Paper 12

Advances in Slimline Borehole Geophysical Logging

LoCoco, J. [1], Korth, T. [2], Alpers, W. [2], Legros, B. [2]

1. Mount Sopris Instrument Company, Inc.
2. Advanced Logic Technology, Sa

ABSTRACT

The last 10 years in slimline borehole geophysics has seen numerous advancements. Borehole imagery logging has reached resolutions that allow investigators to visualize true-color borehole wall attributes, grain size features, rock fabric, and structural integrity. These slimline tools allow us to perform high resolution fracture characterization, casing thickness evaluation, along with many other applications. Acoustic televiewer amplitude logs are semi-quantitative and proportional to rock strength. Advances in data acquisition systems allow increased logging speeds, even at very high circumferential and vertical sampling intervals.

Nuclear Magnetic Resonance (NMR) logging has evolved with much smaller diameter tools, running on standard commonly available geophysical wirelines, thus allowing entry into the mining and ground water communities. These tools operate in a borehole, like an inside-out MRI scanner, to provide direct sensitivity to hydrogen (groundwater and hydrocarbons). The tool projects a magnetic field several inches beyond the borehole axis, creating a cylindrical-shaped "sensitive region" from which the NMR signal is captured. This thin sensitive region is ideally located within the undamaged region of the formation, where the rocks and sediments are not disturbed by drilling. Direct detection and quantification of groundwater (including capillary and clay-bound water) is possible, along with detection and quantification of hydrocarbons and fluid diffusion, precise determination of porosity and water content, estimation of permeability, mobile/bound water fraction, pore-size distributions, and sensitivity to geometric and geochemical pore-scale properties.

Advances in slimline borehole gravity tools over the past several years has found importance in mining applications, including bulk density determination, rock properties, and verification of surface and airborne gravity anomalies. Borehole gravity measurements have been used for detecting the presence of oil and gas, and reservoir mapping, delineating salt domes, in addition to typical applications to determine density with greater investigative area than traditional radioactive source tools.

Advances in borehole Spectral Induced Polarization (SIP) are revealing its unique sensitivity to interfacial properties of porous materials. SIP is sensitive to fundamental pore geometric properties controlling fluid flow and recent case histories indicate the measurement can be a good estimation of permeability. Numerous authors have described links between SIP parameters and permeability. SIP methods are also very sensitive to changes in the interfacial properties that result from biogeochemical processes occurring in porous media due to natural and enhanced mechanisms. Many papers that link SIP properties to biogeochemical alterations of mineral surface area and/or mineral surface chemistry have been published in recent years. It is now considered a unique geophysical method regarding its sensitivity to geochemical and biogeochemical processes. This provides unique opportunities to monitor geochemical and biogeochemical processes associated with remediation strategies for example. One of the most exciting opportunities is related to biomineral transformations resulting in sulphide mineral formation.

New generation downhole Energy Dispersive X-ray Fluorescence (EDXRF) spectrometry tools have been developed further in the determination of minor and major concentrations of elements in borehole. These instruments can aid in ore body/seam mapping (Ni, Cu, Zn) and the estimation of tracer elements, blast hole profiling, and grade control. EDXRF can also potentially help address issues related to mineral recovery programs.

Well-calibrated slimline downhole spectral gamma geophysical logging tools are yielding near quantitative results in real time. Advances in scintillation material and tool characterization have contributed to recent advancements. Borehole properties such as diameter, fluid, casing and probe diameter strongly influence the outcome spectral gamma logging tools. From recent Monte Carlo simulations, it appears that borehole diameter, probe diameter, borehole fluid and casing thickness have a significant effect on the observed gamma spectrum, above 300 keV. Calibrations for these effects are now implemented in newer tools built over the last decade or so.

Geophysical well-log analysis and presentation software, along with 3D modelling and database programs have advanced significantly, becoming an advanced universal borehole, mine site or well-field data tool box. It's more common nowadays for petrophysicists, mining engineers, geologists, researchers, and drillers to combine data into one layered summary for use and interpretation in multi-disciplinary applications.

In "Proceedings of Exploration 17: Sixth Decennial International Conference on Mineral Exploration" edited by V. Tschirhart and M.D. Thomas, 2017, p. 159–168

INTRODUCTION

This paper highlights only a few of the many advances in slimline borehole geophysics over the past decade with quick summaries of these methods. Slimline geophysical logging tools generally refer to downhole sondes up to 45–50 mm in diameter, which is the focus of this manuscript. Slimline televiewers, both optical and acoustic, nuclear magnetic resonance (NMR), energy dispersive x-ray fluorescence (EDXRF), borehole gravity, and spectral gamma downhole geophysical logging tools have all seen resurgence in use and application over the last decade. Other slimline downhole measurements, including spectral induced polarization (SIP), and others have seen significant development.

Although geophysical logging tools have been stackable since the 1980s the last decade has presented us with innovative mechanical design and improved telemetry performance on electrical wirelines allowing us to combine slimline logging tools in custom configurations to acquire more physical parameters in a single logging pass. Nowadays, tools are combined according to the specific requirements of the applications (hydrology, mineral prospection, etc.). This flexibility saves time and cost in field acquisition. Some of these linkable sondes are considered "bottom subs" which means they are generally placed at the bottom of the stack. Other measurements can be thought of as "inline subs." Many inline and bottom subs provide multiple measurements, for example, a typical ELOG sub may have SP, SPR, 8-16-32-64" (~ 20, 40, 80 160 cm) normal resistivity, current and induced polarization (IP).

Common Inline subs (slimline applications)

Natural Gamma (CPS and/or API units)
Gamma/CCL
Spectral Gamma (Full Spectrum)
ELOG (as mentioned above)
DLL3 (dual lateralog)
Caliper (3-arm, 4-arm)
Temp. / Fluid Conductivity (more typically a bottom sub)
Water Quality (Temp., Pressure, ReDox, pH, DO, Cond.)
Deviation (3-axis magnetometer / accelerometer)
Full Waveform Sonic (numerous configurations)

Common Bottom subs

Acoustic Televiewer (natural gamma option)
Optical Televiewer (natural gamma option)
Spinner Flow Meter
Density (generally with single-arm caliper)
Neutron-thermal-Neutron (single or dual detector)
Induction (several coil configurations and measuring ranges)
Magnetic Susceptibility (several measuring ranges)

Induction and susceptibility are sometimes combined in one tool, depending on application.

Borehole Imaging Tools

Borehole imaging tools deliver a high resolution direct or indirect 360° image of the borehole wall. Thus, in contrast to traditional logging probes, these tools deliver a two-dimensional image of the borehole wall. As the tools are equipped with an orientation sensor, measuring the tilt and azimuth, the recorded images can be oriented with respect to magnetic north or high side. Up-to-date well logging software enables a virtual 3D core display of these data. The optical tools are equipped with a digital camera to record a true color image of the borehole wall. The acoustical and the electrical borehole imaging tools deliver a 360° unwrapped image of the physical properties of the rocks exposed on the borehole wall.

In open holes these tools are mainly used for lithology differentiation, derivation of structural information such as fracture qualification and determination of the borehole shape including caliper and washout identification. When combined with other basic tools like temperature and fluid conductivity, we can draw inference about hydraulically important fracture features that intersect the borehole. Optical and acoustical imaging tools can also be applied in cased wells, where they are used generally for casing inspection and cement bond evaluation.

Due to worldwide resurgence in slimline borehole imagery over the last decade, this manuscript emphasizes acoustical and optical imaging tools. As both tools deliver a high amount of data, progresses in the real-time data processing and data transmission (telemetry) were essential to get an acceptable logging speed with these tools.

These implied improvements regarding the electronics of the tool such as faster digital signal processors, ADC's with a larger dynamic range and sophisticated buffer systems. Additionally, surface systems have been enhanced to acquire data at a higher baud rate, which is finally equivalent to a higher logging speed, very important to drillers and others at a well site. During the last 10 years, logging speeds have doubled from about 250 kbps to 500 kbps in slimline applications. Furthermore, numerical filters that compensate for the distortion of the transmitted signals through the wirelines have been developed to increase the transmission rate on long wirelines.

Optical Televiewer

Optical borehole imaging tools have seen a huge technical progress over the last years. The data acquisition rate has been increased through the combination of powerful processors performing real-time compression of the digital image and a high frame rate of the digital cameras which finally increases the maximum achievable logging speed.

Up-to-date technology includes high resolution CMOS digital cameras with fish eye lenses and LED light sources which deliver a high quality true color image of the borehole wall. Moreover, the exposure can be adjusted by the operator to adjust the luminance to get the good data quality even in difficult wells. Figure 1 shows a comparison between two optical images recorded with a QL40 OBI 1G (2009) and with a QL40 OBI 2G (2015).

Figure 1: Comparing between two different generations of optical borehole imaging tools (QL40 OBI, 1st generation, right track) and QL40 OBI 2G, 2nd generation, left track) demonstrates the enhanced image quality and resolution that is achievable nowadays with these tools.

Typical azimuthal resolution has increased to 1800 ppt (points per turn or circumferential stack) from about 360 ten years ago. 1800 pixels is equal to a pixel arc-width of 0.26 mm for a borehole with a diameter of 6 inches (15 cm). This high resolution in combination with enhanced true color quality enables us to get a detailed picture of the borehole wall up to a point where single minerals can be identified as shown in Figure 1. In fact, this resolution is with 8 pixels/mm in a NQ hole close to the low-resolution limit of a core scan which provides a resolution of about 5–40 pixels/mm. Hence an analysis of mineral phases, grain size distribution and porosity can be performed with optical images in conjunction with dedicated software applications as for instance a colorimetry method illustrated in Figure 2 below.

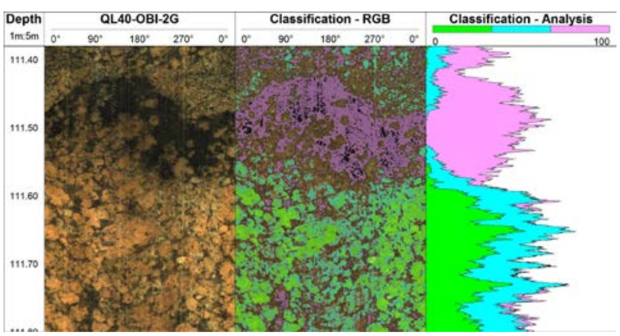


Figure 2: High resolution images of optical imaging tools enable mineralogical analysis (e.g. the colorimetry method).

Acoustical Televiewer

Basically, two different types of acoustical imaging tools are available. Firstly, tools which have a rotating transducer and secondly tools with a fixed transducer and rotating mirror. Both techniques provide the user with a 360° unwrapped image of the borehole wall. The frequency of the transducer can be varied and should be selected according to the specific requirements of the target.

Ten years ago, very slow logging speeds led to limited acceptance of these tools in industry. Nowadays, logging speeds of acoustic borehole imaging tools has increased significantly. This is mainly due to implementation of new components in the acoustic heads (e.g. stepper motor which allows a higher rotation speed of the mirror). Azimuthal resolution has also improved and can go up to 360 ppt. This is equivalent to an azimuthal resolution of 1.3 mm in a borehole with a diameter of 6 inches (15 cm).

In open hole applications, recorded parameters are travel time and amplitude of the reflected echo. If the velocity of the borehole fluid is known, borehole radius can be derived and a two-dimensional image of the radius can be generated. Besides determining the borehole diameter, these maps are very useful for the identification of washouts, fractures, stress analysis, and other borehole wall attributes. Additionally, the amplitude of the reflected echo is semi-quantitative and can used to derive physical properties of rocks exposed on the borehole wall. The combination of the two images allows for a detailed lithological and structural analysis of the borehole wall with appropriate software. A common application for such tools, for example, is the detection and qualification of fracture zones in geotechnical, hydrological or mining investigations.

Casing inspection applications of the slimline acoustical borehole imaging tools has developed over the last few years. Acoustical imaging technology has been optimized for these applications. Among other solutions, exchangeable acoustic heads have been designed; consequently, the same tool can be employed in a diameter range from 2⅞ to 24 inch (73–610 mm) simply by exchanging the acoustic head. In Figures 3 and 4, two examples are shown. The first one has been measured in a 2⅞ inch (73 mm) tubing and the second in a 20 inch (508 mm) casing.

Significant progress has been achieved on the real-time processing algorithms of the tools. This is partly due to enhanced processing capabilities of the latest digital signal processors and analog to digital converters and partly due to more sophisticated algorithms. Nowadays these slim hole tools deliver thickness and qualitative cement bond images of cased wells in real time.

These new technologies allow us to evaluate the integrity of casings and tubings of production wells (oil and gas, water wells, gas storage). In addition, the thickness and qualitative cement bond information are valuable information for well abandonment and well plugging projects. Other applications are the evaluation of the well integrity of new wells or during their live cycle.

The availability of high temperature electronic components has allowed us to upgrade temperature ratings of tools to 170°C so we deploy in high temperature environments such as geothermal investigations in the open hole as well as in the cased hole applications.

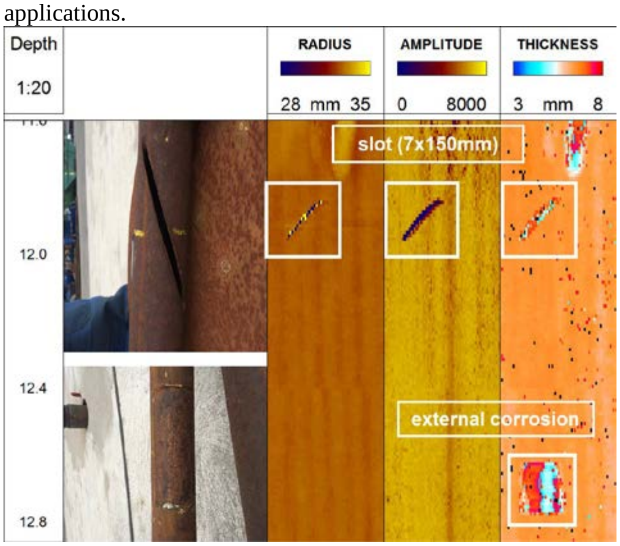


Figure 3: Cased hole application in a 2⅞ inch (73 mm) test tubing**.**

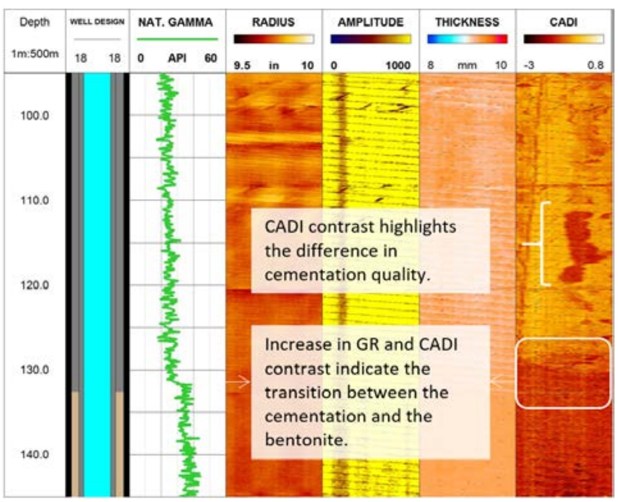


Figure 4: Cased hole application in a 20 inch (508 mm) cased well.

NUCLEAR MAGNETIC RESONANCE

Nuclear Magnetic Resonance (NMR) logging has evolved with much smaller diameter tools, running on standard commonly available geophysical wirelines, thus allowing entry into the mining and ground water communities. Figure 5 illustrates this point vividly. Now more widely accessible and available due to developments of the past several years, slimline NMR tools will find applications in many industries.

Direct detection and quantification of groundwater (including capillary and clay-bound water) is possible (see Figure 6), along with detection and quantification of hydrocarbons and fluid diffusion, precise determination of porosity and water content, estimation of permeability, mobile/bound water fraction, pore-size distributions, and sensitivity to geometric and geochemical pore-scale properties.

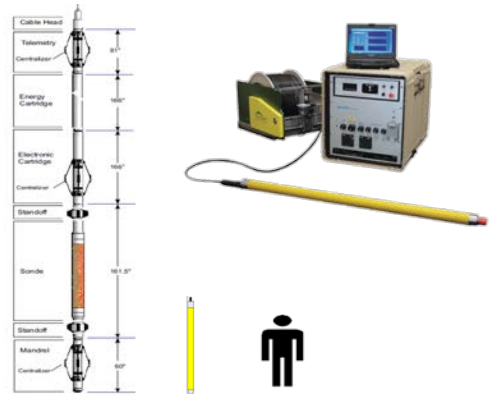


Figure 5: New generation **s**limline NMR tools incorporate oil-field tool design and pulse sequences but smaller and easier to handle in the field, thus opening the door to less expensive field operations. Weight of slimline NMR tools vary with diameter, but generally weigh between 15 and 25 kg. (Graphics curtesy Vista Clara, Inc.)

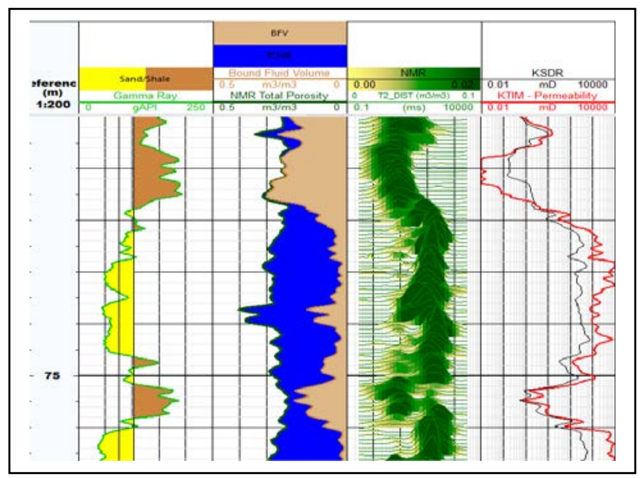


Figure 6: Basic NMR log with slimline tool, stacked with natural gamma. Data is inverted to give a continuous T2 distribution for the logged interval (~3 samples/m). T2 distribution readily interrogated to derive total porosity, along with bound fluid (clay and pore bound), free fluid (readily movable), and permeability. Track 3 is the NMR T2 distribution, which represents a pore size distribution (small pores to the left, large pores to the right). (Graphic curtesy of NMRSA Pty Ltd)

Since NMR tools directly measure moisture content (bound fluid), specific yield (free fluid), and hydraulic conductivity, mine site planners and hydrogeologists will use these tools at mine dewatering sites. Also, mine site crushers are set up to handle a specific moisture content range. Borehole NMR data can be collected as mine expands and resulting moisture content data can be fed into mine crusher operations.

SPECTRAL INDUCED POLARIZATION

In 1998, Yanzhong Luo and Guiqing Zhang published a thorough and valuable summary of their research on the spectral IP method, noting that the colourful history of IP goes back to the Schlumberger brothers many decades ago (Lou and Zhang, 1998). That said, SIP methodology is a relatively new technique in exploration and near surface geophysics, and borehole SIP has not come to the mainstream yet; however, proof of principle testing and validation is ongoing. Borehole SIP testing and comparison to NMR and other classical porosity and permeability estimation tools will be published in future manuscripts.

Rutgers University and others are leading the way in the advancement of SIP into the borehole environment. Kemna et al. in 2012 described recent results of laboratory testing. Slater (2007) reviewed geophysical literature focusing on the estimation of saturated hydraulic conductivity (K) from SIP and other measurements. Figure 7 below is from Slater's work.

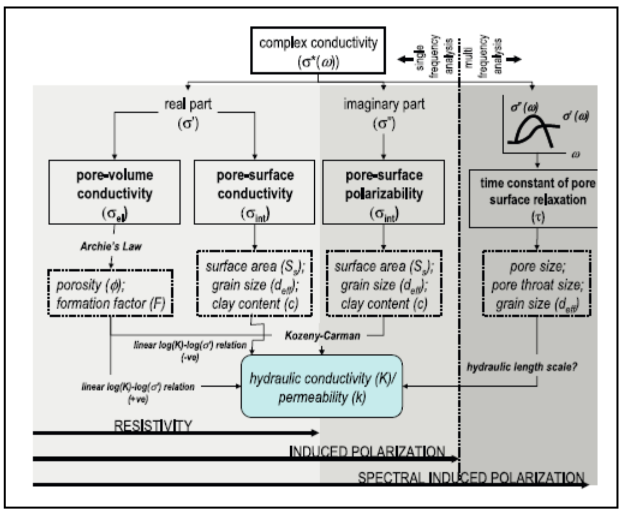
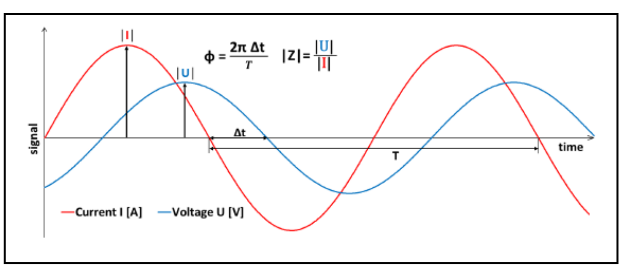


Figure 7: Flowchart showing how SIP methodology may be used to determine hydraulic conductivity.

The SIP measurement sweeps the surrounding geo-media with a range of sine wave currents at frequencies ranging from about 1 mHz to about 20 kHz. Impedance |Z| and phase ϕ are determined by correlating induced voltage U and stimulus current I. Graphic below illustrates the concept (curtesy Ontash and Ermac, Inc.).



The real-life applications of SIP are related to its unique (relative to other geophysical methods) sensitivity to the interfacial properties of porous materials. Firstly, SIP is sensitive to fundamental pore geometric properties (surface area to pore volume, critical pore diameter) controlling fluid flow and therefore offers outstanding opportunities for geophysical estimation of permeability. There has been an explosion of papers describing links between SIP parameters and permeability in the recent literature (L. Slater, pers. comm., 2016).

The SIP method is also very sensitive to the changes in the interfacial properties that result from biogeochemical processes occurring in porous media due to natural and enhanced mechanisms. Many papers that link SIP properties to biogeochemical alterations of mineral surface area and/or mineral surface chemistry have been published in recent years. SIP is recognized as a unique geophysical method regarding its sensitivity to geochemical and biogeochemical processes. This provides unique opportunities to monitor geochemical and biogeochemical processes associated with remediation strategies for example. One of the most exciting opportunities is related to biomineral transformations resulting in sulphide mineral formation (think time variable SIP response from sulphide deposits) (L. Slater, pers. comm., 2016).

In the coming years principles behind SIP will be tested in the marketplace. Common borehole logging field situations, which differ from laboratory conditions that may test SIP are highly saline and stratified borehole fluid conductivity profiles, invasion, borehole rugosity, and other borehole environmental borehole factors.

BOREHOLE GRAVITY

Borehole gravity has been applied to oil reservoir evaluation since the 1950s. While density tools (which deploy an active radioactive source) only "see" a few inches from the borehole wall, the borehole gravimeter is insensitive to borehole conditions (casing, rugosity, fluid properties) and can produce density measurements far away from the borehole axis. This can lead to applications such as monitoring saturations and fluid contacts in gas reservoirs, and downhole calibration of surface geophysical mapping of geological structures. Highly accurate density information from borehole gravity meters has been used in seismic modelling because, among other things, these gravity meters have very large depth of investigation, to hundreds of feet.

Over the last decade and more, borehole gravity surveys have seen more traction and entered a new era of dependability and consistency. Measurements can be made in NQ drill rods commonly used in the mining industry, and to 3000 metre depths at 60° from vertical, and with < 7 microGal repeatability. Newer generation sondes incorporate natural gamma, CCL and other sensors. Efficient survey procedures continue to improve the utility of borehole gravity by lowering the cost of logging. This migration of borehole gravity to the mining industry finds example applications in remote sensing of massive sulphide deposits, ore grade delineation, overburden density determination, void detection, and some perhaps yet to be determined facets of mining exploration. One exciting application is the association of excess mass to conductivity anomalies and a realistic estimation of tonnage from gravity measurements in a limited number of boreholes.

BOREHOLE XRF ADVANCES

Slimline borehole EDXRF (Energy Dispersive X-ray Fluorescence) spectrometry for the determination of minor and major concentrations of elements in boreholes, blast holes, ore seams, tailing piles, pipes, and other applications has benefitted from significant improvement over the last decade. New generation downhole probes run on standard 3/16" (4-conductor) wirelines. In-situ characterization provides real-time concentration so that important decisions can be made in the field without waiting on lab results.

Currently available tools can "see" or resolve elements between aluminum (Z=13) and uranium (Z=92), typically with very good reliability and repeatability, to the concentration levels below.

Fe, Ni, Cu, Zn, Hg, Pb	~10 ppm
Cr, Mn, Co	~20 ppm
As, Se	~10 ppm
Ag, PMG	~50 ppm
Cd, Ba	~25 ppm
S, P	~0.01%
Al	~0.2%

The X-ray window must be sealed on the sonde housing and well connected to the borehole wall to achieve the measurement.

Figure 8a: X-Ray window. (curtesy Austin AI, Inc)

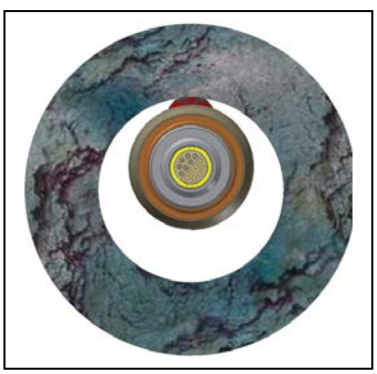


Figure 8b: Sidewall coupling XRF tools. (from Scientific Drilling, GFZ, Potsdam presentation)

Important issues constraining field logging operations includes the fact that water is strongly absorbing so the thickness should be no more than 0.5 mm and the sonde must be firmly pressed against the borehole wall allowing a mudplow (Figure 8a) to clear the way for the X-ray measurement. The window must be strong and thin to minimize absorption and is usually made from beryllium or carbon (diamond). All this said, a clean borehole wall is best suited for this measurement. X-ray penetration is in the micrometre range.

SPECTRAL GAMMA

For many decades, natural gamma ray logging for lithology and other attributes has been ubiquitous in all geophysical logging applications, including natural resource exploration and production, ground water, geotechnical, university research and much more. The most common naturally occurring radionuclides are potassium, thorium and uranium. Knowledge about the concentrations of each of these radionuclides enables the interpreter to perform a lithological analysis, including sand /shale discrimination and clay typing, as well as uranium/potash ore grade evaluation and even the monitoring of radioactive contamination plumes. Good progress over the last decade, particularly in calibration techniques has led to continued use of spectral and total count gamma.

Spectral gamma ray tools measure the energy spectrum of the gamma rays emitted by the rocks surrounding the well. As the energy of the gamma rays emitted by each of the three naturally occurring radionuclides or the elements of their decay chain is unique, they can be identified by analyzing the spectrum.

The classical approach to analyze the gamma ray spectrum consists of the "windows stripping" approach as illustrated in Figure 9 (Limburg and Tijs, 2014). This method analyses the counts within several predefined energy windows, each covering a characteristic peak of the three main radionuclides or elements of their decay chain. The low-energy part of the spectrum covers beside the low-energy peaks of the thorium and uranium decay chain, the energy range of the gamma rays emitted by Compton scattering and the photoelectric effect. Therefore, generally the high energy part of the spectrum is processed as this part of the spectrum is not disturbed by the emissions of these processes and contains the most characteristic peaks of the three radionuclides. However, it represents only ten percent of the spectrum in terms of counting rates which increases significantly the statistical error rate. Much-improved results can be obtained if the low-energy portion of the detectable spectrum is taken into consideration (Serra, 1984).

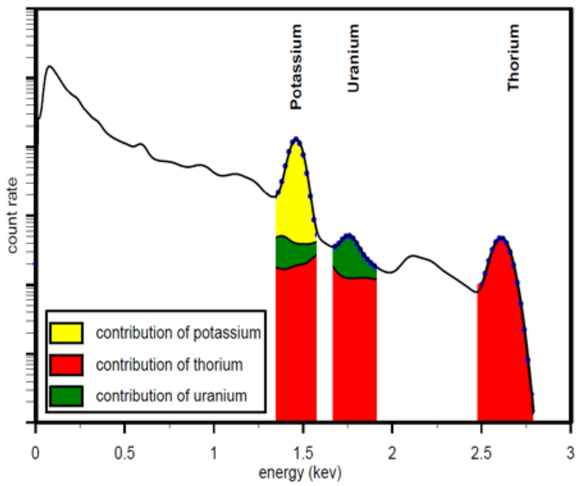


Figure 9: The window stripping method processes the spectrum within distinct windows (Limburg and Tijs, 2014).

To correlate count rates with concentrations the tool needs to be calibrated. A good calibration of spectral gamma ray tools is crucial for a correct interpretation. The conventional way to calibrate these tools is to run the tool in a reference calibration pit and to correlate the counting rates within the predefined windows with the concentration of radionuclides in these pits. However, this method is only reliable for applications in environments with similar borehole conditions. Moreover, it does not account for the fact that the tools specifications change with temperature and above all with detector age.

Within last decade, another method to calibrate spectral gamma ray tools has been employed. Medusa Sensing BV based in the Netherlands developed a new processing and calibration method that can be applied to just about any SGR sonde. It is based on a full spectrum analysis (FSA) which encompasses (almost) the full energy spectrum as illustrated in Figure 10 (Hendriks et al. 2001). The first step is to generate a Monte Carlo model of an SGR tool inside their calibration set-up, the Medusa Stonehenge set-up, including the tool housing and all major components of the probe. A simulation is then performed computing the tool response to a pure source of ^{40}K, ^{238}U or ^{232}Th inside the Stonehenge set-up. From these theoretical spectras the tool specific standard spectra can be derived through fitting them to the actual measured spectra in the Stonehenge set-up (which nuclide concentrations are well-known). A detailed description of this calibration method can be found in (Tijs and Limburg, 2015) and (Van der Graaf et al., 2011).

This innovative calibration method presents several advantages. Firstly, this process compensates automatically for the drift of the spectra, due to the inherent temperature dependency of the scintillator assembly, without the liability of handling a tool equipped with a radioactive source as reference or applying correction charts. Secondly as it considers the full energy spectrum, even the low energy part, it allows for a more elaborated determination of the concentrations of the radioisotopes.

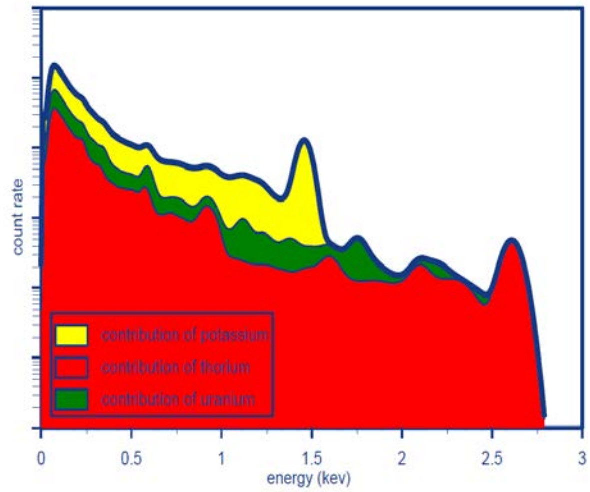


Figure 10: FSA of the recorded energy spectrum takes into account the full spectrum (from Limburg and Tijs, 2014).

This new calibration method has been validated recently with a QL40 SGR logging tool. Measurements have been carried out in the well-known calibration pits in Adelaide, Australia, and Grand-Junction, USA. The measurements were performed in a short time period of six weeks following the same procedure. The recorded spectra were analyzed using the calibrated standard spectra while applying a full spectrum analysis. The concentrations measured with the QL40 SGR were compared with the reference values of each pit. Generally, concentrations of the main radionuclides were well determined. After applying borehole corrections considering the diameter, porosity and saturation, the concentrations of the minor radionuclides could be determined as well.

SOFTWARE

Well-log analysis and presentation software, along with 3D modelling and database programs have advanced significantly over the last decade. The driving force being on one hand major shifts in the information technology. On the other hand, deployment of new devices and sensors in the borehole logging industry (see previous pages) can be held responsible.

Figure 11 shows the five major shifts in the information technology which occurred over the last decade. In 2007 the first iPhone was released. The first iPad followed three years later in 2010. Since these days we can observe a seemingly real-time flow of useful and highly innovative new mobile and web based consumer apps for managing travel, money, news, communication, productivity, and countless other key functions. Thus, consumer applications have become a companion of our private and professional lives. There is an omnipresent demand to see most of the innovations from consumer apps in enterprise solutions provided by companies to their employees.

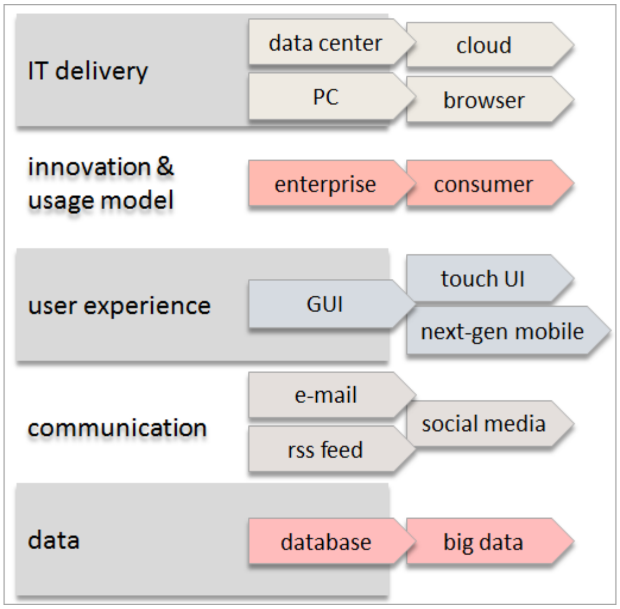


Figure 11: The major shifts in information technology over the last decade.

What has been a database accessible from a local network server ten years ago has nowadays developed into a geoscientific information management system with 24/7 accessibility through web interfaces independent of geographical location, easy to use and offering a high level of integration with technology partners [1]. High resolution core images and hyperspectral core scans, each many megabytes in size, are available in online libraries accessible anywhere at any time [2].

Being able to control software using a touch user interface (UI) on phones and tablets generated a completely new user experience. There are attempts to deliver well-log analysis software to iPad and Windows tablets (see Figure 12) [3] or to use smart phones and tablets for core descriptions (see Figure 13) [4]. But most of the known providers of well-log analysis and presentation software as well as 3D modelling programs—WellCAD, LogPlot, Viewlog, Oasis Montaj, Leapfrog, GOCAD, Micromine, Surpac—take a rather conservative approach in this respect. The latter is not surprising, looking at the complexity and versatility these software packages have grown into over the last years. Users require powerful workstations and work with large or multiple high-res monitors to achieve the best possible results. An adaptation of the entire application for tablets would be unrealistic. Nevertheless, we may see spin-off products such as data viewers for smartphones and tablets in the future.

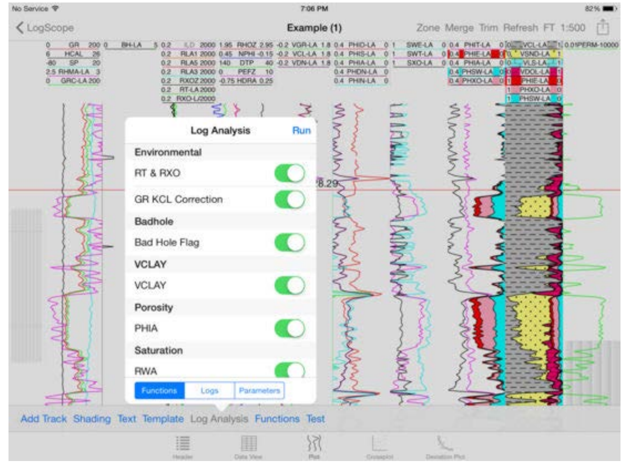


Figure 12: LogScop well-log analysis software on iPad or Windows tablet.

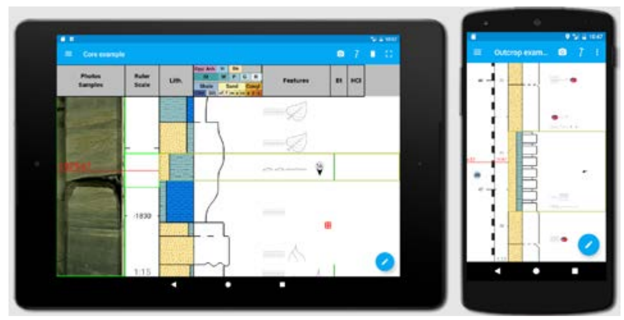


Figure 13: LithoHero core description software on tablet and phone.

Even though PC based applications did not adapt to a touch and slide user control, the graphical UI design has seen many enhancements to follow the expectations of a changing user profile. Aging and slow-to-evolve dialog box dominated graphical UI have been uprooted by navigation and property bars, docked at custom positions inside or outside the application frame or being able to slide in on demand (see Figure 14). The user is presented with useful additional details about availability, type and distribution of data. The user can access display and process properties without the need to click through multiple levels of menus and dialog boxes.

Instead of developing and releasing a multitude of task specific apps we can observe for instance in the wellbore data processing package WellCAD the approach to use dedicated workspaces (e.g. for Image and Structure, NMR or Casing Integrity processing) [5]. These workspaces combine individual processing steps, like zonation, image pre-processing, structure picking, pick classification, structure correction, etc., into a single logical workflow all controlled through a dedicated user interface. For the user, it is like a task specific, easy to use app within a greater framework (see Figure 15).

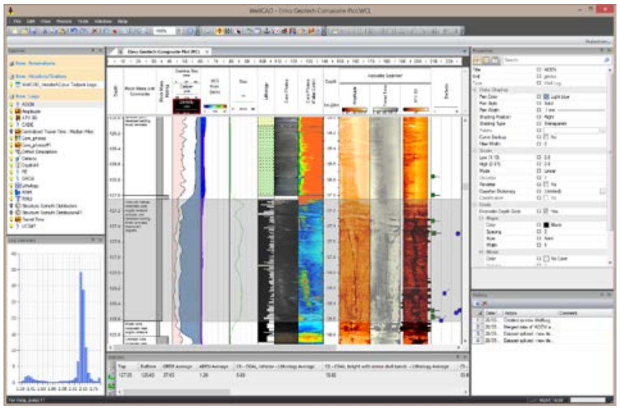


Figure 14: Enhanced graphical UI using navigation, information and property bars (WellCAD).

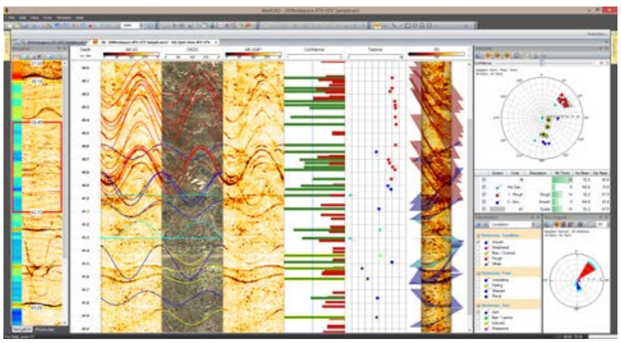


Figure 15: Task specific "app" like workspace within greater software framework (WellCAD).

The past decade has presented us with a revolution in the way we communicate and share information. It has been in 2006 that Facebook opened up to everyone and Twitter launched its service. Today software users want the ability to quickly connect, communicate and collaborate via social media. We expect from enterprise software to communicate with us and that it allows us to easily collaborate with the software developer (e.g. support via chat, online seminars, video tutorials on demand, user blogs). Figure 16 shows an example of a welcome page presenting itself to the user as soon as the application launches. It communicates to the user important details about software version and license status. Latest news about availability of software updates, new documentation or downloadable resources are streamed from the developer's server onto the welcome page. Links to latest help documentation and tutorials are provided. With a single click the user can contact the developer's software support team.

Businesses are drowning in data more than ever before. We have learned in the previous chapters about the availability of more and new logging tools, increased logging speeds and better data transmission. All these factors play their part in throwing more data into the direction of the analysts and interpreters. We see today an order of magnitude or two more data than what we dealt with ten years ago. At the same time data turnaround cycles are getting shorter and shorter. As a consequence, data analysis software programs have been adapted to this challenge. For instance, it is nowadays possible to receive real-time data streams from the data acquisition units in the field directly into the processing software (e.g. WellCAD-Browser) for faster data quality assessment and decision making.

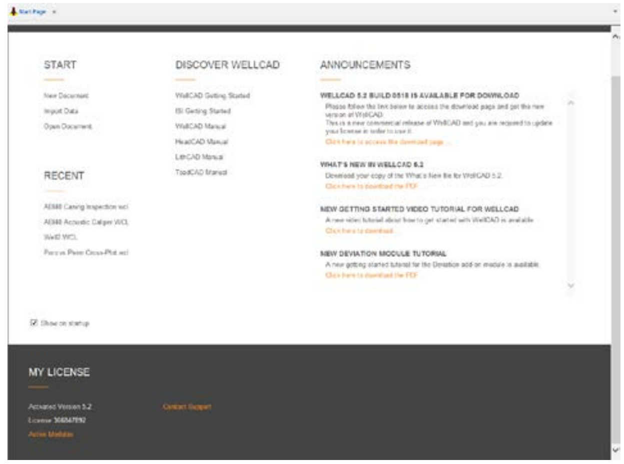


Figure 16: A welcome page allowing bidirectional communication between user and developer.

Another strategy to deal with the growing data volume and already implemented in software solutions (e.g. GIM Suite, WellCAD, Techlog, Geolog) is the possibility to automate recurrent tasks or to develop custom algorithms to gain time and reduce human mistakes. Either an integrated script editor is provided or the software exposes a specific syntax that can be used with high level programming languages like VB, VC++, C# or Python.

Sophisticated software solutions to manage, store and guarantee the accessibility of big data anywhere at any time have been developed as mentioned at the beginning of this chapter.

Developers of data management, analysis, presentation and modelling solutions will face challenging times. The mantras of the new generation are: easy, highly mobile and social. These want to be recognized in solutions, from which it is expected to run complex algorithms, produce stunning data presentations and get the most sophisticated results out of big data. It will be interesting to observe how this act of balancing will be performed.

CONCLUSIONS

What will the next ten years yield in slimline borehole geophysics bring? Our discussions above have only very briefly summarized a few of the innovative advances, but we did not discuss advancements in slimline neutron generators utilizing D-D neutron generation to provide safer alternative to traditional AmBe tools, or slimline LWD or MWD tool string advances. Optical televiewers with bright LEDs emitting at user-specified wavelengths of light could find its way to marketplace in the future. Borehole SIP technology looks promising and with upcoming field trials we will know in the next year or two if less expensive SIP can provide permeability information that compares to NMR and other methods.

REFERENCES

Kemna, A., A. Binley, G. Cassiani, E. Niederleithinger, A. Revil, L. Slater, K.H. Williams, A.F. Orozco, F.H. Haegel, A. Hoerdt, and S. Kruschwitz, 2012, An overview of the spectral induced polarization method for near-surface applications: Near Surface Geophysics, 10, 453-468.

Hendriks, P., J. Limburg, and R. de Meijer, 2001, Full-spectrum analysis of natural gamma-ray spectra: Journal of Environmental Radioactivity, 53, 365-380.

Limburg, J., and M. Tijs, 2014, When every count counts, http://wiki.medusa-online.com:8090/display/GW/Whitepapers+and+techdocs.

Serra, O., 1984, Fundamentals of Well-Log Interpretation - 1. The Acquisition of Logging Data: Elsevier.

Slater, L., 2007, Near surface electrical characterization of hydraulic conductivity: from petrophysical properties to aquifer geometries—a review: Surveys in Geophysics, 28, 169–197.

Tijs, M., and J. Limburg, 2015, Towards better borehole logs: 14th ASGA Biennial Technical Meeting and Exhibition, Extended Abstracts.

Van der Graaf, E., K. Limburg, R. Koomans, and M. Tijs, 2011, Monte Carlo based calibration of scintillation detectors for laboratory and in situ gamma ray measurements: Journal of Environmental Radioactivity, 102, 207-282.

Lou, Y. and G. Zhang, 1998, Theory and Application of Spectral Induced Polarization: Geophysical Monograph Series, SEG.

SOFTWARE REFERENCES

[1] GIM Suite mining software, http://www.acquire.com.au/technology/gim-suite/, accessed 17 May 2017.

[2] CORESHED, http://www.coreshed.com/, accessed 17 May 2017.

[3] LogScope, https://itunes.apple.com/au/app/logscope/id616544920?mt=8, accessed 17 May 2017.

[4] LithoHero, http://lithohero.com/, accessed 17 May 2017.

[5] WellCAD, http://www.alt.lu/pdf/wellcad_brochure.pdf, accessed 17 May 2017.