Kasahara, J., Stephen, R.A., Acton, G.D., and Frey, F.A. (Eds.)
Proceedings of the Ocean Drilling Program, Scientific Results Volume 200

6. DATA REPORT: 4-KHZ PROFILING WITH VERTICALLY SEPARATED SOURCE AND RECEIVER: A MINI REFLECTION SURVEY AROUND A DEEPWATER DRILL HOLE[1]

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ABSTRACT

The spatial resolution of hull-mounted 3.5-kHz echo sounding systems is limited in deep water by the large footprint (Fresnel zone) of the insonifying energy on the seafloor. At Ocean Drilling Program (ODP) Site 1224, we tested a simple system that can be used from the drillship while on station to significantly improve reflection profiling resolution. In 4970 m water depth, a 4-kHz pinger was mounted on the ship's video camera frame and lowered down the drill string to a few meters above the seafloor. The ship's 3.5-kHz transceiver recorded the returns.

Having the source and receiver at differing distances above the seafloor provides two advantages: (1) the area returning reflections is greatly reduced, and (2) the amplitudes of the subseafloor reflections are less affected by the spreading effect since the traveltime into the seafloor is much less than in the water column.

Reflections were observed to 40 ms beneath the seafloor on 10 lowerings at three closely spaced holes. The heave of the ship and camera frame shifts the traveltimes of the reflection sequences. A level-discriminator and correlation routine was used to align the traces and stack them to enhance the signal. The reflections were commensurate with the geotechnical data obtained from the limited number of sediment cores obtained.

These measurements do not take rig time. In addition to use on the drillship, this system could provide a low-cost, shallow-penetration pro-

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[1] Bolmer, S.T., Hoskins, H., and Stephen, R.A., 2006. Data report: 4-kHz profiling with vertically separated source and receiver: a mini reflection survey around a deepwater drill hole. *In* Kasahara, J., Stephen, R.A., Acton, G.D., and Frey, F.A. (Eds.), *Proc. ODP, Sci. Results,* 200, 1–17 [Online]. Available from World Wide Web: <http://www-odp.tamu.edu/publications/200_SR/VOLUME/CHAPTERS/005.PDF>. [Cited YYYY-MM-DD]

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Initial receipt: 8 July 2004
Acceptance: 13 September 2005
Web publication: 18 April 2006
Ms 200SR-005

filing system from remotely operated vehicles and autonomous underwater vehicles deployed while the ship is drilling.

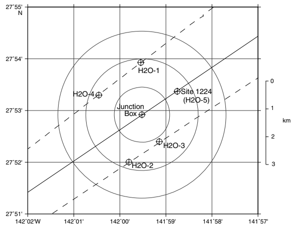
INTRODUCTION

A good local map of the sedimentary sequence and basaltic basement topography is of special interest at ocean observatory sites. The deployments of some of the instrument suites at these sites need to take into account the attributes of sediments and basement in the immediate area. The imaging described here of the acoustic interfaces in the immediate vicinity of a borehole provides an estimate of the small-scale topography of the interfaces immediately around the borehole, thereby complementing the recovered samples and logging results.

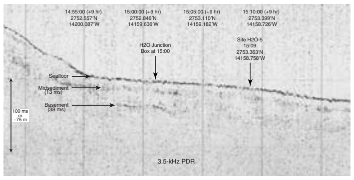
Echo sounding profiles made with sound sources operating in the lower kilohertz range commonly show reflections from interfaces beneath the seafloor in sedimented areas. An early example was reported by Smith (1958). At these frequencies, the wavelength of the sound in water is ~0.37 m, and in unconsolidated sediments it ranges from 0.4 to 0.5 m, depending on their compressional wave velocity. Echo sounding surveys of drill sites with hull-mounted sounders (3.5 kHz) have commonly been performed throughout the Deep Sea Drilling Program (DSDP) and Ocean Drilling Program (ODP). Jacobi et al. (1985) is a good example from Leg 86.

At Site 1224, a suite of holes was drilled 1.5 km northeast of the Hawaii 2 Observatory (H2O) junction box (Fig. **F1**; from Stephen, Kasahara, Acton, et al., 2003). The shipboard 3.5-kHz echo sounding profile (Fig. **F2**; from Stephen, Kasahara, Acton, et al., 2003) across the drill site shows that the seafloor dips smoothly ~6 m from the H2O junction box to the drill site. One subbottom horizon at ~9 m is fairly uniform throughout the area. Based on drilling (incomplete recovery), this is a midsediment section reflector. A second reflector at ~30 m below the junction box is basaltic basement; it appears only occasionally in the recording. The objective of lowering the 4-kHz source to the seafloor was to improve the resolution of the sediment and basement reflections. Note that with using the 3.5-kHz hull-mounted source (Fig. **F2**), the basement reflector could be identified at the H2O junction box but not at the drill site.

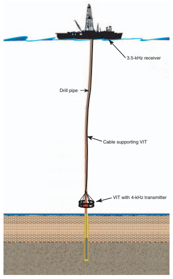
F1. Location map, p. 7.



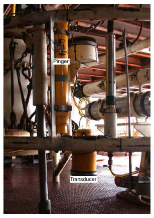
F2. 3.5-kHz receiver recording, p. 8.



F3. 4-kHz experiment schematic, p. 9.



F4. VIT frame, p. 10.



EXPERIMENTAL SETUP

The area of the seafloor insonified (within the first Fresnel zone) is greatly reduced by lowering a broadbeam source to a few meters above the seafloor (Figs. **F3**, **F4**). The first Fresnel zone is defined as the area within the circle whose circumference is one-half wavelength longer than the distance normal to the seafloor. For the ORE Accusonics Technology model 263Z 4-kHz source used, this is 0.18 m greater than the distance normal to the seafloor. The source transducer has single front and rear lobes. Pulse length was set at 2 ms. By comparing the echo sequences observed at three holes at Site 1224 and at four elevations above the seafloor, inferences as to the lateral character of drilled interfaces can be made. There was little amplitude difference in the direct arrival and seabed reflections due to spreading loss as the direct and reflected returns were recorded on the ship's 3.5-kHz transceiver nearly 5 km above the source and seafloor. The ship's 3.5-kHz transducer is designed to chirp and is sufficiently broadband to receive the 4-kHz deep source.

The 0.25-s data window, digitized at 24 kHz, was triggered by the direct water arrival from the back lobe of the transducer as illustrated in Figure **F5.** A traveltime alignment program (see "MATLAB" in the **"Supplementary Materials"** contents list) was written to align the returns from the free-running source (Fig. **F6**). Ten groups of aligned traces were stacked to reduce noise and are shown in Figure **F7.** Six interfaces were found to be common to the ten reflection stacks, and their attributes and interpretation are given in Table **T1.**

Taken together, the 32-, 36-, and 39-ms reflections suggest basement relief of up to 7 m in the vicinity of Site 1224.

DISCUSSION

The drill pipe provides a fixed alignment which served as the acoustic equivalent of an optical bench. This mechanical alignment allowed looking in detail at the changes in the seafloor and subseafloor reflections as a function of source distance above the seafloor. Unlike conventional 3.5-kHz profiling, these data are not changing because of horizontal movement of the source but solely because of the height of the source. Because the difference in spreading losses of the different reflections with elevation above the seafloor are miniscule, the amplitudes and duration of the reflections can be directly compared.

The aperture of the Fresnel zone varies with source depth. Table **T2** shows the change in Fresnel area of the 4-kHz source with depth. At 5 m above the seafloor, the reflecting area is ~4 m in diameter, compared to 120 m when sounded from the sea surface. For a given transducer beam width, the area insonified at approximately normal incidence changes as the square of the transducer elevation.

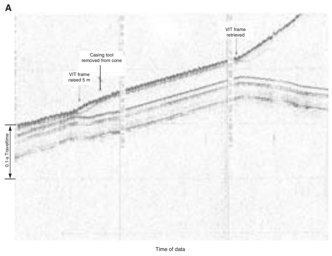
Roughness of the seafloor and subseafloor reflections exaggerates this effect, as there are in-phase interfaces normal to the wavefront beyond the Fresnel zone. These combine to lengthen the reflection wavelet.

Figure **F7** shows significant differences in the amplitudes of the subseafloor reflections at five heights examined. Note that the amplitudes, durations, and travel times of the peak amplitude of the reflections differ between the traces (Table **T3**). Each trace is normalized to the amplitude of the seafloor reflection. The amplitude of the portion of the trace before (above) the seafloor reflection indicates the noise background. Data were taken on different days during which the background noise of the receiver on the ship varied. The wash of the ship's forward port thrusters across the 3.5-kHz transducer pod occluded recording when it was thrusting to port. The heavy weather during initial lowering of the vibration-isolated television (VIT) frame to view the proposed spud-in location prevented gathering horizontally changing data. The number of "clean" traces available for stacking differed in each data set. The arrival 4 ms after the seafloor reflection on the fourth trace is from the reentry cone. The drillers measurement indicated that it settled 1.7 m between deployment and setting the casing 9 days later. The acoustic data indicate it settled about 2.8 m.

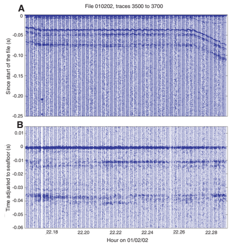
Two attributes of the subseafloor reflecting interfaces that affect their reflections are as follows:

1. Areal extent of the reflecting interface relative to the overall area insonified at normal incidence. As the source is raised, the return

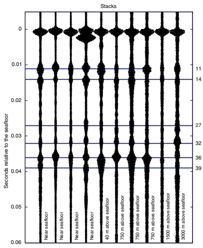
F5. Deep-source records and digital plot, p. 11.



F6. Direct water wave and waveform data, p. 13.



F7. Profile stacks, p. 14.



T1. Reflection sequence interpretation, p. 15.

T2. Insonified seafloor area, p. 16.

T3. Relative amplitude changes, p. 17.

from a small planar reflector becomes progressively a smaller percentage of the area returning sound to the receiver. This allows making an estimate of the areal extent of an interface relative to other reflecting interfaces.

2. Shape of the reflecting interface. Concavities in the basement surface tend to focus and defocus as the source is raised. See the 32-ms basement reflection in Table T3. The return from convex interfaces decreases more rapidly that from a planar one.

Applying these criteria, the six reflecting interfaces are characterized in Table T1.

The 0.25-s digitizing window triggered on the direct arrival did not allow a continuous recording of the reflection sequence as the source was lowered and raised. Only those intervals during which the direct water wave (which triggered the acquisition cycle) and seafloor reflections were within the quarter-second were recorded. For the 1-s repetition of the source, this is each 750 m above the seafloor. If there is opportunity to do this experiment again, we would refine the data digitizing scheme to digitize the seafloor reflection continuously. Varying the source repetition rate would be one means for getting additional recording windows capturing both the direct vertical and seabed reflections. This would allow a more detailed examination of the geometric character of the seafloor and deeper reflecting interfaces as a function of source elevation. Because the VIT frame slides on the drill string, there was no azimuthal control. Mounting the source on a remotely operated vehicle or autonomous underwater vehicle would allow freedom of both vertical and horizontal movement.

CONCLUSIONS

Two subseafloor reflecting interfaces in the sediments were identified and drilled. There were four reflection sequences from the basalt basement. Based on the changes in acoustic impedance indicated by the reflections, the following stratigraphic sequence is suggested:

1. The 11-ms interval between the seafloor and the first subsurface reflection corresponds to unconsolidated yellow to brown clay of which 9 m was recovered. The sound velocity of this material is near that of water.
2. The 25-ms interval between the first and second subseafloor reflectors corresponds to a somewhat more consolidated sedimentary sequence ~19 m thick. Little core was retrieved from this interval.
3. Basaltic basement is an irregular surface at a depth of ~28 meters below seafloor. Taken together, the 32-, 36-, and 39-ms reflections suggest basement relief of up to 7 m within 40 m of Site 1224.

ACKNOWLEDGMENTS

This research used samples and/or data provided by the Ocean Drilling Program (ODP). ODP is sponsored by the U. S. National Science Foundation (NSF) and participating countries under management of Joint Oceanographic Institutions (JOI), Inc. This work was supported by

U.S. Science Support Program (user reference: 418920-BA372; task order F001602).

William Mills of ODP/Texas A&M University provided the LabView shipboard digitizing routine. The aligned and stacked traces and data processing scripts are appended, and the pinger is available for future drilling project work.

Thanks are extended to Roger Flood and an anonymous reviewer for helpful suggestions to this manuscript.

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Smith, W.O., 1958. Recent underwater surveys using low-frequency sound to locate shallow bedrock. *Geol. Soc. Am. Bull.,* 69(1):69–98.

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Figure F1. Site 1224 is near the Hawaii 2 Observatory (H2O) midway between Hawaii and California (from Stephen, Kasahara, Acton, et al., 2003).

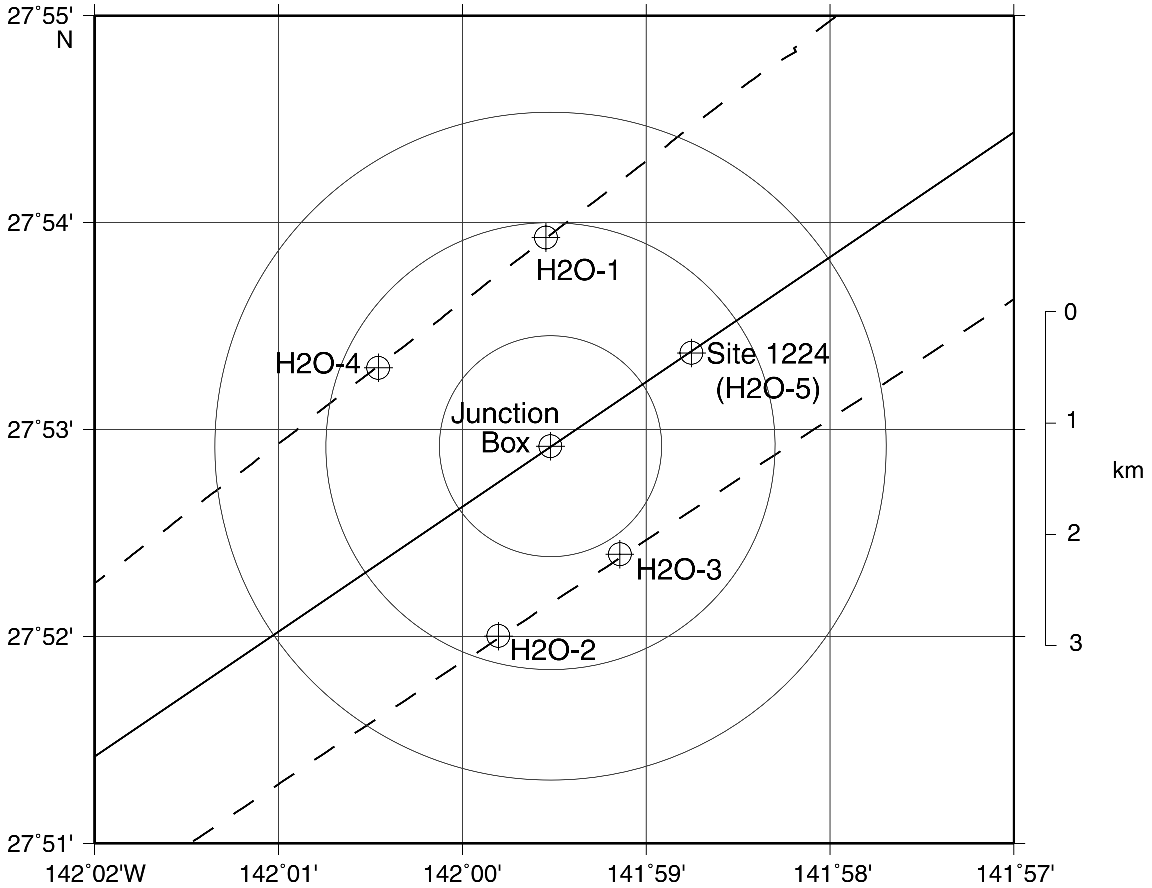

Figure F2. 3.5-kHz ship echo sounder recording from southwest to northeast across the Hawaii 2 Observatory (H2O) junction box and Site 1224 (from Stephen, Kasahara, Acton, et al., 2003). PDR = precision depth recorder.

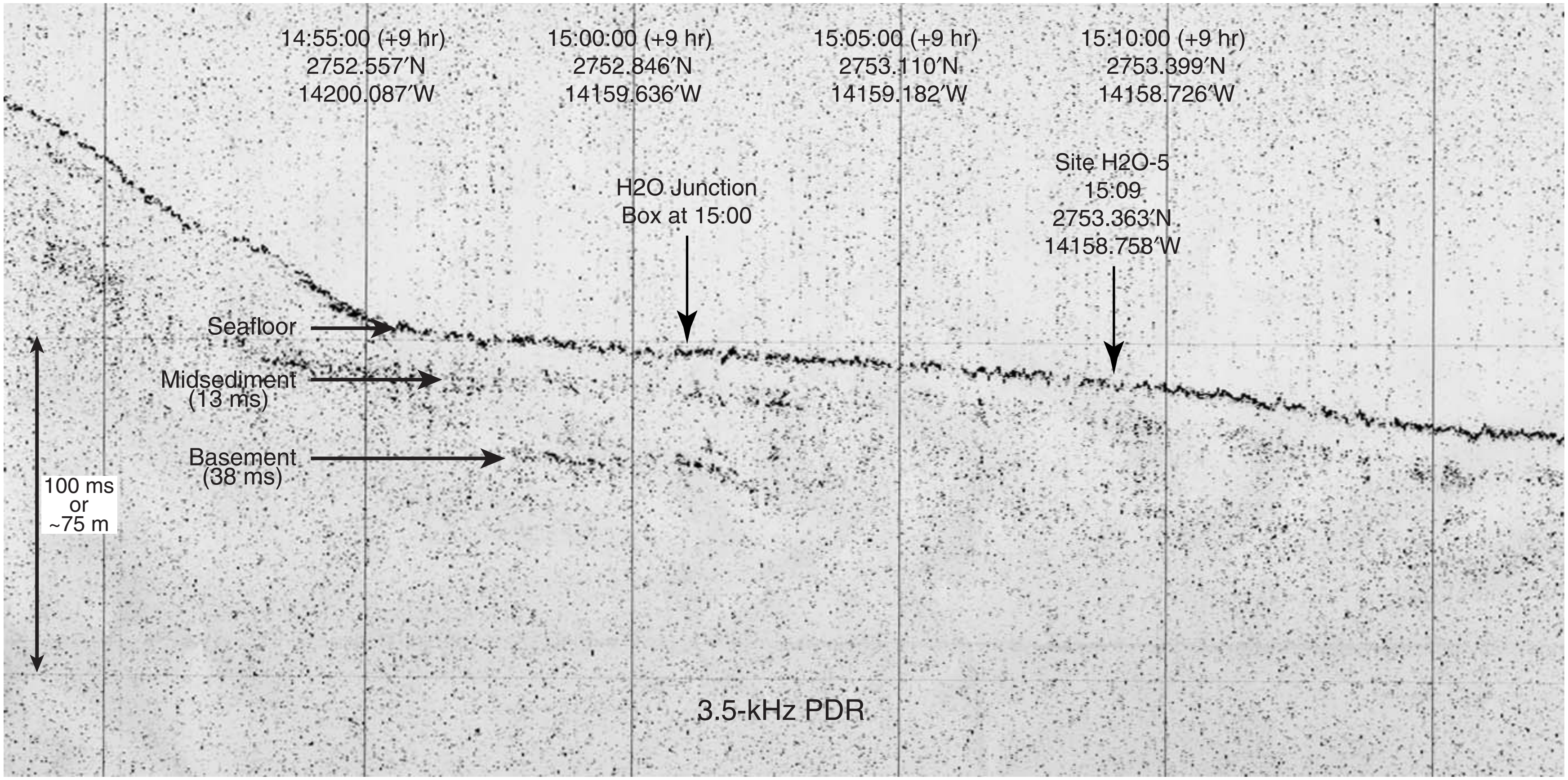

Figure F3. Schematic of the 4-kHz experiment. The 4-kHz source was on the vibration-isolated television (VIT) frame. The ship's hull-mounted 3.5-kHz transducer was used to receive the signals (adapted from Stephen, Kasahara, Acton, et al., 2003).

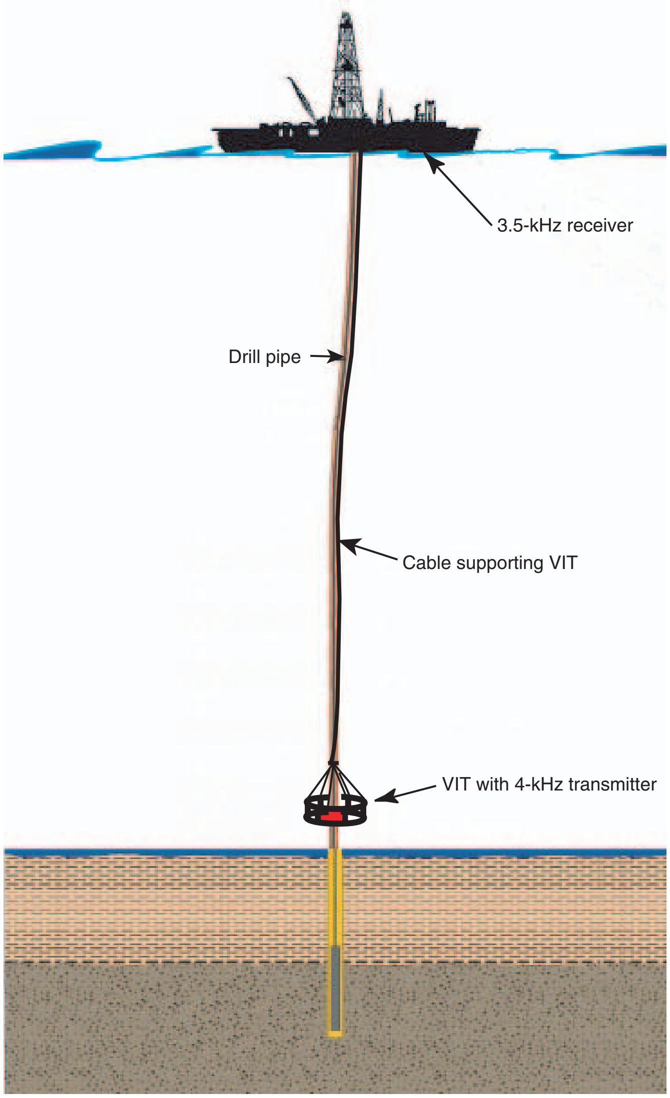

Figure F4. On the VIT frame, the 4.252-kHz transducer is the squat cylinder in the middle under the frame's lower horizontal member. The batteries and electronics are in the yellow cylinder to the upper left marked "Pinger."

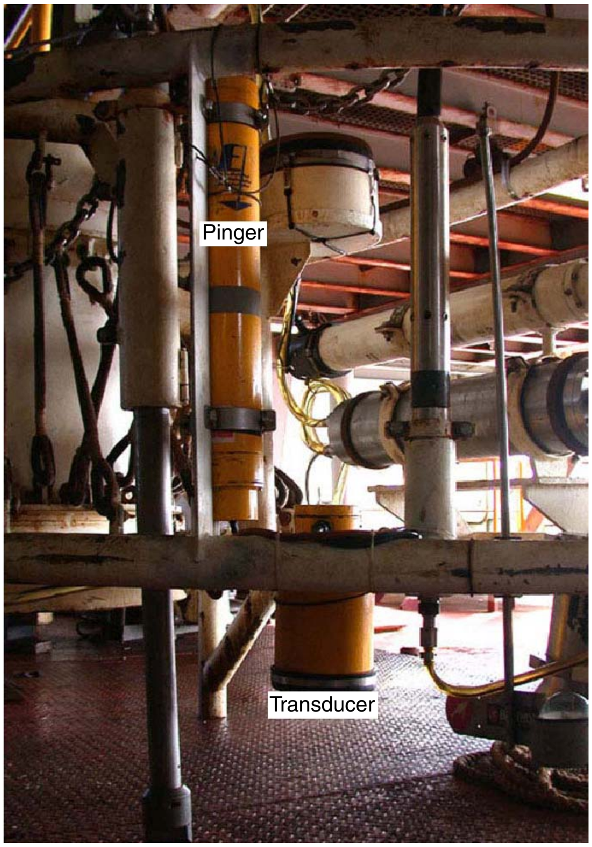

Figure F5. A. Installation of the reentry cone and steel casing in Hole 1224D as observed on deep-source records. This figure is excerpted from the EPC graphic recording on 2 January 2002. The traveltime interval shown is ~410 ms; the light horizontal traces are spaced at 100 ms. The heavier vertical traces are 5-min marks. The fluctuation of up to 4 ms in the traveltime of the direct water wave is primarily due to the heave of the ship pulling and slackening the vibration isolated television (VIT) frame cable. The 1- to 2-ms fluctuations in the traveltime for the reentry cone is a measure of the VIT heave plus the uncompensated heave of the drill string because the cone is rigidly linked to the ship's heave compensator by the drill string. (Continued on next page.)

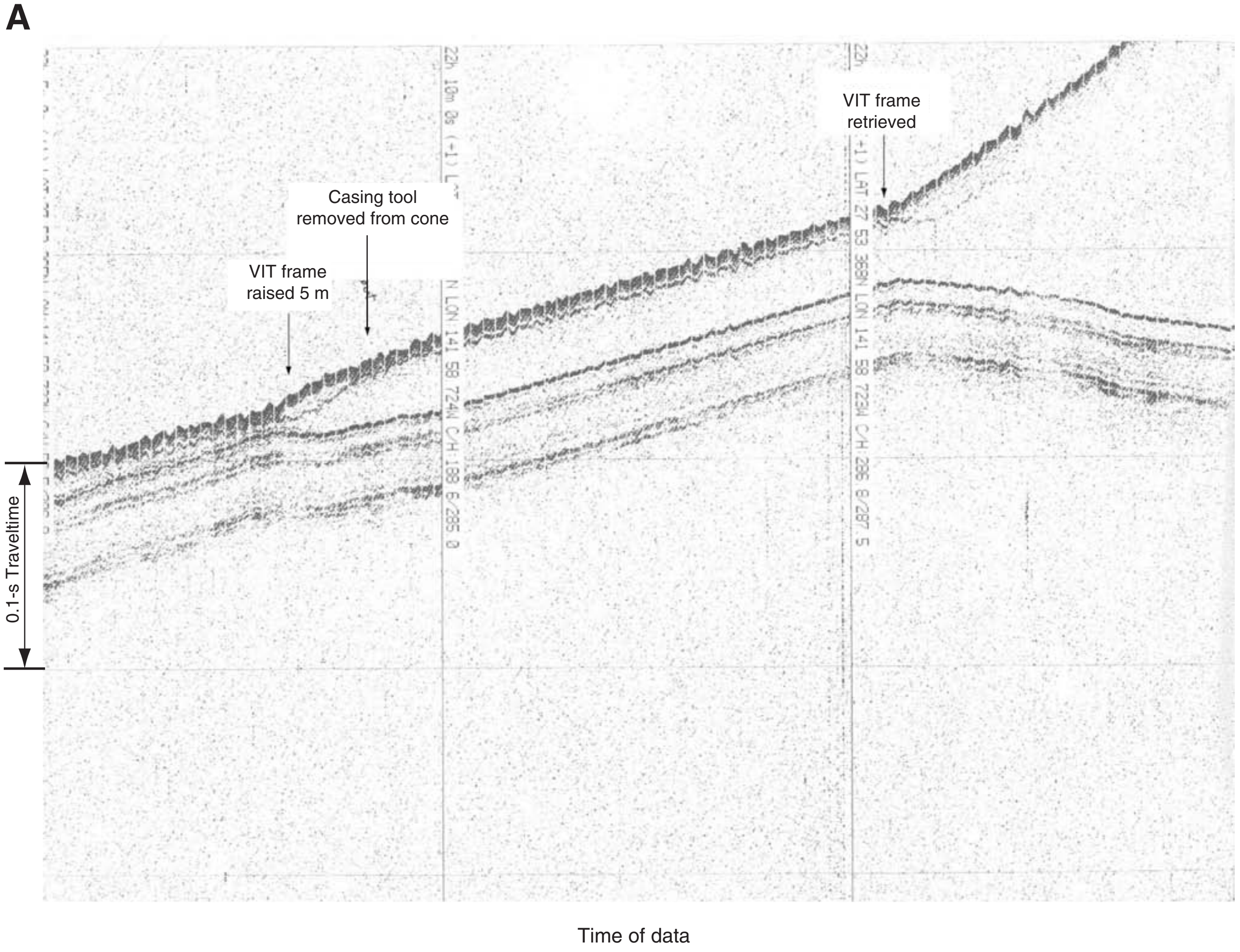

Figure F5 (continued). B. Digital plot, windowed on the direct water wave arrival, showing the same data as the analog PDR recording in A.

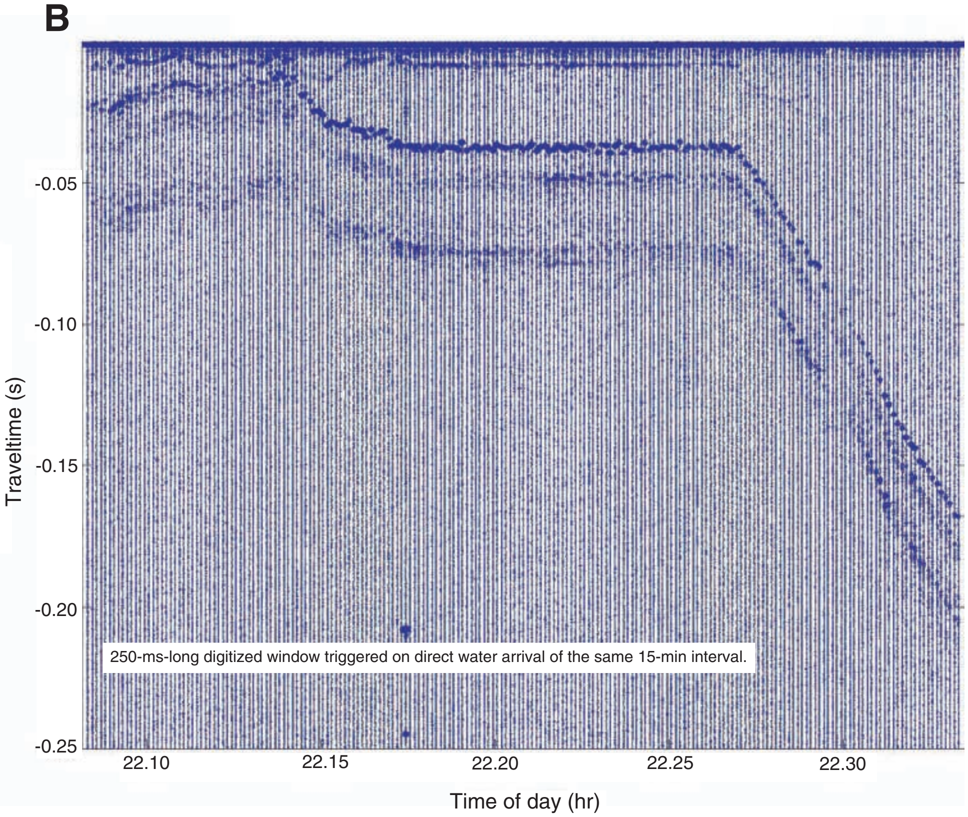

Figure F6. **A.** 0.25-s data window with time 0 starting at the direct water wave arrival. The data at ~0.035 s is the seafloor arrival. Note the roughness due to ship's heave. **B.** Data lined up at the first motion of the waveform representing the seafloor. Only 0.060 s of data are shown below the seafloor. Note how the subbottom reflectors line up coherently.

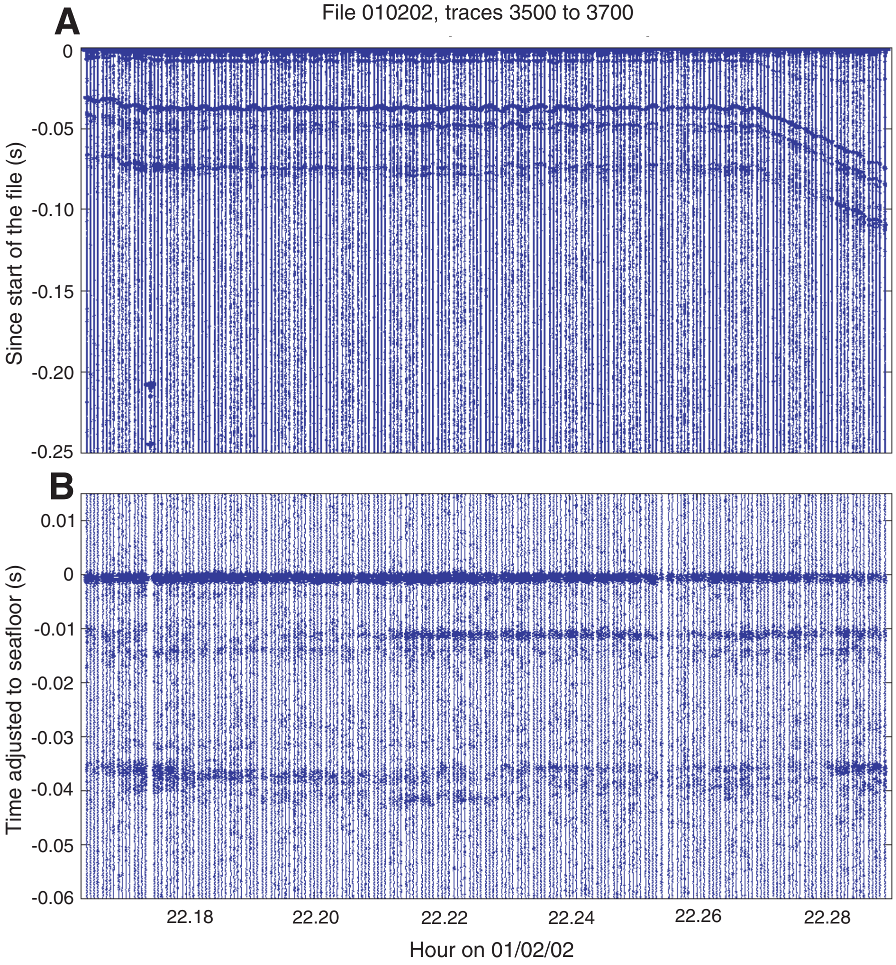

Figure F7. Stacks from 10 different windows at Site 1224. Good agreement of the data was obtained for each height of the source off of the seafloor. The different horizontal lines are summarized in Table **T1.** Nine of the traces are in Hole 1224D, and the tenth is in Hole 1224F, 14 m to the southwest.

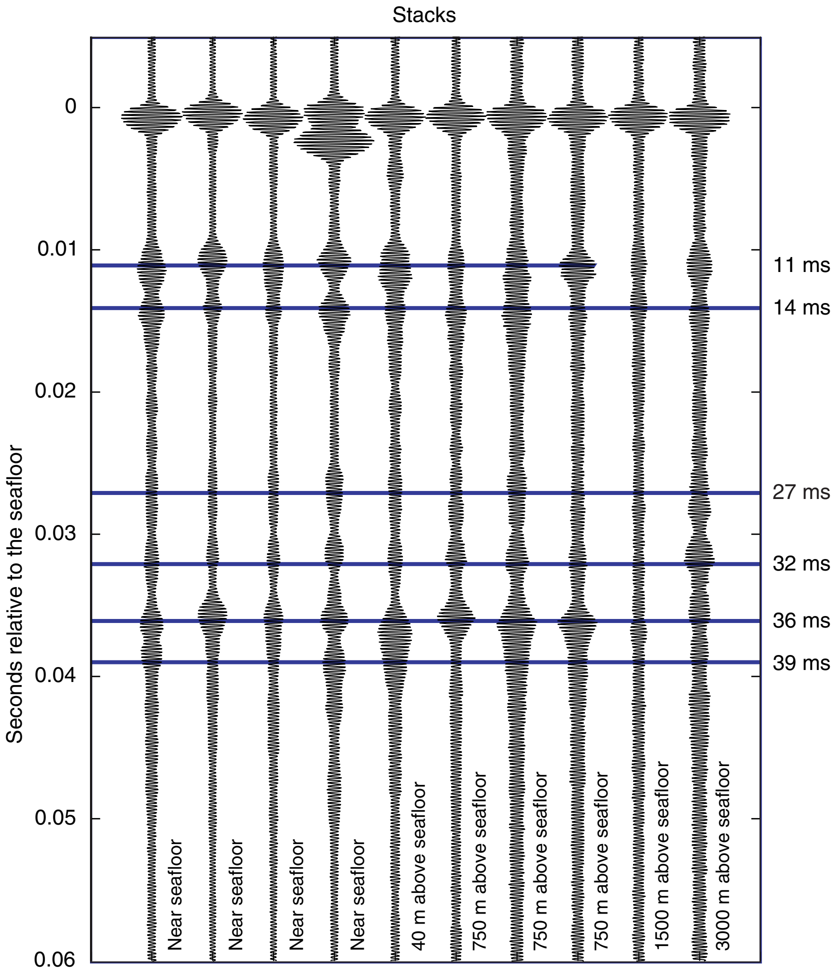

Table T1. Reflection sequence interpretation.

Reflector traveltime (ms)	Approximate depth (m)	Comments
11	9.4	Consistent between lowerings and differing source elevations; appears to be an extensive interface.
14	11.9	Varies between lowering and with different source elevations; probably a less extensive planar interface.
27	24.5	Weak return which varies between lowerings and source elevations; perhaps a prominence in basement.
32	29.5	Strength varies with elevation; perhaps indicating a concave surface which focuses and defocuses.
36	33.5	Strong basement reflector; change of echo envelope between lowerings suggests irregular topography.
39	36.4	Large change between lowerings and with source elevation; perhaps represents a small hollow in basement surface.

Table T2. Seafloor area insonified as a function of source elevation.

Distance above seafloor (m)	Aperture (°)	Diameter insonified (m)	Area as seen from sea surface (%)
3	26.8	3	0.1
5	21.1	3.9	0.1
10	15.1	5.4	0.2
15	12.4	6.6	0.3
20	10.8	7.6	0.4
50	6.9	12	1
100	4.9	17	2
750	1.8	46.5	15
1500	1.3	65.7	30
2250	1	80.5	45
3000	0.9	93	60
3750	0.8	103.9	75
4500	0.7	113.8	89.9
5000	0.7	120	100

Table T3. Relative amplitude changes of subseafloor reflections with varying 4-kHz source elevations (traces normalized on seafloor arrival).

	Source elevation (ms)							
	Seafloor	11	14	27	32	36	39	Background
Near	20	10	9	4.5	6	8.5	7	3
Near	20	11	6.5	3	4	10.5	5	2
Near	20	8	6	3.5	4	7	5	2
Near	20	11	11	6	6	10	7	2.5
40 m	20	11	7	5.5	5	12	10	3
750 m	20	6	7	4.5	7.5	13	4	3
750 m	20	10	10	7	8	13	9	4
750 m	20	12	6	4	6.5	13	7.5	4
1500 m	20	6	6	4	4.5	5.5	4.5	3.5
3000 m	20	9	7.5	7	10.5	8	6	4
Average reflection amplitude:	Near	10.2	7.9	4.5	5	9.6	6.8	2.5
	750 m	9.3	7.7	5.2	7.3	13	6.8	3.7