within the lateral variability between holes. These comparisons corroborate the reliability of the wireline, LWD, and VSP data below the minimum depth and the local variability due to formation properties, methane hydrate, and gas occurrences at these sites.

Comparison with core

Core data were acquired shipboard under ambient laboratory conditions in the 20 m below the seafloor at each site [2]. Figure 5 illustrates Vp estimates from both whole and split core over this interval as well as the LWD-derived Vp and fluid velocity estimates. In general, variations between core and log data can be attributed to one or more of the following effects: 1) lateral changes in properties between the core and LWD holes, 2)

sampling bias due to incomplete core recovery, 3) differential porosity rebound of the core samples under ambient laboratory conditions due to local changes in lithology and cementation, or 4) local fracturing and structures that are not sampled through coring.

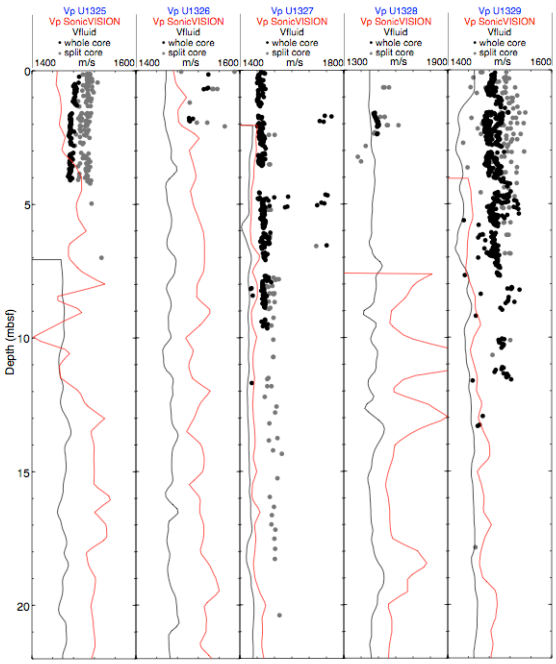

Figure 5 Comparison of LWD logs and core velocity estimates 20 m below seafloor at sites U1325-U1329

Because of these effects, comparisons of laboratory and in situ data are often difficult over short intervals and most useful for overall trend analysis with depth. Due to rebound expansion when cores are recovered and measured at surface pressure conditions, core Vp estimates can be considered as a lower bound on the formation velocity. At these sites, however, it is important to observe that core Vp data are systematically greater than LWD measurements (Fig. 5). Therefore, the core results provide strong evidence that the LWD logs significantly underestimate Vp over the interval immediately below the seafloor and are unreliable.

Estimation of gas hydrate saturation

We estimate gas hydrate saturation from porosity and resistivity logs using Archie's equation [7] and from acoustic logs using a pore-scale cementation model [8] in Holes U1326A (LWD) and U1326D (wireline). Gas hydrate-bearing intervals correspond to intervals of anomalously high measured resistivity and high measured velocity. Archie's equation gives a quantitative estimate of the water saturation and these estimates were calculated by comparing the measured electrical resistivity to the resistivity predicted from the porosity assuming that the formation is fully water saturated. The cementation model has been used to predict velocity log results in other clay-dominated marine hydrate settings [9] and assumes that hydrate forms on the surface of sediment grains, cementing the formation to some extent [8, 9]. The cementation model requires computation of the bulk modulus of the formation. Because the LWD sonic tool does not measure Vs, we derive a linear relationship between Vp and Vs using wireline logs in Hole U1326D (i.e., Vs = 0.606Vp - 634.3), and apply this to the LWD Vp data to compute bulk modulus in Hole U1326A. The results of both resisitivity- and velocity-based estimation of gas hydrate saturation are shown in Figure 6.

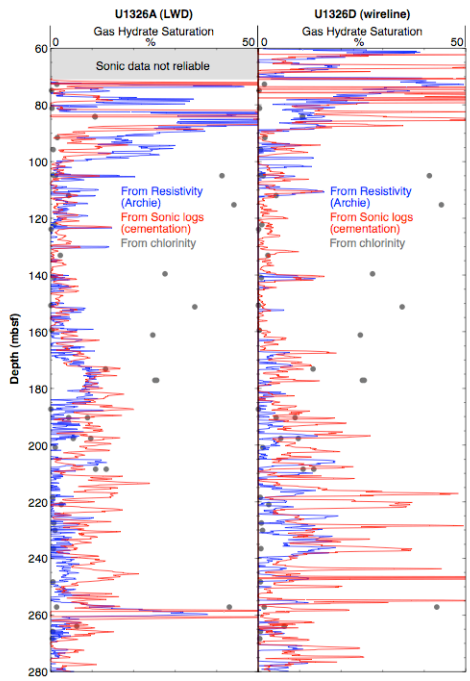

Figure 6 Comparison of gas hydrate saturation estimated from acoustic and resistivity logs in Holes U1326A (LWD) and U1326D (wireline)

Comparing results of the cementation model applied to the velocity logs and application of

Archie's relationship to the resistivity logs in the same wells, we observe an overall agreement on the location and on the concentrations of gas hydrate at Site U1326. Further, the same velocity- and resisitivity-based saturation models applied to both wireline and LWD data in Hole U1326A and Hole U1326D, respectively, produce overall agreement given the ~25 m lateral distance between these LWD and wireline holes. Differences in these profiles between Hole U1326A and Hole U1326D may in part be attributed to the geological heterogeneity in the formations encountered in each hole and the local distribution of hydrate within sand layers and fractures that are not continuous between holes.

Figure 6 also shows the gas hydrate saturations obtained on core samples by measuring the freshening (decrease in chlorinity) of interstitial pore waters due to gas hydrate dissociation [7]. The well log and chlorinity estimates of gas hydrate saturation differ in detail because many of the chlorinity data were taken in sand layers that are only a few cm thick and are below the resolution of the well logs. In addition, the chlorinity data were obtained in holes U1326C and U1326D, and there may be additional differences with well logs measured in different holes due to lateral heterogeneity.

SUMMARY

LWD sonic data were recorded during Integrated Ocean Drilling Program (IODP) Expedition 311 at five sites transecting the Cascadia margin. Dispersion of LWD sonic data in low-velocity formations was observed and we attribute this to the presence of the tool in a borehole and to leaky-P mode propagation. The extraction of accurate velocity information in the shallowest sediments is difficult because the waveforms are dispersive and both leaky-P (Airy) phases and fluid modes affect the recorded arrivals. Vp logs were estimated from the LWD sonic data at these sites using high-resolution dispersion analysis and limiting Vp calculation below a minimum depth where the dispersive leaky-wave speed can be distinguished from fluid velocity. Estimates of Vp using this approach compare quite reasonably with wireline logging and VSP results at all sites, with observed differences attributed to lateral variability between holes and the presence (or absence) of methane hydrate and free gas. Mismatch between the core and LWD Vp estimates are observed above the minimum depth, and are attributed to the very slow and inseparable fluid and leaky-P wave modes in shallow sub-seafloor sediments. In future uses, care is advised when interpreting LWD waveforms in shallow sub-seafloor formations and high-resolution dispersion analysis in the frequency domain is recommended for LWD sonic data interpretation. Using velocity- and resisitivity logs with established model assumptions, a comparison of saturation estimates agree quite well through the hydrate occurrence zone at one site, and using both wireline and LWD data, considering lateral variability between holes drilled on the Cascadia margin. We attribute this agreement to the reasonable, but independent assumptions in these models and critical evaluation of the well log data.

ACKNOWLEDGEMENTS

This research used samples and data provided by the Integrated Ocean Drilling Program (IODP). We greatly appreciate the efforts of the crew and staff of the JOIDES Resolution during IODP Expedition 311 to collect these data. C. Brenner assisted with preparation of Figure 3. The velocity data described here are available directly via the ODP online logging database at www.ldeo.columbia.edu/BRG/ODP/DATABASE/index.html.

REFERENCES

[1] Paillet, F. L., and C. H. Cheng, 1986, *A numerical investigation of head wave and leaky modes in fluid-filled boreholes,* Geophysics, 51, 1438-1449.

[2] Riedel, M., Collett, T.S., Malone, M.J., and the Expedition 311 Scientists, 2006. *Proc. IODP v 311.* Integrated Ocean Drilling Program, Texas AM University, College Station TX. iodp.tamu.edu/publications/exp311/311title.htm,

[3] Aron, J. Chang, S., Dworak, C. Hsu, K., Minerbo, G., and Yogeswaren, E., 1997, *Real-time sonic logging while drilling in hard and soft rocks,* Trans. Soc. Petrophys. and Well Log Analysts, 35th Ann. Logging Sympos., Houston, TX (USA) paper HH.

[4] Ekstrom, M., 1995, *Dispersion estimates from borehole acoustic arrays using a modified matrix pencil algorithm,* 29th Asilomar Conf on Signals, Systems and Computers, Pacific Grove, CA.

[5] Blanch, J., Cheng, A., Varsamis, G. and Araya, K., 2003, *Evaluation of dispersion estimation methods for borehole acoustic data,* Trans. of Soc. of Expl. Geophys., 73rd Ann. Int'l Mtg, Dallas, TX (USA) pg. 305-308.
[6] Goldberg, D., A. Cheng, S. Gulick, J. Blanche, and J. Byun, 2005. *Velocity analysis of LWD sonic data in turbidites and hemipelagic sediments offshore Japan, ODP Sites 1173 and 808,* In: Mikada, H. Moore, G. F., G.F. Taira, A., Becker, K., and Klaus, A. (Eds), Proc. Ocean Drilling Program, Sci. Results, 190/196, 1-15, Texas AM University, College Station TX. www-odp.tamu.edu/publications/190196SR/352/352.htm.
[7] Malinverno, A., Kastner, M., Torres, M.E., and Wortmann, U.G., 2008. *Gas hydrate occurrence from pore water chlorinity and downhole logs in a transect across the Northern Cascadia Margin (IODP Expedition 311)*, J. Geophys. Res., in review.
[8] Dvorkin, J., and Nur, A., 1996, *Elasticity of high-porosity sandstones: Theory for two North Sea data sets,* Geophysics, 61, 1363-1370.
[9] Guerin, G., Goldberg, D., and Meltser, A., 1999, *Characterization of in situ elastic properties of gas hydrate-bearing sediments on the Blake Ridge,* J. Geophys. Res., 104, 17,781-17,796.