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1. Drill String Vibration: A Proxy for Identifying Lithologic Boundaries while Drilling[1]

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ABSTRACT

During Ocean Drilling Program (ODP) Leg 179, we recorded drill string vibration data to investigate the subseafloor environment as part of two seismic-while-drilling experiments in May 1998. Holes 1105A and 1107A were drilled in 714 and 1660 m water depth, respectively, in the Indian Ocean, where these experiments were conducted. To our knowledge, such measurements have never before been recorded by ODP or on other deepwater drilling rigs.

By comparison of vertical and horizontal drill string acceleration with wireline logs and core data, variations in the formation properties are correlated to drilling parameters. Drill string acceleration signals vary inversely with porosity measured from logs and core data. The signal amplitude in sediments is roughly half that in either basalt or gabbro. These signals illustrate characteristics of the advancing drill bit—significant energy radiates through the seafloor and differently through various formations; thus, it may provide a useful tool to evaluate drilling conditions and formation properties encountered at the bit. Determining these properties while drilling, therefore, could assist both drillers and geologists in identifying lithologic contacts and sediment/rock interfaces, even in cases where core and log data are not available.

INTRODUCTION

In the course of everyday operations aboard the *JOIDES Resolution,* the drill string vibrates continuously. These vibrations are characteristic

[1]Myers, G., Goldberg, D., and Rector, J., 2002. Drill string vibration: a proxy for identifying lithologic boundaries while drilling. *In* Casey, J.F., and Miller, D.J. (Eds.), *Proc. ODP, Sci. Results,* 179, 1–17 [Online]. Available from World Wide Web: <http://www-odp.tamu.edu/publications/179_SR/VOLUME/CHAPTERS/SR179_01.PDF>. [Cited YYYY-MM-DD]
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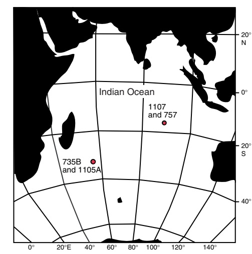
and can be acquired at the rig floor or at the drill bit, although the latter provides a more accurate signature of the environment being drilled. Our goal is to evaluate whether these reverberations generated from the formation and environment encountered at the bit, by ship heave motions, and from other extraneous noise sources that can be used to improve operations and provide some understanding of the rock properties while drilling.

Drill string acceleration data were acquired at two sites reoccupied during Ocean Drilling Program (ODP) Leg 179 (Pettigrew, Casey, Miller, et al., 1999). Figure **F1** shows the location of our drill sites. Our primary location, Site 1105, is situated in the southwestern Indian Ocean on the eastern flank of the Atlantis II Fracture Zone. The rocks encountered at this site are characterized as anisotropic metagabbro containing alternating layers of olivine and Fe-Ti oxide (Pettigrew, Casey, Miller, et al., 1999). Numerous intervals of increased porosity associated with fractures are observed in the log data acquired at Site 1105 during Leg 179. The increased porosity zones are associated with intense regional uplift and deformation along the fracture zone (Robinson, Von Herzen, et al., 1989). Core recovery at this site was exceptional, on average >87%, and the structure of these igneous and metamorphic rocks may be readily observed. These features were oriented using borehole image logs (Goldberg et al., 1991). The foliation and fracturing that crosscut these cores dip steeply and strike north-northwest.

F1. Site locations for two seismic-while-drilling experiments, p. 9.



Site 1107 is located on the Ninetyeast Ridge in the eastern Indian Ocean, near ODP Site 757 drilled in 1988. At this location, coring demonstrated, subaerially emplaced basaltic lava flows are overlain by >350 m of unconsolidated silt, clay, volcanic breccia, and tuff (Peirce, Weissel, et al., 1989). In this paper, we describe the drill string acceleration recorded during Leg 179 and investigate its correlation with the available log and core data at these sites.

Seven key data sets are used in the analysis presented in this paper:

1. Stacked spectra of drill string acceleration data (The sampling interval of the accelerometers is 0.1 m.);
2. Autocorrelations of drill string acceleration to check for the presence of drill string multiples;
3. The root-mean-square (RMS) value of the acceleration vs. depth at Holes 1105A and 1107A (Depth smoothing of 1.5 m was applied.);
4. Drilling depth (Depth resolution of the driller's log is roughly 0.5 m.);
5. Logs acquired at Site 1105 (Vertical log resolution is ~0.15 m.);
6. Core data from Site 757; and
7. Analog drilling parameter data.

METHODS AND OPERATIONS

In typical seismic-while-drilling (SWD) experiments, the force of a roller-cone drill bit impacting the formation generates energy, which radiates axially and is received by sensors located on the seafloor (Rector and Marion, 1991). The energy generated at the bit is translated into the drill string in the form of vibrations with horizontal and vertical components. During Leg 179, two geophones were placed on the seafloor adjacent to the borehole to record the energy transmitted into the formation. The drill string vibrations are recorded uphole with a rig floor mounted accelerometer. The vertical component of these vibrations is most commonly associated with the rock properties, whereas the horizontal component is associated with the drilling parameters and hole conditions. For this study, we do not attempt to integrate the uphole drill string vibration data with the geophone data recorded at the seafloor; we focus on the data recorded by the uphole three-axis accelerometer, the pilot sensor.

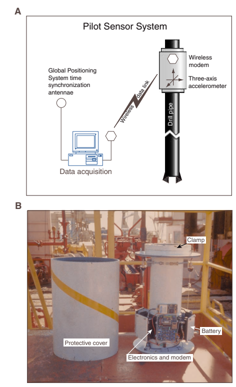
The pilot sensor is used to record the axial vibrations that travel up the drill string, representing the drill bit source signal. This type of experiment can be described as a "reverse" vertical seismic profile, where the source is usually at the surface and the receivers are placed at various levels in a borehole (Meehan et al., 1998). To measure uphole data, a pilot sensor system was designed and manufactured at the Lamont-Doherty Earth Observatory specifically for the experiments conducted during Leg 179 (Goldberg et al., 1998; Myers et al., 1999). The system includes an acceleration measurement module attached to the drill string below the top drive using alloy wedge clamps (Fig. F2) and a PC-based data acquisition system (DAS) located in a laboratory adjacent to the rig floor. The pilot sensor system records drill string vibrations at the rig floor using a three-axis accelerometer with a measurement range of up to ±10 g. A ±5-g unit was utilized at both sites during Leg 179. Accelerometer signals in the 0.5- to 50-Hz frequency range were digitized in the measurement module with 16-bit resolution at a rate of 400 samples/s. Data blocks were transmitted 1/s through a wireless telemetry link to the DAS where they were time-stamped with Global Positioning System time to ensure correlation with other data. A LabVIEW data acquisition program stored recorded data on a hard drive, provided real-time monitoring of signal quality and spectral content, and allowed the operator to control gains and sampling rate during acquisition. The pilot sensor battery is sufficient for continuous 72-hr operation. The wireless data link greatly simplified system deployment and provided reliable data transmission at a 57-kB baud rate, despite high level electromagnetic interference on the rig floor.

The water depths at Holes 1105A and 1107A are 714 and 1659 m, respectively. Both are considerably greater than conventional SWD experiments used in industry applications. A four roller-cone bit was used to drill gabbro at Site 1105, and a three roller-cone bit was used in sediments and basalt at Site 1107. Drilling parameters including drill pipe rpm, pump strokes, weight on bit, and bit depth were recorded in analog format. Drill pipe rotation and pump rates varied during both of these experiments between 44 to 56 rpm and 70 to 110 strokes per minute, respectively. The average weight on bit increased from 10,000 to 20,000 lb during drilling. As for all ODP drilling operations, dynamic positioning thrusters are utilized to position the ship over a site. Sea states during this experiment were 3 to 5 m; therefore, thruster activity for positioning the ship was moderate to high. The thruster activity did not appear to have an effect on drill string acceleration based on the lack of correlation between dynamic positioning load data and pilot sensor data.

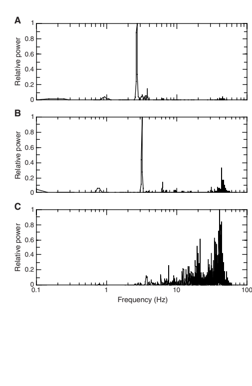
At Site 1105, the pilot sensor recorded data from 33 to 80 meters below seafloor (mbsf) and from 91 to 107 mbsf. The 11-m break in the deployment was the result of an operational requirement to remove the unit from the drill string during a hole reaming operation. At Site 1107, the pilot sensor recorded data continuously from 170 to 422 mbsf.

In Figure F3, three spectra are displayed illustrating the relative power of the components of acceleration at one depth in basalt at Site

F2. Schematic drawing of the pilot sensor system and photograph of key components of the pilot sensor, p. 10.



F3. Spectra of acceleration signals, p. 11.



1107 and in gabbro at Site 1105. In Figures F3A and F3B, the rate of rotation of the drill pipe is identified by the small peak in the spectra at 0.8 to 0.9 Hz, corresponding to 48 to 54 rpm. The large peaks between 2.7 and 3.2 Hz are associated with the rotation rate of each roller-cone as the bit turns one revolution. The four rollers used in the gabbro generate a slightly higher number of measured cycles compared to the three rollers used in the basalt. The vertical acceleration in the gabbro also contains significant energy at high frequencies, which is absent in basalt, and considerably more energy on the horizontal than on the vertical axis component. In Figures F3B and F3C, the ratio of signal amplitude between horizontal and vertical axes for the peak at 3.2 Hz is ~10:1 at this depth.

NOISE EFFECTS

A first-order data quality assessment was accomplished by determining the existence of drill string multiples in the autocorrelation of the recorded pilot sensor data. According to Rector and Marion (1991), the observation of drill string multiples in the correlation suggests a high data signal-to-noise ratio with respect to the response of the drill string vibrations to the formation. Drill string multiple arrivals travel up and down the drill string as they reflect off the air-water interface and then at the bit. After three reflections, the multiples are recorded at the top of the drill string by the pilot sensor. Figures F4 and F5 depict the pilot signal autocorrelation functions for Holes 1105A and 1107A, respectively (J. Rector and Z. Liu, unpubl. data, 1998). At Site 1105, associated drill string multiples are clearly seen at regular 300-ms intervals. Drill pipe multiples at Site 1107 are not as easily identified. This is primarily due to the softer sediments being drilled at this site.

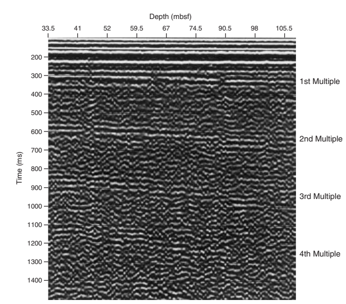
Other signals are also present in the recorded vibration data. Rig floor operations, as well as other ship vibrations, create noise. Spectral signatures are observed, for example, when rig floor equipment is used to connect sequential lengths of pipe, when the main motors rev to rack or pick up pipe joints, or when the elevators are clamped on a drill collar. Rig floor and ship operations punctuated the spectra. Of these, the most important sources of noise appear to be the ship's motors at 15–16 Hz and the lab fans at 41 Hz, both of which overlap with the formation signals generated during drilling (see Fig. F3). These noise sources increased as loads were added (e.g., motors picking up pipe), but their overall amplitude was measured to be 7–10 times lower than that generated during drilling and is likely of minor importance in the drill bit signal for this deep water setting.

Other noise may be generated from nonperiodic sources. The hydraulic pumps labor when the top drive is rotating; pipe connections are made or broken; thruster activity increases substantially in rough seas; the drill string bangs the rig floor equipment; and residual low-frequency heave may not be completely removed by signal conditioning. Such noise sources have not been isolated or removed in this analysis.

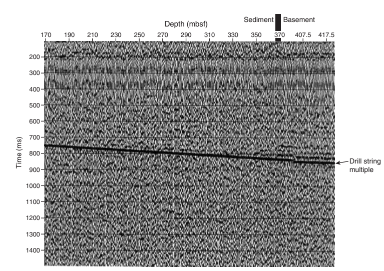
RESULTS

The variation in the vertical acceleration vs. depth in three separate frequency bands is shown in Figure F6. RMS amplitudes are computed

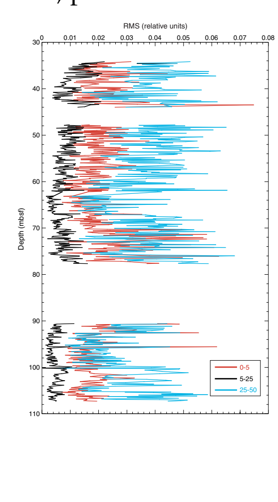
F4. Vertical acceleration autocorrelation function, Hole 1105A, p. 12.



F5. Vertical acceleration autocorrelation function, Hole 1107A, p. 13.



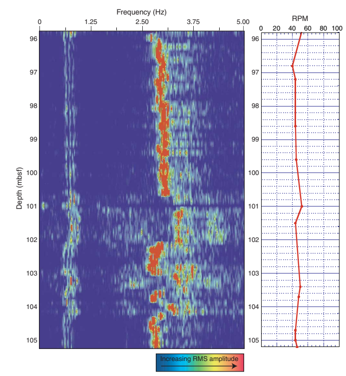
F6. Computed RMS amplitudes for the vertical-axis pilot sensor data, Site 1105, p. 14.



over 0- to 5-Hz, 5- to 25-Hz, and 25- to 50-Hz frequency bands. The RMS amplitude profiles have similar characteristics over all three bands, although greater variation is observed in the 0- to 5-Hz and 25- to 50-Hz frequency bands. The high-frequency band (25–50 Hz) consistently has the largest amplitudes, likely resulting from high noise associated with rig operations and the ship's motors. The low-frequency band (0–5 Hz) has intermediate to high amplitudes that are generated by the resultant thrust and torque of the roller-cone bit (Eustes et al., 1995). The intermediate-frequency band (5–25 Hz) has the lowest overall amplitudes and the least variation vs. depth. Although the entire spectral response depends on the rocks encountered at the bit, this intermediate-frequency band is often used to isolate the formation response in SWD experiments (e.g., Rector and Marion, 1991).

To illustrate the broadband effect of the formation properties on the vertical acceleration data, a spectral image is computed over a 10-m interval at Site 1105 (Fig. F7). The spectra are stacked over 5-min recording intervals, corresponding to ~0.10 m depth at the average drilling rate. A comparison to the computed depth to driller's depth indicates errors no greater than 0.5 m. The image shows a large decrease in amplitude (as indicated by the color scale) and frequency shift over the 0- to 5-Hz band near 100 mbsf. The low amplitudes are associated with fracturing and hole enlargement, which, of course, reduce the thrust and torque generated at the bit. The vertical acceleration, therefore, appears to encounter broadband effects that result from the formation and borehole properties. Drill pipe rpm has been included with the stacked spectra to compare the response of the acceleration signal to changes in the drill pipe rotation rate. Assuming that this kind of relationship will be robust when drilling in relatively consistent rock types, such as in these examples, we correlate these data to log and core data acquired at Site 1105 and then to core data alone at Site 1107.

F7. Stacked vertical-axis spectra showing the effect of high porosity on drill string acceleration, Site 1105, p. 15.



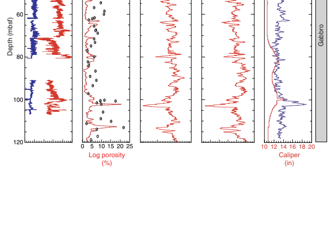
DISCUSSION

Site 1105

A comparison of the acceleration data with the log and core information at these sites illustrates that the drill string vibrations are related to the porosity and hole conditions encountered at the bit. Intuitively, fractured or softer rocks drill easily and transmit less energy back into the drill string; strong thrust and torque at the bit are needed to break competent rock, generating large signals transmitted up the drill string. The existence of drill string multiples in the Site 1105 data also suggests that the signal-to-noise ratio will be high (J. Rector and Z. Liu, unpubl. data, 1988). This increases our confidence that the observed variations in drill string acceleration result from lithologic features.

In Figure F8, RMS amplitude of the horizontal and vertical acceleration is compared to the caliper, gamma ray, and porosity logs at Site 1105. The amplitude curves were smoothed and resampled at a 0.125-m interval in order to compare these data with the logs. The horizontal components show between four- and sixfold higher amplitude than the vertical component over the entire depth interval. The horizontal and vertical data tend to be anticorrelative over 2- to 5-m intervals, with the horizontal component ranging considerably. This indicates that more noise is generated by the lateral action of the cutting surfaces at the bit than by the downward weight on the drill string in these rocks. The

F8. Vertical and horizontal axis acceleration, a drill string model, and log and core data, Site 1105, p. 16.



horizontal component is generally associated with drilling parameters and hole conditions, whereas the vertical component reflects the formation signal. When used together, both horizontal and vertical components may provide insight into the locations of lithologic boundaries; however, caution should always be exercised when interpreting the horizontal component alone.

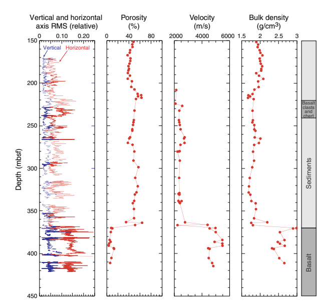
Over this depth interval, the acceleration amplitude correlates with the enlarged zones observed in the caliper log near 102 mbsf. An increase in porosity between 62 and 65 mbsf shows no caliper enlargement but corresponds with a decrease in natural gamma ray. This may indicate a compositional change in the gabbro, which causes an apparent increase in porosity as well as a reduction in the vertical acceleration. A simple drill string model was generated using the formation and drill pipe moduli, $K_f/(K_f+K_{dp})$, consisting of density and porosity acquired from Site 1105 log data and drill pipe density and velocity at the bit and compared to the observed vertical accelerations. Subtle variations are difficult to quantify, but in general, this trend is reflected by an inverse relationship between vertical acceleration and the porosity (see Fig. F8). The relationship between drill string acceleration and formation properties suggested by these observations may be useful at other sites.

Site 1107

Using a similar approach at Site 1107, spectral amplitudes of the drill string acceleration data are correlated to core data collected in silty sediments and volcanic basement. Interactions between the drill bit and formation in soft sediments do not generate significant energy, and drill string multiples are not readily identified (see Fig. F5). In the basement section where drill bit/rock interactions produce a significant amount of radiated energy, the autocorrelation function of vertical acceleration indicates the presence of a formation signal.

The amplitude of horizontal and vertical acceleration at Site 1107 and the core data from Site 757 are shown in Figure F9. We used porosity, density, and velocity from core recovered at nearby ODP Site 757 located on the Ninetyeast Ridge in approximately the same water depth and rock types (Peirce, Weissel, et al., 1989). Both holes were drilled through ~365 m of sediment and into basaltic basement rocks. The sharp porosity decrease at 365 mbsf at Site 757 is due to the sediment/basalt contact. An increase in the drill string acceleration data in both horizontal and vertical components corresponds to this contact at approximately the same depth at Site 1107. Another anomalous increase at 235 mbsf is less pronounced but may represent a hard ash layer containing cherts and basaltic clasts observed at Site 757 (Peirce, Weissel., et al., 1989) and Site 1107. Over the entire interval, the horizontal component is roughly three times higher than the vertical component and shows pronounced excursions that are in phase with the vertical component. Although the horizontal component is more closely associated with hole conditions and drilling parameters, both components may be used together with some confidence to identify lithologic boundaries. At Site 1107, like Site 1105, an inverse relationship between drill string acceleration and porosity is suggested.

F9. Vertical and horizontal axis RMS amplitude data, Site 1107, with core porosity from adjacent Site 757, p. 17.



CONCLUSIONS

The use of drill string acceleration for acquiring information about the formation and borehole environment has been demonstrated in two deepwater drilling environments. A qualitative correlation between drilling and log data was made in low-porosity gabbro and basalt rocks. Although this experiment depends strongly on drilling conditions, our results suggest that an inverse relationship is observed between the amplitude of the drill string acceleration and porosity and may be useful in identifying lithologic contacts and fracturing when limited or no core and log data are available.

The results can be improved by addressing the current limitations of the system. Improvements in depth control and digital recording of key drilling parameters will certainly aid in reducing uncertainties in the data. Future deployment of this system will potentially serve to assist both drillers and geologists in understanding the in situ conditions encountered at the bit.

ACKNOWLEDGMENTS

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Rector, J.W., III, and Marion, B.P., 1991. The use of drill-bit energy as a downhole seismic source. *Geophysics,* 56:628–634.

Robinson, P.T., Von Herzen, R., et al., 1989. *Proc. ODP, Init. Repts.,* 118: College Station, TX (Ocean Drilling Program).

Figure F1. Site locations for two seismic-while-drilling experiments conducted during ODP Leg 179.

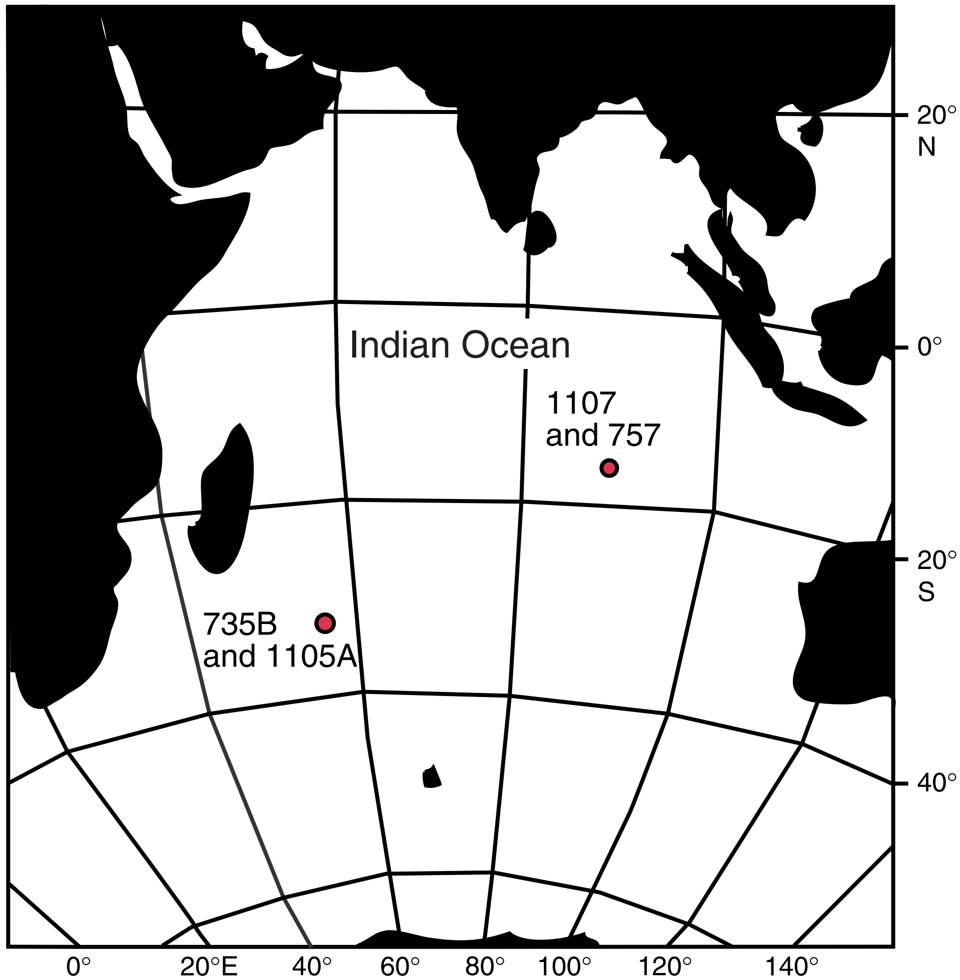

Figure F2. **A.** Schematic drawing of the pilot sensor system used in seismic-while-drilling experiments conducted during ODP Leg 179. **B.** Photograph of the pilot sensor with key components depicted.

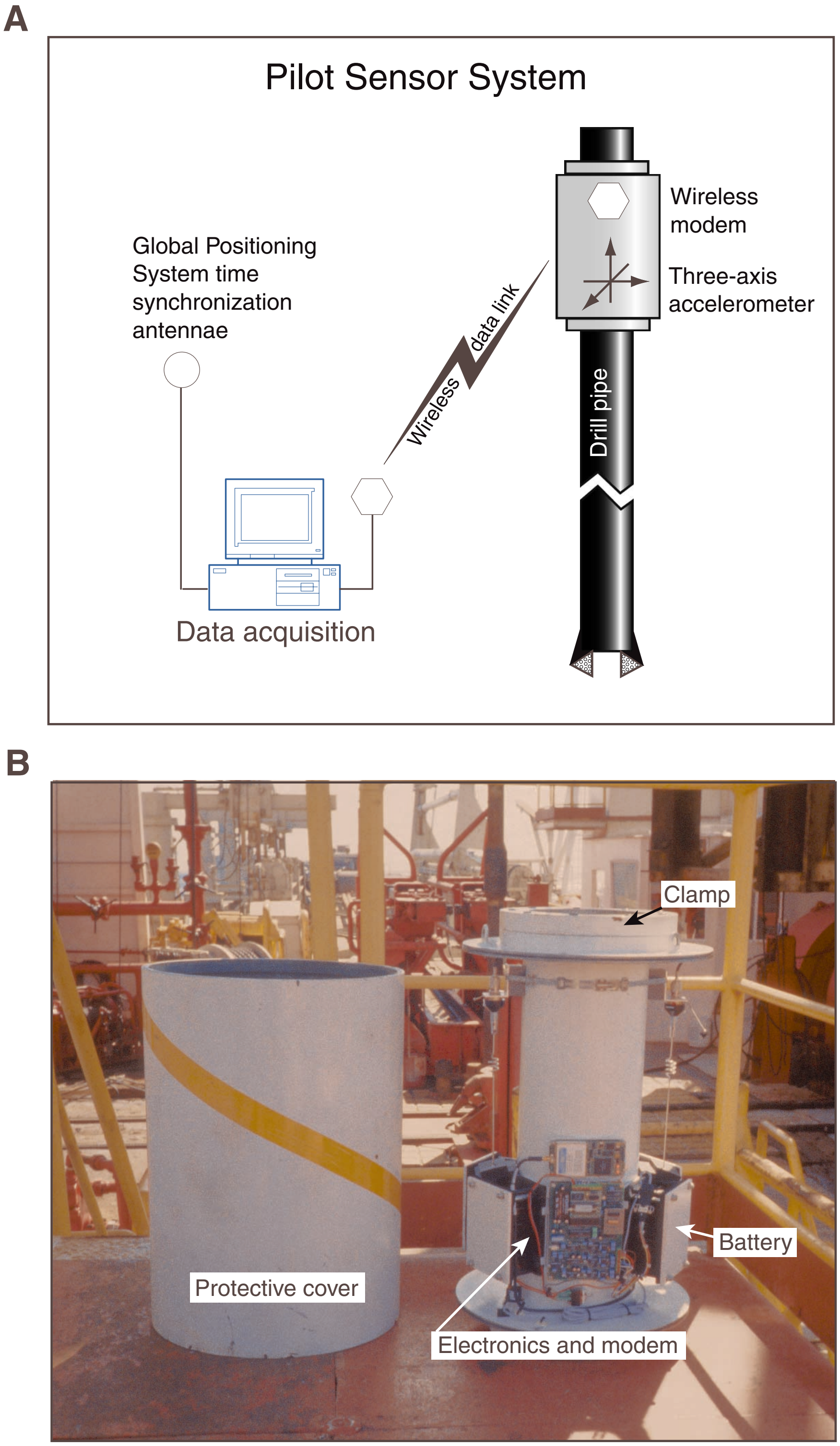

Figure F3. Spectra of acceleration signals recorded over a 20-s period. **A.** Vertical acceleration in Hole 1107A. Note the spectral peaks at 0.9 and 2.7 Hz are attributed to the pipe rpm and three roller-cone bit rotation rates. **B.** Vertical acceleration spectra in Hole 1105A. Spectral peaks at 0.8 and 3.2 Hz are attributed to drill pipe and four roller-cone bit rotation rates. The signal amplitude in A and B is roughly equal, although more high-frequency energy is present in B. **C.** Horizontal acceleration spectra in Hole 1105A. The ratio of signal amplitude between C and B at 3.2 Hz is 10:1.

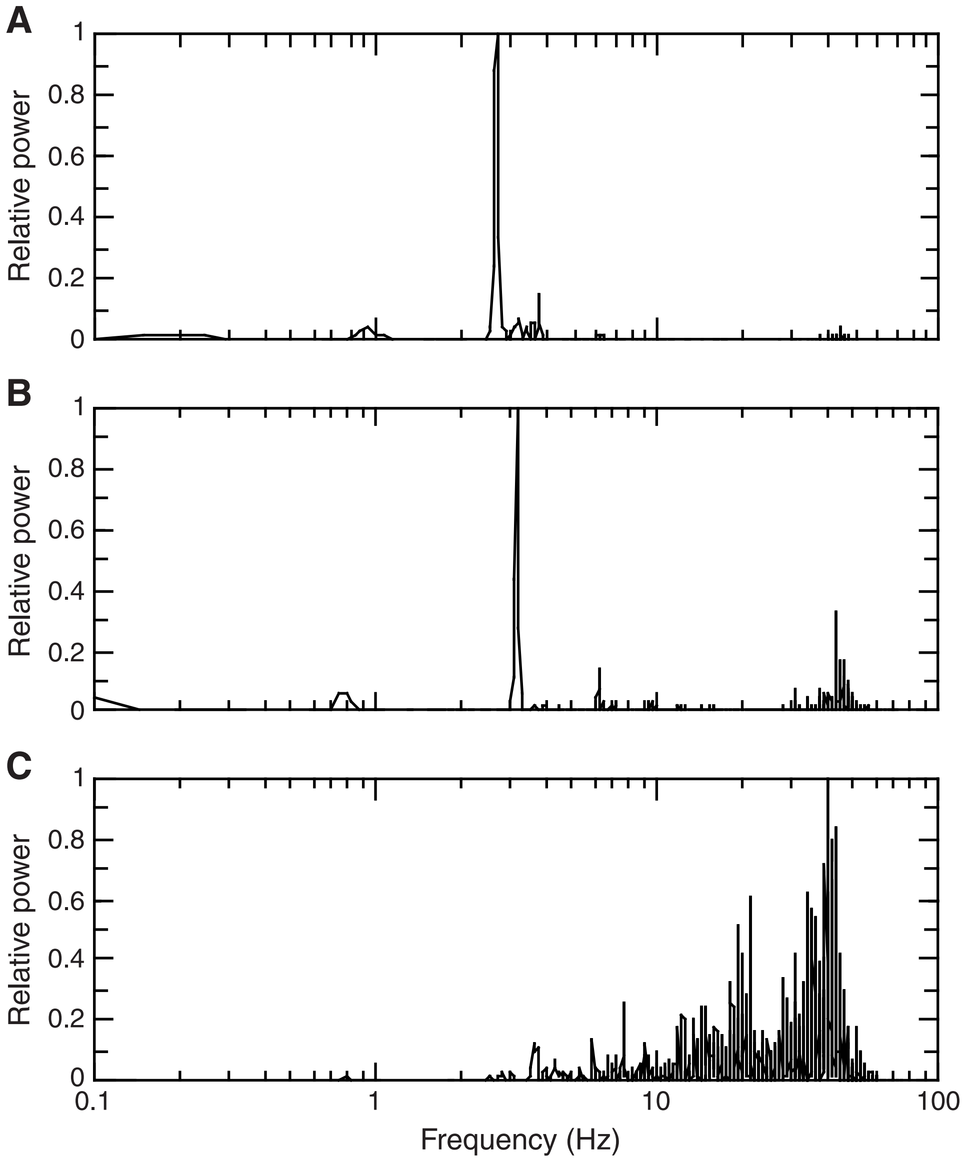

Figure F4. Vertical acceleration autocorrelation function for Hole 1105A depicting drill string multiples.

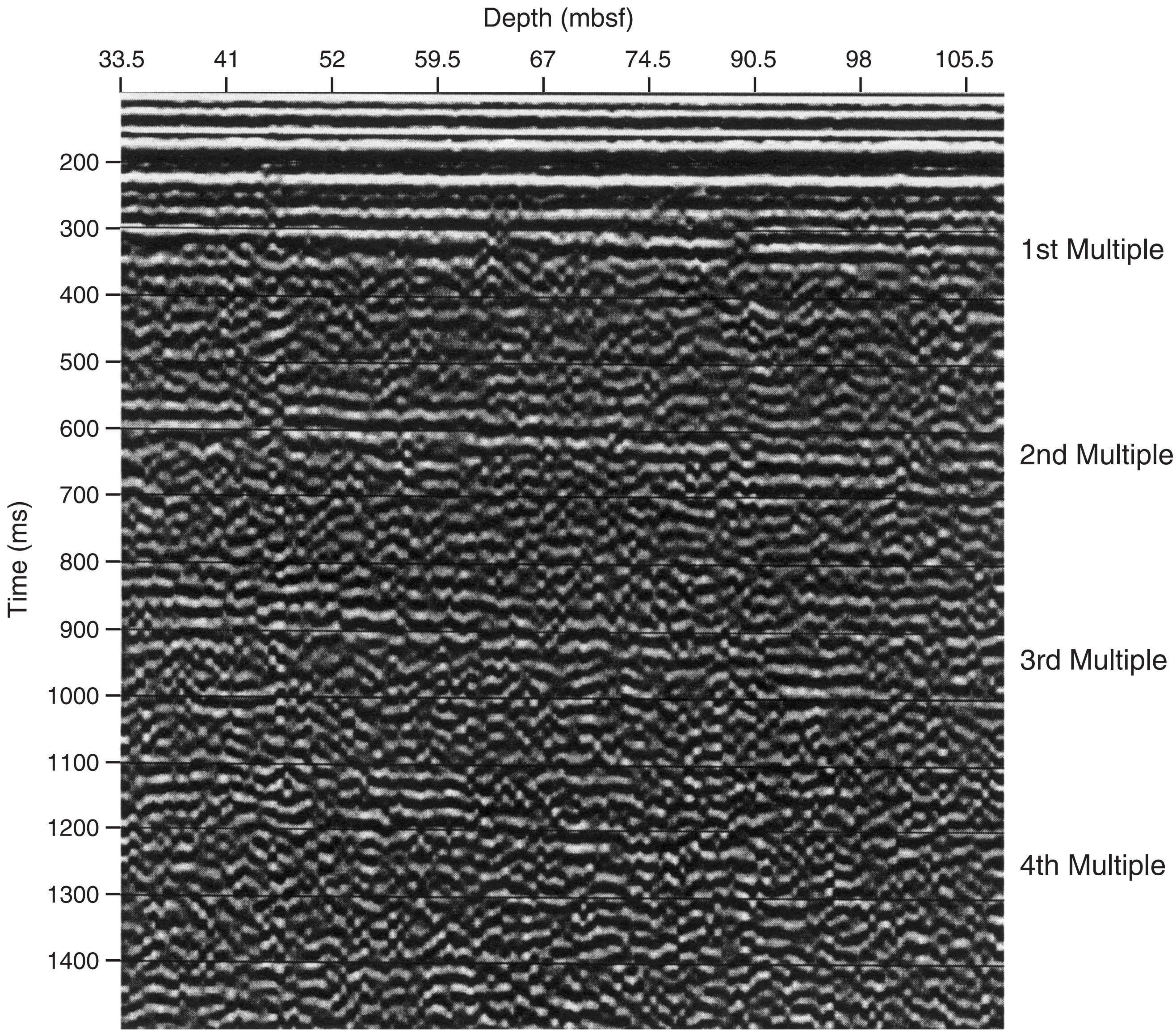

Figure F5. Vertical acceleration autocorrelation function for Hole 1107A calculated first occurrence of drill string multiples.

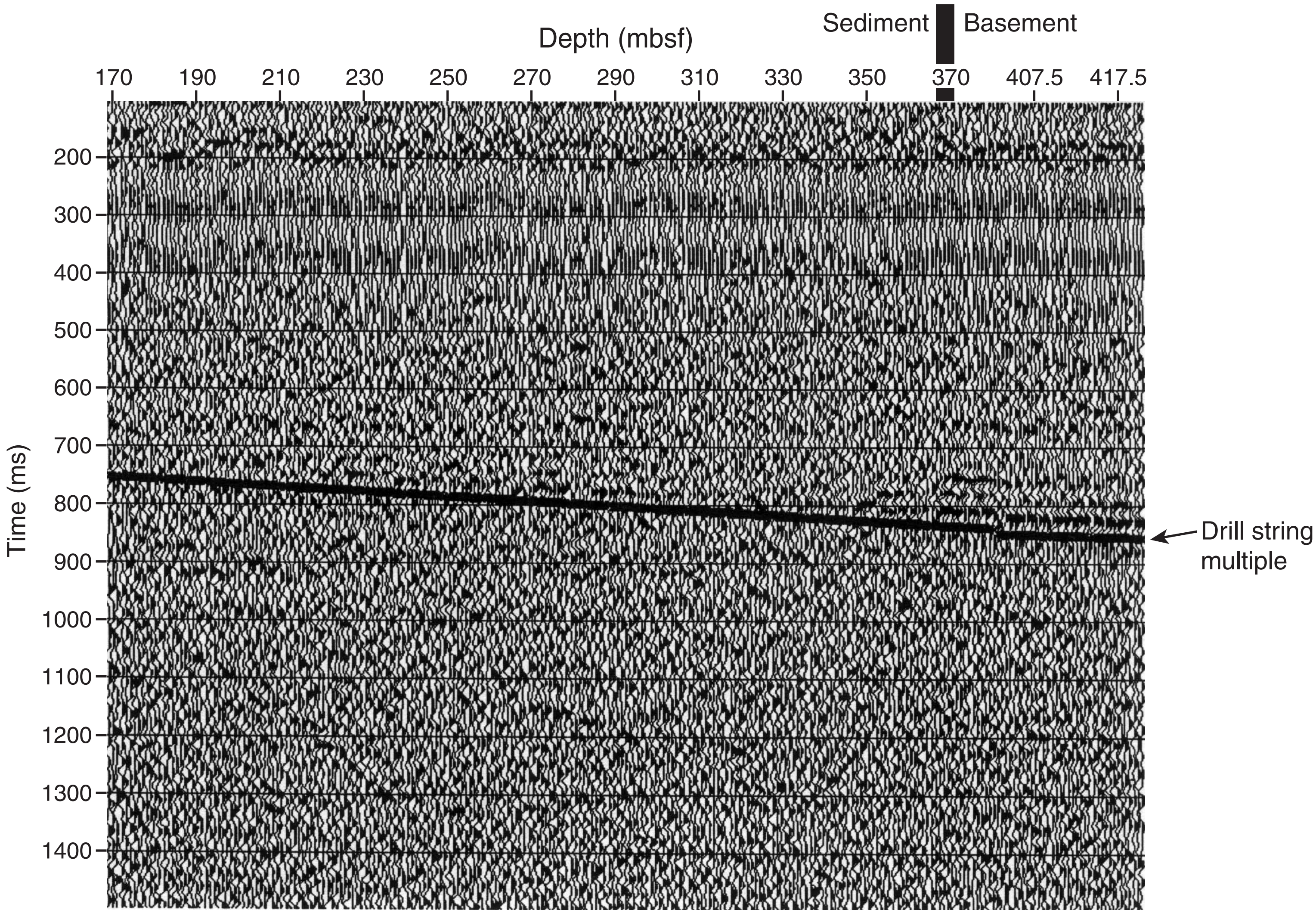

Figure F6. Computed root-mean-square (RMS) amplitudes over three frequencies (0–5, 5–25, and 25–50 Hz) for the vertical-axis pilot sensor data at Site 1105.

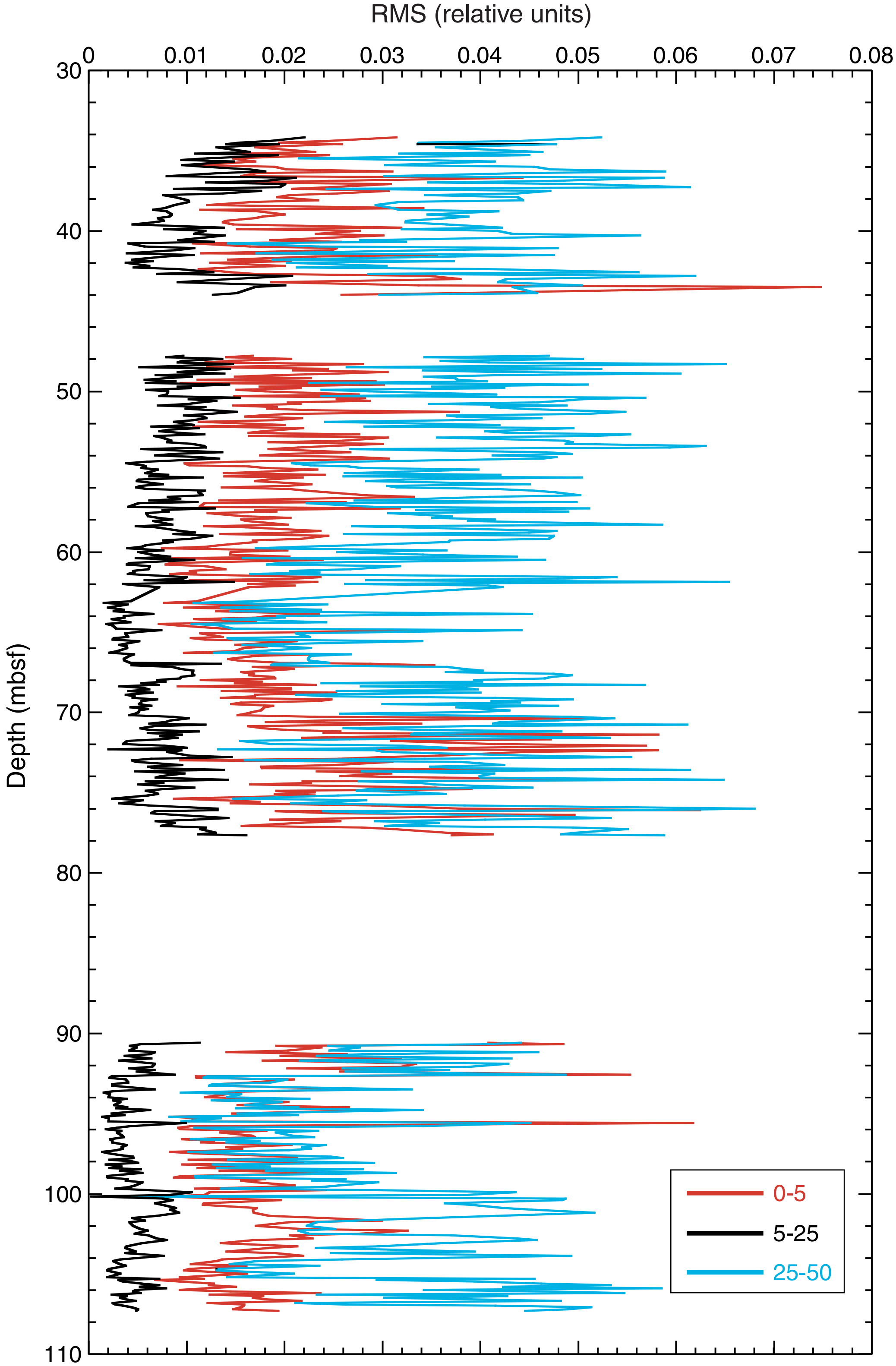

Figure F7. Stacked vertical-axis spectra between 0 and 5 Hz showing the effect of high porosity on drill string acceleration at Site 1105. Color scale indicates root-mean-square (RMS) amplitude in relative units. Drill pipe rpm values are also plotted to compare the vertical acceleration signal to changes in drill pipe rotation rates.

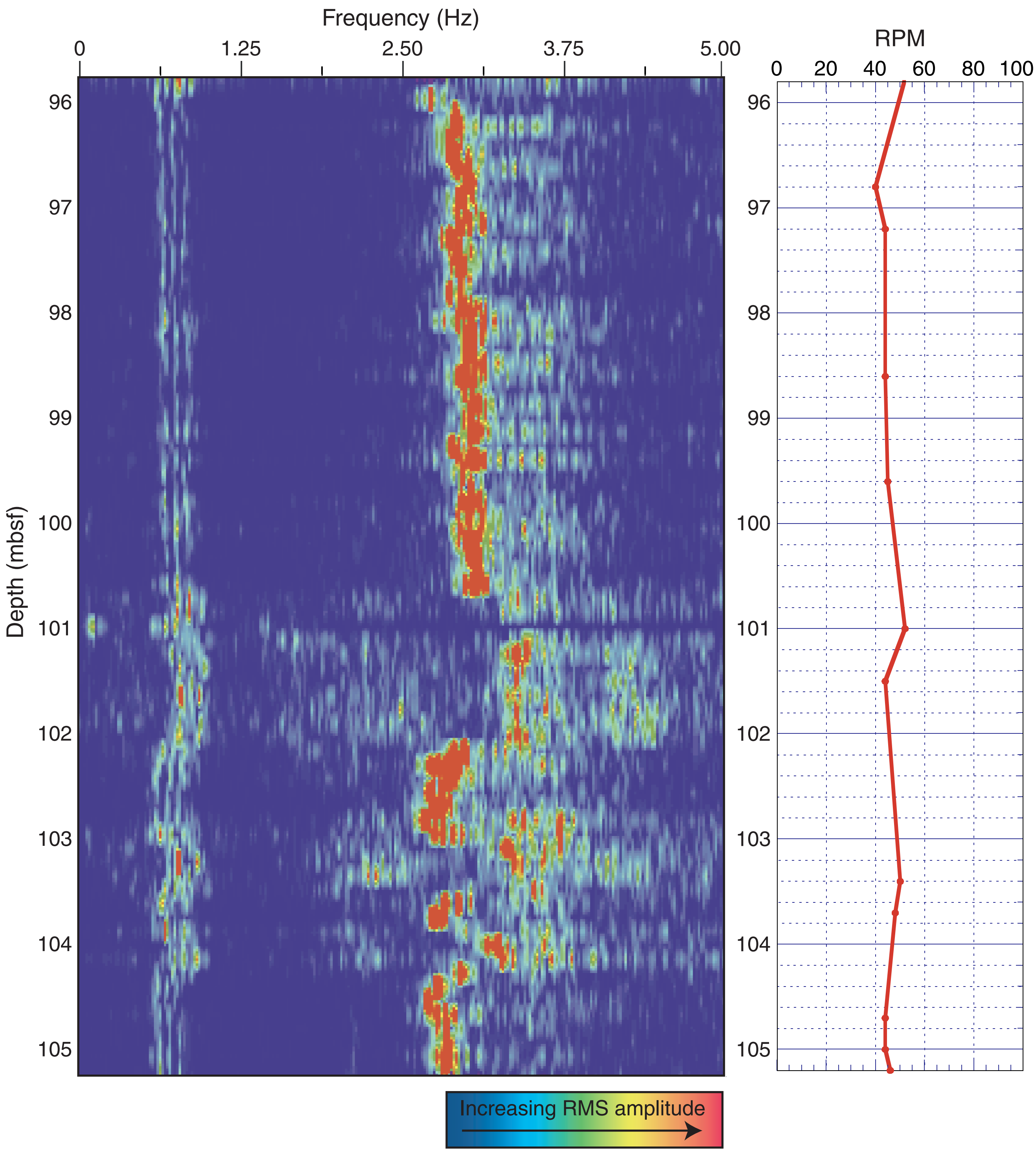

Figure F8. Vertical and horizontal axis acceleration, a drill string model, and log and core data at Site 1105. RMS = root mean square.

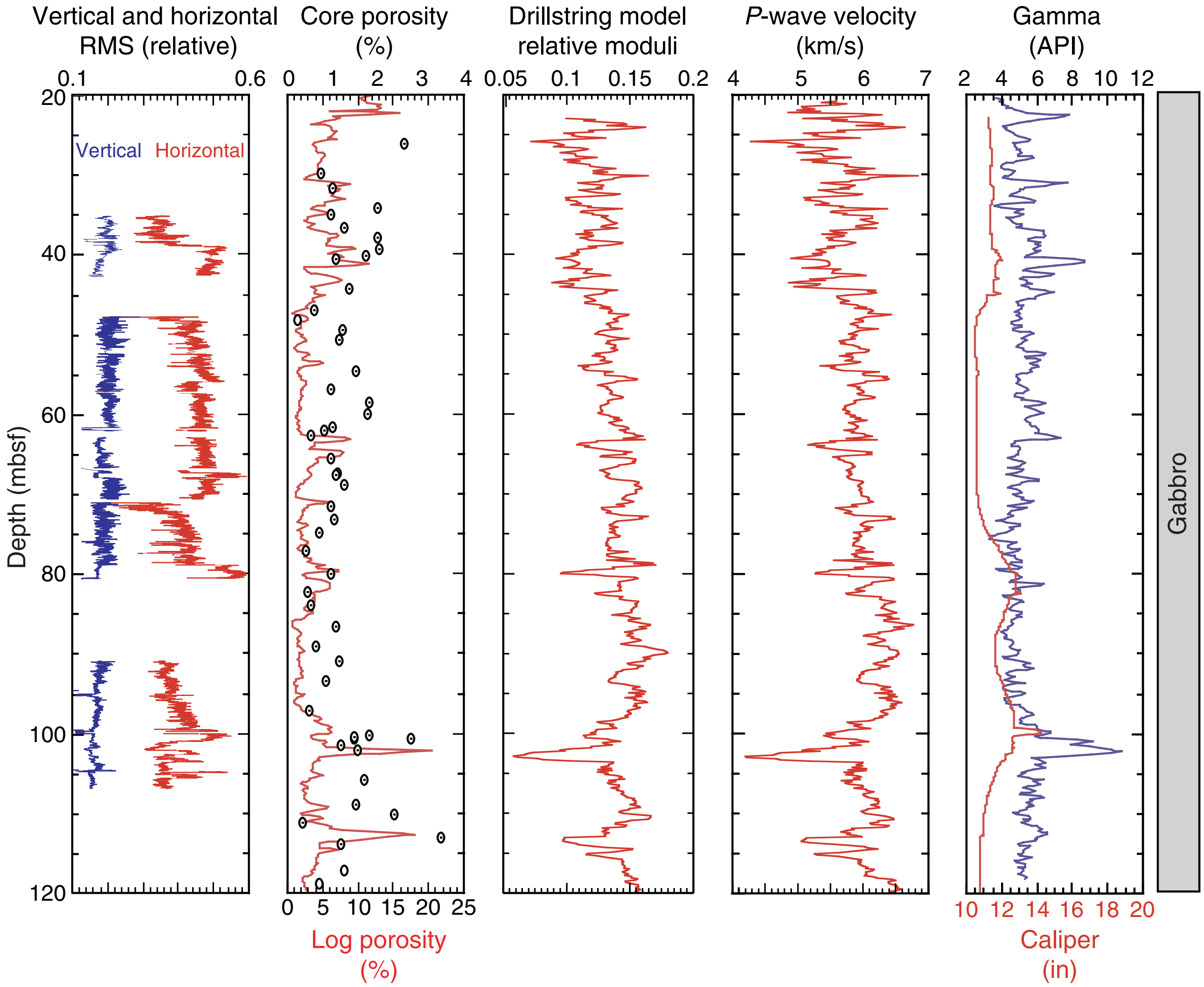

Figure F9. Vertical and horizontal axis root-mean-square (RMS) amplitude data from Site 1107 with core porosity from adjacent Site 757.