1. Overview

The logger’s job is not an easy one. We work outdoors. It can be raining or bitterly cold. The wind might be blowing up a storm in the middle of the night. The sonde might emerge from the borehole covered in thick grease or with a centraliser or caliper arm missing. The wireline (comprising slip rigs, cable, cable head, sonde head) regularly gives us problems...in fact, 90% of equipment issues seem to relate to the cable head.

All these things are sent to annoy us and distract us from doing the important things thoroughly...calibrate, run the sonde correctly, check log quality, complete the report, back-up the data, work safely.

One of the goals of the Wireline Workshop bulletin is to inform and to encourage the logger to bear all the minor vexations associated with the job and to conscientiously complete the important work that results in precise measurement. Precision relies on the logger and he will perform better and enjoy the job more if he understands the basic principles of wireline logging.

This issue celebrates our anniversary and reviews the first six bulletins and their overall message.

The geologist should help. All the logger asks for is a borehole that he can access with minimum risk...that is properly cased and capped and, where possible, smooth-side and full of fresh water.

<table>
<thead>
<tr>
<th>Eight Basic Questions for the Geo</th>
<th>More Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Is site access safe?</td>
<td>Directions? Road/track condition? Security required?</td>
</tr>
<tr>
<td>2. Is there a rig on site?</td>
<td>Will the rig be manned during logging operations?</td>
</tr>
<tr>
<td>3. What is the borehole name?</td>
<td>Name, run number, project, map location?</td>
</tr>
<tr>
<td>4. Is the borehole cased?</td>
<td>Casing type, internal diameter, depths?</td>
</tr>
<tr>
<td>5. What is the borehole depth?</td>
<td>Depth, diameter, any deflections, any drilling problems, caving?</td>
</tr>
<tr>
<td>6. Is there fluid in the borehole?</td>
<td>Water table depth, type of fluid, water loss during drilling?</td>
</tr>
<tr>
<td>7. Is the borehole nominally vertical?</td>
<td>What angle was the borehole drilled at from surface?</td>
</tr>
<tr>
<td>8. What measurements are required?</td>
<td>Zone of interest... TD to casing, TD to surface or other?</td>
</tr>
</tbody>
</table>
The object is to work safely and efficiently, avoiding delays and the need to hurry. It should be about making a careful and precise measurement in an environment that is as controlled as possible.

2. Review

A summary first six issues of the bulletin

The first borehole log, captured by Henri Doll, was a set of point measurements of depth against formation resistance...a log sampled at 1 metre intervals. Joining the dots resulted in a wiggly line (issue 1).

As an aid to oilfield exploration, this new tool was a great success. Why was it so well received in the marketplace? What is its appeal?

From the geologist's perspective (and that's the one that matters), the first wireline log would have been seen as an abstraction at first, appearing to be disassociated with the rock formations that it represented. The graphic description offered by the resistance log at Péchelbronn was unfamiliar but it was soon apparent that the wiggly line was defining something of interest - variations in the formation. If the log, and the various shapes within it, was a precise representation of rocks intersected by a borehole, it should describe the same formations intersected by other boreholes, in a similar way...it should correlate.

So the geologist was provided with an objective means of identifying unique rock formations and their boundaries and was able to correlate these hole to hole. The depth measurement had to be good, of course, and, as a bonus, the geologist could then check the veracity of the driller's metreage report.

Cross-hole correlation from linearly plotted single-point resistance logs

The wireline log was accepted in the oil exploration business immediately. It took a bit longer in mineral exploration but, as the range of measurements was expanded over time, obvious applications soon became apparent. Gamma ray for uranium exploration, density for coal and iron ore.

The logger harbours some disappointment that his density log is not used to measure coal quality despite laboratory estimations of in situ density being, at best, uncertain and lacking precision. However, density logging is not easy. In fact, it is the most difficult log to get right. The author has witnessed differences in logged density produced by different sonde designs. Calibrated measurements in coal varied by 0.1gm/cc. There is a need for the geologist to be part of the QA process. Perfect accuracy in coal is elusive.

A relevant test well is a fundamental requirement for log quality assurance in coalfield exploration...precision is the goal!

The object is to first assure measurement precision and then derive other parameters empirically using site specific formulae. Empiricism is the key.
Oilfield-quality logging tools for mines.

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Your mining operation demands exact data. Our proven Slimline evaluation tools and services acquire precise logging information, that empowers you to make informed decisions on how best to extract your resources.

With 40 years of experience in mineral exploration geophysics, we can help you accurately define your asset whether your target is coal, minerals, or unconventional hydrocarbons. Using small-diameter tools, we deliver high-resolution lithology, geomechanical properties, and ore boundary definitions for any asset.

Contact and collaborate with us at slimline@weatherford.com
Potentially then, the geologist can use logs of, among many, resistance, natural gamma and density to describe the rocks intersected by a borehole in precise terms that relate directly to the geology and can be compared hole to hole. If his gamma and density logs are quality assured, he can derive accurate measures of uranium grade and coal quality.

The standard **sonic** log is a measure of the transit time of a compression (P) wave through the formation. Sonic is a valuable log because it is largely unaffected by borehole conditions. Variables like fluid type and borehole diameter are deducted out of the equation. No calibration is required. Compensation for minor caving and near hole fracture effects is also possible. The sonic log is, fundamentally, precise.

The sonde can only work in a fluid-filled environment. Gas bubbles in the borehole column will adversely affect log quality, often making the measurement impossible. In hard rocks, the first arrival (the P front) is very weak (small amplitude). An eccentrically positioned sonde will cause a smeared rather than discrete arrival. So logs run through an angled borehole drilled through hard formations are particularly vulnerable to poor first arrival discrimination and result in a spiky log. Logs run in (non-gassy) sedimentary rocks are expected to be of good quality.

The log below illustrates the sensitivity of the sonic log to small changes in physical properties of clastic sedimentary rocks. Coal is described similarly by both density and sonic logs but the sonic description of the baseline sediments offers a better definition of the mudstone layer between 210 and 225 metres. Like density, P-wave sonic is a log of porosity in clean (sandstone, limestone) formations but reacts rather differently to the presence of clay minerals (longer transit time).

The **full waveform sonic** log offers a bit more than the standard version. A recording of the full waveform at regular depth intervals allows discrimination of the important shear wave and, when required, the Stoneley (tube) wave and its reflections as well (see log below). Again, there is no requirement for calibration and the measurement is, fundamentally, precise. The data processing effort is usually significant.
An extended full waveform sonic log showing reflected tube waves

The FWS log, discussed in issue 2 (November 2013), offers several advantages:

- The FWS log may be captured through PVC pipe
- Poorly discriminated logs can be repaired (manually if necessary)
- Fractured zones are clearly described (the shear wave is not supported by water)
- The reflected tube wave (RTW) chevrons point to open fracture apertures
- The amplitude of the first arrival can be measured and used as a cement bond log
- Logs can be captured in very slow formations and big diameter boreholes

The main uses of the FWS log are QA (very necessary in some boreholes) and, importantly, measurement of the shear-wave transit time, as a geotechnical tool.

The S-wave front may be picked manually on two images and a transit time log arrived at by deduction. More often, if three or more waveforms are available, semblance analysis is employed. This results in a more precise measurement of S-wave transit time. The shear front vanishes in soft/slow formations.

When the P-wave velocity through the borehole fluid is higher than the S-wave velocity in the formation, the sonic energy is refracted away from the borehole and does not reach the receivers.

The resulting gaps in the shear wave log are bridged using one of several empirically based formulae that convert density and/or other sonic logs to an estimation of the shear wave transit time in slow formations. These processes will not be perfectly accurate but, importantly, they will be precise.

The full wave sonic log (VDL image) and its derived P-wave and S-wave logs are regularly used, with density, in estimations of geotechnical parameters such as rock strength and elasticity. The precision offered by the sonic log is a major benefit in rock mechanics.

The capture of a precise and (within tolerance) accurate density log, however, is less straightforward.
The density log is discussed in issue 3 (January 2014). Given a well designed calibration system, a precise density log of smooth-sided cored boreholes should be expected. The test well offers a check on logger performance in this regard. It also allows the geologist to ascertain log accuracy assuming that he has conducted a rigorous analysis of core densities in his laboratory. Ultimately, on this basis, he may chose between the logger’s measure of in-situ density and his own version that might be extrapolated from crushed samples or measured using the Archimedean emersion technique. If there is a significant difference between densities the geologist should enquire as to whether an effective Z/A (chemistry) compensation has been applied to the data.

Problems occur in borehole conditions that diverge from the standard. A different bit size, caving, wet or dry hole environment. All these changes result in a telltale separation of calibrated long and short spaced density curves.

Separation results from the fact that the shorter spaced log measures a smaller volume of rock/ fluid than the longer spaced version and is therefore more affected by anomalies on the borehole wall. Density logs may be calibrated and borehole diameter compensated for using empirically-based corrections. This should result in good log overlay in straight borehole conditions. If the logs’ different but proportional responses to mud cake and minor caving can be characterised, they may be used to correct at least one of the logs (issue 3).

A properly calibrated and borehole compensated density log combined with the very precise sonic log offers a measure of intact rock properties that are of interest to the geotechnical engineer (issue 4 March 2014). The logs, or combinations of them, have been proved to have a strong relationship with both intact rock strength (IRS) and rock mass elasticity. The "dynamic" derivatives of wireline logs do not agree perfectly with "static" (laboratory) measurements. The elastic moduli values are greater than corresponding static moduli obtained in laboratory testing. These differences are attributed to the differences in the strain (rock particle displacements) between the very small strains caused by the propagation of seismic waves (order of microstrains) and the much larger strains imparted on a rock during laboratory testing and during mining (order of millistrains). Presumably rocks appear stiffer under the small strains imparted by the propagation of sonic waves because micro-cracks and pores do not experience as much closure (Hatherly, issue 4).

Notwithstanding the fact that an absolute measurement is not reliable, the shape of the various derived logs fits well onto scattered static data and may be empirically corrected...offering more detail, no gaps and a high level of precision.
Having established a rigorous method of describing intact rock properties, the logger can consider also provide an in-situ and objective analysis of the fracture regime. He can capture an orientated map of all discontinuities, both natural and drilling-induced, as well as a reliable indication of the prevailing stress orientation. The tool is the sonic-based acoustic televiewer. This tool has, over the last few years, reinvigorated the mineral logging industry.

**An acoustic televiewer log with density**

The televiewer log offers very high resolution, resulting in a description of most relevant fractures as well as excellent boundary definition. The log presentation on the right is typical, with reflection time (grey image) and reflected amplitude displayed side by side. Compare the density log on the right with the acoustic amplitude image in the centre.

The latest televiewer sondes offer an image resolution of about 2mm, depending on borehole diameter.

![An 1:1 scale amplitude image in HQ bore](image)

The televiewer is an excellent geotechnical tool because the image is described in terms of rock hardness. The returning sonic pulse has a higher amplitude if reflected off a harder surface. In the two examples on this page, lighter colours represent higher amplitude. The images are orientated by a navigation system that incorporates magnetometers...so magnetic formations will affect the quality of the data set. There are ways around this problem that are described in issue 5.

Events on the image are normally manually picked and classified although there are some automated picking systems available in the marketplace.

The geologist should not assume that the supplied image is orientated correctly every time. There have been numerous examples of errors in this respect. A log of an orientated test jig should be a standard deliverable.

**Loggers - use the Test Jig routinely to QA your data!**
Data processing and analysis is complex. Generally, from a geotechnical perspective, the identification of drilling-induced fractures (DIFs) is the key. This can be difficult, particularly in hard rocks that are intersected by an angled borehole (with respect to the current stress regime). Fracture identification is dealt with in issue 5.

Sonic-based measurements require a fluid-filled environment in order to function. In dry boreholes, the logger can either top-up with water or employ the optical televiwer. This device offers a light-based image of the borehole wall...a continuous orientated photograph. There is no time image but, perhaps, more geological knowledge is available from the log. It will not work well in opaque borehole fluids, for obvious reasons. Examples of the optical televiwer image are shown in issue 6.

The optical tool is particularly effective in metamorphosed sediments. Iron ore deposits with complex folded and faulted structure are well described and, very often, the borehole fluid in these environments remains clean. Running optical televiwer with density and, when relevant, a magnetic susceptibility sonde, provides a very powerful iron ore logging suite. Factors affecting the logging of high density associated with iron ore prospects is discussed in issue 6.

Given the correct compensation for the Z/A ratios applying to haematite or magnetite (they are very similar) and given a smooth-sided borehole, density logs in iron ore should be very accurate. If the borehole walls are not smooth and regular, either caving or percussion-drilled, then any sonde, regardless of whether its source of radiation is caesium or cobalt, will understate density to some degree. In severely caved boreholes, the data will be difficult to interpret reliably.

3. Measurement Focus (part 1)
A review of one wireline log measurement

The (Total) Natural Gamma Ray Log

When we discuss the natural gamma ray log, we are normally referring to total gamma radiation emitted by the formation. The radiation detector, most often a sodium iodide (NaI) crystal, is usually one of several measuring devices housed in a sonde. The gamma ray log is employed as a descriptor of lithology and a measure of uranium or (recently) potash grade. It is also used to depth match multiple logs from independent tool runs, where each tool carries a gamma ray detector.

This is a log of formation chemistry (it logs the matrix not the pore spaces) and it is largely unaffected by borehole condition or fluid level.

Some homespun science for the logger

Gamma radiation is one type of energy. It is excess energy no longer required by the nucleus of an atom after it has disintegrated. Disintegration occurs because a particular atom is unstable and, spontaneously, at an unpredictable moment, discharges some nucleons (protons and neutrons) in an attempt to decay to a stable and smaller form and a different element. The radiating nucleons, two protons and two neutrons (equivalent to a helium atom) are referred to as Alpha radiation which has both velocity and mass but very limited range or penetration. Losing two protons results in the atom being transformed into a different element, dropping by two atomic numbers on the periodic table of elements. Alpha radiation is not used in wireline logging.
In some instances, disintegration occurs when a neutron decays to a proton within the nucleus by ejecting an electron (a neutron can be thought of as a proton and an electron combined, hence no charge). With an extra proton, the atom climbs one elemental place on the periodic table. This form of isotopic decay is known as Beta radiation. It is not used in wireline logging.

After Alpha radiation, the now smaller nucleus requires less energy to bind together, so a package of all the excess energy is jettisoned in the form of a photon called a gamma ray. It is pure energy, having velocity and some effective mass based on that velocity (relativistic mass). It can interact with objects that have very low mass, electrons for instance. Gamma radiation is very useful to the logger in more than one application.

When a gamma ray strikes an electron it might have sufficient energy to eject the electron from its location in an atom. The atom, with one less negative particle, becomes a positively charged ion. This type of high energy interaction is referred to as ionising radiation. Ionising atoms in human tissue can be harmful.

Why are some atoms unstable? Each atom is an isotope (version) of a particular element. It will have a prescriptive number of protons (that's the unique atomic number associated with an element) but a variable number of neutrons. Protons exert repellent electromagnetic force as well as binding nuclear force. Neutrons, having no charge, exert only the binding force. Bigger atoms need more neutrons to hold their nuclei together but, quite often, the combination is not quite right and the atom is unstable. It will disintegrate, sooner or later.

All elements may have unstable isotopes, many of which are synthetically made by man. Some elemental atoms, all those above atomic number 82, are so large that they have no stable isotopes. These will all, ultimately, decay to the largest stable isotopes of lead or thallium (see table below).

<table>
<thead>
<tr>
<th>Z</th>
<th>Name</th>
<th>Symbol/isotope</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hydrogen</td>
<td>(^1\text{H})</td>
<td>Stable, Z/A = 1, 1 proton</td>
</tr>
<tr>
<td>12</td>
<td>Magnesium</td>
<td>(^{24}\text{Mg})</td>
<td>Stable with 12 protons and 12 neutrons</td>
</tr>
<tr>
<td>13</td>
<td>Aluminium</td>
<td>(^{27}\text{Al})</td>
<td>Stable with 13 protons and 14 neutrons</td>
</tr>
<tr>
<td>17</td>
<td>Chlorine</td>
<td>(^{35}\text{Cl})</td>
<td>Stable with 17 protons and 18 neutrons</td>
</tr>
<tr>
<td>14</td>
<td>Silicon</td>
<td>(^{28}\text{Si})</td>
<td>Stable with 14 protons and 14 neutrons</td>
</tr>
<tr>
<td>19</td>
<td>Potassium</td>
<td>(^{40}\text{K})</td>
<td>Unstable with 19 protons and 21 neutrons</td>
</tr>
<tr>
<td>26</td>
<td>Iron</td>
<td>(^{56}\text{Fe})</td>
<td>Stable with 26 protons and 30 neutrons</td>
</tr>
<tr>
<td>55</td>
<td>Caesium</td>
<td>(^{133}\text{Cs})</td>
<td>Stable with 55 protons and 78 neutrons</td>
</tr>
<tr>
<td>79</td>
<td>Gold</td>
<td>(^{197}\text{Au})</td>
<td>Stable with 79 protons and 118 neutrons</td>
</tr>
<tr>
<td>81</td>
<td>Thallium</td>
<td>(^{205}\text{TI})</td>
<td>Stable with 81 protons and 124 neutrons</td>
</tr>
<tr>
<td>82</td>
<td>Lead</td>
<td>(^{207}\text{Pb})</td>
<td>Stable with 82 protons and 125 neutrons</td>
</tr>
<tr>
<td>83</td>
<td>Bismuth</td>
<td>(^{209}\text{Bi})</td>
<td>Unstable with 83 protons and 126 neutrons</td>
</tr>
<tr>
<td>88</td>
<td>Radium</td>
<td>(^{226}\text{Ra})</td>
<td>Unstable with 88 protons and 138 neutrons</td>
</tr>
<tr>
<td>90</td>
<td>Thorium</td>
<td>(^{232}\text{Th})</td>
<td>Unstable with 90 protons and 142 neutrons</td>
</tr>
<tr>
<td>92</td>
<td>Uranium</td>
<td>(^{235}\text{U})</td>
<td>Unstable with 92 protons and 143 neutrons (fissile)</td>
</tr>
<tr>
<td>92</td>
<td>Uranium</td>
<td>(^{238}\text{U})</td>
<td>Unstable with 92 protons and 146 neutrons</td>
</tr>
<tr>
<td>95</td>
<td>Americium</td>
<td>(^{241}\text{Am})</td>
<td>Unstable with 95 protons and 146 neutrons</td>
</tr>
</tbody>
</table>

The periodic table is useful to the mineral logger in density measurement, where he is interested in the number of nucleons versus the number of electrons counted by his density sonde (see issue 3). The complete list also describes the common radioactive elements. Emboldened in the table are the four naturally occurring radioactive isotopes that matter to the logger, due to their long half-lives and relative abundance (the rest are found in only trace amounts). Note that the U atom (Z is 92) has a long journey to reach stability at Pb (Z is 82).
The term **half-life** is used because, due to the unpredictable nature of radioactive decay, it is impossible to measure the total radioactive life of an isotope. In any teaspoon of uranium, there will probably be at least one atom that stubbornly refuses to decay even by the time the lights go out in the Universe. However, by measuring the activity (disintegrations per second) of a sample, it is possible to determine at what time half the atoms will have disintegrated. This is the half-life of the isotope.

<table>
<thead>
<tr>
<th>Element</th>
<th>Isotope</th>
<th>Half-life</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potassium</td>
<td>$^{40}$K</td>
<td>1.25 billion years</td>
<td>Comprises 0.012% of K on Earth. Stable $^{39}$K is far more common (93%).</td>
</tr>
<tr>
<td>Uranium</td>
<td>$^{235}$U</td>
<td>0.704 billion years</td>
<td>Sought-after, due to fissile nature (only 0.72% of all U on Earth).</td>
</tr>
<tr>
<td>Uranium</td>
<td>$^{238}$U</td>
<td>4.47 billion years</td>
<td>99.3% of all U on Earth.</td>
</tr>
<tr>
<td>Thorium</td>
<td>$^{232}$Th</td>
<td>14.05 billion years</td>
<td>This isotope represents, effectively, 100% of all Th on Earth.</td>
</tr>
</tbody>
</table>

Such long half-lives make the term unstable seem inappropriate but in our spoonful of uranium ($^{238}$U) there would be enough atoms to average a disintegration rate of about 220,000 per second (by definition; 220 kilobecquerels).

Surprisingly perhaps, the gamma ray produced by the decay of a uranium atom is very weak (low energy) and cannot normally be measured by the logger. He can, however, detect the gamma rays produced by the decay of some of the element's progeny (daughter isotopes). Refer to the diagrams in section 4. Each unstable atom expels a gamma ray of unique energy when it decays to the next isotopic stage in its journey to stability.

The total gamma ray log is a measure of just that, all sources of radiation in the formation. These comprise potassium ($^{40}$K has no unstable progeny), the uranium family and the thorium family.

**Why do we log Total Gamma Ray?**

K, U and Th are found throughout the Earth's crust. K is a significant element of feldspar which weathers to clay. K ions fit particularly well into the silicate structure of the mica group of clay-sized minerals, particularly illite. Note that $^{40}$K, the radioactive isotope, comprises just 0.012% of all K but the radioactivity of feldspar, for instance, is relatively high.

Clay minerals have a negatively charged platelet structure within which potassium, thorium and uranium cations are adsorbed in order to balance its electric charge. Larger atoms tend to carry a higher charge. In sedimentary rocks, the gamma log is a measure of clay-shale fraction. 'Clean' sandstone exhibits low gamma readings whereas shale counts are relatively high, often over 100 API. Clean coal and limestone, are described by very low natural gamma values. Mudstone is middle to high counts. Most mafic igneous rocks have very low gamma signatures. Uranium is often associated with organic deposits such as black shale. Thorium is deposited within clay lattices but also independently as part of clay-sized detrital grains.
In sedimentary rocks, high natural gamma counts normally mean high clay fraction.

API (American Petroleum Institute) is a unit of total gamma radiation based on a standard housed at Houston University in Texas. All industry calibrators are referenced to that standard, which is given a value of 200 API or twice that of a typical mid-continental shale in the USA.

The log on the right represents a common presentation of total gamma ray counts calibrated to API units. Vertical resolution depends on bore diameter but is in the order of 20 centimetres in slim boreholes.

Notice the fining upward trends. These represent gradual reductions in depositional energy over time...channel sandstone grains to fine clay-rich mud.

There is one anomalous peak at 534 metres, towards the bottom of the log. Of the K, U and Th contributors to the total gamma log, U is the odd man out in the sense that uranium salt is soluble in and easily transported by groundwater. Discrete peaks on the total gamma log often represent transported U concentrations in fractured formations.

The natural gamma ray log is normally used qualitatively.

In oilfield logging, the gamma ray measurement, introduced in 1939 by Well Surveys Inc., is, with the exception of some application in shale volume calculation, a qualitative measurement. It is considered an unreliable lithological typing tool if employed in isolation. It is however a powerful correlation device and general depth reference. The log retains significant value due to it being able to describe lithology through casing or drill pipe.

In mineral logging, the measurement is used for lithological analysis (a grain size log), depositional sequencing, for coal seam thickness and can be used quantitatively in uranium and potash logging. The
measurement has value in both sedimentary and igneous environments as a cross-hole correlation tool.

**Gamma signatures in igneous rocks**

The log on the right shows gamma ray logs (plotted on logarithmic scales) captured in two vertical exploration boreholes, drilled 500 metres apart, through ultramafic igneous rocks. The multiple sharp peaks are intrusives but, ignoring these, one can clearly correlate the various magmatic layers.

The author recently conducted an underground logging trial where horizontal boreholes were drilled through dolomite host rocks into a kimberlite pipe. The geologist wanted to describe the boundary between dolomite and kimberlite, in terms of distance from the collar, without having to drill core (an expensive option).

The sonde was manually delivered to the end of a 24 metre long borehole by means of a set of drain rods. It was then logged outwards, using a small electric winch, at a constant (low) speed. The key was to maintain tight wireline contact with the depth wheel throughout the job.

**For best results - log slowly.**

The gamma log is not an absolute measurement. It is stochastic in nature, an average of statistics. Logging slowly results in more statistics averaged per depth datum and so a better representation of the formation and a less 'noisy' log curve.

A simple gamma ray log from a horizontally drilled borehole with blocks defined and averaged

It was expected that dolomite would exhibit low gamma values and kimberlite higher ones. Several boreholes were logged using a simple gamma sonde and the prediction was proved to be correct. Added value was gained by comparing count rates within the kimberlite formations.

This was a simple but very effective use of a natural gamma ray sonde.

Normalisation of the total gamma log usually involves attaching a calibrated radium jig (half-life of $^{226}\text{Ra}$ is 1602 years). These jigs normally fall within the activity range that requires permissions from the local Department of Health.

One can build calibrators from readily available materials when necessary but one would have to calibrate these against a known reference that is based on the Houston standard. Some potash fertilisers, for instance, include over 35% potassium and are sufficiently radioactive to make a base jig after mixing with cement and pouring into a drum.
4. Guest Article 1
A quick guide to a related discipline

Airborne Radiometric Surveys

Introduction
To extend the topic of this issue, which is natural gamma logging, to something rather different but still closely related, we will present an introduction to airborne radiometric surveys. Airborne radiometric surveys, using non-invasive, passive recording methods, are used in environmental, engineering, mining, mapping, mineral exploration and petroleum exploration.

In this article the theory behind radiometric surveys is exposed in simple terms. It is also shown how important calibrations and corrections of the measured signal are to obtain good data that can be interpreted in terms of ground concentrations of the radio-elements.

Theory
All rocks and soils naturally emit different amounts of radiation (i.e. radioactivity). The radioactivity originates from the disintegration of unstable isotopes (elements with the same number of protons but different numbers of neutrons) into stable elements. There are three types of common radiation: alpha particles, beta particles and gamma rays. Alpha (2 protons) and beta (one electron) particles are short-lived particles that cannot travel very far from their point of emission as they interact with the surroundings atoms and lose their energy very quickly.

Gamma radiation, on the other hand, is part of the electromagnetic spectrum (cf. visible light, infra-red radiation, ultra-violet light, radio waves and X-rays). Gamma rays are highly energetic and are poor at interacting with other atoms and molecules in air. They can travel several hundred metres in the air, but are rapidly absorbed when passing through solid material (measured gamma-rays reflect concentrations in the upper 50 cm of the earth). The gamma ray count decreases as an exponential function with distance from the source.

Gamma rays have energy characteristic of the isotope from which they originated. Although many naturally occurring elements have radioactive isotopes, only potassium (K), thorium (Th) and uranium (U) decay series, have radio-elements producing high energy gamma rays of sufficient intensities to be recorded by gamma ray instruments.

Potassium abundance (concentration) is measured using the 1.46 MeV gamma-ray photons emitted when $^{40}$K decays to $^{40}$Ar (argon). Uranium and Thorium concentrations are measured from daughter nuclides in their respective decay series. Distinct emission peaks associated with $^{214}$Bi (bismuth, a daughter product in the $^{238}$U decay series) and $^{208}$Tl (thallium, a daughter product in the $^{232}$Th decay series) at 1.76 MeV and 2.614 MeV, are used to estimate the concentrations of U and Th, respectively (see below).

The estimation of U and Th using daughter isotopes in their respective decay series is based on the assumption that their radioactive decay series are in equilibrium. However, disequilibrium is not uncommon in the $^{232}$Th and $^{238}$U decay series and it is customary to use the units of "equivalent" parts per million (eU and eTh) to give the concentrations of thorium and uranium.

The radiometric method samples and digitizes a complete gamma-ray spectrum over a finite number of windows (typically 256) every second.

The average concentrations in common rocks and soils of the naturally occurring K, Th and U radio-elements is given in the table below. Potassium represents about 2% of Earth’s crust, while uranium and thorium represents ~1.2 ppm and ~9 ppm of Earth’s crust respectively.

<table>
<thead>
<tr>
<th>Rock types</th>
<th>Average concentrations of rocks</th>
<th>Average concentrations of soils</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K (%)</td>
<td>U (ppm)</td>
</tr>
<tr>
<td><strong>Intrusives</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Granitoids</td>
<td>2.4</td>
<td>3.3</td>
</tr>
<tr>
<td>Gneissic rock</td>
<td>2.4</td>
<td>2.5</td>
</tr>
<tr>
<td>Pegmatite</td>
<td>3.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Aplites</td>
<td>2.4</td>
<td>3.3</td>
</tr>
<tr>
<td>Quartz-feldspar porphyry</td>
<td>2.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Intermediate intrusives</td>
<td>2.7</td>
<td>0.8</td>
</tr>
<tr>
<td>Mafic intrusives</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Extrusives</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Felsic volcanics</td>
<td>3.7</td>
<td>2.4</td>
</tr>
<tr>
<td>Intermediate volcanics</td>
<td>2.7</td>
<td>2.3</td>
</tr>
<tr>
<td>Low-Kandesites</td>
<td>0.8</td>
<td>1.6</td>
</tr>
<tr>
<td>Mafic volcanics</td>
<td>0.9</td>
<td>0.7</td>
</tr>
<tr>
<td>Ultramafic volcanics</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td><strong>Sedimentary rocks</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Archaean shales</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Other shales</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Arenites</td>
<td>1.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Carbonates</td>
<td>0.2</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Average concentration of K, U & Th in rocks and soils (modified from Dickson and Scott, 1997)
Gamma-rays emitted from each radio nuclide occur at specific frequencies and can then be measured. A spectrometer instrument records the gamma radiation from the ambient radio-activity that hits the spectrometer’s crystal detectors (usually made of sodium-iodide, NaI).

Distinct parts (windows) of the gamma-ray spectrum are used to compute the K, eU and eTh concentrations and the Total Count, which encompasses most of the gamma-ray spectrum. A typical gamma-ray spectrum in shows high counts (y-axis) at low energies (x-axis) evolving to low counts at high energies. This is due to Compton scattering: a contamination of high energy gamma-rays into low energy gamma-rays. Compton scattering is the dominant gamma radiation process at the energies under consideration.

In airborne surveys, gamma-rays recorded by the radiometric system originate from the very top layer of outcropping rocks/soil (less than 50 cm deep) but also from other, non-geological, sources: i.e. cosmic radiation, aircraft radiometric signature and radon radiation.

The recorded spectra thus need to be corrected from those non-geological sources to obtain the radiation from the ground only. The entire system is further complicated by the fact that the source-detector geometry also affects the recorded gamma rays rates (IAEA, 2003). The corrections involve the computation of empirical coefficients obtained by calibrations of the entire system.

Calibrations are either periodic (recommended period is every 12 months (IAEA, 2003) or after significant changes in the system) or in-survey. The periodic calibrations are the pads calibration (for Compton scattering and sensitivity changes) and the calibration range (for height attenuation, aircraft background, cosmic background, radon calibration and detector and spectrometer resolutions). The in-survey calibrations are the detector and spectrometer resolution tests, the thorium source tests, the survey test line and the spectrum stability monitoring.

**Conclusions**

The theory behind airborne radiometric surveys has been introduced and it has been shown why calibrations are an essential part of the method.

Some applications of airborne gamma ray include uranium exploration, regolith mapping, alteration halo mapping for mining exploration, seepage detection in petroleum exploration, environmental application such as nuclear contamination mapping or nuclear debris search (e.g. radioactive parts of fallen satellites), soil mapping for agriculture and land use studies, geological mapping and hydro-geological mapping.

**References**


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5. The logger on site

Check the fluid level

The fluid level is quite important to gamma and density logs, particularly if both are run as part of the same tool combination. Of the density logs, the Long Spaced Density (LSD) is most affected and will shift to the left if no compensation is applied, causing LSD and BRD (or HRD) to separate. This is diagnostic of fluid level depth.

As the radioactive source leaves the fluid, natural gamma counts increase
because there is no longer water between source and distant gamma detector. This is more marked in large diameter boreholes. It is not diagnostic of exact fluid depth because the detector is some distance above the fluid as the source emerges from its shielding effect. If a good gamma log is required and/or fluid levels are deep, the logger should relog the combination sonde with source removed. This will result in a good gamma log that is easily depth-matched with the original.

6. Measurement Focus (part 2)

The Spectral Gamma Ray Log

The mineral gamma ray detector normally comprises a scintillation crystal observed by a photo-multiplier tube. The use of Geiger Muller (gas) tubes has fallen away due to their relative lack of efficiency although they retain a role in oilfield measurement while drilling (MWD) operations because of their ruggedness.

A scintillation crystal

Various crystal types are available and they each have positives and negatives in terms of applicability. The standard mineral scintillation detector is a sodium iodide crystal doped with a stable isotope of thallium (\(^{205}\text{TI}\)).

An incident gamma ray interacts with electrons in the crystal, scattering them. These in turn scatter other electrons, with gradually diminishing energy, until these are captured within the large cloud of electrons surrounding the thallium nuclei. Resulting excess energy is released as a photon of visible light. The flash of light is converted to an electronic pulse by a photo-multiplier tube. The brightness of the photon (by then the amplitude of an analogue pulse) is a function of the incident gamma ray’s energy.

If the crystal becomes opaque, it will be far less efficient and should be discarded. If it cracks badly or is shattered it should be disposed or carefully and responsibly (not on the local dump) due to the risk of thallium poisoning. The problem with the sodium iodide crystal is that it is rather fragile; it is not wise to drop a sonde. A cracked crystal remains effective enough as an uncalibrated gamma detector used for depth reference only.

Handle the spectral gamma sonde with care - watch both ends.

The Spectral gamma sonde records count rates at energy gates throughout the KUT spectrum, usually 254 or 1024 channels to 3MeV. It has a large crystal and is run very slowly; usually at 1 metre per minute in mineral exploration boreholes. The object is to measure K, U and Th contributions. In the case of U and Th, their prominent daughters, Bismuth and Thallium respectively, are much easier to measure than the parent isotope.

Seen on the spectrum (refer to the diagrams in section 4), the various peaks can look confusing. They are not discrete events because of the additional effect of Compton scattering - all the gamma rays are gradually losing energy and, in effect, drifting to the left on the spectrum. So each window below \(^{208}\text{TI}\) might include counts from a particular isotope plus lots of decaying gamma rays from isotopes of (originally) higher energy.

A typical spectral gamma sonde employs three windows, centred on the energy peaks of the relevant K, Bi and Tl isotopes.

<table>
<thead>
<tr>
<th>Isotope measured</th>
<th>Isotope (daughter) targeted</th>
<th>Characteristic energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potassium K(^{40})</td>
<td>Potassium K(^{40})</td>
<td>1.46 MeV</td>
</tr>
<tr>
<td>Uranium U(^{235}) and U(^{238})</td>
<td>Bismuth Bi(^{214})</td>
<td>1.76 MeV</td>
</tr>
<tr>
<td>Thorium Th(^{232})</td>
<td>Thallium Tl(^{208})</td>
<td>2.62 MeV</td>
</tr>
</tbody>
</table>

Calibration is performed by recording count rates at each window while sources of K, U, Th and background are positioned next to the detector. These become constants within an algorithm that transforms raw data from three channels to K (percentage by weight), U and Th (parts per million).
The variable thereafter is signal drift caused by temperature. NaI crystals perform differently as temperature varies. The traditional way to overcome this problem is to use a reference to track and correct the drift, either the potassium peak or, more often, a $^{137}\text{Cs}$ peak created within the spectrum (at 662KeV) by the inclusion of a very small radioactive source within the sonde.

**This is a lithological analysis tool.**

The automatically stabilised spectral gamma sonde provides logs of K, U and Th and their ratios for use in cross-hole correlation and clay typing studies (see section 8). It will also work well in potash exploration. **It is not a uranium logging tool** because the reference source peak will be swamped by counts from U daughters. In uranium exploration, separation of U and Th might be useful in some circumstances and the spectrum offers a view on equilibrium. In this case no automatic stabilisation is applied in the sonde. It is performed retrospectively. Uranium logging is discussed in a later issue of the Bulletin.

### 7. Guest Article 2

**A calibration system for Spectral Gamma sondes**

**When every count counts**

**Introduction**

Spectral Gamma-ray (SGR) logging is an effective way to obtain **lithological** information of the subsurface. SGR tools are very useful in mining exploration. 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 type etc.

Traditionally, the acquisition and analysis of spectral gamma data employed the so-called 3-window method described in section 6.

**Full Spectrum Analysis**

By using only peak counts, a large part of the spectral data is thrown away. This was already recognized in the early 1980s, for instance by Grasty et al, who proposed a multi-window approach rather than the limited 3-Windows method. Computers are now powerful enough to allow for FSA, even to analyze spectral data while logging.

To compare the analysis methods, one should define a measure for quality of data. For SGR tools, quality is a mix of **accuracy** (how well the tool/analysis method reproduces the KUTh concentrations) and **precision** (the spread in the concentrations).

The effect on data quality of including all spectral data in the analysis is illustrated on the right. This figure plots the uncertainty in the $^{238}\text{U}$ concentration extracted from spectra taken inside the Medusa calibration pit with a QL-40 tool from ALT/Mount Sopris. The **accuracy** of 3-Windows and FSA is the same (they yield the same average $^{238}\text{U}$ concentration). However, the **precision** of FSA is better. The spread in the FSA-found $^{238}\text{U}$ numbers is about a factor 1.5 smaller 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.**
The log on the right illustrates the reduction in noise one can achieve using FSA instead of 3-Windows.

The plot on the right shows $^{40}$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-Windows. The orange (top) curve is $^{40}$K calculated using FSA. The curves follow the same pattern, however, the FSA data is visibly less noisy.

**Calibration of SGR tools**

FSA needs detector calibration curves. Originally these were obtained using calibration sources. However, the amount of source-detector geometries that can be calibrated this way is limited. Moreover, it is almost impossible to obtain pure, clean spectra.

That is where modern-day computing technology comes into play. Delicate source-detector modelling codes, originally developed for the nuclear industry, can now be run on desktop PCs. We use one of these codes, MCNP-X, 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 creation of responses against any source type of any geometry – something which 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.

The graph on the right plots data taken with a 1”x4” BGO tool (QL-40, ALT/Mount Sopris) 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.

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.

<table>
<thead>
<tr>
<th></th>
<th>$K$ (%)</th>
<th>$EU$ (PPM)</th>
<th>$ETH$ (PPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-ZONE</td>
<td>3.9 (4.3)</td>
<td>0.1 (0.8)</td>
<td>2.4 (1.7)</td>
</tr>
<tr>
<td>U-ZONE</td>
<td>0.2 (0.1)</td>
<td>32.2 (34.1)</td>
<td>3.5 (2.0)</td>
</tr>
<tr>
<td>TH-ZONE</td>
<td>0.1 (0.1)</td>
<td>1.0 (3.8)</td>
<td>60.6 (62.7)</td>
</tr>
</tbody>
</table>

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

**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 1764keV 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. 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. On the right, 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 100-300keV 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. The data were fitted using both the 238U and the 234Rn spectra from the figure on the right. This helped to show that the extremely high concentrations found inside the borehole could fully be attributed to Rn, and not to matrix-bound U.

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 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...a vision which for instance is shared by ALT, who implemented the FSA algorithms in the latest version of WellCAD. Moreover, ALT/Mount Sopris, Robertson Geologging and Antares Datensysteme, use the model-based calibration for their SGR tools and in their logging software.

**Dr. j. Limburg and Dr. M. Tijs; Medusa Sensing BV, Groningen, The Netherlands.**

8. Wireline data processing and analysis

How to get the best from the logs

Spectral Gamma Analysis

A calibrated spectral gamma log provides K, U and Th logs in percentage, PPM and PPM respectively. A log of total gamma is usually included in the data set. If presented to best effect, the logs provide a more complete description of the rock mass than total GR alone and might point to important facies changes within the formation. For clay typing studies, it is better to look at the proportional contributions of the three elements rather than absolute counts. High and low values may relate to depositional factors rather than source rock chemistry.

In oilfield sedimentary logging, U is deducted from total gamma in order to provide a log of clay content that does not include organic shales and transported uranium salts deposited in fractures. The new log is referred to as the computed gamma ray (CGR) log and is regarded as a good indicator of shale volume.

A further refinement is to consider thorium versus potassium contribution. Thorium is found throughout sedimentary deposits carried within detrital mineral grains as well as being adsorbed, at the atomic level, in clay lattices. It is an excellent grain size log and is so evenly distributed that it forms a baseline to which potassium and uranium contributions are compared.

The mineral exploration geologist is usually less interested in shale volume than his oilfield counterpart. What he needs is a diagnostic measurement of chemistry that discriminates between different rock types, whether sedimentary or igneous. It is not always necessary to calibrate a spectral gamma log to achieve this. If presented with an uncalibrated gamma ray spectrum, the log analyst can extract values for the three standard energy bins and take their ratios or the ratio of each with the total gamma log from another tool. The object is to produce something that is diagnostic.

From a deep kimberlite pipe - total gamma (NGAM), left, and NGAM/Window 3 (U) in the centre.

The example on the right illustrates this. The described combination just happened to be the only one that worked well and this was an effective way to extract value from an uncalibrated data set. Far better to calibrate but, again, we might not be looking for shale or clay mineralogy. There have been many attempts to produce a universal descriptor of clay mineral composition using spectral gamma logs. Many of these have been found to be overly site specific but the practice of cross-plotting potassium with thorium, as a starting point for any type of analysis, is recommended.

The classic Th/K cross-plot looks something like the one below.
The mineral log analyst should first create the same cross-plot and look for clusters. Where values are low, a logarithmic scale is a good option.

Th/K cross-plot (theoretical mineral fields based on Rider - The Geological Interpretation of Well Logs 2000).

A cross-plot of Th/U describes uranium-rich zones, often associated with organic compositions and the environment in which they were deposited. U-rich indicates reducing (marine) conditions and U-poor indicates oxidising (terrestrial) conditions (Adams & Weaver 1958). This interpretation might not be important in a mineral geological setting but the practice of investigating gamma-based chemistry via cross-plot is valid.

The author contends that the KUTh log is under-utilised in mineral exploration and, in a complex depositional environment, could be run early in the exploration programme to determine if it has an ongoing application.

Example of a spectral gamma log with derivatives

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