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6. Comparison of Multi-Sensor Spectral Gamma Ray Tool (MGT) and Conventional Spectral Gamma Ray Logs, ODP Site 1179[1]

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ABSTRACT

The Multi-Sensor Spectral Gamma Ray Tool (MGT) developed for the Ocean Drilling Program (ODP) utilizes common-depth stacked data from an array of small detectors to improve the vertical resolution of natural gamma ray logs. The first field results using the MGT were obtained at ODP Site 1179 in the northwest Pacific, which penetrated clay and ash-bearing marine ooze. Data were processed postcruise to correct for borehole size effects and logging speed variations, and the tool was recalibrated at a commercial testing facility. The standard Schlumberger gamma ray tool (HNGS) was also run over the same depth interval at this site. Comparisons of the MGT and HNGS logs agree closely in total measured gamma ray counts (gAPI), although the vertical resolution of the MGT was observed to be significantly greater than the HNGS. Estimates of elemental concentrations from both tools agree well for K but differ for U and Th. Based on this comparison, the HNGS underestimates U concentration by ~1–2 ppm and the MGT underestimates Th concentration by 70%–80%. Enlarged borehole size (>42 cm) and the low gamma ray levels in these sediments, as well as the intrinsic differences in detector geometry and gamma ray processing methods, may explain the observed differences in U and Th estimates. The MGT log provides the enhanced vertical resolution critical to resolve the geochemical signature of thin beds and high-frequency periodicity in complex stratigraphic sequences.

[1]Goldberg, D., Meltser, A., Myers, G., and Masterson, W., 2004. Comparison of Multi-Sensor Spectral Gamma Ray Tool (MGT) and conventional spectral gamma ray logs, ODP Site 1179. *In* Sager, W.W., Kanazawa, T., and Escutia, C. (Eds.), *Proc. ODP, Sci. Results,* 191, 1–21 [Online]. Available from World Wide Web: <http://www-odp.tamu.edu/publications/191_SR/VOLUME/CHAPTERS/004.PDF>. [Cited YYYY-MM-DD]
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INTRODUCTION

Natural gamma radiation in sedimentary rocks originates primarily from the isotopes ^{40}K (0.0118% of naturally occurring K), ^{238}U, and ^{232}Th and their daughter products (e.g., Hearst et al., 2000). Variations in the content of these radioisotopes and elemental concentrations often reflect changes in mineralogy because clay minerals and feldspars are associated with higher contents of K and Th. The content of U in sedimentary rocks is more variable and is commonly related to transport by ground water or to the presence of organic matter. The total gamma radioactivity resulting from these isotopes is therefore a useful physical property and logging measurement because it provides an indication of the mineralogy of the rock. Thin marker beds such as the zeolitic clay layers, as observed at Site 1179, typically have high characteristic gamma ray values (Kanazawa, Sager, Escutia, et al., 2001). Natural gamma ray logs also enable the depth extent of these beds to be accurately defined and correlated between core and log measurements.

Increasing vertical resolution of downhole measurements over currently available commercial logging tools provides the capability to define marker beds, resolve finer sedimentary cycles, and correlate to core measurements with improved accuracy. Given known borehole geometry and an optimal logging speed and sampling rate, the vertical resolution can be enhanced by decreasing the vertical length of the detector. The low counting efficiency and high statistical fluctuation inherent in small crystals, however, limit the improvement in resolution achievable in this manner. To overcome these limitations, the Multi-Sensor Spectral Gamma Ray Tool (MGT) was developed using an innovative approach based on common-depth stacking and summing the received data from an array of small detectors (Pirmez et al., 1998). Details of this data stacking approach and the specifications and preliminary testing of the MGT are summarized below and presented in full by Goldberg et al. (2001).

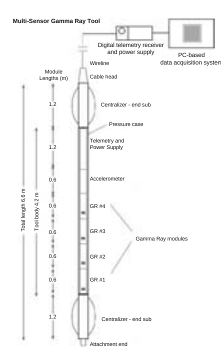
At Ocean Drilling Program (ODP) Site 1179, drilled during Leg 191 in the northwest Pacific Ocean, layered clay-bearing sediments were penetrated and the sequence was logged using both the MGT and conventional Schlumberger Hostile Environment Natural Gamma Ray (HNGS) tool (Kanazawa, Sager, Escutia, et al., 2001). The geological characterization of Site 1179 for long-term instrument emplacement, which was one of the primary objectives of Leg 191, is enhanced by understanding the mineralogy of the thin-bedded sedimentary sequences drilled and by the detailed correlation of these downhole logging data sets. This paper focuses on the processing and calibration of the MGT and the comparison of MGT to conventional HNGS data at ODP Site 1179.

TOOL SPECIFICATIONS

The MGT uses an array of four independent, self-contained gamma spectrometry modules with 2-ft spacing between detectors (Table T1). Figure F1 illustrates the geometry of the MGT, which enables the received gamma ray counts from the four detectors to be stacked at sequential depths. Common-depth stacking is based on the known logging speed and known detector geometry of the MGT. This maintains both signal strength and the high vertical resolution of the MGT. Each detector module comprises a cylindrical, 2-in-diameter NaI crystal fixed

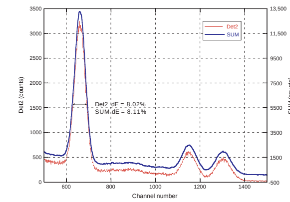
T1. MGT specifications, p. 18.

F1. Block diagram of MGT and ODP data acquisition system, p. 11.



along the centerline of the tool. The NaI crystals are each 4 in long and packaged with a programmable 256-channel amplitude analyzer in the detector module. The spectrum stabilization system is based on an ^{241}Am calibration source in each detector, enabling the spectral resolution of stacked data to be maintained at the same level (~8%) as individual detectors (Fig. F2).

F2. MGT spectral resolution and stacked gamma ray data, p. 12.



Goldberg et al. (2001) report preliminary tests that indicate the vertical resolution of the MGT to be increased by a factor of three or four over conventional logging tools (e.g., Schlumberger Natural Gamma Ray Tool) while maintaining high gamma ray count statistics comparable to commercial tools at typical logging speeds. The tool also includes an accelerometer for improving data stacking based on logging speed. The MGT may be deployed in series with the Schlumberger tool string, as configured during ODP Leg 191, or as a stand-alone tool.

CALIBRATION

Each of the MGT detectors was individually calibrated at a commercial gamma ray calibration facility by recording in standardized test pits with known concentrations of U, Th, and K as well as total gamma ray levels (see **"Appendix A,"** p. 9, for details of the calibration tests and results). The pits are 23 cm in diameter and are filled with water. The response of each detector to the known concentration standard in each pit yields a calibration coefficient. Calibration coefficients for the stacked data are derived from statistical processing of individual channel counts. A stacking algorithm uses these coefficients to compute the K, U, and Th concentrations and total gamma ray response in gAPI units from the MGT data.

Each detector module internally records 256-channel natural gamma spectrometry data downhole. For transmission and processing, these channels are compressed into eight synthesized energy windows emulating the conventional five- and three-window systems that are used in commercial logging systems (Table T2). There are advantages and disadvantages to each. The three-window system gives the concentrations of K, U, and Th directly and can be used for real-time computations. The five-window system includes lower energy windows as well as second-order spectral peaks but may also introduce cross-window errors at certain spectral frequencies. The comparison of K, U, and Th concentrations between tools may be affected by the assumptions made in either window processing systems as well as by the detection threshold of the sensors.

T2. MGT synthesized energy windows, p. 19.

EXPERIMENTAL CONDITIONS: ODP SITE 1179

ODP Site 1179 is located in ~5500 m water depth (Kanazawa, Sager, Escutia, et al., 2001). Five holes were drilled at this site during Leg 191 to characterize the stratigraphy and to achieve the primary objective of installing a borehole seismometer at this location. The sediment stratigraphy consists largely of siliceous oozes and clays with numerous volcanic ash layers and some interbedded cherts in the deeper section (Kanazawa, Sager, Escutia, et al., 2001). During Leg 191, Hole 1179D was logged using the MGT as well as the standard Schlumberger HNGS logging tool used by ODP (Kanazawa, Sager, Escutia, et al., 2001). This was the first at-sea deployment of the MGT in marine sediments, and high-resolution gamma ray logging data were successfully recorded.

The logged interval consisted of the shallow upper Miocene clay-rich sediments and ashes above 300 m below seafloor (mbsf). The average core recovery was nearly 99%, allowing for high-resolution core sampling to be conducted (Kanazawa, Sager, Escutia, et al., 2001). The borehole conditions during logging in Hole 1179D were difficult, however. Extensive enlargement of the borehole (>42 cm) occurs above 256 mbsf and constrictions of the borehole diameter (<20 cm) occur below (Kanazawa, Sager, Escutia, et al., 2001). The effect of the borehole enlargement on these measurements is discussed below. Two passes of each tool, first the HNGS and then the MGT, plus short repeat runs of each for data quality assurance, were planned in Hole 1179D. After the first HNGS pass upward from 300 to 203 mbsf, however, the constriction at 256 mbsf precluded further logging below. Two passes of the MGT and the repeat HNGS pass were recorded above this depth. Hence, this paper compares results from the MGT and HNGS tools only over the interval where both logs were recorded, from ~160–230 mbsf.

LOGGING SPEED

For all ODP logging operations, tool depth is measured by the length of cable spooled out from the logging winch. The recorded depth is then shifted to depth below seafloor, as identified by the gamma ray log (Kanazawa, Sager, Escutia, et al., 2001). Because the ship oscillates at the sea surface due to wave motion, among other sources of irregular tool motion, the actual tool depth departs from the measured cable length and the logging speed is not constant. Both the MGT and HNGS data were collected at cable speeds of 250–300 m/hr. The tools experienced variations in logging speed due to ship heave and hole conditions, and during the repeat MGT pass, an electronic fault in the wireline heave compensator resulted in further increases in vertical tool motion. Such differences in operational conditions likely contribute, in part, to differences observed between logs.

For the MGT, accurate common-depth stacking depends on the precise time shift of data from detectors in the sensor array. Rapid variations in the logging speed must be carefully taken into account. To accomplish this, time shift corrections are applied to restack the data based on depth and cable speed. The effect of residual ship heave on the count statistics of the stacked MGT log is therefore minimized.

ENVIRONMENTAL CORRECTIONS

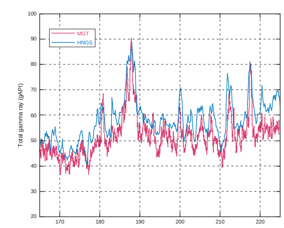
The effect of enlarged borehole size on the MGT and HNGS logs can be significant. In smaller-diameter holes, the reduced volume of borehole fluid attenuates fewer gamma rays transiting from the formation to the crystal detector; larger-diameter holes contain a greater volume of fluid that attenuates more gamma rays. Each detector's counting effectiveness depends on the actual borehole diameter, the position of the tool in the hole, and mud weight. Thus, under field conditions, appropriate corrections are necessary. The borehole diameter is difficult to control, in particular for ODP holes, and empirical corrections based on the caliper log are commonly used to correct for environmental effects to the extent possible. The HNGS total gamma ray log is corrected in real time based on the single-axis caliper reading provided by the Schlumberger tool string. Unfortunately, the maximum caliper reading is ~42 cm, and in the interval of interest above 250 mbsf, Hole 1179D is enlarged beyond this maximum dimension (Kanazawa, Sager, Escutia, et al., 2001).

For the MGT total gamma ray log, we apply corrections for borehole size in Hole 1179D based on the maximum caliper log extension. This assumption provides a partial correction for borehole size, which is reasonable given the reliable response of other logging tools in this hole. The correction was applied to the MGT data in post-processing using an algorithm adapted from experimental data by Mathis et al. (1984) and from Schlumberger charts (Schlumberger, 1994), taking both hole size and tool geometry into account. The equations describing these corrections are given in **"Appendix B,"** p. 10. For more precise estimates of these parameters, calibration of the tool under varying environmental conditions and an accurate caliper log must be acquired. For our purposes, the environmental corrections to the MGT and HNGS total gamma ray logs are comparable.

COMPARISON OF TOTAL GAMMA RAY LOGS

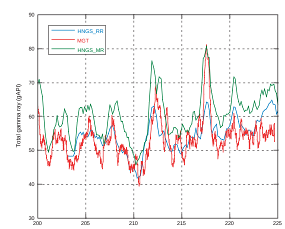
The corrected and calibrated MGT and HNGS logs from 160 to 230 mbsf in Hole 1179D are shown in Figure **F3.** In general, the comparison of the total gamma ray values from both tools is excellent, whereas substantially greater vertical resolution is observed in the MGT log. Peaks in gamma ray intensity can be largely attributed to ash-bearing and clay-rich layers in marine ooze. A number of ash layers were observed in the recovered core over the interval from 180 to 230 mbsf (Kanazawa, Sager, Escutia, et al., 2001). These correlate to sharp, well-defined peaks in the MGT log and broader peaks in the HNGS log. Double peaks at 187–188 mbsf in the MGT log, for example, form a single broad peak in the HNGS log. Overall, the MGT resolves layers several times thinner than the HNGS. The slight offset in gamma ray values between the logs may be attributed to difference in the borehole size between the two passes.

F3. Comparison of total gamma ray logs, p. 13.



In Figure **F4,** the main and repeat HNGS passes are shown in comparison with the MGT over an expanded depth scale from 220 to 225 mbsf. The peak-to-peak correlation among these logs is very good. The offset in gamma ray values between the main and repeat HNGS logs is attributed to the difference in the borehole size between the two passes above 256 mbsf. This difference far exceeds the offset in gamma ray values between the MGT and HNGS. The MGT nevertheless correlates peak to peak with both the main and repeat HNGS logs.

F4. Expanded depth scale, p. 14.



COMPARISON OF K, U, AND Th ESTIMATES

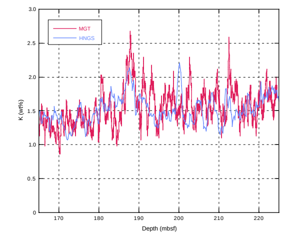
To compute K, U, and Th concentrations from the MGT, data from the four detectors are stacked in post-processing using the three-window processing system (see Table **T2**). The influence of enlarged borehole size is greater on K, U, and Th computations than on the total gamma ray measurements because of their lower count levels. The corrections given in **"Appendix B,"** p. 10, should be computed using accurate caliper logs, and detector calibration coefficients should be measured under similar large-hole conditions. Neither of these corrections are possible for the data collected in Hole 1179D. However, environmental corrections were not applied in real time to the HNGS or in post-processing to the MGT data, so the field results from both tools may be compared with confidence. The absolute values of elemental concentrations cannot be precisely estimated, however, and very low concentrations may be below the detection threshold in these tools. Comparison of natural K, U, and Th concentration logs from the MGT and HNGS are shown in Figures F5, F6, and F7, respectively, over their common depth interval from 160 to 230 mbsf in ODP Hole 1179D. Their correlation and differences are discussed below.

Figure F5 shows the comparison of K concentrations. The MGT and HNGS logs are in excellent overall agreement. The processing differences for K concentration with either windowing system are minimal (Mathis et al., 1984). Concentrations range from 1 to 2.5 wt% in this interval and appear to increase slightly with depth. Higher vertical resolution of the MGT highlights some offset in gamma values from the HNGS log across thin layers.

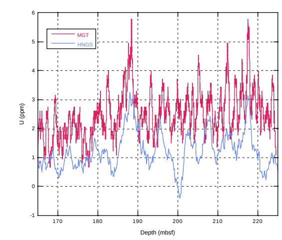
In Figure F6, the comparison of U concentrations indicates that the MGT estimates are ~1–2 ppm greater than the HNGS on average and that differences reach 35%–40% at particular depths. Good peak-to-peak correlation is apparent only for HNGS values of ~2 ppm or more, and the MGT log shows a slightly increasing trend with depth. Some HNGS values are negative, which indicates that the low U concentration in these rocks may be below its detection threshold or that processing may introduce an estimation error.

Figure F7 shows the comparison of Th concentrations with large differences between the MGT and HNGS estimates. The HNGS log increases slightly with depth, and, in general, peak-to-peak correlation with the MGT log is poor. The MGT estimates are 26 ppm (70%–80%) lower than the HNGS, on average. The low Th concentrations in these sediments may be below the detection threshold of the MGT at this logging speed, which is further suppressed by the effects of borehole enlargement. A comparison in another environment with higher Th concentration would provide more reliable estimates for both tools and a more valuable comparison.

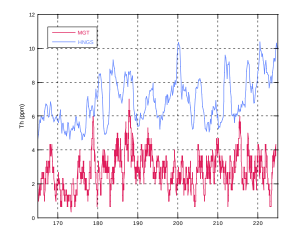
F5. Comparison of natural K concentration logs, p. 15.



F6. Comparison of natural U concentration logs, p. 16.



F7. Comparison of natural Th concentration logs, p. 17.



CONCLUSIONS

This comparison study of high-resolution MGT and conventional HNGS gamma ray logs at Site 1179 shows that the total natural gamma ray values from both agree well, with substantially greater vertical resolution observed in the MGT log. Uncertainties in both data sets are introduced by enlarged borehole size and changes in the in situ conditions over time. Corrections for borehole size may be accurately applied with the acquisition of reliable caliper logs and calibration data.

Comparison of K and U concentration estimates from these tools agree well, measuring between 1 and 2.5 wt% for K and 2 and 5 ppm for U over this interval. The higher vertical resolution of the MGT highlights some offset of gamma values from the HNGS log in thin layers, primarily consisting of ash-bearing clays within the study interval. The HNGS measures lower U concentrations by ~1–2 ppm in these rocks, which may be explained by the processing system used or the detection threshold. The MGT measures lower Th concentrations by 70%–80% at this site, which may be explained by its small detector size, enlarged borehole size, and the low Th concentration in these sediments. Differences between the logs may be attributed to the intrinsic differences in vertical resolution as well as to the effects of borehole size on natural gamma ray measurements. Further comparisons of the MGT and HNGS logs in other environments, preferably at sites with good borehole conditions, will provide a range of different geochemical concentrations for study and improve the accuracy of these estimates.

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APPENDIX A

Calibration Testing of the MGT

The MGT was calibrated at a commercial test facility at the Halliburton Energy Services campus in Houston, Texas (USA) (Gadeken et al., 2000). These tests enable the comparison of the MGT detector responses to known concentrations of K, U, and Th and gamma ray levels in separate, 150-cm-thick test zones (Table AT1). Background measurements were also made for all detectors. The three water-filled pits contain 23-cm-diameter cased holes as the test zones. Gamma ray counts were measured independently for each of the four MGT sodium iodide detectors over an acquisition time of 10–20 min in each zone. Preliminary MGT calibration tests were also completed at the American Petroleum Institute/University of Houston, Texas (USA), facility and reported by Goldberg et al. (2001).

Based on these standards, we compute coefficients normalizing the response of each detector to the appropriate K, U, and Th and total gamma ray levels. Table AT2 provides the calibration coefficients for processing raw MGT counts and computing the log responses. Calibration coefficients for the stacked data are also derived from statistical processing of individual channel counts.

AT1. Summary of Halliburton calibration facility, p. 20.

AT2. MGT calibration summary, p. 21.

APPENDIX B

Hole Size Correction for MGT Data

The hole size correction of total gamma ray is based on environmental parameter t (Schlumberger, 1994), which takes into account hole and tool geometry and mud weight, as follows:

$$t = (W_{mud}/8.345) \times [(2.54 \times d_{hole}/2) - (2.54 \times d_{tool}/2)], \qquad (1)$$

where

W_{mud} = mud weight (lb·m),
d_{hole} = borehole tool diameter (in), and
d_{tool} = logging tool diameter (in).

For the holes drilled to moderate depths (up to 5000 m) and filled with seawater, equation 1 can be simplified to:

$$t = 1.316 \times d_{hole} - 3.5. \qquad (2)$$

The total gamma ray (gAPI) value computed from the MGT data should be multiplied by a correction factor, CF, to account for the hole conditions described by parameter t.

The correction factor to gAPI units for the MGT tool, centered in a borehole, is

$$\mathrm{CF} = 0.82 - (1.31 \times 10^{-3})t + (5.59 \times 10^{-3})t^2 - (2.45 \times 10^{-4})t^3 + (4.7 \times 10^{-6})t^4. \qquad (3)$$

For the eccentered MGT tool, CF can be calculated by:

$$\mathrm{CF} = 0.812 + (2.44 \times 10^{-2})t + (1.36 \times 10^{-4})t^2 - (8.22 \times 10^{-6})t^3. \qquad (4)$$

To compute corrected values for U, K, Th values from the MGT, the correction factors are determined by equations 5, 6, and 7, respectively:

$$\mathrm{CF_U} = 0.6 + (2.37 \times 10^{-2})D + (2.17 \times 10^{-3})D^2, \qquad (5)$$

$$\mathrm{CF_K} = 0.6 + (2.19 \times 10^{-2})D + (2.44 \times 10^{-3})D^2, \text{ and} \qquad (6)$$

$$\mathrm{CF_T} = 0.61 + (2.6 \times 10^{-2})D + (1.68 \times 10^{-3})D^2, \qquad (7)$$

where D = borehole diameter (in).

These equations are based on experimental data in a model environment (Mathis et al., 1984) and the MGT calibration results presented in Table AT2. The MGT data for K, U, and Th values should each be multiplied by their corresponding CF value. The K, U, and Th correction factors are calculated for a centered MGT tool in a water-filled borehole. If the borehole conditions differ from this case, equations 5, 6, and 7 represent only an approximation of the environmental correction.

Figure F1. Simplified block diagram of Multi-Sensor Spectral Gamma Ray Tool (MGT) and the ODP data acquisition system. The MGT was deployed in series with the Schlumberger triple-combo tool string at Site 1179.

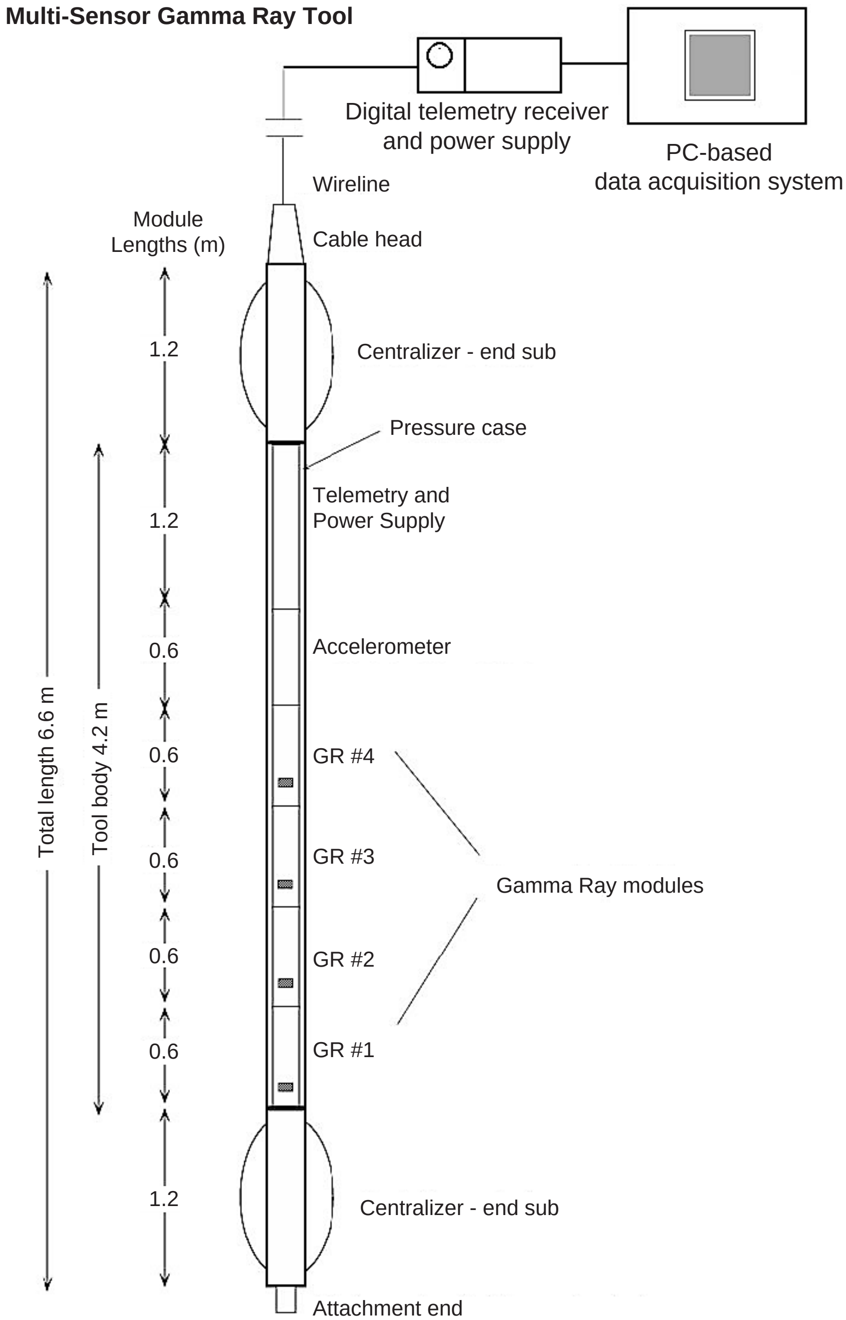

Figure F2. Multi-Sensor Spectral Gamma Ray Tool (MGT) spectral resolution for detector 2 (Det2) and the stacked (SUM) gamma ray data from all four detectors. The resolution of the stacked measurement is maintained at ~8%. dE = spectral resolution.

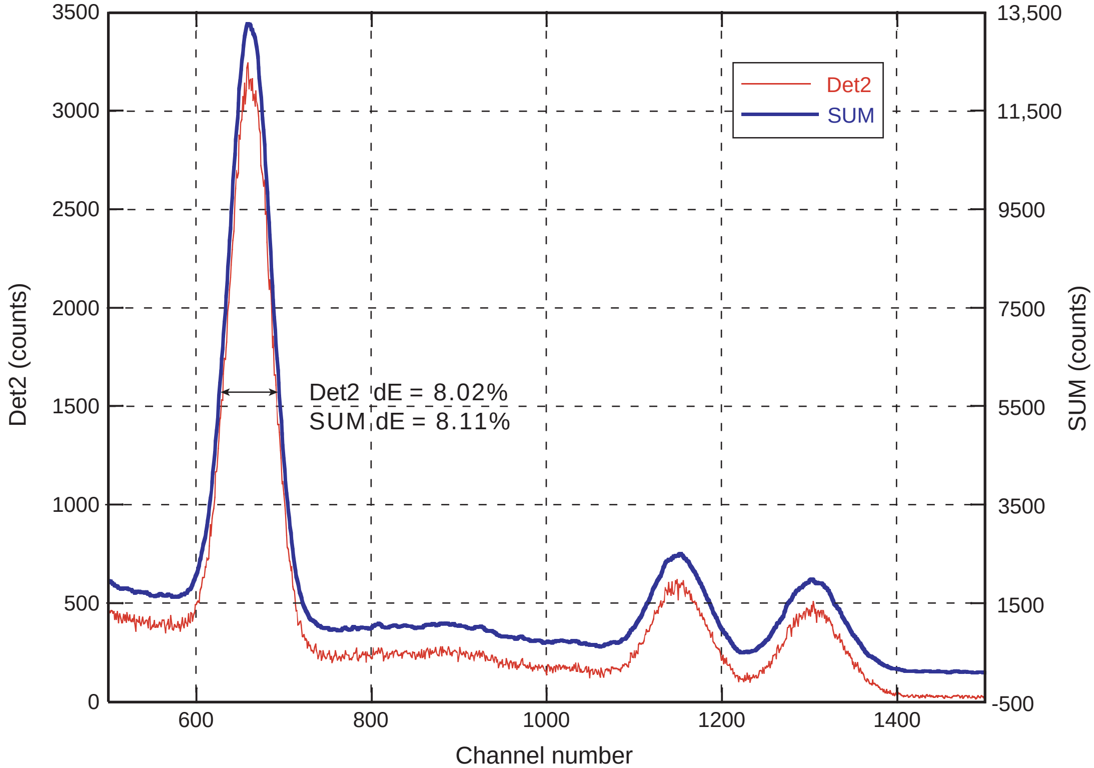

Figure F3. Comparison of total gamma ray logs (main passes). Stacked, corrected, and calibrated Multi-Sensor Spectral Gamma Ray Tool (MGT) and Schlumberger gamma ray tool (HNGS) data are shown from 160 to 230 mbsf in Hole 1179D. The correlation is excellent, with higher vertical resolution apparent in the MGT data. High gamma ray peaks are attributed to ash-bearing layers.

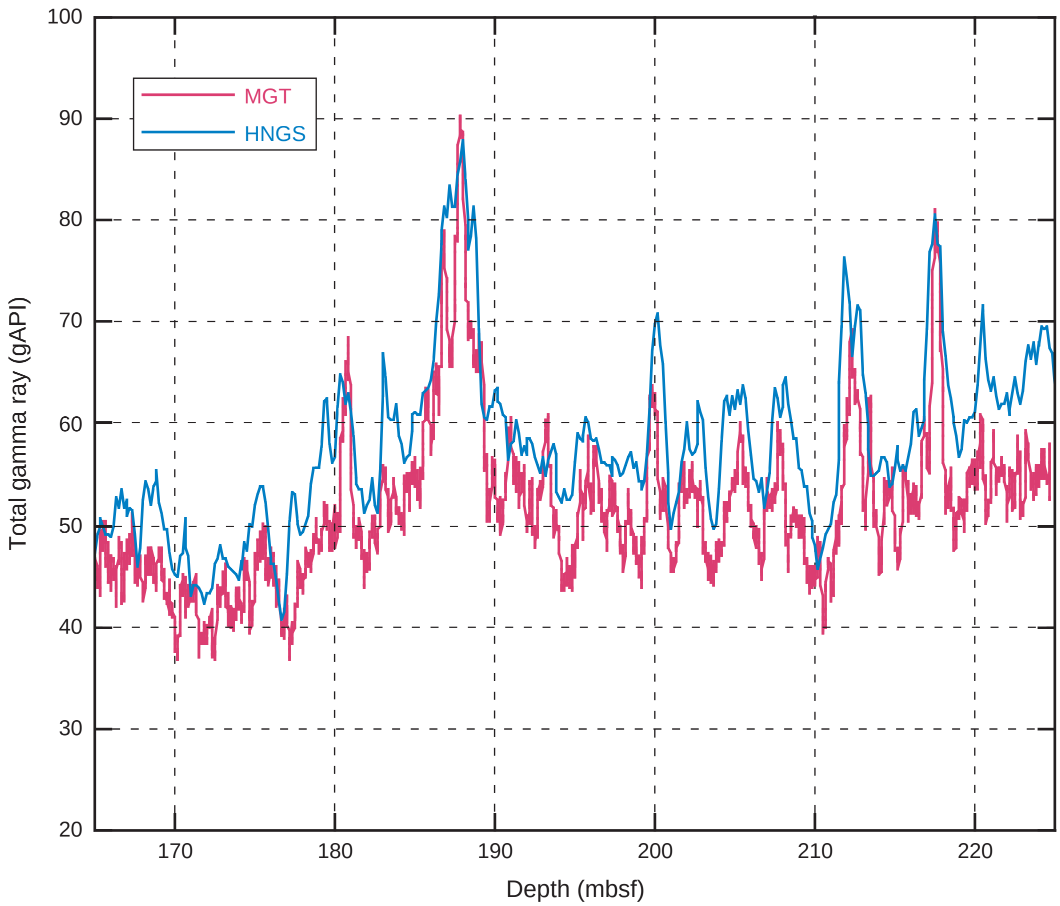

Figure F4. Expanded depth scale of the total gamma ray logs shown in Figure F3, p. 13 (200–225 mbsf), plus the repeat Schlumberger gamma ray tool pass (HNGS_RR) in Hole 1179D. The correlation among these logs is very good, in particular for the Multi-Sensor Spectral Gamma Ray Tool (MGT) and repeat HNGS logs.

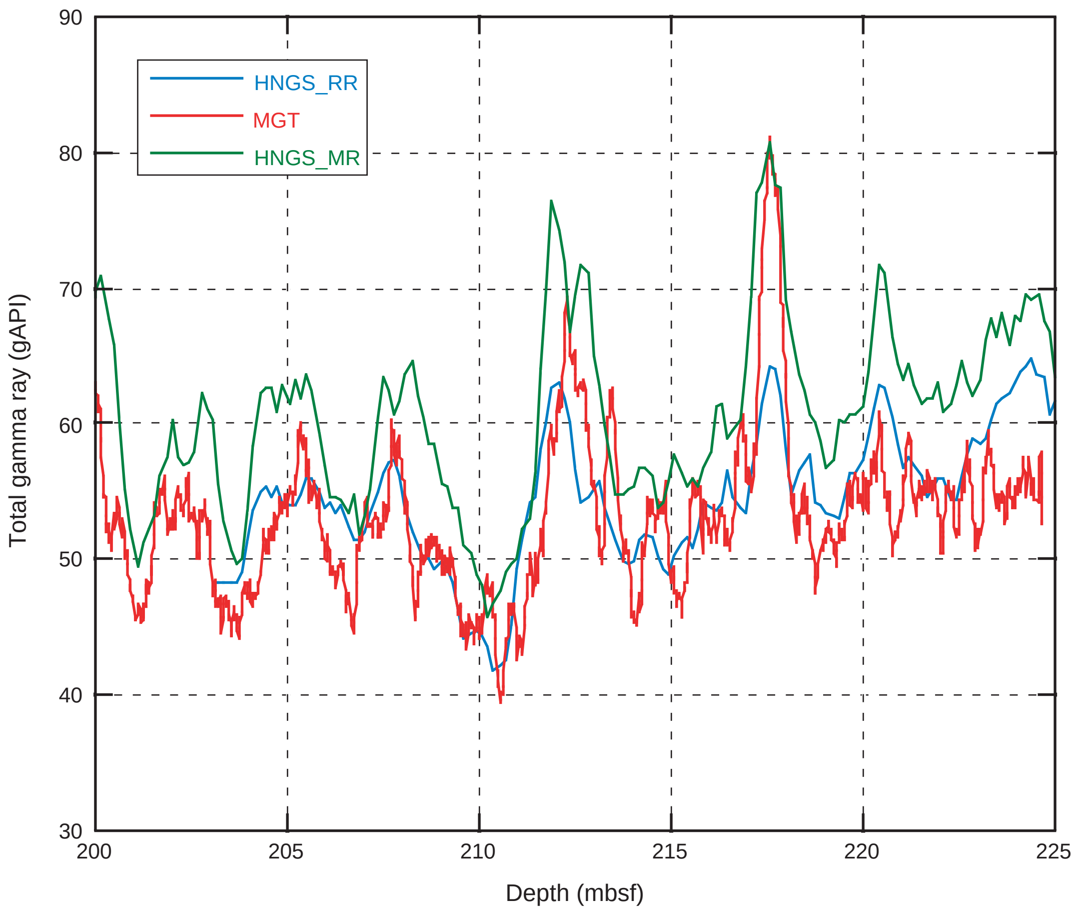

Figure F5. Comparison of natural K concentration logs. Stacked Multi-Sensor Spectral Gamma Ray Tool (MGT) and Schlumberger gamma ray tool (HNGS) data are shown from 160 to 230 mbsf in Hole 1179D. The correlation is excellent with K concentration ranging between 1 and 2.5 wt% and increasing slightly with depth in these sediments.

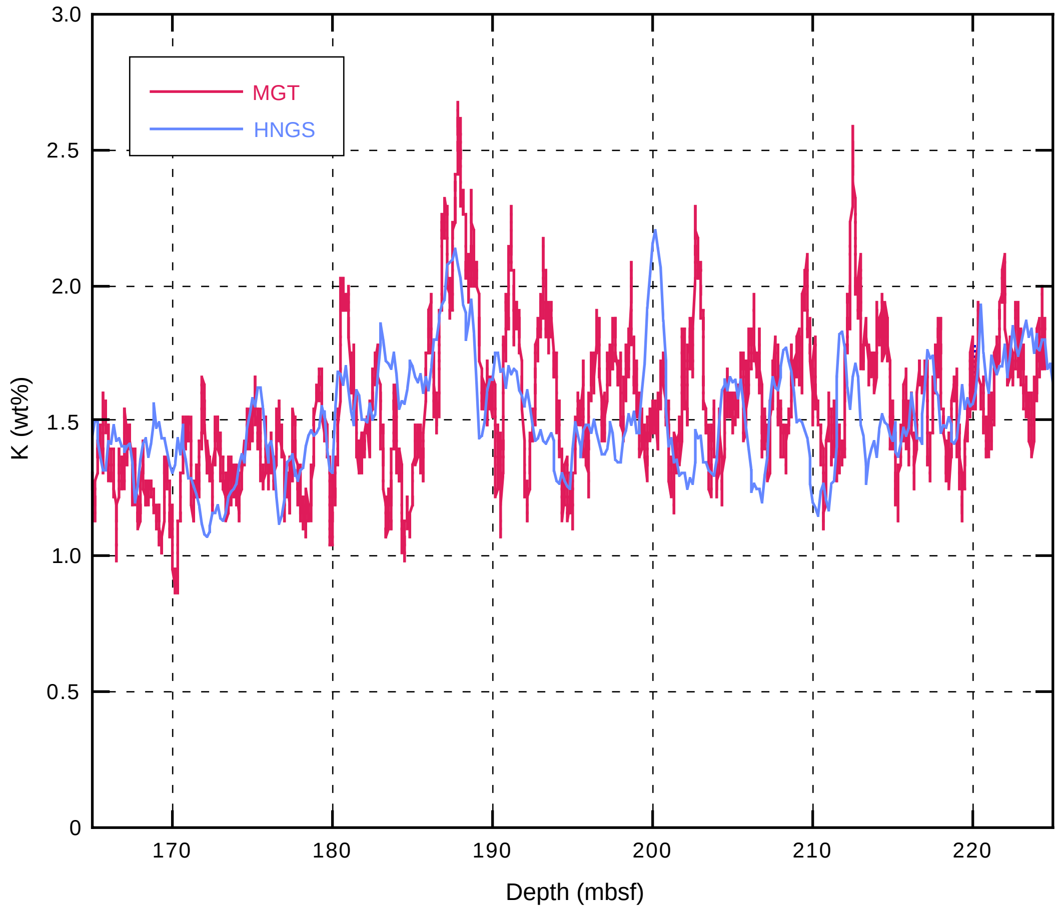

Figure F6. Comparison of natural U concentration logs. Stacked Multi-Sensor Spectral Gamma Ray Tool (MGT) and Schlumberger gamma ray tool (HNGS) data are shown from 160 to 230 mbsf in Hole 1179D. The peak-to-peak correlation is good only for HNGS values of ~2 ppm or more. MGT values are ~1–2 ppm higher than the HNGS.

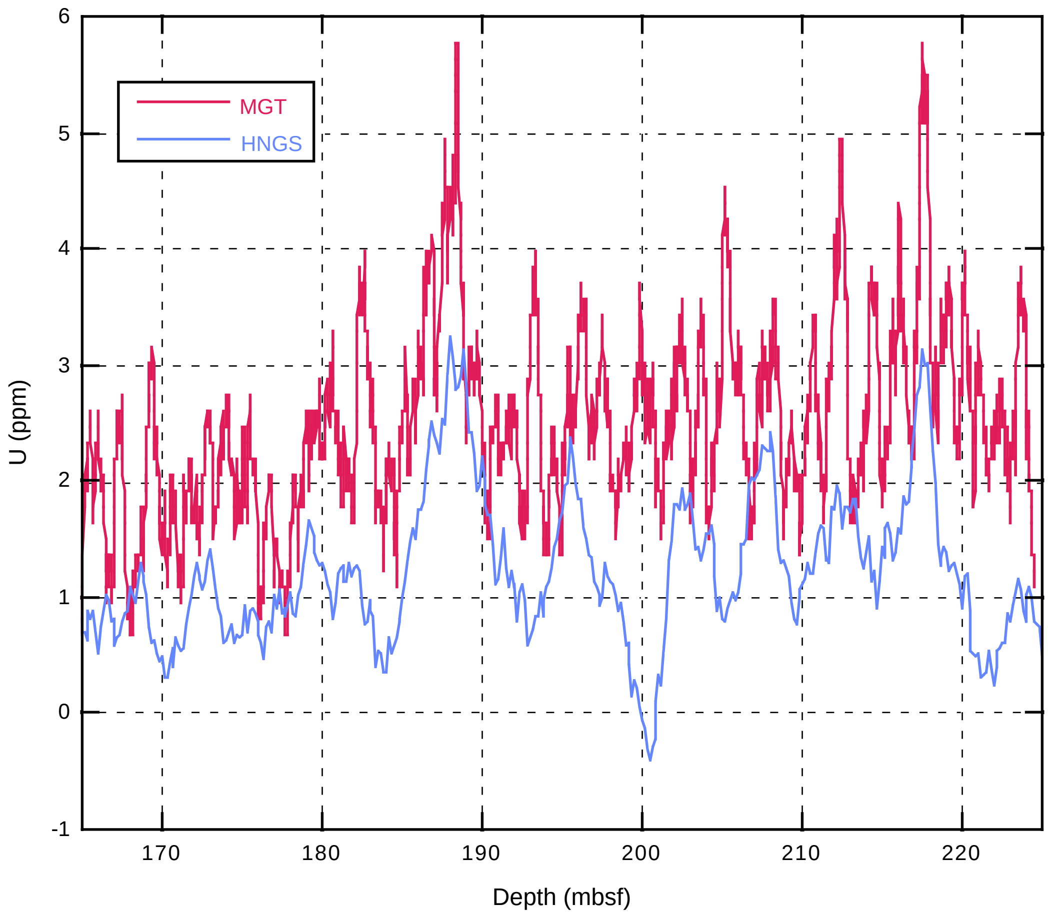

Figure F7. Comparison of natural Th concentration logs. Stacked Multi-Sensor Spectral Gamma Ray Tool (MGT) and Schlumberger gamma ray tool (HNGS) data are shown from 160 to 230 mbsf in Hole 1179D. The correlation is poor and the MGT values are generally 2–6 ppm (70%–80%) lower than the HNGS.

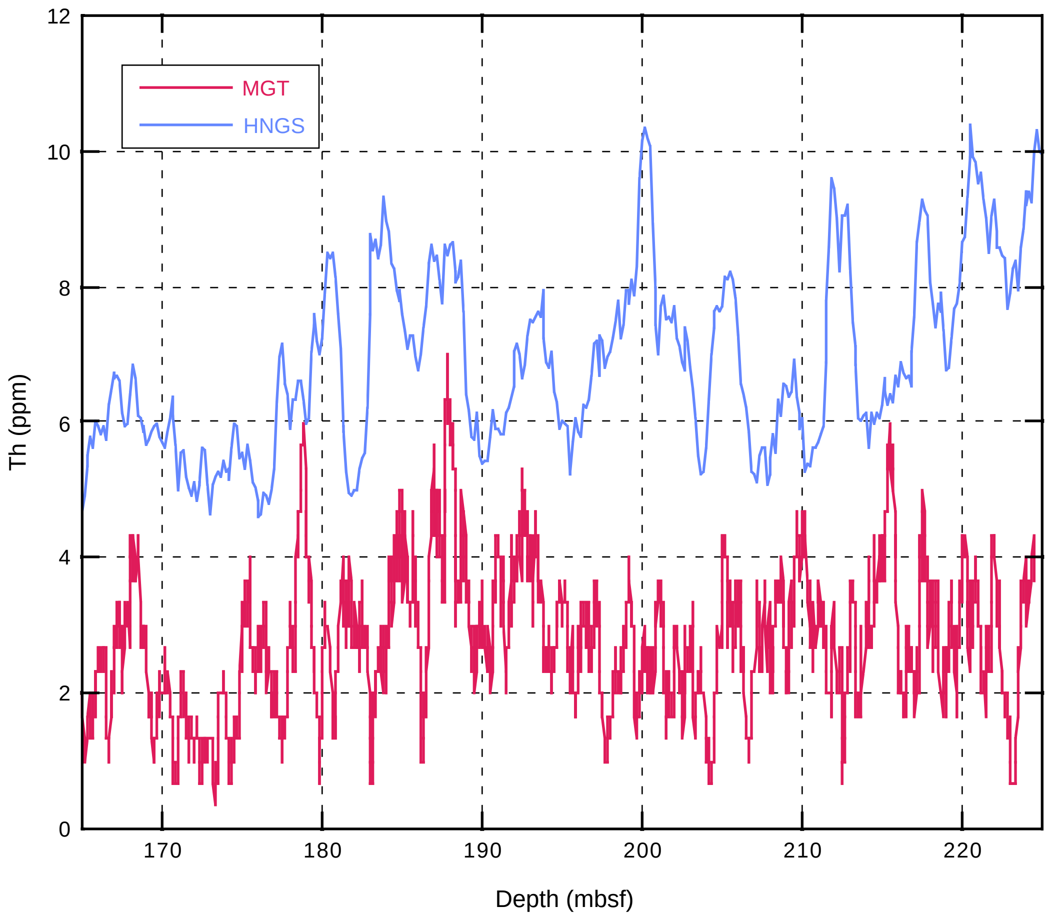

Table T1. Multi-Sensor Spectral Gamma Ray Tool (MGT) specifications.

Property	Specification
Number of gamma spectrometry detectors	4
Module spacing (m)	0.64
Detectors type and dimensions (in)	NaI (Tl), 4 x 2
Spectral measurement range (MeV)	0.2–3.0
Spectral resolution (keV)	40
Tool length (m)	6.6
Tool diameter without centralizers (in)	3.375
Maximum cable length (ft)	28,000
Maximum ambient temperature (°C)	100
Maximum pressure (psi)	20,000
Power requirements	AC; 47–63 Hz; 160–250 V
Power consumption (W)	30

Table T2. Multi-Sensor Spectral Gamma Ray Tool (MGT) synthesized energy windows.

	Five-window system					Three-window system		
	W1	W2	W3	W4	W5	W1	W2	W3
Element	—	—	—	—	—	K	U	Th
Energy (MeV)	0.20–0.50	0.5–1.11	1.11–1.59	1.59–2.00	2.00–3.00	1.37–1.57	1.58–1.95	2.30–2.80
Channel numbers	16–41	42–90	91–130	131–164	165–246	112–128	129–160	188–229

Note: — = not applicable.

Table AT1. Summary of Halliburton calibration facility.

Test pit	Concentration	API units
Th	82 ppm	309
U	20 ppm	199
K	5.4 wt%	101

Table AT2. Multi-Sensor Spectral Gamma Ray Tool (MGT) calibration summary.

	U (cps/ppm)	Th (cps/ppm)	K (cps/wt%)	Total counts (cps/gAPI)
Detector 1	0.195	0.074	0.600	0.709
Detector 2	0.222	0.092	1.140	1.058
Detector 3	0.219	0.081	0.951	0.937
Detector 4	0.247	0.117	1.385	1.104
Stacked data	0.221	0.091	1.019	0.953