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25. Near-Offset Vertical Seismic Experiments during Leg 204[1]

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ABSTRACT

Three successful vertical seismic profiles (VSPs) were acquired during Ocean Drilling Program (ODP) Leg 204 at South Hydrate Ridge. The data confirm earlier results from ocean bottom seismometer data and analysis of moveout from common midpoint reflection data that the average velocity between the seafloor and the bottom-simulating reflector (BSR) is <1600 m/s throughout the region and is lowest near the summit, where the amount of hydrate is greatest. This result supports the conclusions that free gas and hydrate coexist beneath the summit and that the average amount of gas hydrate present elsewhere is low. The data also indicate that low-velocity zones (LVZs) resulting from free gas beneath the BSR must be thin and stratigraphically controlled. The only LVZ resolvable from traveltime analysis of the VSP data is associated with Horizon A, which has been interpreted to be the primary conduit transporting free gas to vents at the summit of South Hydrate Ridge. Thin LVZs associated with Horizons B and B′, however, are indicated by sonic logs as well as by strong negative polarity reflections in the multichannel seismic data. This limited distribution of sub-BSR free gas contrasts with previous results at North Hydrate Ridge (Leg 146) and Blake Ridge (Leg 164), which indicate the presence of free gas zones several hundred meters thick that result in distinct LVZs in the VSP data from those earlier ODP legs.

INTRODUCTION

Primary objectives of the near-offset vertical seismic profiles (VSPs) conducted during Ocean Drilling Program (ODP) Leg 204 were to deter-

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mine (1) the subsurface velocity structure at frequencies similar to those in the three-dimensional (3-D) seismic reflection data, thus enabling precise conversion of the reflection data to depth in the vicinity of the drill sites; and (2) the extent of free gas beneath the gas hydrate stability zone. Earlier results at north Hydrate Ridge (MacKay et al., 1994; Tréhu and Flueh, 2001) and at Blake Ridge (Holbrook et al., 1996) suggested that the free gas zone was tens to hundreds of meters thick. When extrapolated to gas hydrate–bearing zones worldwide, the conclusion of a thick free gas zone has a significant impact on the total amount of gas stored in this system and on the response of the system to perturbations.

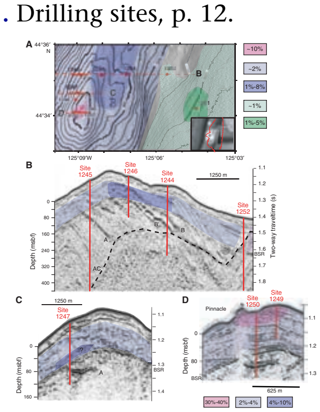
In this paper, we discuss the results of near-offset VSPs and compare the velocities thus obtained to velocities obtained from sonic logs at the same sites. For a more detailed discussion of the sonic log, including estimates of gas hydrate and free gas content of the sediment derived from the sonic log data, see **Guerin et al.** (this volume). For other examples of VSPs conducted in ODP drill holes, see Swift et al. (1991, 1996), Bolmer et al. (1992), MacKay et al. (1994), Moore et al. (1995), and Holbrook et al. (1996). We note that velocities obtained from sonic logs and the resulting depth/traveltime relationship can differ significantly from the velocities obtained from VSPs because the sonic logs measure the velocities of 10- to 20-kHz waves, whereas the VSPs measure velocities of 50- to 100-Hz waves. These velocities can differ significantly because of velocity dispersion due to micro- and macrostructure within the sediments. Moreover, the sonic logs measure waves traveling along the borehole wall, whereas the VSPs measure waves traveling farther from the borehole and deeper within Earth. These potential differences contain information on the scale of heterogeneities and other processes near the boreholes.

FIELD OPERATIONS

During Leg 204, near-offset, large-offset, and walkaway VSPs were attempted at five sites using three different downhole seismic tools (Well Seismic Tools [WSTs]-1 and 3 and Versatile Seismic Imager [VSI]); good data were obtained at Sites 1244, 1247, and 1250 (Fig. **F1A**). See the **"Appendix,"** p. 9, for a detailed discussion of operations at all sites. All data were recorded on the *JOIDES Resolution*. Shots for the near-offset VSPs were from a single generator-injector (GI) gun, fired on the *JOIDES Resolution* using control hardware in the Schlumberger MAXIS unit. Shots for offset and walkaway profiles were fired on the *Maurice Ewing* under radio control from the recording unit on the *JOIDES Resolution*. For a description of the offset and walkaway profiles, see Bangs and Pecher (2002).

The primary downhole seismic data acquisition tool planned for Leg 204 was the VSI, a state-of-the-art high-dynamic-range borehole seismic wireline tool designed for downhole seismic work in both cased and open holes and in vertical and deviated wells. The VSI, which was leased from Schlumberger by the ODP Lamont-Doherty Earth Observatory Borehole Research Group, consists of multiple modules in series separated by acoustically isolating spacers. Each module includes three orthogonal geophone sensors and three mechanical arms that couple the module to the borehole wall. Because of difficulty coupling more that one receiver module at a time to irregular borehole walls, we separated the modules and used only one at a time. The other modules were

F1. Drilling sites, p. 12.



used as spares and were needed because the coupling arms turned out to be too fragile and too short for use in soft sediments from a moving platform. Several coupling arms were broken during the course of the experiment, although high-quality data were successfully obtained using this tool when seas were very calm (Sites 1247 and 1250).

As a backup for the VSI, a Schlumberger WST-3 was flown out to the *JOIDES Resolution*. The WST-3 is an older Schlumberger three-component check shot tool containing a single recording station with three orthogonal geophones. A single clamping arm presses the recording module against the borehole wall. This arm is more robust and longer than the arm on the VSI. It was used at Site 1244.

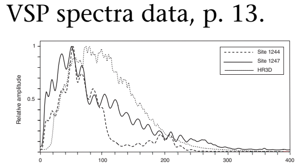
At each station, the sensor package was first lowered to the bottom of the hole. Shots were repeated 5 to 15 times, and waveform data were stacked by the MAXIS recording software and output in LDF (internal Schlumberger format) and SEG-Y formats with a 1-ms sample rate. The recording tool was then moved up 5 m and the process was repeated until hole conditions deteriorated. Some stations could not be occupied because of difficulties clamping the receiver unit in the hole. Although we encountered a number of technical difficulties, we obtained good-quality data at three sites (1244, 1247, and 1250), which represent distinctly different parts of the South Hydrate Ridge system (Fig. F1) (Tréhu et al., 2004b).

DATA ANALYSIS

While at sea, multiple shots were fired at each VSP tool depth and the median of automatic picks was logged (Table T1). These data were used at sea to get a first look at the data and to convert the seismic reflection data to depth at each site. Traveltimes were repicked from the stacked data after the cruise (Table T1). Picking uncertainty is estimated to be ±1 ms. Relative uncertainty between stations in depth beneath the seafloor is estimated to be ±1 m. Depth was determined from the wireline length; uncertainty arises because the receiver tools may have slipped in the borehole when tension on the wire was released to decrease noise transmitted to the geophones or because of temporal changes in water depth due to tides. We note here that a less impulsive, “ringier” signal was observed at Site 1244, which was recorded using the WST-3, compared to Sites 1247 and 1250, which was recorded using the VSI (Fig. F2), and attribute this to different borehole coupling characteristics for the two tools. Undetected differences in source depth or pressure may also have contributed to the different response. The resultant velocities are more variable for Site 1244, and we speculate that this is also related to poor borehole coupling and/or greater tool slippage with the WST-3.

T1. Traveltime picks, p. 22.

F2. VSP spectra data, p. 13.



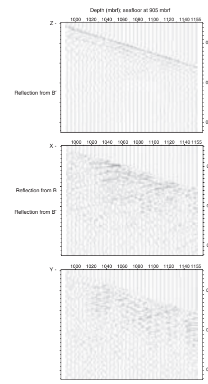
The velocity-depth functions were determined from the local linear best fit to the data within a sliding window that moved by one data sample. After testing several different window lengths, a 20-m window (generally 5 data points) was determined to provide the best tradeoff between spatial resolution and uncertainty. Velocity is estimated to be determined to ±150 m/s, considering both picking errors and depth errors.

RESULTS

Site 1244

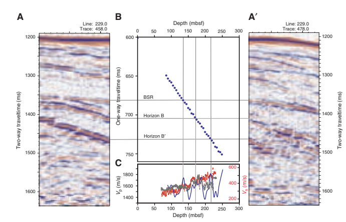
Site 1244 was located on the northeastern flank of South Hydrate Ridge in a region marked by pervasive normal faulting and several anomalous bright reflections located beneath the bottom-simulating reflector (BSR). Primary targets for the VSP at Site 1244 included strong reflections B and B′ beneath the BSR (Fig. F1B). Data acquired at this site using the WST-3 are shown in Figure F3. Measurements extend from ~50 m above the BSR to ~120 m below it. In addition to clear first arrivals, an upgoing wave reflected from Horizon B′ is clearly seen on all three components, and a possible upgoing wave is observed on the x-component from Horizon B. The strength of the signal on the horizontal components is somewhat surprising and probably results from scattering and from the fact that actual distance between the source and the receiver is ~70 m, leading to an incident angle of ~4° on Horizon B′, leading to cross-coupling between the vertical and horizontal components. No upgoing waves are seen originating at the BSR. Drilling indicated that Horizons B and B′ result from relatively coarse grained layers; in addition, Horizon B′ contains abundant detrital volcanic ash shards. Where these horizons were sampled updip within the gas hydrate stability zone at Site 1246, they contained relatively high concentrations of gas hydrate (Tréhu et al., 2004b).

F3. Three-component VSP, Site 1244, p. 14.



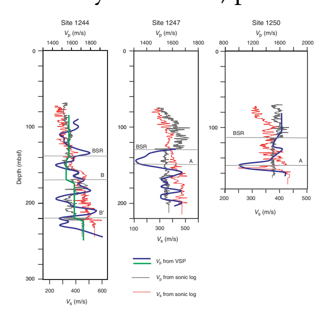
Traveltime picks (Fig. F4B) show very little departure from a straight line and indicate a best-fit apparent velocity of 1613 ± 7 m/s. The velocity-depth function obtained from the sliding window analysis with window length varying with depth around this velocity by up to 200 m/s (blue line in Figs. F4C and F5). The latter estimates have larger uncertainty because of the smaller number of points and smaller distance range used for the detailed velocity estimate. If the data are broken into segments separated by the BSR and reflections B and B′, then the velocity shows a small (not statistically significant) decrease from 1570 m/s above the BSR to 1540 m/s between the BSR and Horizon B before increasing to 1630 between Horizons B and B′ and to 1730 beneath Horizon B′ (green line in Figs. F4C and F5).

F4. VSP results, Site 1244, p. 15.



Above the BSR, which is located at ~138 meters below seafloor (mbsf), ~10 m deeper than previously reported (see table T1 in Shipboard Scientific Party, 2003a), the mean velocity obtained from the VSP corresponds closely to velocity obtained from sonic logging, in spite of several orders of magnitude difference in the frequency of the signal and the distance from the borehole wall sensed by the different data sets. The increase in variability of V_P with depth ~10–25 m above the BSR in the sonic logging data (gray line in Figs. F4C and F5) may reflect the presence of gas hydrate lenses; however, the gas hydrate concentration is not large enough to have a resolvable influence on velocities measured with the VSP data. Low average gas hydrate content at this site is consistent with the result reported by Tréhu et al. (2004b) that gas hydrate occupies, on average, 5%–8% of the pore space in this region. We note that at such low concentrations, the effect of gas hydrate on velocity depends strongly on how the gas hydrate is distributed in the pore space. The lack of a significant acoustic signature in the VSP or sonic log data suggests that gas hydrate at these low concentrations has little effect of sediment strength.

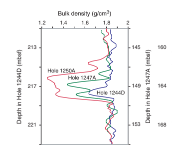
F5. Velocity functions, p. 16.



Below the BSR, the V_S sonic logging data (red line in Figs. F4C and F5) show a sharp increase in velocity at ~160 mbsf, ~10 m above Horizon B. A proportionally smaller increase is observed in V_P at this depth compared to V_S. Magnetic susceptibility also shows a change at this depth, suggesting a stratigraphic change to turbidite-rich sediments (see fig. F11 in Shipboard Scientific Party, 2003a). Lithologic variations thus appear to have a stronger effect on seismic velocity than the presence of gas hydrate or free gas at this site.

Finally, we note that no clear velocity inversions or low-velocity zones are resolved in the VSP or sonic log data at the BSR or at Horizons B or B′, indicating that these negative polarity reflections probably result from very low concentrations of free gas and that the gas may have escaped during drilling. The strongest of these reflections, Horizon B′, however, is marked by a 1-m-thick zone of anomalously low density and high electrical resistivity in data acquired by logging-while-drilling (LWD); these data are less affected by gas escape and may better indicate in situ conditions. A relatively coarse grained volcanic ash-rich layer is also found at this depth (Fig. F6), similar to Horizon A at Sites 1247 and 1250. Using bulk and grain density and porosity data from Leg 204, this density anomaly implies an in situ gas saturation of 15%–20% (Tréhu et al., 2004a).

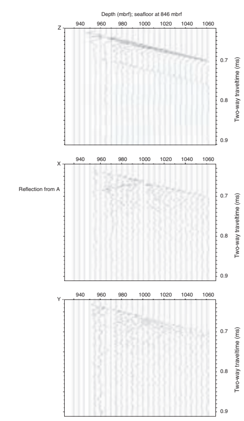
F6. Density profiles, p. 17.



Site 1247

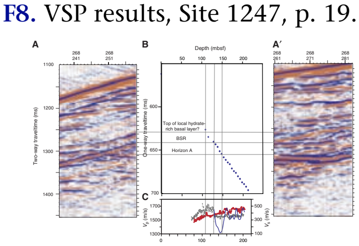
The primary target for the VSP at Site 1247 (Fig. F7) was Horizon A, a bright reflection thought to be a fluid conduit to the South Hydrate Ridge summit (Figs. F1, F8). Drilling confirmed that Horizon A is a coarse-grained, volcanic glass–rich, gas-charged stratigraphic conduit (Tréhu et al., 2004a). Data were acquired at this site using the VSI. Hole quality was good beneath the BSR, and there were only a few depth stations where the tool could not be clamped to the borehole wall. Above the BSR, however, clamping became problematic; only two measurements could be made above the BSR and the depth of those measurements is uncertain. The signal-to-noise ratio of first arrivals is high, but no upgoing waves are observed on the vertical component; however, a clear reflection from Horizon A is observed on the x-component. The traveltime for this event indicates that it is a P-wave. We do not have an explanation as to why this is present on the horizontal component and not detectable on the vertical component.

F7. Three-component VSP, Site 1247, p. 18.



Analysis of traveltimes indicates low velocity between Horizon A and the BSR. The best linear fit to all data points indicates a mean velocity of 1517 m/s; above 160 mbsf it is 1414 m/s, and below 160 mbsf it is 1567 m/s. The sliding window velocity analysis shows a 40-m zone with a minimum velocity of ~1300 m/s, indicative of the presence of free gas. Below Horizon A, the velocity seems to vary with depth by ~100 m/s, which can be attributed primarily to uncertainties in traveltime picks and sensor depth. P-wave sonic logs do not show this low-velocity zone, perhaps because the gas escaped and was replaced by drilling fluid adjacent to the borehole wall prior to logging.

F8. VSP results, Site 1247, p. 19.



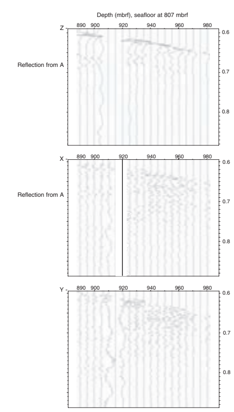
Unlike at Site 1250, no decrease in V_S is observed on the sonic logs at Horizon A even though the density and resistivity logs obtained from LWD are similar (Tréhu et al., 2004a). We note that Hole 1247B, which was cored and then used for wireline logging and the VSP, was offset by 100 m from Hole 1247A, which was sampled by LWD. The strength and character of the Horizon A reflection changes significantly between these two holes. Whereas the LWD resistivity and density signatures of Horizon A in Hole 1247A are similar to those at other sites that sample Horizon A, the ash-rich layers that characterize Horizon A elsewhere are not present in Hole 1247B. We interpret this to mean that a coarse-grained ash layer is required to achieve gas pressures high enough to strongly affect V_S and that this ash layer pinches out between Holes 1247A and 1247B. The VSP, however, detects the free gas because it is sensitive to structure in a larger radius around the borehole.

Immediately above the BSR, where we had difficulty coupling the VSI to the borehole, the sonic logs show an increase in variability in a layer ~40 m thick. A strong but local reflection overlies the BSR in this region. Chloride concentration anomalies (Bangs et al., 2005) and modeling of the constant-offset VSP data (Bangs et al., 2003) suggest the presence of a basal hydrate-rich layer at this site, similar to that documented at Site 1251 (Tréhu et al., 2004b). We speculate that gas hydrate decomposition in response to drilling destabilized the hole in this interval.

Site 1250

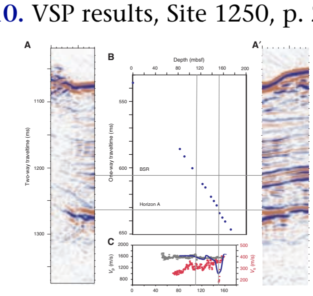
This site samples Horizon A updip and near the summit of South Hydrate Ridge. Data were acquired with the VSI, and coupling of the sensors to the borehole was problematic in most of the borehole. We were not able to achieve 5-m station spacing (Fig. F9), and only a few stations were possible above the BSR. In spite of the sparse trace spacing, a clear upgoing *P*-wave reflected from Horizon A is observed on the vertical component.

F9. Three-component VSP, Site 1250, p. 20.



The velocity model derived from the traveltimes shows a clear velocity decrease associated with Horizon A to 1100 m/s averaged over 15 m (Figs. F10). Actual velocity in the 4-m-thick gas-charged layer defined on the basis of LWD density (Fig. F6) and resistivity data must actually be much lower. For example, a 4-m layer with a velocity of 595 m/s surrounded by material with a velocity of 1600 m/s is also compatible with the data. The average velocity above the BSR is 1575 m/s, including the observed traveltime to the seafloor. Between Horizon A and the BSR, only a small decrease in velocity, if any, is detected in the VSP data. This contrasts with the large decrease in V_P distributed over tens to hundreds of meters observed during Legs 146 and 164.

F10. VSP results, Site 1250, p. 21.



As for the other sites, V_P measured from sonic logs is more variable above the BSR than below the BSR. A small but distinct decrease in V_P below the BSR can be attributed to a small increase in the amount of distributed free gas in the sediment pore space between Horizon A and the BSR. No drop in V_P, however, is observed at Horizon A, an observation that is inconsistent with the VSP data. On the other hand, a large drop in V_S is associated with Horizon A in the sonic logging data. This is surprising because V_S should not be affected by whether the pore-filling fluid is liquid or gas, whereas V_P should be very sensitive to the composition of the pore fluid. We interpret this result to indicate (1) that gas escaped from Horizon A and was replaced by water near the borehole wall prior to logging and (2) that high gas pressure in Horizon A (Tréhu et al., 2004a) has disrupted the sediment structure, leading to a large decrease in the shear modulus of the sediment. For a bulk density of 1700 kg/m^3 and V_s of 350 m/s away from Horizon A and 1100 kg/m^3 and 150 m/s within Horizon A, this implies a decrease in shear modulus from 2.1×10^8 to 2.5×10^7 Pa. Alternatively, the decrease in shear modulus within Horizon A might be due to its ash-rich lithology; however, lithology alone is unlikely to result in an order of magnitude decrease in shear modulus.

CHECK SHOT SURVEYS

Check shots were done at the base of logged holes using the Inline Checkshot Tool as part of wireline logging operations. Table T2 shows the average velocity between the base of the hole and the seafloor (using the traveltime to the seafloor measured from the 3-D reflection data, which is shown in Figs. F4, F8, and F10). These velocities are generally consistent with the velocities obtained from the VSPs and show a general increase in velocity with depth. These velocities can be used for depth conversion at Site 1245, at which a full VSP was not successful because of hole instability, and further supports the conclusion that there is no thick widespread free gas zone beneath the BSR at South Hydrate Ridge.

T2. Check shot survey results, p. 23.

SUMMARY

During Leg 204, three near-offset vertical seismic profiles were acquired at sites representing different parts of the gas hydrate system at South Hydrate Ridge. The results generally confirm precruise estimates of velocity, resulting in only minor changes in estimates of depth to key reflections. Although velocities are generally quite low throughout the region, the only significant velocity inversion in the VSP data is associated with a relatively coarse grained and volcanic-ash-rich stratigraphic horizon (known as Horizon A) that appears, on the basis of a variety of different data sets, to be the major conduit feeding free gas to summit vents. This horizon appears as a strong reflection that can be traced regionally in the 3-D seismic reflection data. Bulk density and shear wave velocities from logging data indicate the presence of a second gas-rich zone also associated with volcanic ash at Horizon B′, another strong reflection that can be mapped in the 3-D seismic data. The strong effect on V_S measured in sonic logs in Horizon A and Horizon B′ indicates a decrease in shear modulus of nearly a factor of 10, indicating that these zones are overpressured. No regional thick free gas zone is present, in contrast to results from two previous VSP studies in gas-hydrate–bearing regions.

ACKNOWLEDGMENTS

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APPENDIX

A narrative description of VSP operations during Leg 204, in the order in which they were attempted, is included here in case they are of interest to others when planning similar experiments in the future.

Hole 1245E

After completion of the conventional wireline logging (CWL) operations, rig-up of the three-node VSI for the VSP survey started on 15 August 2002 at 0830 hr local time. The plan was to conduct three types of survey during this run: vertical, constant-offset, and walkaway. At this time, the *Maurice Ewing* was navigating nearby to provide support for the constant-offset and the walkaway surveys.

Despite the generally good hole conditions that were observed during the standard logging runs, it became clear after a few attempts that it would be difficult to achieve simultaneous clamping of all three sensor packages. In fact, very poor signal-to-noise ratios when shots were fired from either the *JOIDES Resolution* or the *Maurice Ewing* indicated that none of the sensor packages were well coupled to the borehole. After some discussion with the Schlumberger engineer responsible for the VSI downhole seismometer, the reason for this problem became apparent. The average hole size, which ranged from 12 to 16 in based on the caliper log (see **"Downhole Logging"** in Shipboard Scientific Party, 2003b), was equal to or larger than the maximum operational hole size for the VSI (12 in).

Shots were fired from the *JOIDES Resolution* and from the *Maurice Ewing* for several hours without recording a consistent signal at any of the attempted depths. At 1700 hr, it was decided to abort this run and try to use the WST-1 to conduct at least a vertical VSP. When the VSI reached the rig floor it appeared that the arms of the three shuttles had been damaged during our numerous clamping attempts. The WST was lowered by 1945 hr. After several unsuccessful attempts, it was clear that the geophone was not working properly and the tool was brought back to replace the geophone. During the following lowering, and despite the proper behavior of the WST, it was clear that the hole was too large and the formation to soft to get a good clamping. The survey was aborted, and the final rig-down was complete at 0200 hr on 16 August 2002.

Hole 1251H

After completion of CWL operations in Hole 1251H, rig-up for the VSP survey started at 0345 hr on 18 August 2002. The triple combination and Formation MicroScanner-sonic calipers had shown that the hole was irregular, which suggested that the three-component WST-3 would be the most likely to provide data. This tool had been flown in since the previous failure of the VSI at Site 1245. The WST-3 was lowered at 0445 hr, and it proved again difficult to get a consistently good clamping; however, the signal appeared of good enough quality to proceed with a systematic vertical and constant-offset VSP. Stations were made over the entire hole every 7.5 m, starting at 1405 meters below rig floor (mbrf). Considering the overall good quality of the data, it was then decided to attempt a walkaway VSP. It proved impossible to get good clamping at the initial target depths, but a good station was found at 1320 mbrf and the *Maurice Ewing* shot two perpendicular lines, each taking ~2 hr. Final rig-down was completed at 2030 hr on 18 August 2002.

Hole 1244E

After completion of CWL operations in Hole 1244E, VSP rig-up started at 0130 hr local time on 21 August 2002. Both CWL logging runs had indicated very good hole conditions, and the possibility to use a modified VSI was considered until it was pointed out that the modifications that were made to extend its arms would not allow the tool to exit the advanced piston corer/extended core barrel bit. The WST-3 was lowered instead, and the vertical/constant-offset VSP started from the bottom of the hole (~1155 mbrf) at 0400 hr. Stations were made every 5 m and the survey was completed at 0830 hr without any problem in excellent hole and sea conditions. Two walkaway stations, including two orthogonal lines each, were made at 1045 and 1020 mbrf, respectively. The final rig-down ended at 0100 hr local time, 22 August 2002.

Hole 1247B

After completion of CWL operations in Hole 1247B, rig-up of the WST-3 started at 0415 hr local time, 24 August 2002. Considering the good hole conditions, the plan was to conduct a complete survey including two walkaway stations. Initial tests before lowering the assembled tool string indicated serious problems, including the impossibility to properly close and open the arm, and it was decided to use the WST-1 to perform only a vertical VSP. After lowering the tool, several unsuccessful attempts to record a decent signal indicated that the geophone was damaged. Because no spare geophone was available and considering the extremely good hole and sea conditions, we decided to try using one of the shuttles of the VSI, which had been restored to its original configuration. Lowering of the VSI started at 0945 hr, and preliminary tests showed that the tool was working properly. The tool reached the bottom of the hole (1066 mbrf) at 1015 hr, and vertical/constant-offset VSPs were acquired by alternating shots between the *JOIDES Resolution* and *Maurice Ewing* as the tool was raised from 1060 and 930 mbrf with stations every 5 m. After completion of this survey, it proved impossible to get a satisfactory station that would allow a walkaway. Considering the poor quality of the signal, it was suspected that the tool had been damaged and it was brought back to the rig floor for inspection. This confirmed that the arm had been damaged, possibly while the tool was on station too close to the bottom of the pipe. It was decided to abort any further attempt in order to preserve the remaining shuttles for the final VSP survey at Site 1250. Final rig-down was complete at 1730 hr, 24 August 2002.

Hole 1250F

After completion of CWL operations, rig-up of a the single-shuttle VSI started at 0610 hr, 26 August 2002. The tool was lowered at 0715 hr and the vertical/constant-offset survey started from the bottom of the hole (980 mbrf) at 0800 hr. Stations were recorded every 5 m up to 890 mbrf. Coupling between the arm and the formation was poor in the upper part of the hole, and no reliable shots were recorded above 930 mbrf. Because of the generally poor signal, it was suspected that the tool had been damaged, and it was brought back to the surface. Inspection showed that it was in working order, and it was lowered again at 1230 hr to find possible walkaway stations. After systematic attempts along most of the hole, three walkaway surveys were recorded at 945, 898, and 979 mbrf. Final rig-down was completed at 0630 hr on 27 August 2002, a few hours before the Schlumberger VSP engineer was to leave the ship.

Figure F1. A. South Hydrate Ridge and locations of drilling sites. Overlay shows gas hydrate content of the pore space averaged between the seafloor and bottom-simulating reflector (BSR). Inset shows seafloor reflectivity at the summit (from Tréhu et al., 2004b). **B, C, D.** Seismic cross sections through South Hydrate Ridge showing the setting of drill site. Slices were extracted from a 3-D seismic survey that is discussed in detail in **Chevallier et al.** (this volume). Overlay shows average gas hydrate content of the pore space (from Tréhu et al., 2004b). A zone located immediately above the BSR at Site 1247 that is enriched in gas hydrate relative to the regional average was not included in the Trehu et al. (2004b) model but has since been recognized based on sonic logs (**Guerin et al.,** this volume) and chloride concentration anomalies (Bangs et al., 2005).

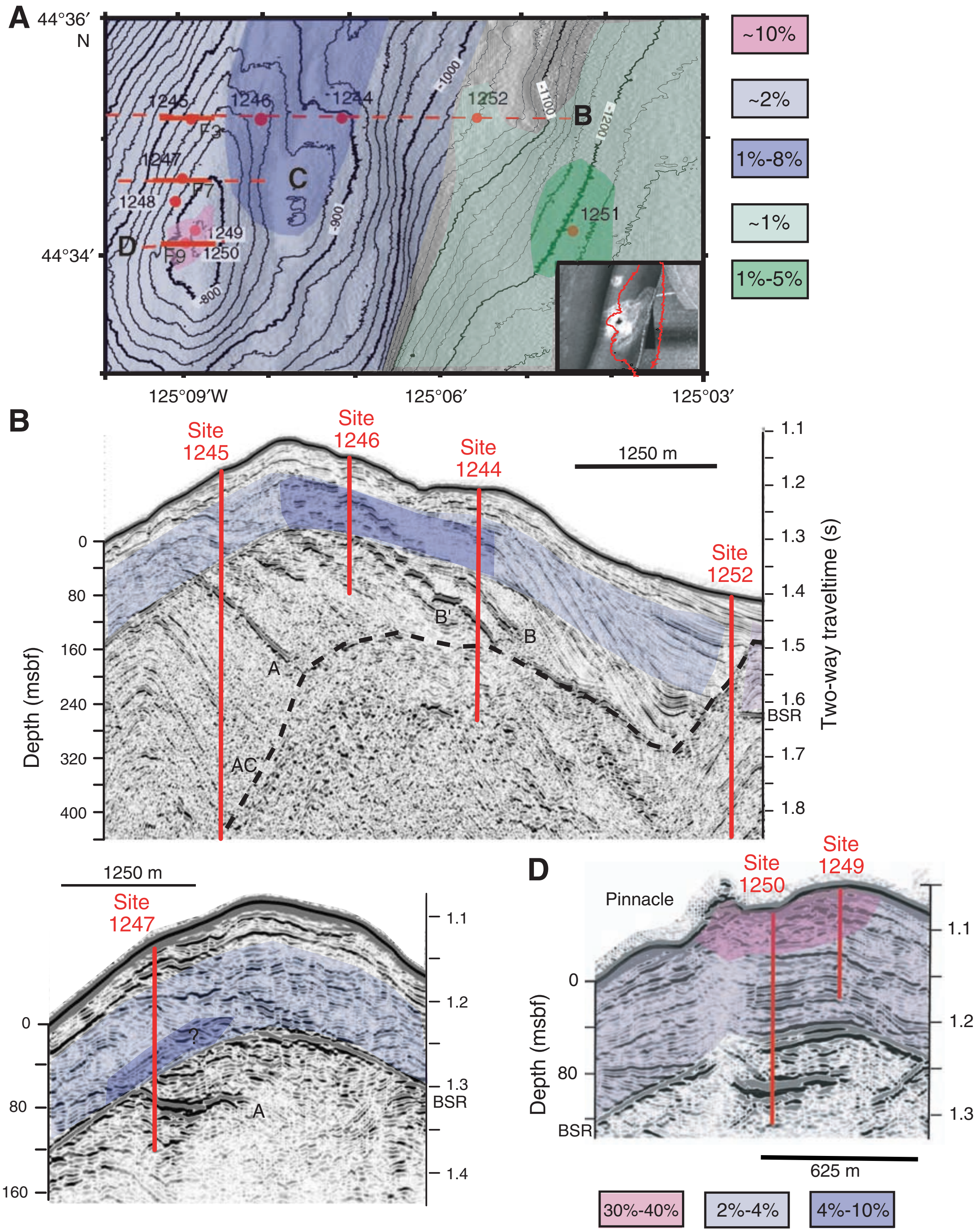

Figure F2. Spectra of near-offset VSP data at Sites 1244 and 1247 compared to the spectrum of a sample of the 3-D seismic reflection data from near the summit of South Hydrate Ridge (HR3D). For the VSP, data from 0.5 to 1.5 s on all traces were included. For the reflection data, a window from 1.0 to 1.5 s from a 0.5-km-long section through Site 1247 (Fig. F1C, p. 12) was used.

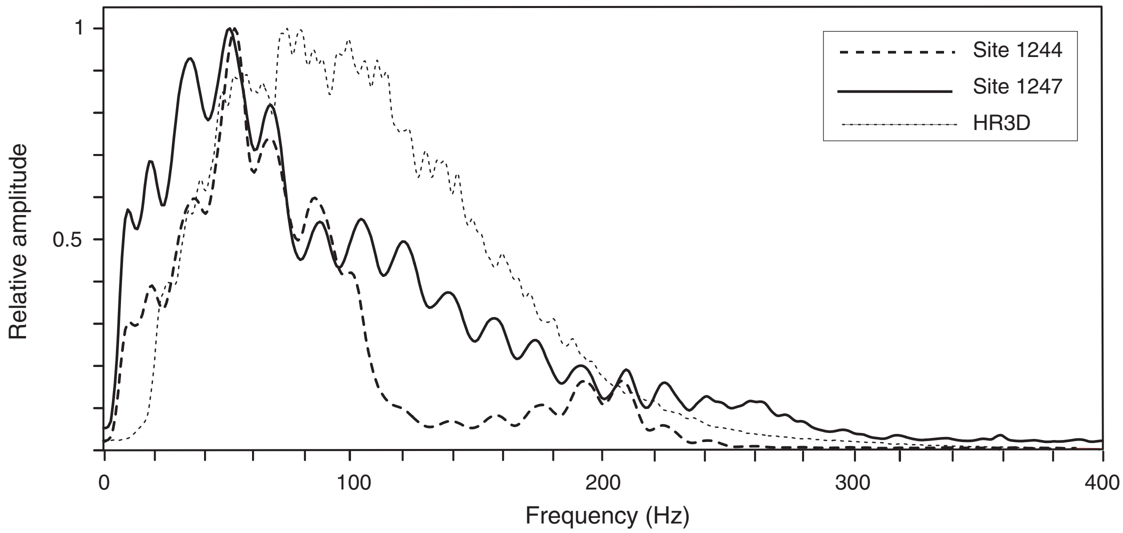

Figure F3. Three-component near-offset VSP recorded at Site 1244. In each section, all traces are plotted with the same amplitude scale. The amplitudes of the horizontal components are scaled up by a factor of 5 relative to the vertical component.

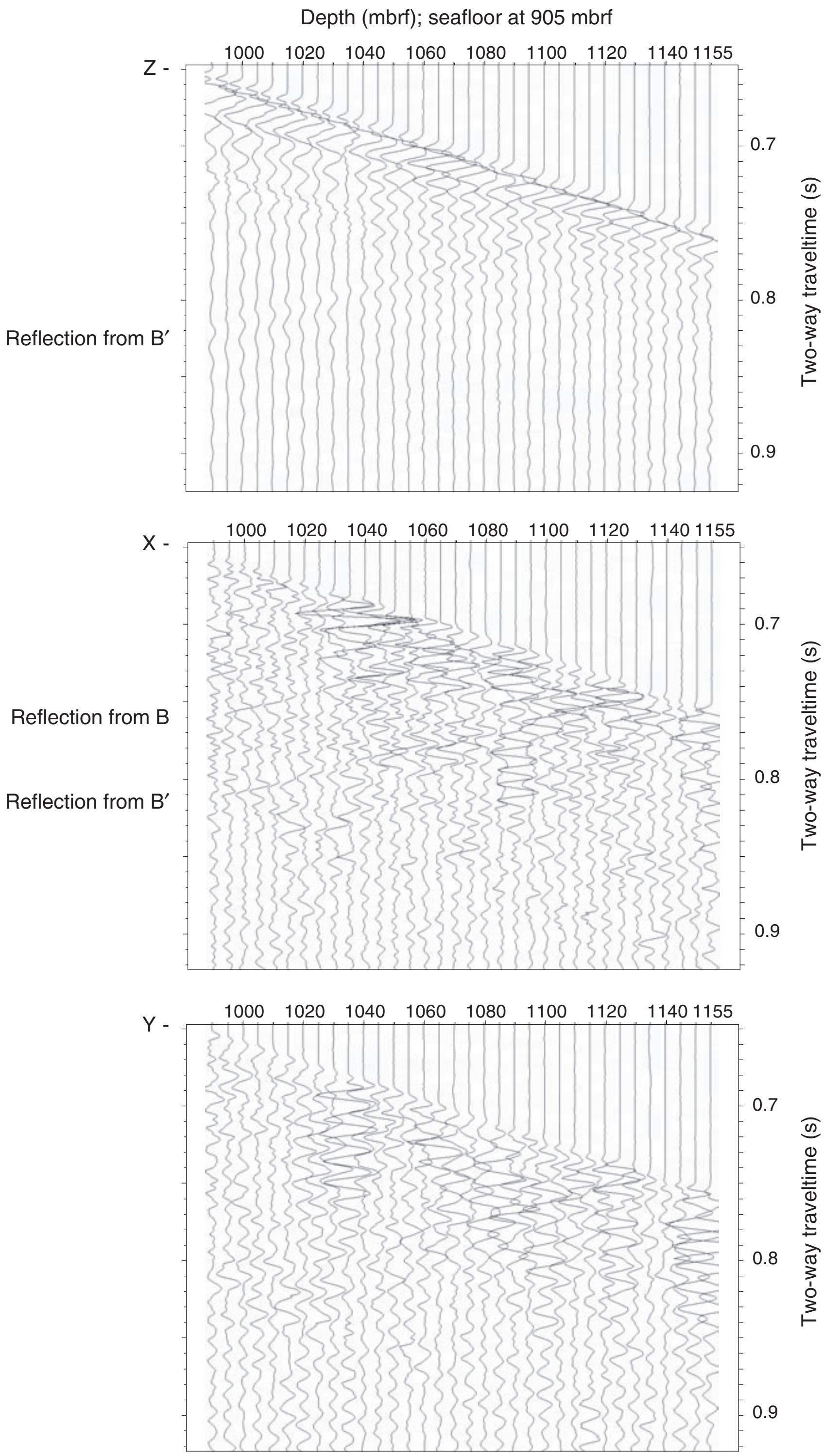

Figure F4. Results of the VSP at Site 1244. **A.** and **A′.** East-west slice from the 3-D seismic reflection data split at the location of the drill hole. **B.** Traveltime vs. depth data. Manual picks were used. Similar results are obtained using the automatic picks. Gray lines trace primary reflections from time to depth. BSR = bottom-simulating reflector. **C.** Velocity function derived from the data in B (blue line) is compared to velocities measured with wireline sonic logs. Gray dots = V_P, red dots =V_S. This plot is included here to illustrate the relationship between time and depth. It is repeated in Figure F5, p. 16, at larger scale.

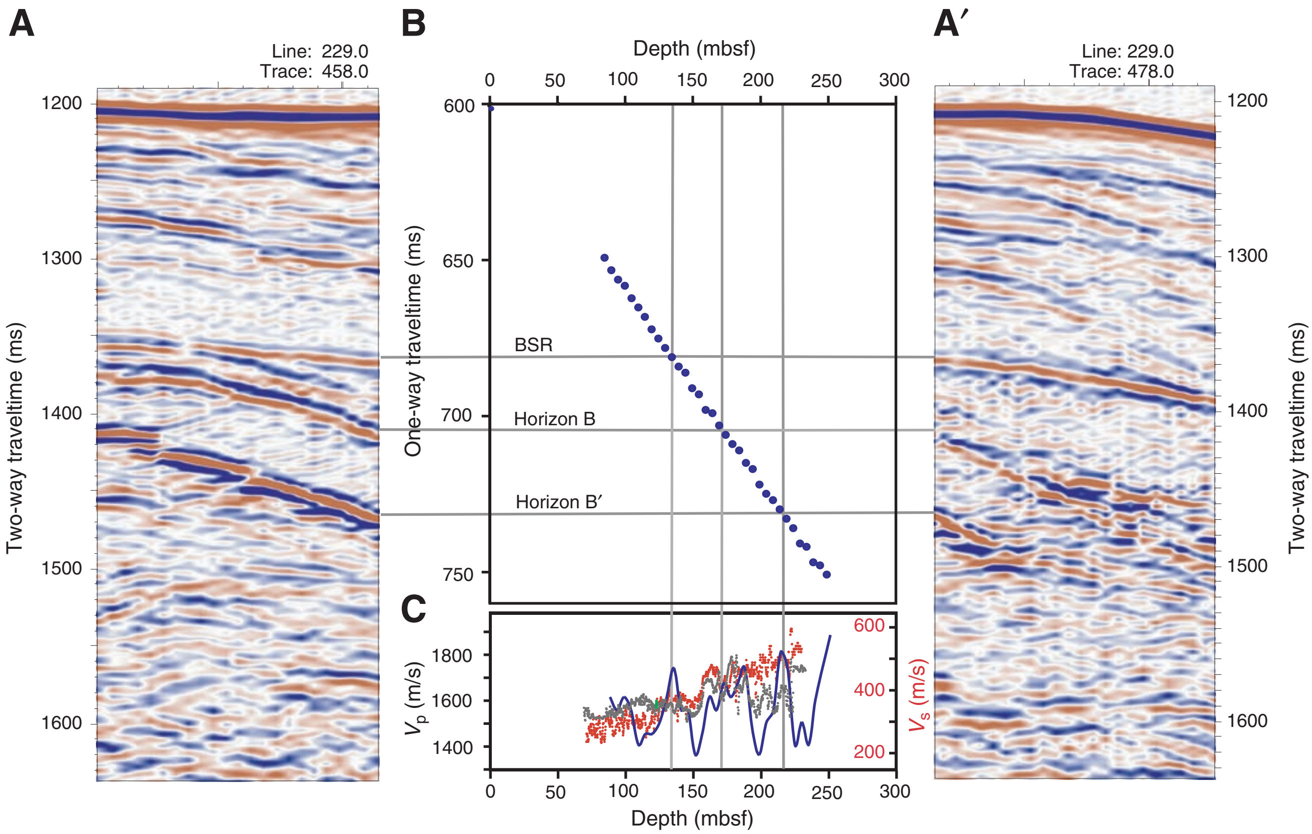

Figure F5. Velocity functions at Sites 1244, 1247, and 1250. The velocity function derived from the near-offset vertical seismic profiles (VSP) using a moving window of 20 m in depth is shown as a bold blue line. The velocity function derived from line segments of data delimited by strong reflections is shown in green. The yellow line shows the results obtained when data are separated into segments based on a lithologic change at 160 mbsf. Sonic logging data are shown as gray and red dots for V_P and V_S, respectively. BSR = bottom-simulating reflector.

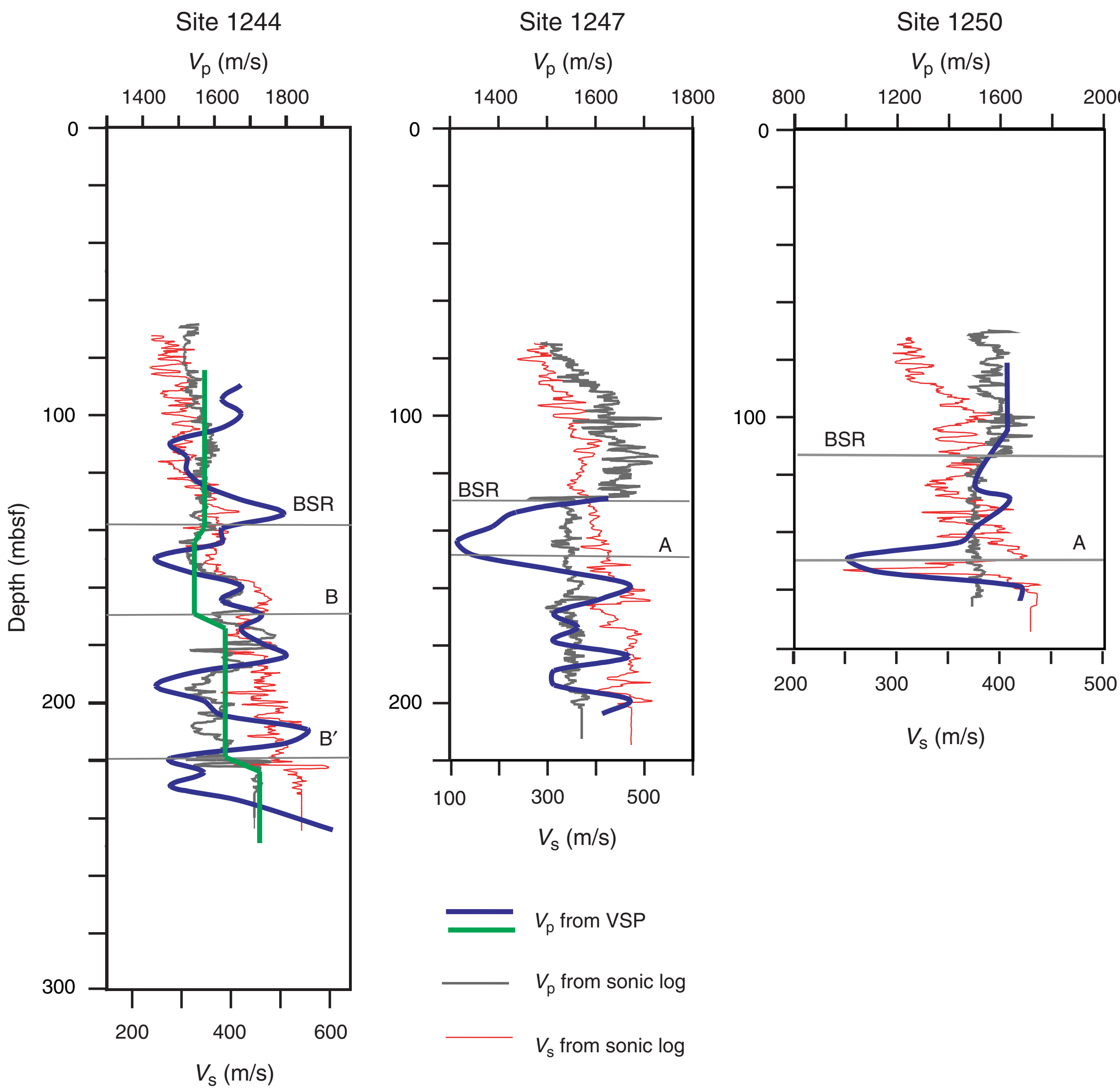

Figure F6. Density profiles from logging-while-drilling data through Horizon B′ at Site 1244 and through Horizon A at Sites 1247 and 1250.

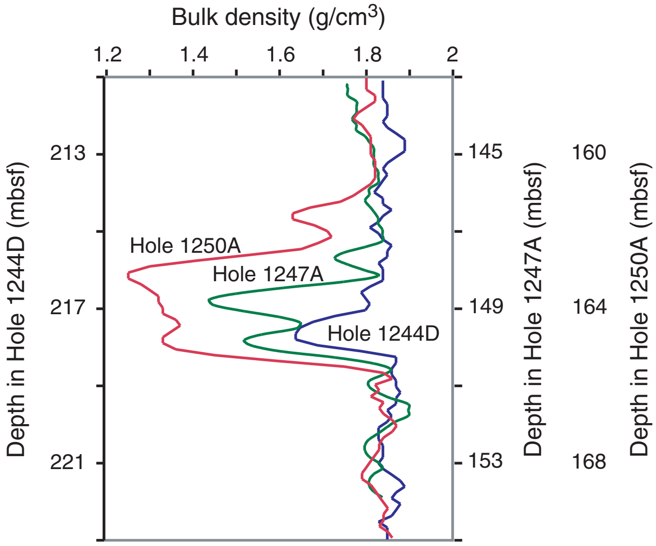

Figure F7. Three-component near-offset VSP recorded at Site 1247. In each section, all traces are plotted with the same amplitude scale. The amplitudes of the horizontal components are scaled by a factor of 5 relative to the vertical component. The arrival that follows 0.06 s after the first arrival is part of the GI gun source signature.

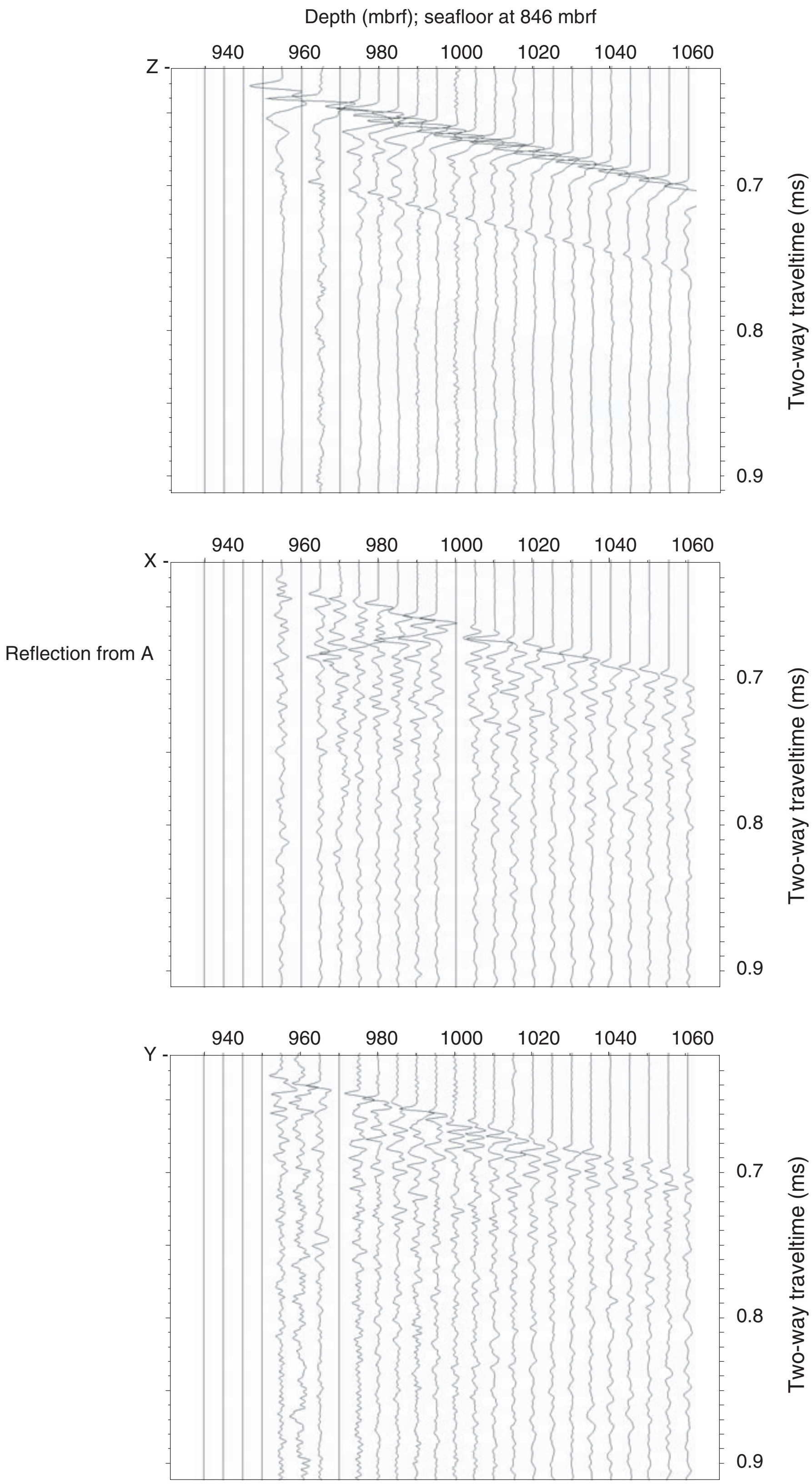

Figure F8. Results of the near-offset VSP at Site 1247. **A.** and **A′.** East-west slice from the 3-D seismic reflection data split at the location of the drill hole. **B.** Traveltime vs. depth data. Manual picks are used. Similar results are obtained using the automatic picks. Gray lines trace primary reflections from time to depth. BSR = bottom-simulating reflector. **C.** Velocity function derived from data in B (blue line) compared to velocities measured with wireline sonic logs. Gray dots = V_P, red dots = V_S. This graph is enlarged and compared in Figure F5, p. 16.

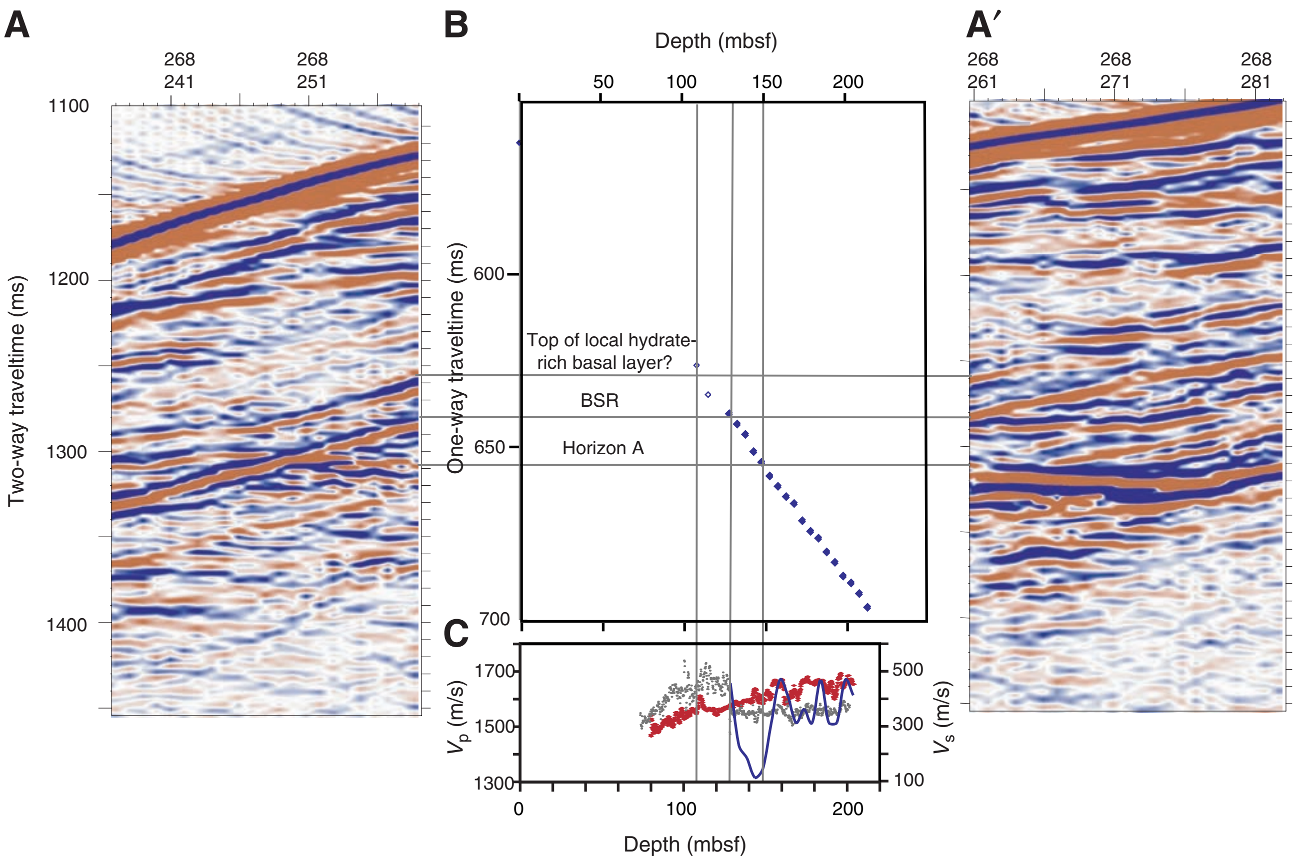

Figure F9. Three-component near-offset VSP recorded at Site 1250. In each section, all traces are plotted with the same amplitude scale. The amplitudes of the horizontal components are scaled by a factor of 5 relative to the vertical component.

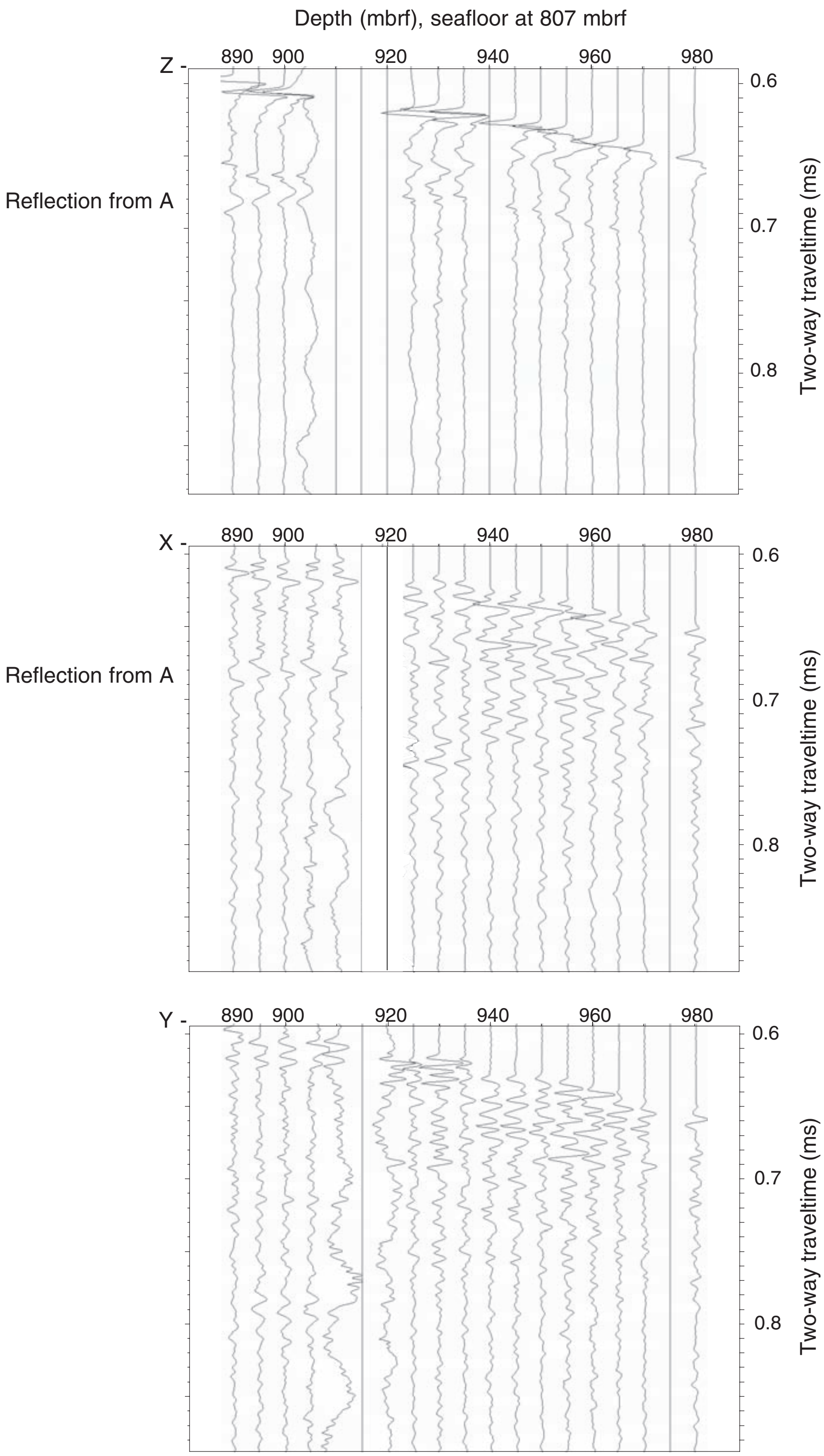

Figure F10. Results of the near-offset VSP at Site 1250. **A.** and **A′.** East-west slice from the 3-D seismic reflection data split at the location of the drill hole. **B.** Traveltime vs. depth data. Manual picks are used. Similar results are obtained using the automatic picks. Gray lines trace primary reflections from time to depth. BSR = bottom-simulating reflector. **C.** Velocity function derived from the data in B (blue line) compared to velocities measured with wireline sonic logs. Gray dots = V_P, red dots = V_S. This graph is enlarged in Figure F5, p. 16.

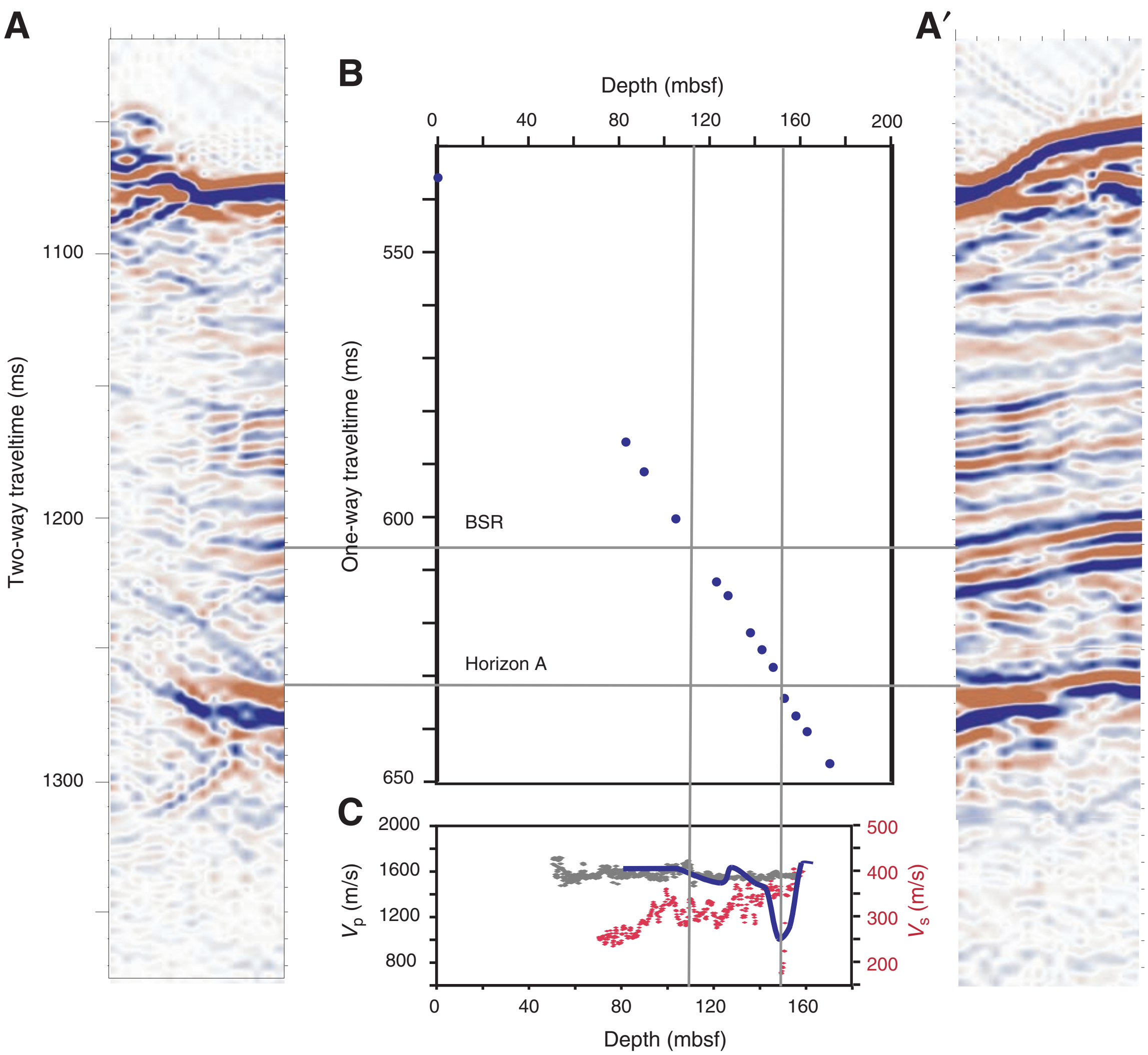

Table T1. Traveltime picks from near-offset VSPs.

	Depth		Picks	
Site	(mbrf)	(mbsf)	Automatic	Manual
1244	1155	249	752.8	751
	1150	244	750.19	748
	1145	239	747.45	747
	1140	234	744.66	742
	1135	229	742.98	741
	1130	224	739.12	736
	1125	219	735.21	733
	1120	214	731.44	730
	1115	209	729.28	727
	1110	204	725.94	725
	1105	199	722.7	722
	1100	194	719.33	717
	1095	189	716.23	715
	1090	184	712.96	711
	1085	179	710.23	709
	1080	174	707.14	706
	1075	169	705.86	703
	1070	164	701.76	699
	1065	159	700.25	698
	1060	154	695.09	693
	1055	149	691.43	691
	1050	144	688.46	686
	1045	139	685.33	684
	1040	134	682.23	681
	1035	129	680.59	678
	1030	124	676.1	675
	1025	119	672.86	672
	1020	114	669.96	668
	1015	109	667.04	665
	1010	104	663.73	662
	1005	99	657.6	658
	1000	94	657.49	656
	995	89	646.03	653
	990	84	651.42	649
1247	1060	214	695	696
	1055	209	691.1	692
	1050	204	687.5	689
	1045	199	684.8	687
	1040	194	681.6	683
	1035	189	678.4	680
	1030	184	675.5	676
	1025	179	672.4	674
	1020	174	669.5	671
	1015	169	666	666
	1010	164	662.8	664
	1005	159	659.8	661
	1000	154	No pick	658
	995	149	652.8	654
	990	144	650.2	651
	985	139	647.2	646
	980	134	642.7	643
	975	129	639.5	640
	955	109	626.4	626
1250	980	173	646.6	648
	970	163	640.6	642
	965	158	637.6	639
	960	153	634.3	636
	955	148	628.4	630
	950	143	625.1	626
	945	138	621.9	623
	935	128	614.9	616
	930	123	612.3	614
	912	105	600.4	601
	898	91	591.5	592
	890	83	585.9	586

Notes: Offset is ~70 m, resulting in an incident angle of ~3× at subsurface interfaces. Automatic picks were made at sea. Manual picks were made later from stacked seismograms.

Table T2. Results of check shot surveys.

Hole	Depth (mbrf)	Water depth (mbrf)	Depth (mbsf)	Time (ms)	Velocity (m/s)
1244E	1157	905	222	735	1669
1245E	1199	883	286	757	1684
1247B	1066	846	190	679	1628
1250F	986	807	149	633	1536

Notes: Depth is corrected for the 30-m offset between the sensors and the bottom of the tool string that includes the Inline Checkshot Tool. Velocity is calculated assuming a velocity of 1485 m/s in the water column and 11 m between the rig floor and the sea surface.