When every count counts…

How to get the most out of your gamma-ray log

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Introduction

Spectral Gamma-ray (SGR) borehole logging is widely recognized as one of the most effective ways to obtain lithological information of the subsurface. SGR tools are therefore key in borehole assessments both in oil&gas exploration and in mining.

Spectral gamma-ray data originates from the naturally occurring radioactive isotopes ^{40}K, ^{232}Th and ^{238}U – trace elements which often are considered as a "fingerprint"[1] of the encapsulating formation or rock type. The *art* of gamma-ray data analysis therefore is in the conversion from spectral information into radionuclide concentrations – an operation which involves not only spectral processing, but also corrections for borehole parameters like casing, borehole diameter, fluid used, etc.

Many, if not most software packages for the acquisition and analysis of spectral gamma data use the so-called "windows", or "3-windows"[2] method to obtain radionuclide concentrations from gamma spectra. The operation basically uses the counts collected in three energy intervals that coincide with the position of the ^{40}K peak, and the high-energy peaks of ^{238}U and ^{232}Th as a measure for source strength or, in other words, for the concentration of the radionuclides.

Full Spectrum Analysis

However, by using only peak counts, a large part of the spectral data is thrown away (see figure 1). This was already recognized in the early 80-ies, for instance by Grasty *et al*[3], who proposed a multi-window approach rather than the limited 3-Windows method. However, at that time computing power was lacking to perform multi-window or "Full Spectrum Analysis" (FSA) on large, multichannel datasets. Some ten years later, computers became powerful enough to allow for FSA, even to have it analyze "live" spectral data, for instance while logging[1].

To properly compare the analysis methods, one should define a measure for quality of gamma-ray data. For SGR tools, data quality is a combination of *accuracy* (how well does the tool + analysis method reproduce the actual radionuclide concentrations?) and *precision* (what is the spread in the concentrations found?).

The effect on data quality of including all spectral data in the analysis is illustrated in figure 2. This figure plots the uncertainty in the ^{238}U concentration extracted from spectra taken inside the Medusa calibration pit[4] with a QL-40 tool from ALT. The *accuracy* of 3-Windows and FSA is the same (they yield the same average ^{238}U concentration). However, the *precision* of FSA is better. The spread in the

[1]German toolmaker *Antares Datensysteme GmbH* has been using a Medusa-developed implementation of the FSA algorithm ("Gammabase") in their Geobase logging suite since 1997. Now, the algorithm is part of WellCAD 5.0 and is being implemented by Robertson Geologging in their logging suite.

FSA-found ^{238}U numbers is about a factor 1.5 smaller[2] than the ones obtained with classic 3-Windows.

The impact of this improvement becomes evident when one remembers that uncertainties scale with the *square root* of the spectrum content. In other words, *better statistics through better analysis allows for faster measurements and/or smaller tools*.

Figure 3 illustrates the reduction in noise one can achieve using FSA instead of 3-Windows. The data shown is taken in a borehole measurement in Deelen, NL[3]. Depicted is the ^{40}K concentration per depth, found using 3-Windows (blue curve). On top of the 3-Windows data, the same data is plotted, now obtained using FSA (red curve). The curves follow the same pattern, however, the FSA data is visibly less noisy.

Calibration of SGR tools

As can be seen in figure 1, FSA needs detector calibration curves. Originally these were obtained using calibration sources (borehole-like setups with known activity, size and density, see e.g. Stromswold[5]). However, the amount of source-detector geometries that can be calibrated this way is of course limited. Moreover, it is almost impossible to obtain pure, clean spectra.

And that is where modern-day computing technology comes into play. Delicate source-detector modelling codes, originally developed for nuclear industry, can now easily be run on desktop PC's. We use one of these codes, MCNP-X [6], to simulate a SGR tool's response to a pure source of ^{40}K, ^{238}U or ^{232}Th for a given geometry. However, the true power of the method is that it allows to create such responses against *any* source type of *any* geometry – something which evidently cannot be done with physical set-ups.

An example: modelling the Adelaide AM-6 pit

Using MCNP-X, SGR calibration boils down to creating a 3D computer model for a given instrument and a given calibration source, and checking this model by a measurement in this source. Figure 3 plots data taken with a 1"x4" BGO tool (QL-40, ALT) in one of the AMDEL calibration pits (AM-6) in Adelaide, Australia. An MCNP-X model was constructed based on a tool drawing and AMDEL's description of the AM-6 pit. A model run which takes about 8 hours on a desktop PC gave the detector response curves as plotted in blue, green and red in figure 4. Using these curves, the measured data was fitted and the results are listed in the table below.

Table 1. AM-6 Activities found using MCNP-calibrated curves. Numbers in parentheses are listed values from AMDEL.

	K (%)	***EU (PPM)***	***ETH (PPM)***
K-ZONE	**3,9 (4.3)**	0,1 (0.8)	2,4 (1.7)
U-ZONE	0,2 (0.1)	**32,2 (34.1)**	3,5 (2.0)
TH-ZONE	0,1 (0.1)	1,0 (3.8)	**60,6 (62.7)**

One should note here that no scaling or whatsoever has been applied to fit the results from the modelling procedure to the activities listed by AMDEL.

[2]Similar numbers are found in other (borehole) datasets, but also for instance in datasets obtained with big airborne gamma-ray systems. The effect is strongest for ^{238}U and ^{232}Th. For ^{40}K the "FSA improvement" is generally smaller.

[3] Data courtesy of TNO, NL

Another example: separating radon from uranium

The "uranium" spectrum as we know it, is made up of more than 400 decay lines, all with different gamma energies and decay probabilities. However, the vast majority (>90%) of the gamma rays seen in a "Uranium" spectrum come from nuclides down the decay chain, i.e. daughters of radon. This especially holds for the 1764 keV peak, which is taken as the ^{238}U-channel in 3-Windows but which actually stems from ^{214}Bi – a Radon daughter. So, designating gamma-ray data as ^{238}U actually implies assuming the ^{238}U-series to be in secular equilibrium. But what happens if it is not? In other words, is there a way to separate gamma-ray data coming from radon and its daughters from radiation from the full ^{238}U series?

Nuclear particle modelling can help out here. As an example we show data taken in a borehole in Canada[4]. In this data, shown in figure 6, a huge ^{238}U peak was seen at a certain depth. However, samples taken from the borehole did not show this spectacular concentration at all. We decided to use MCNP-X modelling to find out what happened. In figure 5, we show simulated spectra for two situations:

(a) ^{238}U and its daughters in secular equilibrium inside a rock matrix (upper, dark-green curve);
(b) ^{218}Rn and its daughters, assuming radon accumulated in the borehole fluid close to the SGR tool;

The difference seen between the spectra is purely coming from the difference in geometry for both situations. That is, the lowest gamma-ray energies are normally heavily scattered while transported through rock, losing all peak information on its way to the SGR tool. However, for radon close to the tool, the situation is drastically different. The low energy radiation can enter the SGR tool unscattered, yielding much sharper peaks at the lowest energies (from 100-300 keV and at 609 keV). In the data processing we used both the Rn and U spectra, together with curves for ^{40}K and ^{232}Th. Figure 6 shows the result. The data above the sharp peak (above 60m depth) is fully fitted by the curve simulated for ^{238}U inside a rocky matrix. However, the data below 60m is completely different and is almost fully fitted by the "radon" curve.

Results like these can only be obtained using a FSA approach. One needs to have all spectral information at hand to be able to distinguish between the subtle spectral differences due to geometrical difference. A similar approach[7] is for instance used to remove radon background from airborne uranium data – without the need for dedicated "upward looking" detectors.

Conclusion

With this article, we have tried to show that there is lots of information present in your borehole data waiting to be extracted. Full spectrum analysis of gamma-ray data, powered by smart modelling-based calibration of SGR tools, has proven to be a very efficient way to get to that information.

[1] R. De Meijer, "Heavy minerals: from Edelstein to Einstein," *J. Geochemical Explor.*, pp. 81–103, 1998.

[2] D. J. Crossley and A. B. Reid, "Inversion of gamma-ray data for element abundances," *Geophysics*, vol. 47, no. 1, pp. 118–127, Jan. 1982.

[4] Data courtesy of Terratec Germany.

[3] R. Grasty, J. Glynn, and J. Grant, “The analysis of multichannel airborne gamma-ray spectra,” *Geophysics*, vol. 50, no. 12, pp. 2611–2620, 1985.

[4] E. R. van der Graaf, J. Limburg, R. L. Koomans, and M. Tijs, “Monte Carlo based calibration of scintillation detectors for laboratory and in situ gamma ray measurements.,” *J. Environ. Radioact.*, vol. 102, no. 3, pp. 270–82, Mar. 2011.

[5] D. Stromswold, “Calibration facilites for borehole and surface environmental radiation measurements,” *J. Radioanal. Nucl. Chem.*, vol. 194, no. 2, pp. 393–401, 1995.

[6] L. S. Waters, G. W. McKinney, J. W. Durkee, M. L. Fensin, J. S. Hendricks, M. R. James, R. C. Johns, and D. B. Pelowitz, “The MCNPX Monte Carlo radiation transport code,” in *AIP Conference Proceedings*, 2007, vol. 896, pp. 81–90.

[7] B. Minty, P. McFadden, and B. Kennett, “Multichannel processing for airborne gamma-ray spectrometry,” *Geophysics*, vol. 63, no. 6, pp. 1971–1985, 1998.

Figures

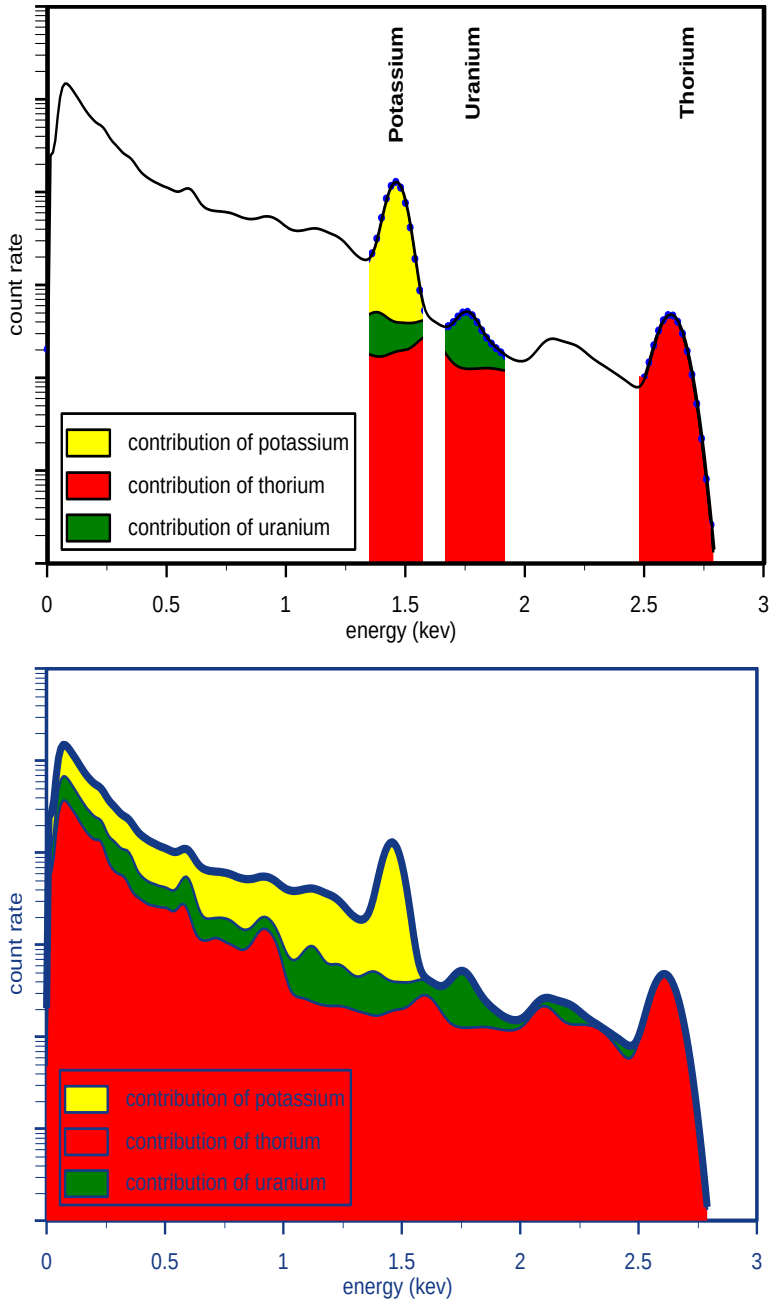

Figure 1 (Top) Spectral windows used in classic 3-Window analysis; (Bottom) in FSA, the full spectrum is used.

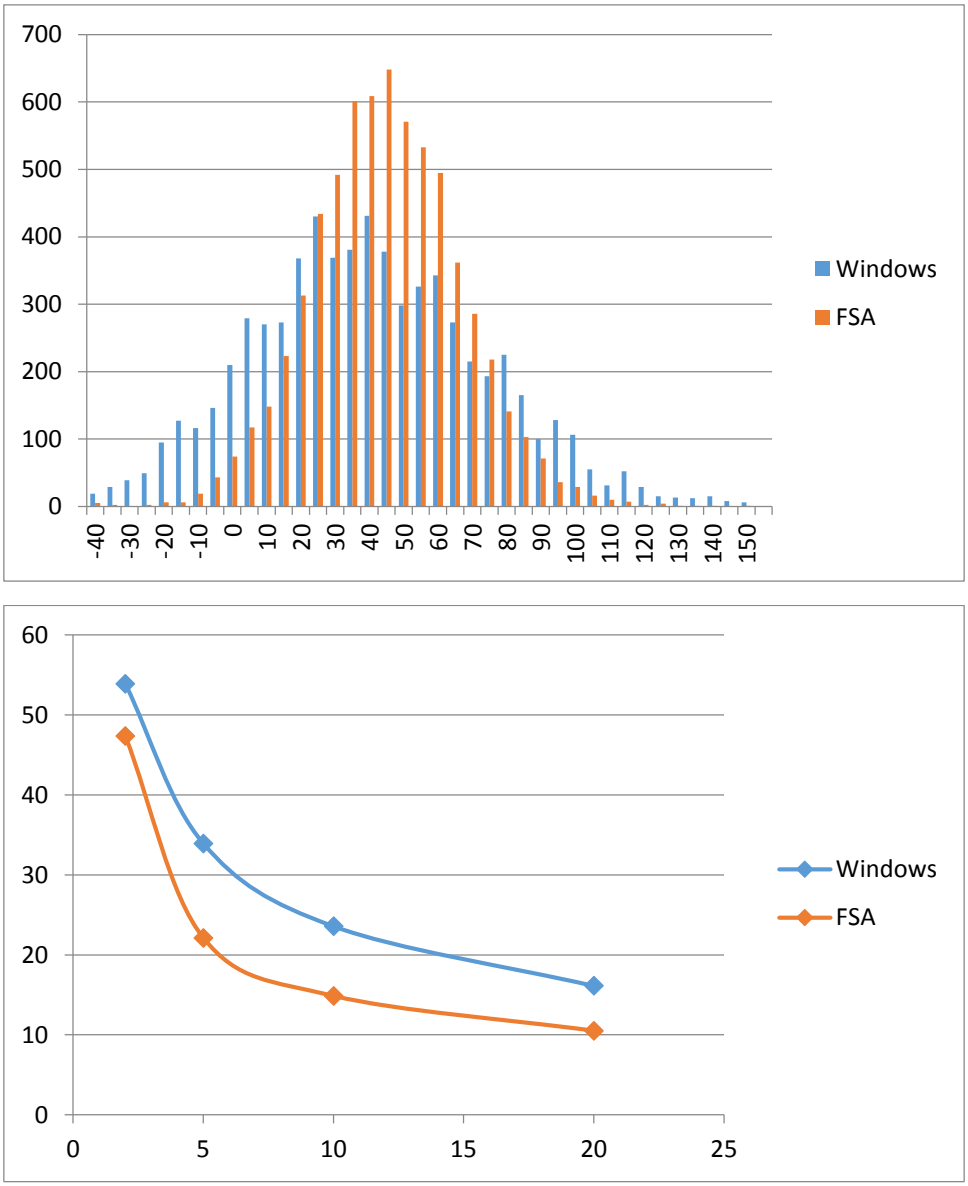

Figure 2 (Top) Distributions of ^{238}U activity concentrations as calculated with “3-Windows” (blue) versus FSA (orange) for a large number of a spectra measured in a fixed setup. (Bottom) Relative uncertainty in ^{232}U concentration found with FSA (lower curve) and 3-Windows (upper curve).

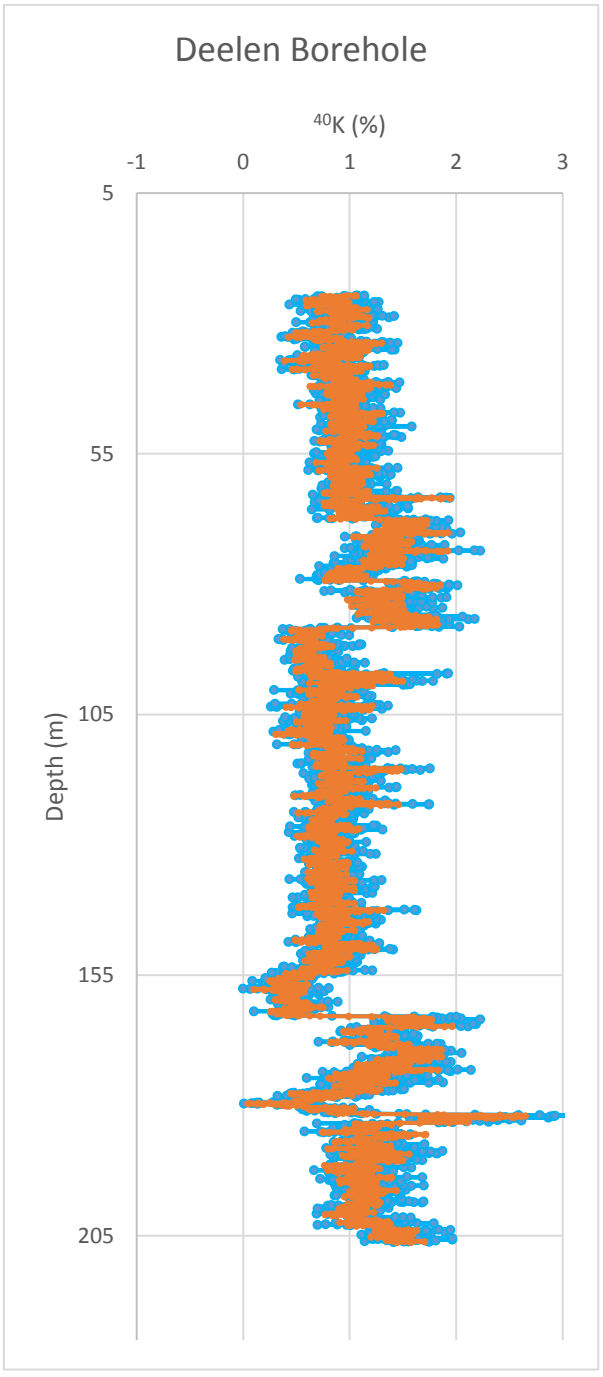

Figure 3. ^{40}K concentrations calculated from a spectral gamma log taken in a 200m deep borehole in The Netherlands. Tool: 50x150mm BGO (Antares Datensysteme). Data courtesy of TNO, NL. The data is plotted as two stacked curves. The blue curve (behind) is ^{40}K calculated using 3-Windeows. The orange (top) curve is ^{40}K calculated using FSA.

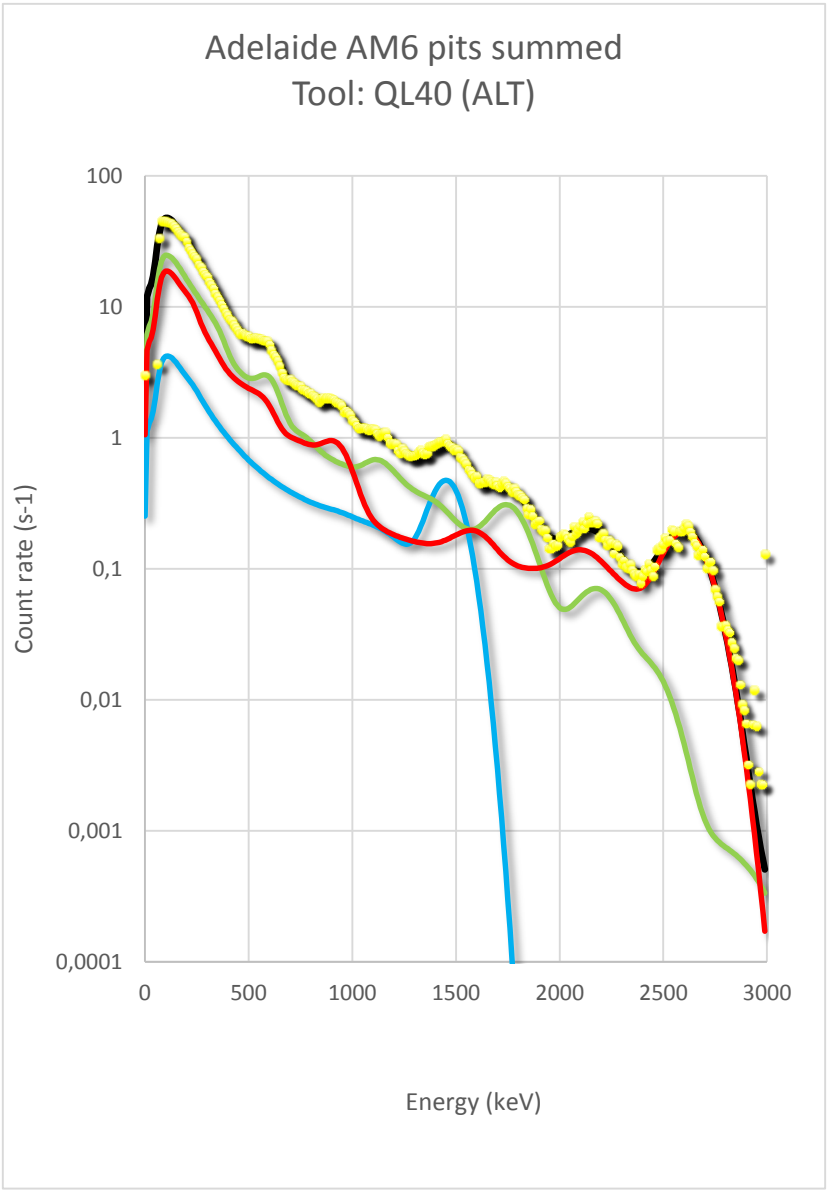

Figure 4. Spectrum (yellow dots) measured inside Adelaide Calibration Model AM6 (summed over K, U, Th regions). The blue, green and red curves are the calibration curves for ^{40}K, ^{238}U, ^{232}Th respectively. The black curve running through the yellow points is the result of fitting the calibration curves to the measured spectrum.

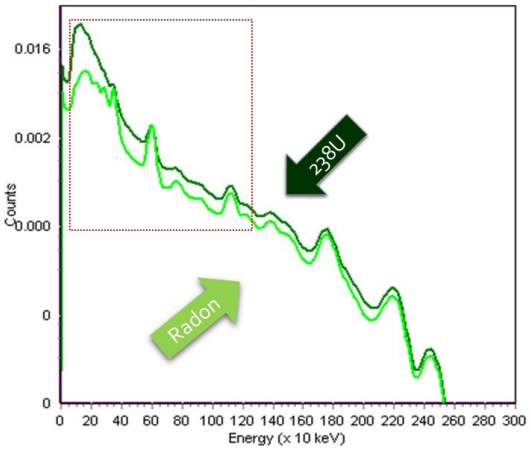

Figure 5. MCNP-X Simulated response curves for rock-bound ^{238}U (dark-green) and radon dissolved in borehole fluid (light-green).

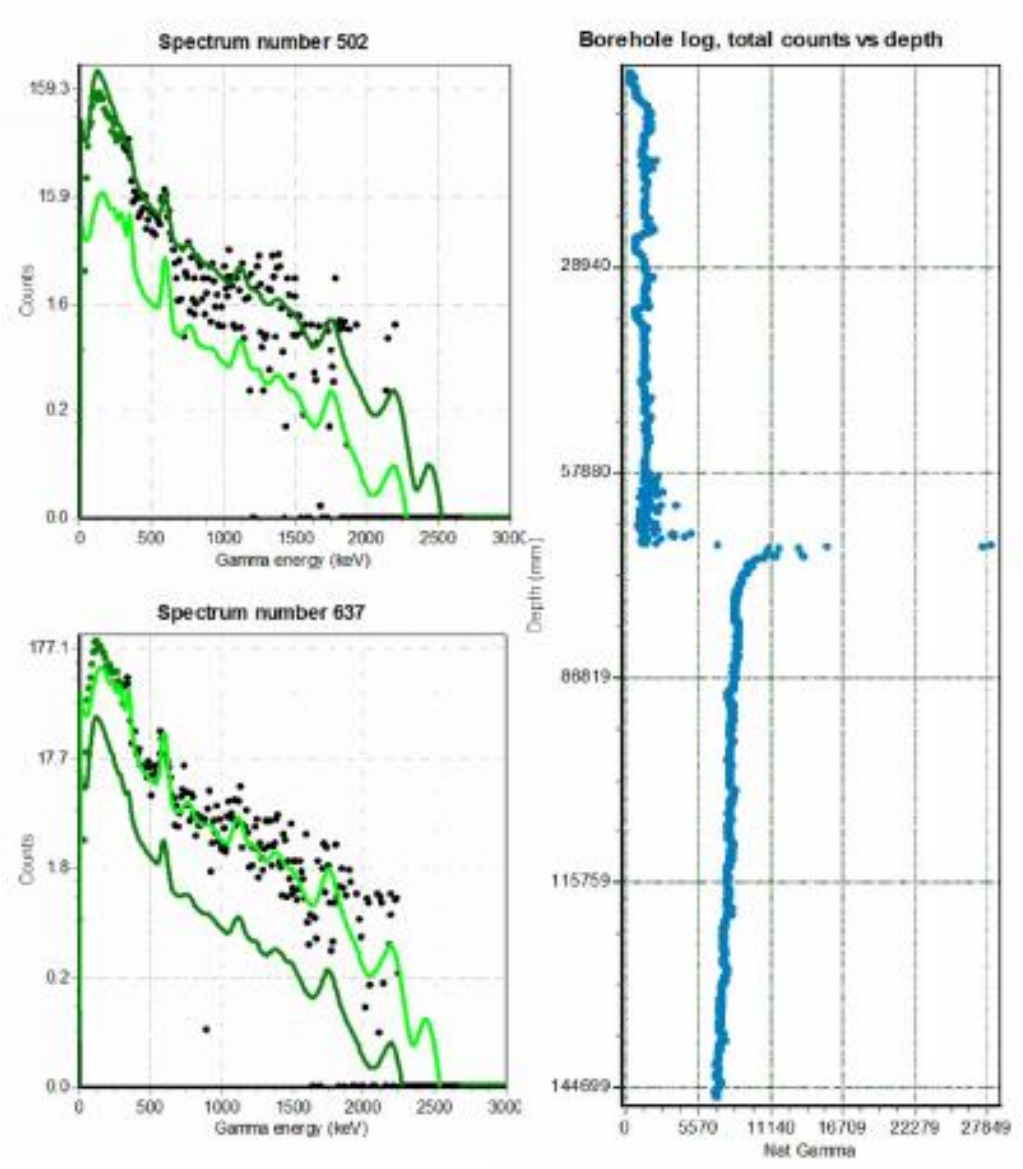

Figure 6. “Radon-suspicious” borehole log. The right part of the figure shows the count rate (nat gamma) per depth. Below about 60m, the nat gamma rate strongly increases. Left: spectra taken above the high countrate spot, and just below. The light-green curve is radon, the dark-green describes rock-bound uranium. Black dots depict the measured spectrum.