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Evidence for gassy sediments on the inner shelf of SE Korea from geoacoustic properties

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Abstract

The inner shelf of SE Korea is characterized by an up to 40 m thick blanket of soft sediments often characterized by acoustic turbidity (AT). This AT is caused by a layer of sub-surface gas, which prohibits the identification of geological structures below that gas layer. Sound speeds were measured directly in these sediments using the Acoustic Lance (AL) in both mid- and late-September 1999. In situ sound speeds obtained in mid-September varied between 1400 and 1550 m/s, and thus did not confirm the presence of gas within the top 3.5 m of the seafloor. However, signal waveforms suggested that a gassy layer might have been just below the depth penetrated by the Lance. In late-September, on the other hand, two sites showed an abrupt decrease in signal amplitudes and in sound speed (less than 800 m/s) at depths as shallow as 2 m below seafloor, indicating the presence of free gas bubbles. Piston-cored sediments were retrieved at the same sites in February 1999. X-radiographs of some of the cores revealed numerous microcracks caused by the expansion of gas bubbles during core retrieval. In contrast to in situ acoustic data, ultrasonic sound speeds acquired in the laboratory in May 1999 on those cores did not differentiate convincingly between gas-bearing and gas-free sediments. Our measurements on the SE Korean shelf with the AL provide new data on the in situ acoustic behavior of gassy sediments and the sediments that overlie them in zones of AT.

Keywords: Acoustic properties; Attenuation; Bubbles; Core analysis; Gassy sediments; SE Korea shelf

1. Introduction

The understanding of acoustic wave propagation through the sediment–water interface and in shallow sub-surface layers of the seafloor is of considerable interest in underwater acoustics,

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geophysics, ocean-engineering, and naval applications (Richardson, 1986; Stoll, 1989; Kibblewhite, 1989). The sediment–water interface and upper several meters of seafloor are characterized by large gradients in physical and acoustic properties (Hamilton, 1979; Richardson, 1986). The reliable measurement of acoustic parameters at the seafloor, such as sound speed and attenuation, has attracted considerable attention as a means of defining geological processes that control acoustic and seismic wave propagation within the shallow seafloor.

Methane-bearing sediments are widely distributed throughout the world's ocean (Fleischer et al., 2001). They concentrate in organic-rich, muddy sediments of coastal waters, estuaries and adjacent shallow seas, including the Baltic Sea (Judd and Hovland, 1992; Wilkens and Richardson, 1998) and the inner shelf of SE Korea (Park et al., 1999) (Fig. 1). Methane in shallow marine sediments is formed mostly from biogenic processes, when bacteria reduce organic matter within the upper 10s or 100s of meters of the sub-seafloor (Floodgate and Judd, 1992; Hagen and Vogt, 1999).

The propagation of acoustic waves and their attenuation in gassy sediments is not well understood, despite the frequent occurrences of acoustic turbidity (AT) (acoustic blanking of sub-surface structures) caused by the absorption and scattering of acoustic energy by gas bubbles in the seabed (Wilkens and Richardson, 1998). Sound speed is typically much lower at acoustic frequencies in

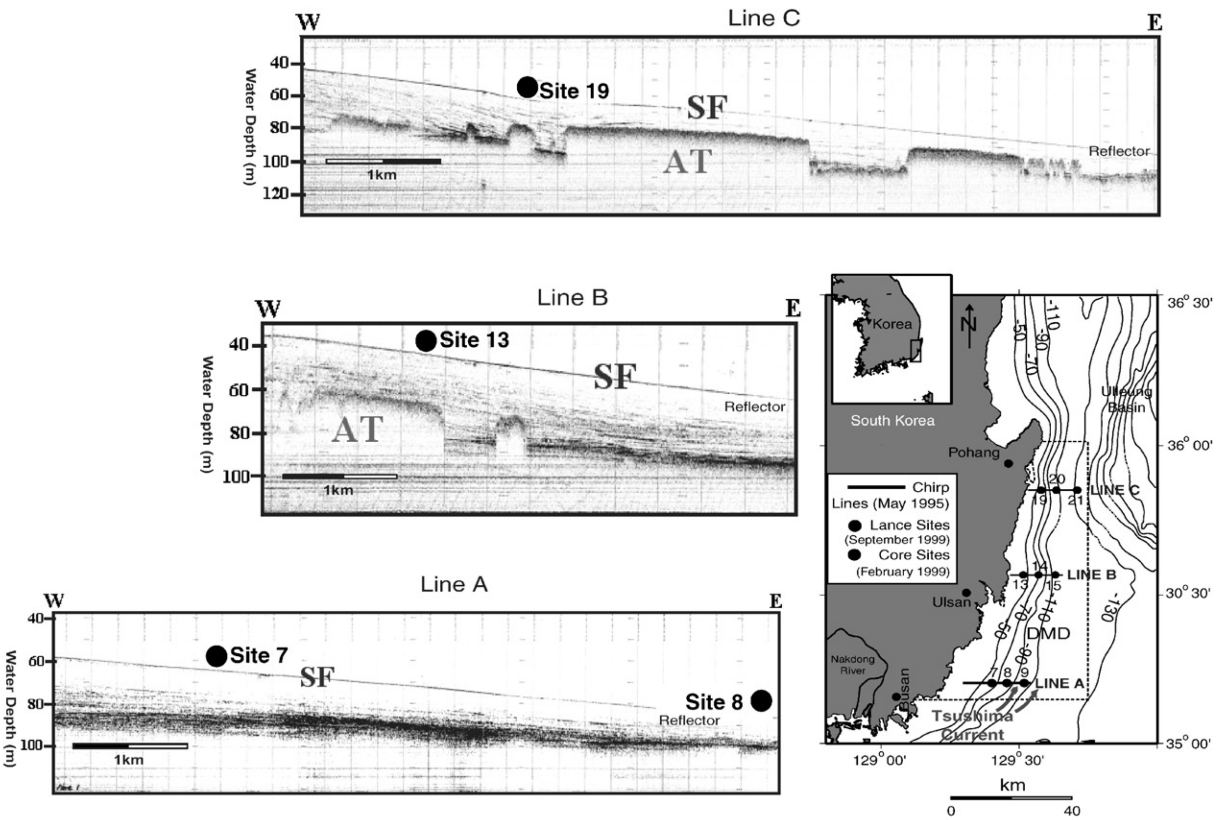

Fig. 1. Map of the study area and sites where the AL was deployed in mid- and late-September 1999. Cored sediments were retrieved in February 1999 (ultrasonic sound speeds measured in May 1999). Grain sizes within the DMD vary from 6ϕ in the south (Sites 7–9) to 8ϕ in the North (Sites 19–21) between 50 and 130 m of water depth. Note the location of the Nakdong River, a significant source of organic matter to the DMD, and the direction of the Tsushima Current in northerly directions. Lines A–C represent chirp sounder profiles, and reveal some of the sub-seafloor structure and possible gas horizons (displayed with permission of Park et al., 1999). SF—seafloor, AT—acoustic turbidity (note that not all core and AL sites are located on available chirp profile images).

gas-bearing sediments than in gas-free sediments, whereas sound speeds measured at ultrasonic frequencies may not indicate the presence of gas (Wilkens and Richardson, 1998). Attenuation across all frequencies increases significantly even in the presence of minute amounts of gas (Anderson and Hampton, 1980a, b; Yuan et al., 1992; Richardson, 1994; Fu et al., 1996b).

In spite of evidence for gassy sediments on the shallow SE Korean shelf in high-resolution chirp sounder profiles (e.g., Park et al., 1999), direct acoustic measurements in these gas-bearing sediments had not been made. This study contributes new acoustic and physical property profiles recorded in the area. Results presented in this paper are compared with those previously obtained with the Acoustic Lance (AL) in Eckernförde Bay, Germany (Western Baltic Sea) (Fu et al., 1996b; Wilkens and Richardson, 1998).

2. Regional setting

The inner and mid-shelf of SE Korea is dominated by an up to 40 m thick accumulation of Holocene mud (4–16 μm) in water depths shallower than 100 m (Park et al., 1999) (Fig. 1). This mud forms a distinct belt, called the Distal Mud Deposit (DMD) that extends approximately from Busan to north of Pohang in the shelf-parallel direction. A fraction of these muddy sediments is transported by the northward flowing Tsushima Current from the Nakdong River through the Korea Strait and along the southeast coast of the Korean peninsula (Kim et al., 1986; Park and Choi, 1986; Kim et al., 1996; Kim et al., 1999; Park et al., 1999). The Tsushima Current is a branch of the Kuroshio Current in the East Sea (Sea of Japan) and its current speeds reach close to 1.0 m/s during the summer (Cho et al., 1999; Park et al., 1999).

Over the last 6000 years, a modern, 0–40 m thick layer of mud has been accumulated over relict transgressive sands, which were deposited during the last glacial lowstand of sea level. Muddy clay-silt fractions are spilled regularly onto the inner shelf from the coastal watershed, whereas the relict sandy sediments are found seaward of the 80 m isobath over a wide portion of the outer shelf (Park et al., 1999). Shell fragments characterize these sandy sediments with grain sizes up to 2 mm (Cho et al., 1999). During summer floods, a large volume of fine-grained sediments and organic matter is discharged from the Nakdong River in the south, and then dispersed by tidal and coastal currents in northerly directions, eventually reaching the outer shelf (Kim and Lee, 1980; Kim et al., 1986; Kim et al., 1999). High sediment accumulation rates (2.5 mm/yr) and water column productivity increase the organic content in the sediments across the DMD, and ultimately lead to the formation of dissolved methane caused by a biochemical degradation of the organic matter within the sediment column (Park et al., 1999). Once methane production exceeds saturation levels, free methane bubbles form in the sediment (Martens et al., 1998). Similar to other shallow water seas, bottom currents on the inner shelf of SE Korea are probably too weak to cause significant erosion of surficial sediments (Nittrouer et al., 1998). The lack of erosion further enhances the production and preservation of free gas within shallow sub-seafloor depths.

High-resolution chirp reflection profiles show a 900 km^2 AT zone underlying much of the DMD (Park et al., 1999). Free gas bubbles in the muddy sediments absorb and scatter acoustic energy, masking deeper sedimentary horizons. The turbidity zones occur at approximately 3–5 m below the seafloor (mbsf), but may reach the water–seabed interface in some places (Park et al., 1999). One of these AT zones extends from Busan to Pohang along the southeastern coast, covering nearly 40 km (Fig. 1). Park et al. (1999) identified a distinct reflector in chirp sounder profiles that were recorded in May 1995 without AT. This reflector was interpreted as the Holocene transgression with changing sedimentary properties from mud to sand (see: Fig. 3 in Park et al., 1999; Fig. 1 of the present paper).

3. Methods

The AL measures in situ interval sound speed and effective attenuation profiles using full-wave-form records in a frequency range between 5 and 15 kHz (Fu et al., 1996a, b; Frazer et al., 1999). The probe has been successfully deployed in a variety of unconsolidated sediments. Mid-Atlantic Ridge pelagic oozes exhibited low velocities and low attenuation (Fu et al., 1996a). Carbonate sands offshore of the island of Oahu, Hawaii, compared to ultrasonic core measurements showed evidence for dispersive behavior of attenuation over this broad frequency band (Fu, 1998). Most recently, the AL was deployed on the Eel River shelf, California, where heterogeneous sediment deposits caused complex spatial variations of sound speed and attenuation (Gorgas et al., 2002).

Results from previous AL operations performed in gassy and gas-free muddy sediments in the western Baltic Sea (Fu et al., 1996b) compare directly to the present study on the inner shelf of SE Korea. In the organic-rich, high-porosity Holocene sediments of Eckernförde Bay, Germany, in situ compressional wave sound speed was as low as 1100 m/s, and attenuation was high when free methane gas bubbles were present (Fu et al., 1996b; Wilkens and Richardson, 1998).

3.1. In situ acoustic compressional wave sound speed

In the present study, eight receivers were mechanically attached to a steel pipe at ca. 0.5-m intervals below a broadband acoustic source (Fig. 2). The source spectrum has a peak signal frequency around 7.5 kHz. The instrument is routinely calibrated by recording the water sound speed before being inserted into the seafloor. Waveforms from this calibration allow determination of the exact spacing between the acoustic centers of the individual receiver elements. After the calibration, the steel pipe penetrates the seafloor to depths that depend on the shear strength of the sediment.

In situ compressional wave sound speed is calculated from different arrival times of acoustic waves and the distance between the acoustic centers of the transducers. Signals from adjacent receivers are cross-correlated to pick first arrivals. Seabed velocities are calculated for the interval

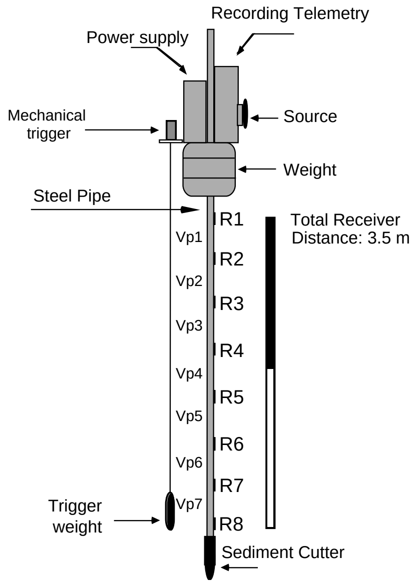

Fig. 2. Diagram of the AL, the in situ sediment sound speed profiler, which was developed at the University of Hawaii—Manoa (after Fu et al., 1996a). For acoustic experiments off SE Korea eight receivers were attached to a steel pipe. Vp_1–Vp_7 represent interval sound speed values obtained to maximal 3.5 m below seafloor (mbsf).

between two receivers. The precision of in situ sound speed measurement is approximately 1% (±15 m/s) (Fu et al., 1996a).

3.2. Laboratory ultrasonic compressional wave sound speed

Laboratory ultrasonic measurements were conducted in May 1999 at 1 MHz on piston-cored sediments that had been previously retrieved (February, 1999). Cores were not kept under in situ pressure, but tightly sealed and stored at 4°C. Although a visual inspection of the sediments suggested that gas had not been released before the cores were split, it must be assumed that the pressure reduction increased the free gas content if the in situ methane concentrations were above or near saturation, and thus destroyed some of the sediment microfabric.

Ultrasonic sound speeds were measured at intervals of 0.1 m using a tabletop system with a pair of source-receiver transducers (PZT 4). Horizontal laboratory compressional wave sound speeds were obtained using a standard pulse transmission technique (Birch, 1960). A specially designed cube-shaped sample holder was used to minimize any error arising from deformation of the soft sediment sample. The measurement was made in two orthogonal directions with a sample length of 2.100 cm in the horizontal and 2.119 cm in the vertical direction. Anisotropy was not observed within the range of the measurement error (2%). Coupling between the transducers and the sample holder was established by applying slight pressure on the piezoelectric elements, and using distilled water as a coupling fluid.

3.3. Physical properties and X-ray imagery

Sediment physical property measurements included the determination of bulk density, grain density, water content, and porosity using gravimetric methods (Boyce, 1976). Wet and dry sample volumes were measured using both manual (Micromeritics, Pycnometer 1305) and automatic (Quantachrome, Ultrapycnometer 1000) pycnometers. X-radiographs were taken of sediment slabs (0.20 m × 0.05 m × 0.01 m) at 65 kV, 4-5 mA, and at an exposure time of 20 s using a Softex M-1005 to investigate the microstructure of both non-gassy and gassy sediment samples.

4. Results

4.1. Geoacoustic properties as a function of seafloor depth

In mid-September 1999, in situ sound speed varied roughly between 1420 and 1545 m/s over all depths at all sites across the entire study area (Fig. 3). At Sites 15, 19, and 20, in situ sound speeds were faster close to the water–seabed interface than at deeper depths, whereas sound speeds slightly increased at the other sites at least within the top 0.9 mbsf (Figs. 3 and 4).

Except at Sites 14 and 19, in situ sound speeds measured in late-September 1999 were similar to those obtained at most sites two weeks earlier. At these particular two sites, values abruptly decreased to 1200 and 1050 m/s below 2.40 and 1.90 mbsf, respectively (Fig. 4). Acoustic sound speeds appear to decrease further, close to 700 m/s below 2.85 and 2.35 mbsf (Fig. 4), although attenuation of the signal makes an arrival pick difficult.

Ultrasonic laboratory sound speeds were measured in May 1999 on unsplit cores that had been retrieved in February 1999. Data were corrected for in situ temperature and pressure conditions. At most sites, ultrasonic sound speeds were uniformly slower than in situ acoustic data, and did not show gradients similar to those observed in situ (Figs. 3–5). This finding is independent of whether in situ values were collected in mid- or late-September 1999. Laboratory ultrasonic sound speeds at the southernmost sites (Sites 7–9), and further north at Sites 13, 15 and 20 increased with depth in most cases (Figs. 3 and 4). In contrast, ultrasonic sound speeds decreased abruptly at Sites 14 and 19 around 1 mbsf. One data point as low as 1300 m/s was recorded at Site 14 around 2.7 mbsf (Figs. 4 and 5).

However, some exceptions to a discrepancy between laboratory and in situ data exist. At Site 13, both acoustic and ultrasonic sound speeds matched fairly well over 2.2 mbsf, although ultrasonic data were collected in May 1999 and in situ data in mid-September 1999. Similarly, at Site 19 ultrasonic data obtained in May 1999 over 2.3 m of core depth varied within a comparable range to in situ records from late-September 1999 for the upper 0.9 mbsf (Fig. 4B). Ultrasonic sound speed values at Site 20 from May 1999 were relatively close to those obtained with the AL in mid-September 1999 for depth intervals between 0.5 and 2.4 mbsf (Fig. 3C). Laboratory and in situ sound speeds at Site 21 often agreed with each other, or at least exhibited a sound speed variability between both ultrasonic and in situ profiles that matched relatively well over the entire core depth, albeit ultrasonic data were collected in May 1999 and in situ data in mid-September 1999 (Fig. 3C).

4.2. Physical and geoacoustic properties and sediment structure at sites 14 and 15

Bulk density (Fig. 5A) and porosity (Fig. 5B) at Sites 14 and 15 often did not show gradients with

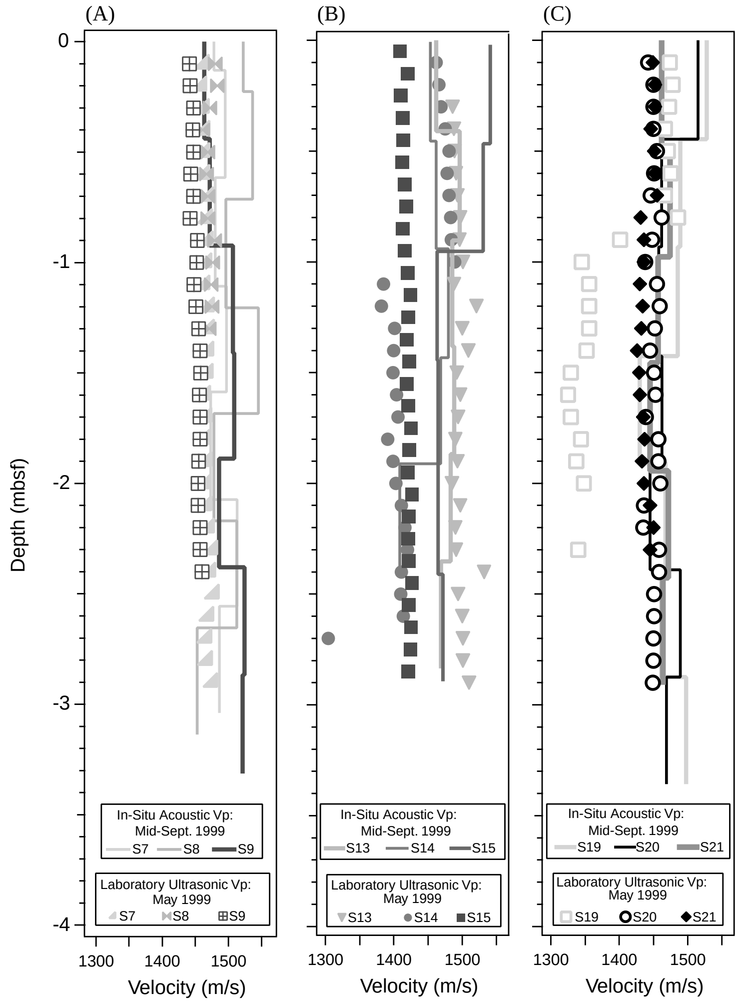

Fig. 3. In situ acoustic sound speed profiles versus sub-seafloor depth (mbsf) at nine sites do not show evidence for gassy sediments in mid-September 1999 in the form of an abrupt sound speed decrease (A, B, C). Although laboratory ultrasonic sound speeds are mostly slower than in situ values, they do not allow a conclusive identification of gassy sediments (A, B, C).

core depth that were either similar to those for corresponding ultrasonic sound speed data that had been taken from the same cores in May 1999, or for in situ sound speeds measured in late-September 1999 (Fig. 5C). One exception from this observation was noted for physical and geoacoustic data obtained at Site 14 for the top 0.8 mbsf. Bulk density at this site showed an overall increase within the first 0.9 mbsf, which corresponded to an expected decrease in porosity (Figs. 5A and B). Below that core depth, corresponding bulk density remains almost constant or decreases with depth (Fig. 5A). As X-ray imagery shows, around this core depth the number of cracks within the sediment structure is growing significantly (Fig. 6A).

Ultrasonic and acoustic sound speeds at the same site increased from about 1450 to 1470 m/s within the top 1 mbsf, paralleling bulk density trends (Figs. 5A and C). Below 1 mbsf, only ultrasonic sound speeds drop to around 1380 m/s, and merely increase to 1420 m/s at a core depth

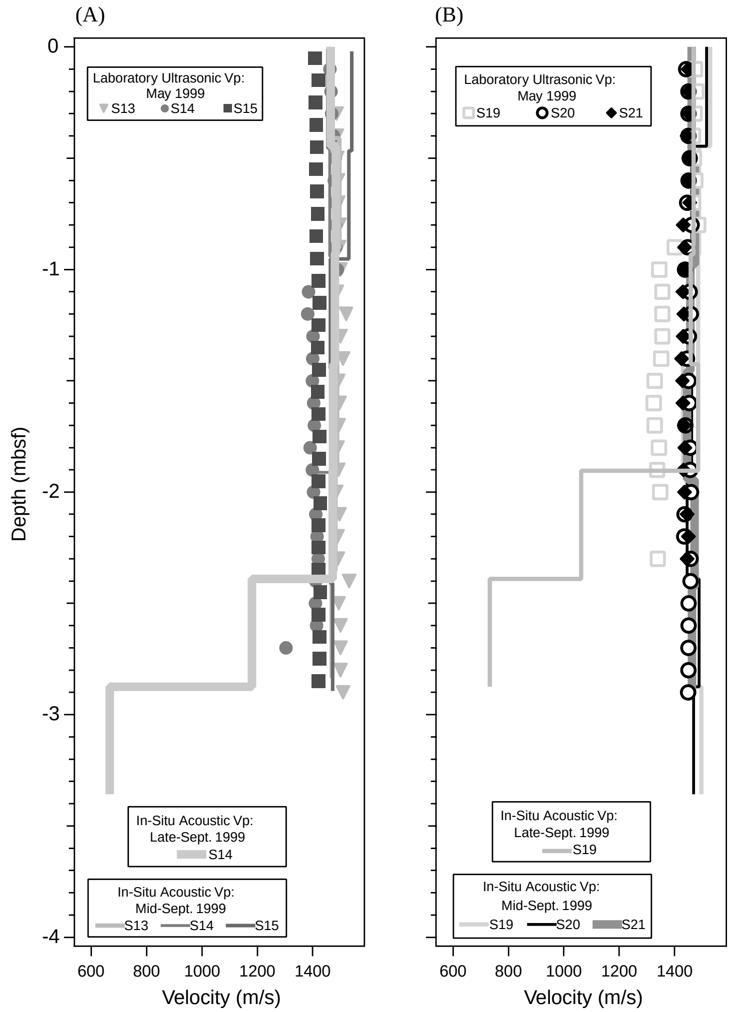

Fig. 4. In situ acoustic sound speed profiles versus sub-seafloor depth (mbsf) in late-September 1999 at Sites 14 and 19 show evidence for gassy sediments in the form of an abrupt sound speed decrease. In comparison, laboratory ultrasonic sound speed data do not allow a clear distinction between gassy and non-gassy sediments ((A), (B)). Note the sound speed decrease of in situ sound speeds occurring in shallower seabed depths at Site 19 further North (B) than at Site 14 further South (A) (see also map in Fig. 1).

of 2.7 mbsf (Fig. 4A and 5C). The decrease in ultrasonic sound speeds corresponds to bulk density data that do not increase down to 2.4 mbsf (Fig. 5A). Ultrasonic laboratory sound speeds matched acoustic in situ values between 1.9 and 2.4 mbsf only for measurements obtained in mid-September 1999 (around 1400 m/s). In contrast, corresponding acoustic in situ values measured in late-September 1999 were 1470 m/s, and decreased below 1000 m/s around 2.4 mbsf (Figs. 4A and 5A).

Bulk density and porosity data measured at Site 15 fluctuated more than those at Site 14, with relative minimal and maximal values throughout core depth (Fig. 5A). Conversely, no similar fluctuations were observed either in laboratory ultrasonic or in situ acoustic data (Fig. 5C). The sediment structure observed with X-ray imagery

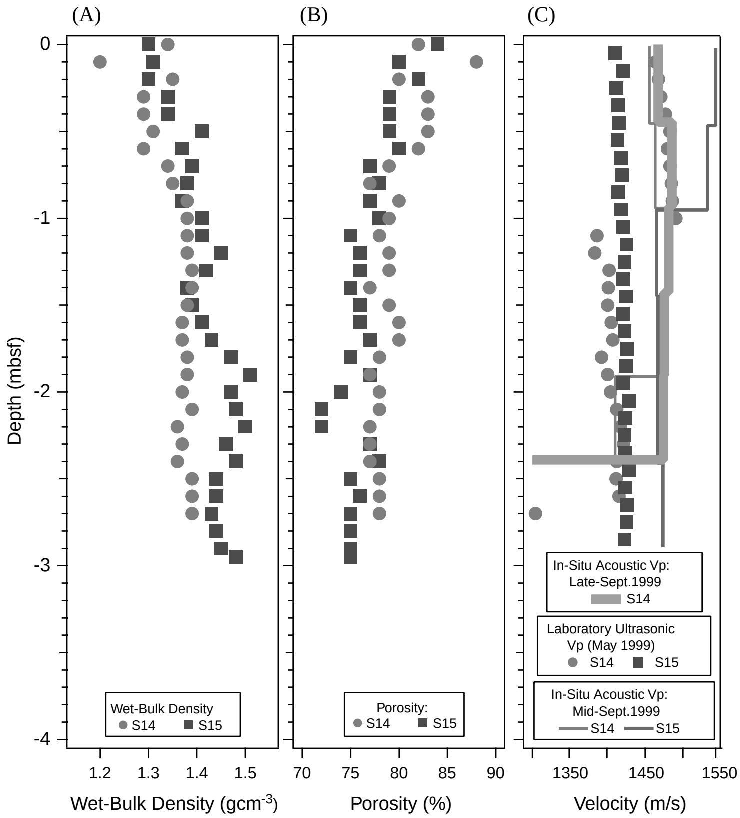

Fig. 5. Bulk density, porosity and sound speed data were obtained at Sites 14 and 15 to ca. 3 mbsf. Density at Site 14 mostly shows the expected negative correlation with porosity. However, in most cases there does not exist a clear correlation between wet-bulk density (A) with laboratory ultrasonic and/or in situ interval sound speeds (C). Ultrasonic sound speeds do not provide clear evidence of free gas at Site 14, unlike in situ sound profiles that were obtained in late-September 1999. The absence of gas at Site 15 is mostly visible in in situ sound speeds that are characteristic of gas-free sediments (C). In contrast, ultrasonic sound speeds at Site 15 are much lower than in situ data, an observation that may be simply attributed to unfavorable measurement effects (C). No clear pattern of correlation exists between ultrasonic and/or in situ sound speed data (C), porosity (B) and bulk density (A) as a function of seafloor depth at Site 15.

does not reveal severe disruptions in the sediment structure as observed in cores that were retrieved at Site 14 in February 1999 (Fig. 6A).

5. Discussion

5.1. Controls on gas abundance in marine sediments

The abundance of free gas bubbles in the seafloor is controlled by temperature, salinity, and pressure, which in turn control bioactivity and chemical processes within the water and sediment columns (Wever and Fiedler, 1995). High water and seafloor temperatures favor an increase in methanogenesis due to elevated productivity within the upper seafloor (Zeikus and Winfrey, 1976; Hagen and Vogt, 1999). Once the solubility (saturation) of methane reaches its limit in the pore water, free gas bubbles form a free gas layer that causes AT, as has been observed in mid-May 1995 across the DMD in chirp sounder profiles (Park et al., 1999).

Sediments in the inner shelf of SE Korea might respond to temperature cycles that are similar to those observed in the gassy sediments of Eckernförde Bay (Wever et al., 1998). In Eckernförde Bay, organic matter accumulates primarily during the

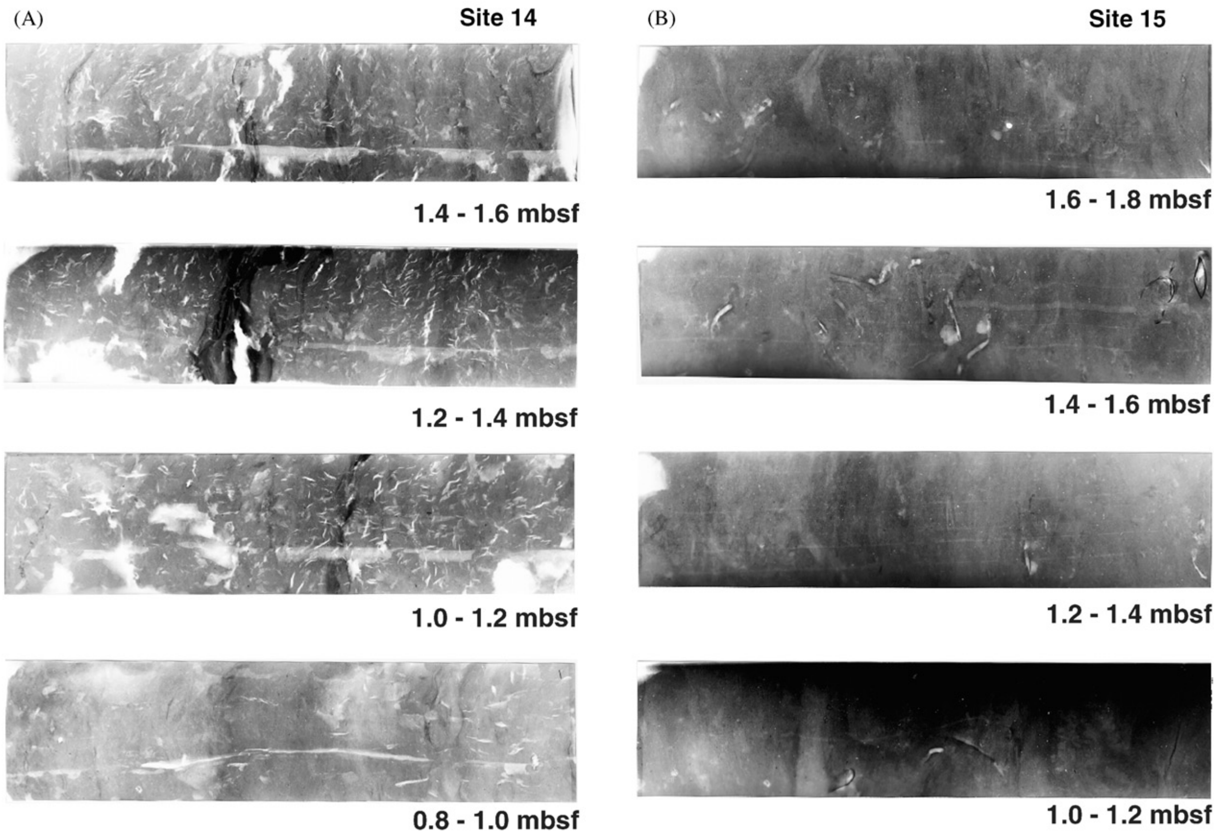

Fig. 6. Sediments recovered at Site 14 (A) exhibit a significant number of cracks and voids as measured with X-rays. This result was interpreted as evidence for gas expansion and release during core retrieval. In contrast, Site 15 (B) does not show signs of gas abundance, with a relatively undisturbed sediment structure.

summer. A maximum of free gas occurs in late-November due to a time lag between the annual surface and sediment temperature cycle—mainly dependent on the thermal conductivity of the muddy sediments and thermal diffusion within the seafloor (Wever and Fiedler, 1995). In contrast, side-scan sonar data collected in the Chesapeake Bay found a free gas maximum in sediments during late-summer, when maximum water and seafloor temperatures change bacterial metabolic activity and pore water methane concentrations (Hagen and Vogt, 1999). In both cases, a seasonal difference is noted in the depth of the free methane horizon. However, from the currently existing data sets obtained on the SE Korea shelf, cyclic variations in gas abundance cannot be conclusively determined.

The mid- and late-September 1999 acoustic data obtained on the SE Korea shelf at Sites 14 and 19 could suggest that a gas layer migrated upwards within a short period of time. It is possible that a typhoon, which passed through the area in mid-September 1999 caused a release of free gas due to rapid pressure variations within the seafloor, followed by an increase in gas abundance thereafter. However, we believe that it is more likely that the depth to the top of the gas horizon varies across the study area on scales that are in the order of meters. Such variability in gas layer depth has been shown for gas horizons that were acoustically detected in the Baltic Sea (see: Fig. 2 in Wilkens and Richardson, 1998). A vertical migration of gas from deeper to shallower sub-seafloor depths on the SE Korea shelf within 2 weeks appears to be less likely than a variable depth to the top of the gas horizon, considering that it took the gas layer in Eckernförde Bay several months to migrate from deeper to shallower sub-seafloor depths (Wever and Fiedler, 1995).

5.2. Acoustic signal characteristics

AT, or acoustic blanking of sub-seafloor structures, has been previously identified across the DMD in the inner shelf of SE Korea in high-resolution seismic and chirp sounder profiles (Kim et al., 1999; Park et al., 1999). In situ acoustic properties collected during the present study clearly show much slower sound speeds in gassy sediments on the inner shelf of SE Korea than in the non-gassy sediments (Figs. 3–5). Gas-charged sediment horizons at Sites 14 and 19 are revealed by an abrupt decrease of in situ sound speeds (Figs. 4 and 5), and by a strong ringing and a decrease in the amplitude of full-waveforms that is not observed in gas-free sediments (Fig. 7A).

Acoustic signals obtained in gas-bearing layers, e.g., at Site 14, exhibited a strong decay in signal amplitude and significant coda, whereas those above the gas layer contained energy reflected back from the deeper gas layer (Fig. 7A). The progressive decay of signal amplitudes at Site 14 in late-September 1999 suggests that gas is present over at least 1 m of depth. In contrast, we did not see similar signal amplitude decays for gas-free sediments that were penetrated at Site 15 (Fig. 7A).

However, it is important to note that signal amplitudes from mid-September at Site 14 records also show signs of reverberations (Fig. 7A), albeit sound speeds were in the range of non-gassy sediments (Figs. 3–5). This suggests that gas was present at that time but not penetrated by the AL.

Down-core power spectral amplitudes of the waveforms recorded with the AL at Site 14 show slightly greater spectral energy at higher rather than lower frequencies in gassy sediments and in sediments underlain by a gas horizon (Fig. 7B).

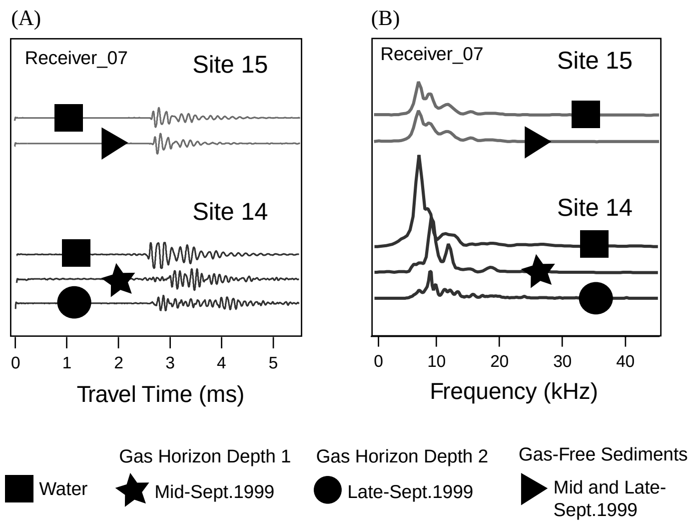

Fig. 7. (A) Acustic Lance (AL) full waveforms recorded in late-September 1999 at Site 14 (circle) clearly display stronger reverberations (ringing), coda and a significant decrease in AL amplitudes than those acquired in water (cube) and in sediments when penetrated in mid-September 1999 (star). This result is interpreted that the AL penetrated a gassy sediment horizon in late-September but not in mid-September. In contrast, characteristic AL full waveforms recorded in gas-free sediments at Site 15 (triangle) do not exhibit reverberations and coda, or a significant AL amplitude decrease compared to those in water (cube). (B) AL power spectra from signals that were obtained in both mid- and late-September at Site 14 reveal a variable gas content in sediments due to a shift in peak source energy from lower to higher frequency components (star and circle). This acoustic behavior is grossly different from that of gas-free sediments (Site 15, triangle), where corresponding AL power spectra do not reveal a shift in peak source energy from lower to higher frequency components. The latter acoustic behavior is commonly observed in soft sediments, which are, in general, characterized by low attenuation.

This acoustic behavior was not seen in AL records obtained in gas-free sediments at Site 15 (Fig. 7B). At Site 15, the waveforms and spectra of the signals looked virtually the same in seawater and in sediment (Fig. 7A and B). This is not surprising since the sediments are fine-grained and consist mostly of water (high porosity). At Site 14, on the other hand, there are significant differences between water and sediment arrivals, whether the AL receivers were within a gas layer or above it.

The observation that low-frequency spectral amplitudes of acoustic signals are reduced more than high-frequency signals is inconsistent with the increase of attenuation with frequency that is commonly measured for seafloor sediments (Biot, 1956a, b). Normal attenuation would dictate that peak power shifts to lower frequencies between water and sediment. At Site 14, the shift is to higher frequencies—the result of the complex influence of gas bubbles on the bulk modulus of the sediment–gas framework.

The nature of this particular relationship observed between amplitude and frequency in our gassy sediment AL data precludes calculation of a single attenuation value. Thus, methods that are frequently used to calculate attenuation, such as the spectral ratio (Tonn, 1989, 1991), are invalid because the assumption of a constant Q is violated.

5.3. Differences between in situ acoustic and laboratory ultrasonic sound speeds

Anderson and Hampton (1980a) hypothesized that sound velocity in gas-bearing sediments can be faster, slower, or the same as sound velocity in similar, but non-gassy, sediment. Slower velocities result when measurements are made below the resonance frequency of the bubbles while faster velocities may be produced precisely at resonance (although this phenomenon has not been observed). Above resonance, velocities revert to that of non-gassy sediment (see also: Fig. 16 in Wilkens and Richardson, 1998). Anderson and Hampton (1980a) further related acoustic attenuation in gas-bearing sediments to grain frictional absorption, internal absorption associated with bubble wall motion, and scattering. Wilkens and Richardson (1998) concluded, based on a comparison of sound speed data (5–400 kHz) with theoretical modeling (Anderson and Hampton, 1980a, b) that the smallest effective bubble radius in the Eckernförde Bay sediments was 0.25 mm and that acoustic data measured below 20 kHz was below the characteristic bubble resonance frequency.

For gas-contaminated sediments on the SE Korea shelf, we therefore should expect a decrease in in situ compressional wave sound speed because of the decrease in bulk modulus of the sediment–gas mixture. Ultrasonic sound speeds might decrease dramatically if there is a gap in the sediment structure due to cracks. However, if those cracks are filled with water, this effect is miniscule. Ultrasonic sound speeds might not show the presence of discrete gas bubbles because the wavelength of the ultrasonic signals is much less than the size of the bubbles, and the waves essentially travel around the bubbles through the pore fluid.

Ultrasonic core data are often used to interpret sub-bottom profiles over wide areas and at different times (Yuan et al., 1992). It needs to be pointed out that cores that were analyzed (in May 1999) for the present study had not been collected (in February 1999) at the same time as the in situ measurements were conducted (mid—and late-September 1999). Nevertheless, it is still informative to compare in situ and laboratory data from the same sites, particularly since one of the cores contained significant amounts of gas—revealed in X-radiographs after core collection (Figs. 5 and 6).

The low ultrasonic compressional wave sound speed (1300 m/s) around 2.7 mbsf at Site 14 (Figs. 4 and 5) is interpreted as the result of core disturbance caused by gas expansion in the core (Fig. 6). Although this is a low velocity caused by the presence of gas in the seafloor, it is a different physical phenomenon than that which causes the low in situ velocities. If a crack opens in the core along the acoustic path and is not filled with pore water, the ultrasonic wave travels with a velocity that is roughly the time average of the part of the path that is gas and the part of the path that is sediment. In situ, where small gas bubbles are present, the velocity is influenced by the volume average-weighted combination of gas and sediment. The results can be the same, but the causes are quite different.

Taking into account the modeling predictions by Anderson and Hampton (1980a, b), and by Wilkens and Richardson (1998), the slow in situ sound speeds at Sites 14 and 19 were most likely obtained at frequencies below the characteristic bubble resonance frequency. On the other hand, ultrasonic (1 MHz) sound speeds were measured well above the characteristic resonance frequency of the gas bubbles (Figs. 3–5). While they would not necessarily show effects of free gas bubbles in sound speed, attenuation (due to scattering) in bubbly sediment would be much higher than in gas-free sediments (Wilkens and Richardson, 1998).

Ultrasonic laboratory sound speeds measured on cored sediments from both non-gassy and gassy sites are in most cases slightly slower than in situ values (Figs. 3–5). This result is in contrast to those of other acoustic experiments conducted in situ and in the laboratory, where ultrasonic sound speeds are either approximately the same as acoustic values in soft mud, or greater than acoustic values in sandy sediments (e.g., Fu, 1998; Baffi, 1999; Gorgas et al., 2002).

In the present case, disturbances, either from gas expansion during core retrieval, from breaking weak bonds between clay particles, or dewatering might have caused the cored material to behave differently. A heavily gas-contaminated layer at Site 14 was not revealed by ultrasonic sound speed measurements in the laboratory (Fig. 3–5), but by in situ interval sound speed and by X-radiography data (Figs. 3–6). Expanding gas caused the formation of numerous microcracks in the gassy sediment cores, but not at the gas-free Site 15 (Fig. 6B). Yuan et al. (1992) concluded from similar laboratory ultrasonic measurements on gassy sediment cores that compressional wave sound speed can be sensitive to small volumes of gas, but remains ambiguous in the interpretation of the geotechnical significance of gassy sediments.

6. Conclusions

In situ measurements at two acoustically turbid sites made with the AL revealed an abrupt decrease of sound speed around 2 mbsf. The water depths of both gassy sediment sites (Sites 14 and 19) were between 60 and 80 m, where both temperature and water sound speed were noticeably consistent. Changes in acoustic signal characteristics, such as strong ringing and coda, and significant reduction in amplitude of signals are all indicative that sediments on the inner shelf of SE Korea with a significant gas concentration were mechanically penetrated in late-September 1999, but not in mid-September 1999. In situ sound speed in gas-bearing sediments in late-September was significantly slower than in gas-free sediments. In contrast, no convincing distinction was possible between gassy and gas-free sediments in ultrasonic sound speed records (measured in May 1999), although X-ray images of a gassy sediment core clearly showed the mechanical disruption of the sediment structure due to abundant gas.

Our results and chirp sound data collected in May 1995 (Park et al., 1999) suggest that a continuous gas layer in the study area exists, and that the depth of the gas horizon is variable on a small-scale. The variability of the gas layer depth on the order of meters, as it has been observed elsewhere (Wilkens and Richardson, 1998) and, to a lesser degree, the inaccuracy of penetrating the exact same seafloor location twice, most likely causes the observed difference of in situ sound speeds over 2 weeks.

Amplitude spectra of full waveforms exhibited a stronger loss of lower rather than higher frequencies when obtained in gas-charged sediments in late-September 1999. This acoustic behavior is contrary to sound wave propagation in non-gassy sediments, but nevertheless consistent with theoretical predictions and field measurements made with the AL in similar sediments in Eckernförde Bay, Germany (Western Baltic Sea).

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