GEOPHYSICAL WELL LOGGING

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1. DESCRIPTION AND HISTORY

Logging is a general term which means to "make a record" of something. Geoscientists use many types of "logging" including core-logging, cuttings-logging, petrophysical logging and geophysical well logging.

Geophysical well logging was first developed for the petroleum industry by Marcel and Conrad Schlumberger in 1927 (Figure 1).

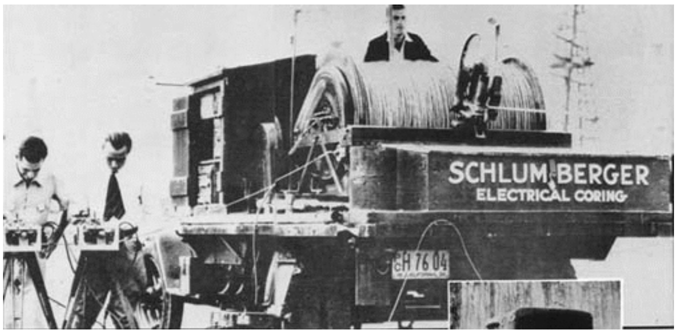

Figure 1. The original geophysical logging equipment used by the Schlumberger brothers in the late 1920's (Schlumberger, 2000).

The Schlumberger brothers developed a resistivity tool to detect differences in the porosity of the sandstones of the oilfield at Merkwiller-Pechelbronn, in eastern France. Part of the Schlumberger brother's original log is shown in Figure 2.

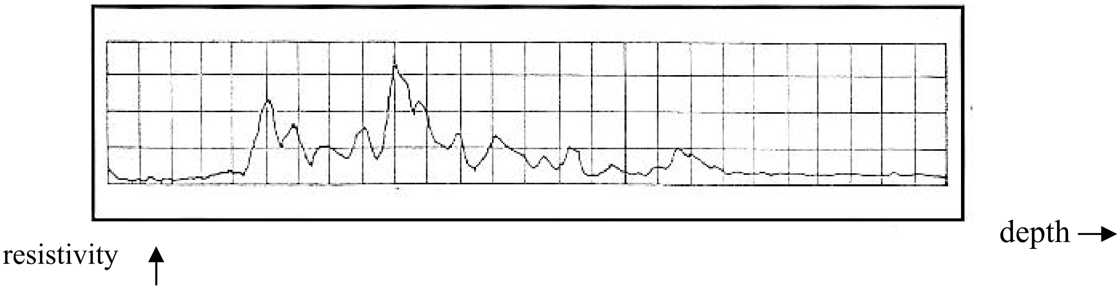

Figure 2. Part of the first geophysical log obtained by the Schlumberger brothers in 1927.

Since this first log was run, geophysical well logging has developed into a billion-dollar global industry serving a wide range of industry and research activities. Geophysical well logging is a key technology in the petroleum industry. In the mineral industry, it is very widely used both for

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exploration activities and for monitoring grade control in working mines. In groundwater exploration and assessment it is also central to the delineation of aquifers and producing zones. In regolith studies, geophysical well logging can provide unique insights into the composition, structure and variability of the subsurface, and is also widely used for ground truthing airborne geophysical data sets, such as airborne electromagnetics.

Geophysical well logging is a mature technology comprising many separate systems. It is well beyond scope of a short article like this to detail the science and the results of the many facets of geophysical well logging. What is intended here is just a short description of some of the more routine well logging methods. These methods are the ones most likely to be included in the suite of tools used for small well logging projects typical for regolith studies.

In geophysical well logging, many different physical properties can be used together to characterise the geology surrounding a borehole. This ability to sense various properties is the greatest strength of geophysical well logging. The different types of information obtained reflect on different aspects of the geology and are often complementary in nature. Thus the porous gravel bed of a palaeochannel, containing detrital maghemite, might have low density, low sonic velocity and natural gamma signal but high magnetic susceptibility and porosity.

2. WHY DO GEOPHYSICAL WELL LOGGING?

Knowledge of the subsurface comes primarily from drilling. This is at once an expensive technique and a limited one. Drilling costs invariably limit the number of holes that can be drilled.

Geophysical well logging offers the opportunity of determining the composition, variability and physical properties of the rocks around the borehole. The actual volume of material sampled in this way varies from technique to technique and with the geological conditions, but it is invariably much larger than is represented by just the borehole. Moreover, depth control with a modern geophysical logging system is often better than a few millimetres. This means that the depth resolution of borehole data, representing the subsurface structure, is generally better than can be obtained even with diamond coring, where core breakage and core loss can be a serious problem, especially in regolith.

Modern geophysical logging systems can be easily deployed from 4WD vehicles, using digital, computerised, small systems, such as the one shown in Figure 3.

Figure 3. Regolith logging with a small, easy-to-use geophysical logging system, mounted in a 4WD vehicle.

3. THE BOREHOLE ENVIRONMENT

The very act of drilling a borehole can perturb the physical properties of the rocks that have been drilled. Fluids and drilling additives can invade the surrounding formations changing resistivities, densities and electric potentials. Drill cuttings created by the drilling bit can plaster themselves over the walls of the hole as "mudcake" and can originate at quite different depths from where they are now found. For these reasons, drilling of regolith is often carried out using compressed air instead of drilling fluid to cool the drill bit and lift cuttings. While this minimises the introduction of drilling contaminants, it is still important to remember that the borehole environment will not always be strictly representative of the properties that you are trying to measure.

4. SOME SELECTED GEOPHYSICAL WELL LOGGING METHODS

Mechanical Methods

Caliper Logging

1. A caliper tool is used to measure the diameter of a borehole and how it changes with depth. It typically works by using one or more spring-loaded arms, which are pressed against the borehole wall as the tool is raised from the bottom of the borehole. Motion in and out from the borehole wall is recorded electrically and transmitted to surface recording equipment.

2. The simplest caliper tool uses just one arm to record diameter. More sophisticated tools may have four or more arms each independently measuring distance to the borehole wall. Multi-arm tools generally give better resolution of the borehole shape than a single arm tool.

Sonic Logging

Sonic tools work by transmitting a sound (ie. P waves) through the rocks of the borehole wall.

A basic sonic tool generally consists of two modules. One contains the transmitter and the other contains two or more receivers. The two parts separated by a rubber connector (Figure 4) to reduce the amount of direct transmission of acoustic energy along the tool from transmitter to receiver.

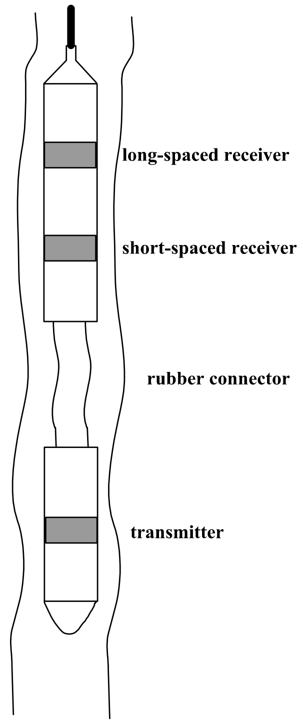

Figure 4. Schematic diagram of a sonic tool with the transmitter and two transceivers.

The transmitter injects a sinusoidal wave-train of acoustic energy into the formation. The detectors subsequently receive a complex signal, because of the multiplicity of ray paths that the wave-train can take through the formation. The fastest arrival (in uncased holes) will generally be through the rocks near the borehole wall.

Detection of this signal uses a signal processing algorithm involving cross-correlation between the original wave train generated by the transmitter and the coda received by the detectors.

In practice, sonic logging actually measures the "time of flight" along the fastest signal path. Because this time of flight is dependent on the density of the medium, it can be used to calculate the average density of the rocks through which the signal passed.

Sonic logging tools were initially developed for the petroleum industry as porosity measuring devices, and they have a similar use in regolith. In hard rock environments, where porosities are generally low, sonic logs can be very useful lithological probes.

A very important use of sonic logs is for the correcting of interval velocities used in seismic processing and interpretation. This leads to better velocity models for seismic processing and analysis. Sonic log data from shallow holes drilled in the regolith can also be particularly useful as inputs for *static corrections* in seismic processing. This can yield useful information about the depth of the regolith.

ELECTRICAL METHODS

Common electrical logs used in hard rock drilling include:

1. resistivity and conductivity;
2. spontaneous potential (SP), and,
3. induced polarisation (IP)

These methods are also used in regolith studies. In particular, conductivity logs are often used for ground-truthing airborne EM data, and resistivity and SP logs are recorded in some water bores.

The factors, which effect the electrical properties of rocks, are, in order of decreasing importance (Hallenburg, 1984):

1. porosity and water content;
2. water chemistry;
3. rock chemistry and mineralogy;
4. degree of rock alteration & mineralisation;
5. amount of evaporites;
6. amount of humic acids; and,
7. temperature.

Resistivity Logs

If a material containing unbound charged particles is subjected to a voltage difference then an electrical current will flow. The impedance to this flow is called the electrical resistance and it is a function of the geometry of the current flow and the intrinsic resistivity of the material. Some materials such as quartz and muscovite have high resistivities, while others have more moderate values (eg. sand) and for some the resistivity is low (eg. clay, saline groundwater).

The resistivity and conductivity of a material are inversely proportional quantities. The measurement is referred to as resistivity when measurements are made with a contact, or focused, resistivity probe by causing a current to flow in rocks. In these cases the resulting voltage drop is measured. (Keys, 1988)

Current flow in a porous clean sandstone (ie. shale-free) is mainly through the fluids within the pore spaces. Thus, in the absence of shale, the resistivity is mainly indicative of the characteristics of the pore spaces (for example pore volume, pore interconnectivity, pore fluid composition).

Pore space character tends to vary significantly from formation to formation. For this reason, resistivity logs are often useful tools for exploring stratigraphy and depositional history, and for the definition of different regolith units.

Simple "single point resistivity" logging typically uses a geometry like that shown in Figure 5. Note that resistivity logs only work if the downhole probe is below the water table. This can be a limitation for some shallow regolith studies unless water can be added to the borehole to artificially raise the level to the area of interest.

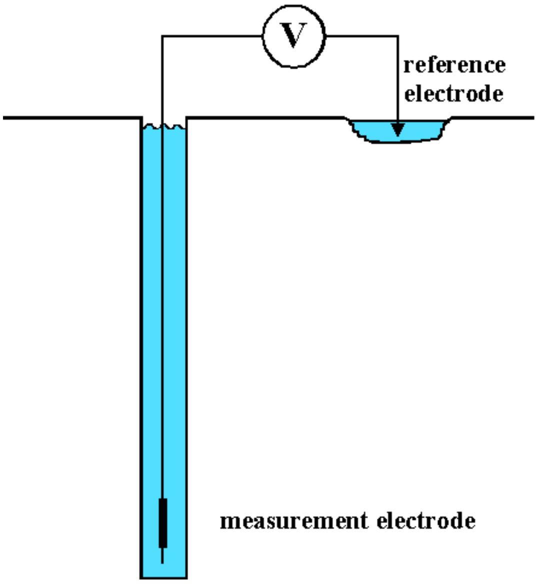

Figure 5. Schematic diagram of logging setup for resistivity and SP logging.

Single-point resistivity logging measures the resistivity between a single moving electrode downhole and an earth connection at the surface. Theoretical analysis and practical observation shows however that the bulk of the signal is in fact generated within a small volume surrounding the downhole electrode. Thus for a 5 cm diameter spherical electrode, 90% of the signal is generated within 50 cm of the electrode.

Electrical conductivity

The term conductivity generally is applied to measurements that are made with an induction probe, utilising principles of electromagnetic induction. These measurements can be made either in fluid-filled or dry holes.

Conductivity measurements are important for calibrating airborne EM data. Physical properties influencing conductivity are:

1. porosity and fracturing;
2. mineralogy;
3. alteration;
4. pore fluid % in pores;
5. salinity; and,
6. pore connectivity.

Knowledge of fluid conductivity and the borehole diameter enables application of corrections for borehole effects.

The accuracy of induction logging systems decreases for high resistivity rocks, often exhibiting a 50% error at 100 Ohm-meters and a 100% error at 200 Ohm-meter. Because of this characteristic, inductive conductivity logging is more often used in regolith than in fresh rock environment.

Self Potential (SP) Logs

SP logs use the same geometry as that shown in Figure 5 and for this reason they are normally run at the same time as resistivity logs, using a composite tool.

SP is one of the oldest applied logging methods and was developed by the Schlumberger company. SP logs measure small differences in potential (ie. voltage) between the downhole movable electrode and the surface earth connection. These potentials can arise from a wide range of electrochemical and electrokinetic processes. The SP method has been used in the oil industry for many purposes, but it is of a limited value in a fresh water environment. The factors that cause SP effects in a bore hole are extremely complex, not very well understood, consequently interpretation of SP logs in regolith can be a challenging exercise.

Electrochemical SP-s can for example arise from preferential diffusion and absorption of cations and anions on and through clays. Cations being much smaller than anions generally have a higher mobility through clays. Saline groundwater which is in contact with clay-rich materials often develop charge imbalances (ie. potentials) as a result of fluid flow. These potentials which are typically in the range of a few mV to a few tens of mV-s, can be measured in an SP log (Figure 6).

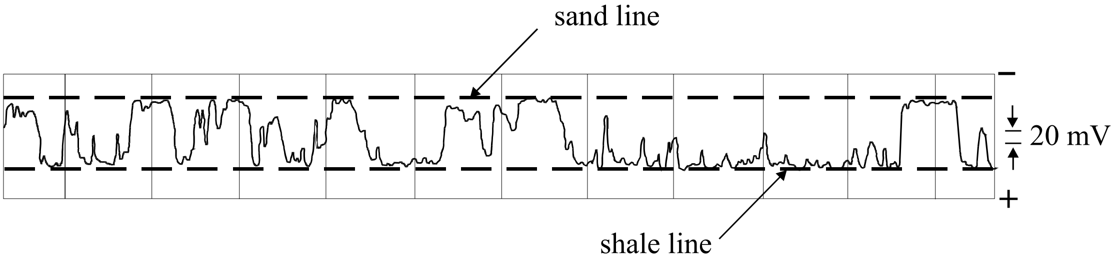

Figure 6. An SP log through interbedded sandstones and shales (modified after Sheriff 1991).

Induced Polarisation (IP) Logs

IP is a technique which is commonly used in surface prospecting for minerals but it can also be used in downhole applications. IP uses a transmitter loop to charge the ground with a high current. The transmitter loop is then turned off and the change in voltage with time is monitored using a secondary loop.

In borehole applications, the primary loop induces a current flow in the rocks beyond the borehole wall. This current flow can lead to a charge build-up on conductive particles such as sulphide ores and carbonaceous material such as coal (Figure 7). The time-dependent dissipation of this charge is reflected as a decaying voltage.

IP logging is widely used in mineral exploration, and has particular value in the exploration for disseminated sulphide targets such porphyry copper deposits.

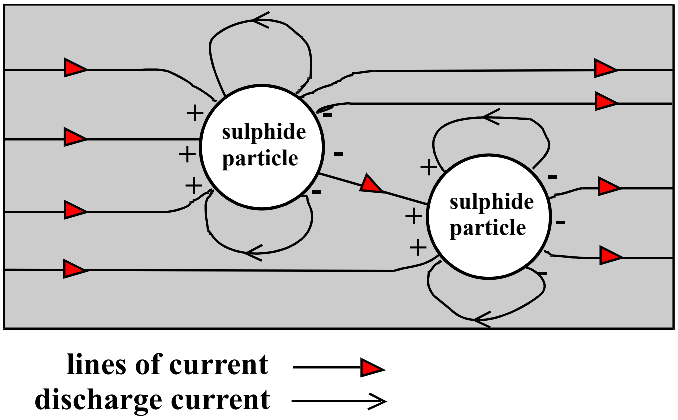

Figure 7. IP logging can be used to detect disseminated conductive grains (modified after Hallenburg, 1984).

The disseminated nature of these targets make them ideal for IP but otherwise difficult to detect. IP has also been used in the detection of zones of alteration and redox trends and it has been used successfully to determine the rank of coal *in situ*.

MAGNETIC SUSCEPTIBILITY LOGS

Magnetic susceptibility is the ratio of the intensity of magnetization of a magnetizable material to the intensity of an applied magnetic field. More formally it is a dimensionless quantity, which expresses the ease with which a substance may be magnetized.

The magnetic susceptibility sonde is similar to the induction conductivity sonde. A detailed description of the tool is given by McNeil, et al. (1996)

In practice, the magnetic susceptibility of a rock depends on the ferromagnetic mineral content. Magnetite is the most important ferromagnetic mineral, due to its widespread occurrence in nature and its high magnetic susceptibility, but other ferromagnetic minerals, such as illmenite, maghemite and pyrrhotite also cause magnetic susceptibility anomalies.

In sedimentary regolith, maghemite clasts are often present in gravelly beds, and so magnetic susceptibility logs can be particularly useful. They can be used to identify layer boundaries (eg. clay versus sand versus gravel. See for example the regolith log in Figure 9). The method is also useful in some cases for correlating lithological facies by identifying differing origins of similar materials, when for example some of the sediments are derived from mafic rocks.

It is important to note that magnetic susceptibility measurements taken in highly conductive material (>200mS/m) need to be corrected for conductive effects.

RADIOACTIVE METHODS

The principal radioactive emissions of interest in borehole geophysics are gamma rays and neutrons. Other radioactive products such as alpha particles (helium nucleii) and beta particles (electrons) can penetrate such small distances through rocks that they are not useful for logging.

Natural Gamma Logging

The simplest radioactive method in geophysical well logging is the natural gamma log. These logging tools record the level of naturally occurring gamma ray emissions from the rocks around a borehole. The simplest of these type of tools records only the total gamma ray signal. This signal is comprised essentially of gamma ray emissions at different energy levels from the radioactive isotopes of the elements potassium (^{40}K), Thorium (^{232}Th) and Uranium (^{238}U) and the daughter products in the decay series of each.

The distribution of K, Th and U (and their daughter products) varies widely in the continental crust and can also be significantly affected by regolith processes and by biological activity. As a result, logging of the gamma ray signal emanating from the rocks around a borehole can provide considerable information about the geology and the processes that have operated.

In sedimentary rock sequences, relatively high natural gamma counts are recorded in shales and other clay-rich sediments and relatively low counts are recorded in clean quartz sandstones and limestones. The high signals observed in clay-rich sediments are largely due to the affinity of clay minerals for potassium. However, many regolith clays are leached and do not contain substantial amount of potassium. Therefore, this interpretation is not always applicable for regolith units.

More sophisticated natural gamma logging tools separately record the gamma ray counts of the three decay series. In this way detailed information about the chemistry of the rocks in the borehole wall can be acquired. In practice, the sensors in these tools aren't directly measuring the parent nuclides ^{238}U and ^{232}Th, instead they record gamma ray emissions from the daughter products ^{214}Bi and ^{208}Tl.

The distance that an emitted gamma ray can travel through rocks is strongly dependent on the electron density of the medium because it is through scattering interactions with electrons that the gamma ray photons lose their energy. In practice, the gamma rays may penetrate as much as 1-2 metres through the rocks, though this depends strongly on their initial energy level and the rock density. Distances are greater in low density rocks such as highly porous sediments and coals and correspondingly much less in dense crystalline rocks. Gamma logs have been successfully used to search for roll front uranium deposits in regolith.

Because gamma rays can travel such distances through rock, the spatial resolution of the method is affected. Boundaries between widely differing natural gamma ray emitters can tend to be somewhat "smeared" in the gamma ray log results. Moreover, because the emission of gamma rays is a physical process with natural statistical variability, gamma response has a temporal variation. In logging, this effect is minimised by averaging response over a fixed time interval.

Neutron Porosity Logging

Neutron porosity logging uses an active neutron source to emit neutrons into the rocks around a borehole. Because free neutrons are almost unknown in the Earth, the flux of neutrons subsequently recorded at the detector in the tool can be used as an indicator of the conditions in the surrounding rocks.

The neutrons entering the rocks of the borehole wall from the tool are at high energy and generally have great penetrating power. The exception is when significant concentrations of hydrogen exist. In this case, the neutrons rapidly loose energy due to collisions with the hydrogen nucleii and become what are known as "thermal neutrons". These thermal neutrons behave in many respects like a diffusing gas and form a spherical shell around the source in the probe. The radius of this sphere will depend primarily on the concentration of hydrogen in the environment around the probe.

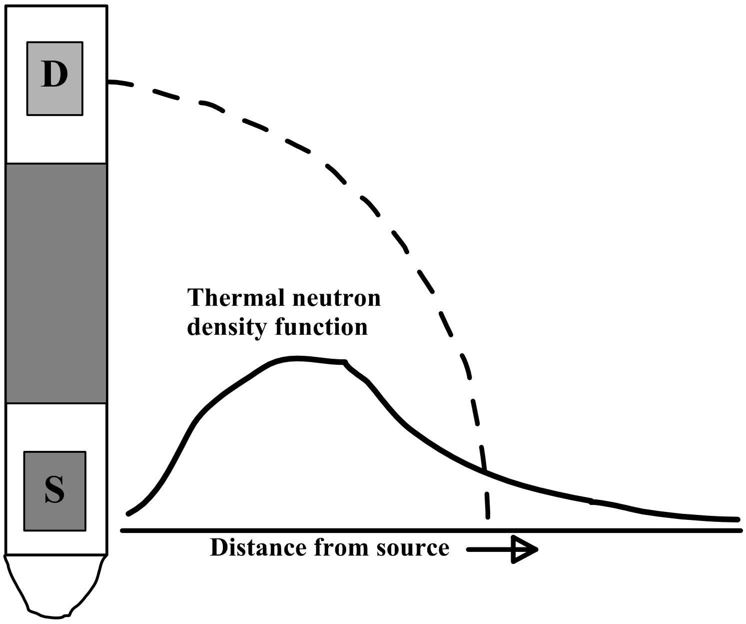

Figure 8. The density distribution of thermalised neutrons around a neutron tool

In general the neutron tool is a very useful tool for measuring "porosity" but it must be remembered that the measurements are model-dependent. In particular:

1. the pores are assumed to be completely water-filled;
2. any hydrogen structurally bound in minerals (eg. clays in the form of OH) will have the same affect of slowing neutrons down. Thus an independent estimate of "shale" content will be needed (eg. an SP or a resistivity or a natural gamma log);
3. the neutron tool only measures the properties of the rocks very close to the borehole (ie. there may be complications with drilling-induced changes); and,
4. the neutron log results are influenced by changes in borehole diameter.

Primary Calibration of the Instrument

Neutron porosity tools are traditionally calibrated in API test pits built from a sequence of limestone samples of differing water-filled porosity. Thus the porosity values obtained from neutron logs actually refer to *equivalent limestone porosities*.

In Australia, AMDEL maintain a series of these API test pits at its suburban Adelaide site and logging equipment is generally taken there on a regular basis to re-check the primary calibrations of the equipment.

In order to make sense of these equivalent limestone porosities, a series of curves are usually provided showing how the limestone porosities correlate with porosities in other rocks

Strengths of the Neutron Porosity Logging Technique

The neutron porosity log can be run in a hole, which has been cased with steel. Logging in shallow holes cased with PVC is a problem though because of the H in the PVC.

Because the technique is sensitive to lithological differences, neutron porosity logs can be very useful in cross plots with other log data to help determine lithology.

In mineral geophysical logging in hard rock environments (low porosities) the neutron porosity log can often be used in place of a resistivity log (since both actually measure water-filled porosity). In cases where the neutron porosity log indicates higher porosities than does the resistivity log, the cause could be hydrocarbons in the fluid, or lack of effective permeability (ie. the pores are not well interconnected).

5. EXAMPLE REGOLITH LOG

An example of wireline logs of a drillhole through regolith is shown in Figure 9. Other data included are grain size (visual estimate of combined one metre composite cutting samples) of the transported alluvial sediments which overlie weathered diorite, and mineralogy (as determined by quantitative XRD).

The magnetic susceptibility log shows several sharp spikes that correspond to the presence of detrital grains (and gravel clasts at 11-12 and 20-21 m) of maghemite in the sediment. The slightly higher readings in the weathered bedrock are probably due to disseminated magnetite.

The conductivity log shows higher conductivity in clayey units of the sediment, and in the clayey saprolite. Conductivity falls dramatically at the saprolite/saprock interface. The higher conductivity portions of the log may be due to more saline groundwater in the clay units, which have around 20% porosity, but low permeability.

The gamma log does not clearly reflect the sand/clay ratios of the sediment, in contrast to the usual responses in sedimentary rocks. This is a result of the predominance of kaolinite (which is devoid of potassium) in the transported regolith clays.

However, the four large spikes and the smaller anomaly at 45 m in the magnetic susceptibility log correspond to small local dips in the gamma log, indicating that these dips are associated with more sandy beds. Many local highs and lows in the conductivity log appear to correspond to local highs or lows in the gamma log. This probably reflects local changes in grain size and mineralogy that aren’t evident from the sampling techniques and laboratory methods used.

6. CONCLUSIONS

Geophysical well logging provides many different opportunities to investigate the material making up the walls of a borehole, be it regolith or crystalline rock. A wide range of different sensors provide information which is complementary in nature. Best results are obtained by running a suite of logs and analysing their similarities and differences.

7. PROBLEMS, LIMITATIONS

The biggest problem in using geophysical well logging is that you must have a “well” (ie. a borehole) in which to operate. The cost of drilling means that boreholes are not always available and hence geophysical well logging will not always be possible for a particular study. In regolith, it may be difficult to stop holes from collapsing while wireline logs are run. Two possible methods of stabilising holes are to drill with foam, which helps prevent collapse, or insert plastic casing into the hole, and log inside the casing.

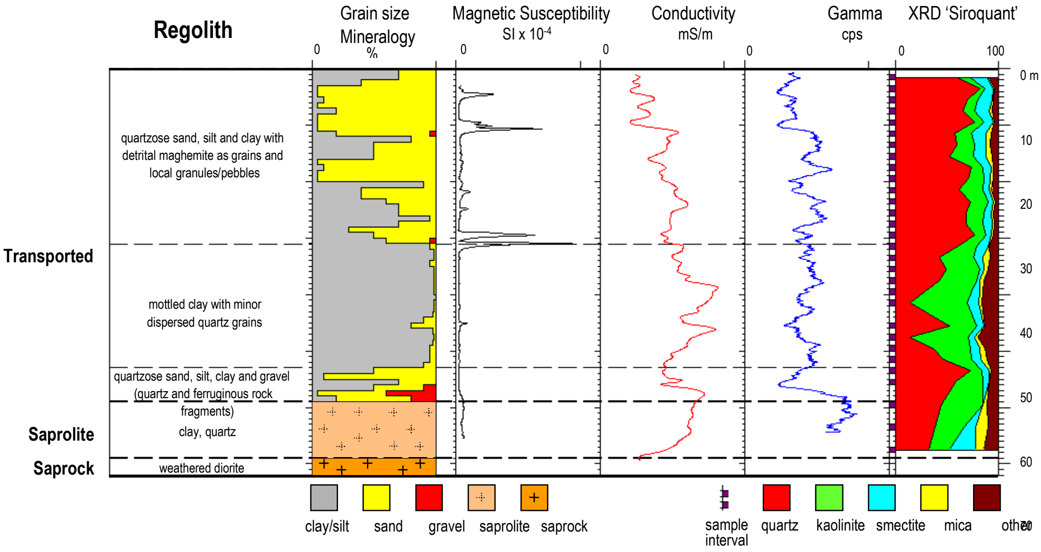

Figure 9. An example of wireline logs of a drillhole through regolith.

When geophysical well logging methods can be used, it is important to recognise that each method has its own particular strengths and weaknesses. The presence of PVC casing for example can prevent electrical logging but has little impact on natural gamma logs. Similarly, such casing presents a problem for neutron logging because of its hydrogen content whereas a steel casing generally does not. The specific problems and limitations vary from log to log and need to be understood on a case by case basis.

8. SURVEY ORGANISATIONS

Geophysical well logging is in many respects a mature technology and as a consequence it is available as a commercial service from many companies.

9. COSTS

Costs of geophysical logging vary depending on the depth of the borehole to be logged and the types of logs to be run. In the extreme case, log runs of exploration and production holes in the petroleum industry often cost upward of A$1 million, particularly in offshore operations. In the mineral industry and in groundwater applications, boreholes are normally much shallower and costs are consequently much lower.

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