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Correlation Between Geological Logs and Geophysical Logs to Estimate Aquifer Positions in the Crystalline Basement Rocks of the Birimian System, Ghana

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Abstract
This study has enabled the lithological units intersected by a well, locate contacts of adjacent beds, locate depth to groundwater and determine the thickness of the units. Records of three geophysical logs parameters; resistivity, gamma ray and self-potential (SP) measured in five boreholes which were drilled as part of a Rural Water Supply Project Phase II in the Juabeso –Bia District were correlated with the geological logs on site from the drill cuttings of the bore hole. The boreholes depths were between 45-52m and were drilled over hornblende, phyllites and granites which constitute part of the various rock types of the Birimian system. Deflections of the SP logs established the presence of permeable rock formations. Alternatively, the long-short- normal logs distinguished between permeable and impermeable beds by recording lower or higher apparent resistivity signals respectively on the log sheet. These anomalies are identified mostly in the weathered zones and also within the fresh rocks. In almost all the boreholes the gamma ray logs indicated low clay content which may be due to the absence of intensely weathered rocks or low concentration of radioactive rocks within the survey area. The application of gamma ray logs rely on the fact that the concentrations of radioactive isotopes varies from one rock type to another and that acidic rocks are more radioactive than the basaltic rocks hence most of the rocks in the project area is more basaltic. Though the SP deflection was able to indicate permeable formations there was no guarantee that the rock formation could contain water. However, the combined interpretation of the three other logs shows that deflections of SP close to the basement rocks and lower resistivity values on the long-short-normal logs generally indicated the presence of water bearing formations. Three lithological units were identified over the various rock types: a top layer predominantly clay of thickness between 0-25m overlying a weathered zone about 16-45m thick above the fresh rocks of the various types.
Keywords: lithological, resistivity, Birimian, geological, geophysical, rock

Introduction

Geological log constitutes a detail record of the geologic formation penetrated by a borehole by visual inspection of samples brought to the surface. It describes the underground features in relation to depth, thickness and type of formation penetrated by the borehole. On the other hand geophysical log involves physical measurement of the geologic formation made by instruments lowered into the hole. Geologic log and geophysical log constitute the practice of well logging. Geophysical logs provide a continuous analog or digital record that can be used to interpret lithology, bed thickness, potential aquifers or confining units, permeability, porosity, bulk density, hydraulic resistivity, moisture content, and specific yield. The source, movement, and chemical and physical characteristics of ground water also can also be inferred.

The value of geophysical logs in evaluating physical properties of the rock matrix and contained fluids has been recognized for many years in the oil and gas exploration but in recent years applications in hydrogeological investigation in shallow boreholes (few 100m) have gained much popularity (Phongpiyah Klinmanee and Helmut Dürrast 2012, Doveton and Prensky 1992). 1994, Jorgensen & Petricola 1995, Kobr et al. 2005), coastal aquifers and fresh/salt water boundaries (Buckley et al. 2001, Hwang et al. 2004). Numerous attempts have been made to equate geophysical-log response to geologic and geohydrologic characteristics of aquifers. In each case, knowledge of local lithology and hydrology and of the response of a particular logging tool to that environment has been the key factor in adjusting a theoretical equation to fit field conditions. (Hudson, 1996)

Although geophysical logs cannot replace adequate drill-cutting samples, drill-cutting samples are sometimes not sufficient to characterize aquifer water quality and define the lithological boundaries precisely because of dynamic disturbances caused by the drilling action, lag time of the drill cuttings, and the introduction of drilling fluid into the aquifer. Conversely, the most intensive analysis of drill cuttings or cores cannot replace the value of in-place measurements of a suite of geophysical logs, but some properly taken and analyzed drill-cutting samples are essential to the interpretation of logs, especially in an unfamiliar geologic environment

(Hudson, 1996) This aspect of groundwater exploration and development is important also to ensure proper placement of well screens and filtering media directly opposite identified productive aquifers for maximum flow of water into the borehole, particularly in areas of low groundwater potential such as in the Voltaian sediments and in Precambrian crystalline rocks of Ghana. (Agyekum et. al. 2013). Many groundwater development projects conducted in the past decades have indicated that low to medium yields can still be a viable source of water for rural communities, but these are often associated to thinner groundwater bearing layers (thickness less than 1–2 m), and which hardly can be identified during the drilling process from the geological logs.

Currently geophysical-logging equipment developed primarily for shallow-hole logging, such as for water wells and mineral exploration, has become readily available for investigating such problems. Most of these shallow-hole logging equipment has digital capabilities and on-board computer software that provides cross plots and on-location log analysis. The results have been an increase in water-well logging activity and a subsequent increased demand for better interpretation principles as applied to ground-water problems. These small-diameter tools have good resolution and accurately measure electrical resistances and natural radiation of geologic formations which can provide detail picture of the thin beds and the aquifer characteristics. This paper correlates geophysical logs (long-short normal, self-potential and natural gamma) and geological logs from six boreholes to determine potential productive aquifers as well as estimate the aquifer thickness and lithological units to enabling well designers position screens or perforated caissons with more accuracy than to rely only on the geological logs.

Geology and Hydrogeological Setting of the Study Area

The study area lies between latitudes 6^0 20'N and 6^0 30'N and longitudes 2^0 38'E and 2^0 40'E in the Juabeso-Bia District, Western region, Ghana. The area falls within the Wet Semi-Equatorial Region zone with relatively mean annual rainfall of about 1250-2000mm recording maximums in June and October each year. The district is underlain by the Birimian System which consists of metamorphosed sediments (metasediments) intercalated with metamorphosed tuffs and lava (metavolcanics). The sediments consist of mainly schists and, slates and phyllites. The formations are intruded by batholitic masses of granites and gneiss (Junner, 1940, Gill 1960, Kesse, 1985). Other rock types also commonly found include amphibolites marble, calc-silicates, quartz-mica-schits, hornblende-schits, greywackes, feldspatic sandstones. These rocks contain only small quantities of water in fractures and joints. However, deep weathering has produced a permeable horizon that is of varying thickness overlying the fresh rocks in many places. Where the horizon lies within the zone of saturation and rainfall is moderate, the probabilities for the completion of successful borehole are generally enhanced. On the other hand weathering may yield clayey products to fill fractures and joints and thus reduce their potential for groundwater accumulation. (Junner, 1940, Gill 1969, Kesse, 1985**).**

Generally the metavolcanics, metasediments as well as the granite and gneiss associated with the Birriman System are typically impervious and have low groundwater storage potential. However, the granite and the gneisses have been found to possess secondary porosity developed as a result of jointing and fracturing and weathering (Gill 1969). These fractures and joints become conduits for channeling runoffs into the underground storage systems which can hold large quantities of water. The fractures can sometimes be many kilometers long and extend to several hundred meters of depth. Also networks of fractures can link together to provide substantial quantities of water.

Methodology

Several boreholes were drilled using the rotary method by the Ghana Water Company under the Rural Water Supply Project II. Six of the boreholes selected for this paper had final depths between 39-60m. The logging was done in uncased boreholes and the long-short normal resistivity, self-potential (SP) and the natural gamma logs recorded at the same time. Figure 1 shows schematically the logging process. The logging was done shortly after drilling in the UP mode due to stable tool configuration resulting from pull force against gravitational force. The geological samples were collected at 1.5m intervals in order to sample thin beds, The output data was produced automatically as traces on a paper strip together with plotting scales based on the measured values which are shown on the logs as a single horizontal axis divided into tracks. From the left of the chart, the first track represents the self-potential log. The axis has a scale readings beginning from negative to positive in milli volts (mV). The long-short normal resistivity logs are represented on the same chart in the second track, with a horizontal axis scale given in ohm-meter (ohm-m), beginning from zero and increasing to the right of the scale.

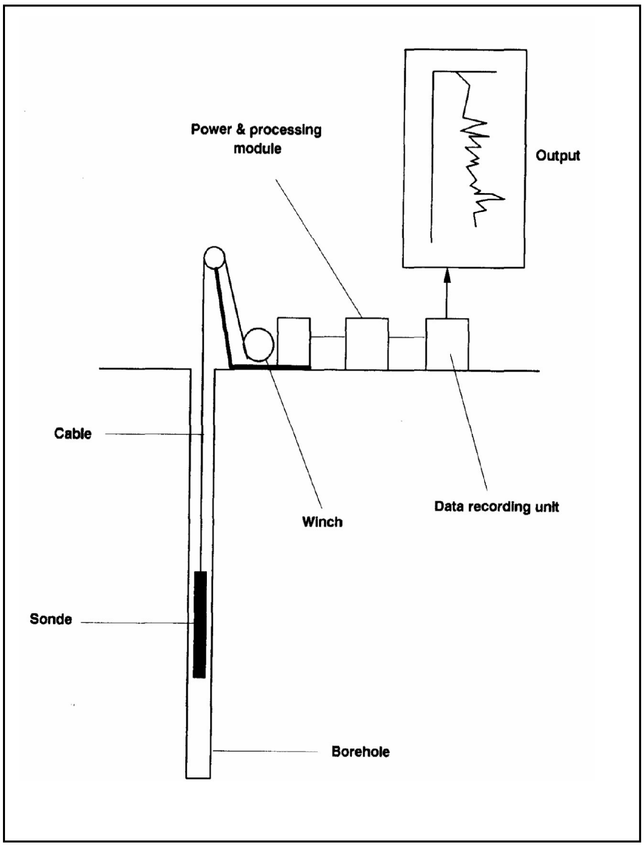

Figure 1: Schematic diagram of the logging process of a geologger

The third track gives the recording of the natural gamma log in counts per second (cps). The value starts from zero and increases to the right. On all the logs recorded, the data is plotted against the depth of probe in the borehole.

The principle and interpretation of long-short normal, self-potential and natural gamma logging has been described in several publications; (Yearsley and Crowder 1990, Keys 1990, Keys and MacCary 1971, Prensky 2002, Hudson 1996, Phongpiyah and Dürrast 2012, Hearst and Nelson 1987, Labo 1985) accordingly, the self-potential log is a graphic plot of small differences in voltage that develop at the contacts between the borehole fluid, the shale or clay and the water in the aquifer. Shale baseline readings against shale/clays formations are relatively constant and are referred as 'shale baseline'. Opposite permeable formations the SP curve typically shows deflections to the left (negative SP) because negative potentials are more commonly encountered. In fresh water, SP anomalies are typically inverted (i.e., they appear to the right of the shale baseline). SP logs are used in combination with resistivity logs to define strata boundaries for correlation and to infer the lithology of the strata as a function of permeability and resistivity. The shape of the SP curve depends on the drilling mud used and the geologic strata encountered. For example, the SP curve for a shale bed would indicate zero deflection, and the resistivity curve would indicate low resistivity because of bound water in the clay and trapped water in the shale.

Generally, the SP and resistivity curves converge opposite shale strata (A in figure 2) and diverge opposite permeable fresh water sands (B in figure 2). A limestone bed, which usually is highly resistive but develops little spontaneous potential, would produce a large resistivity deflection but a subdued SP peak (C in figure 2). A permeable sand bed with pore water of high salinity typically would produce little resistivity deflection but a large negative SP peak (D in figure 2). As noted by several investigators the determination of lithologies from SP logs should be done cautiously because many factors contribute to the magnitudes and directions of the curve deflections. The SP log is best used with resistivity and other logs to detect strata boundaries and to correlate strata between boreholes. The SP log is also used to determine formation water resistivities.

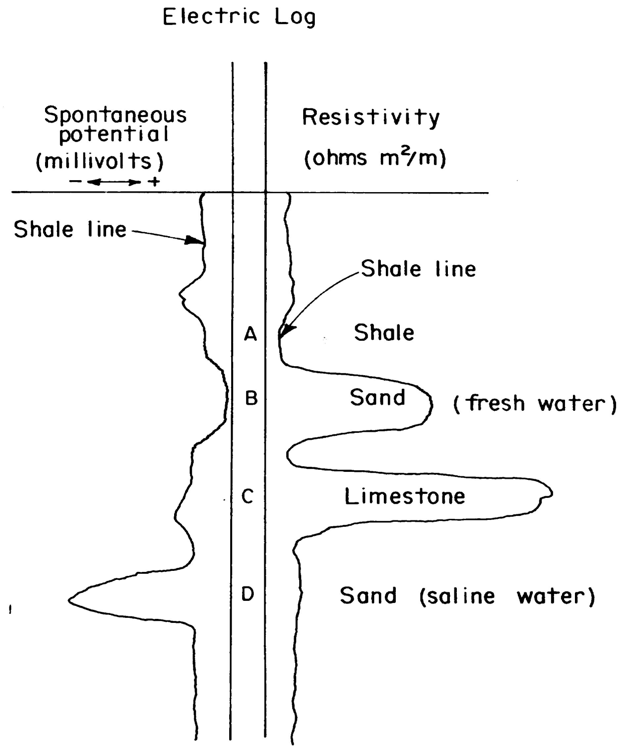

Figure 2: Electric Log showing SP and resistivity in different beds (Hearst and Nelson 1987, Labo 1985)

The conventional resistivity logging is analogous to DC resistivity surveys at the ground surface. A constant current is introduced into the rock between two current electrodes in the logging tool. The potential measured between two other electrodes (potential electrodes) is proportional to the electrical resistivity of the rock. The tools used for conventional resistivity logging have the following lengths (potential electrode spacings): small (L = 10 – 50 cm), large (L = 50 – 200 cm), 16 inch (L = 40 cm), and 64 inch (L = 160 cm). The measured value is called the "apparent resistivity" and is dependent on the size of the borehole, the adjacent rock and the overlying and underlying rock. Figure 3 shows the schematic electrical circuit of the array arrangement in the logging tool. The "true" resistivities of the rock can be derived from the apparent resistivities using master curves. The measured resistivity logs are symmetric. The curve deviates strongly from the true value when the layer thickness h is less than 5L and a reverse curve when $h/L < 1$. The depth of investigation and vertical resolution are determined by the length L of the tool. The depth of investigation and vertical resolution are inversely proportional.

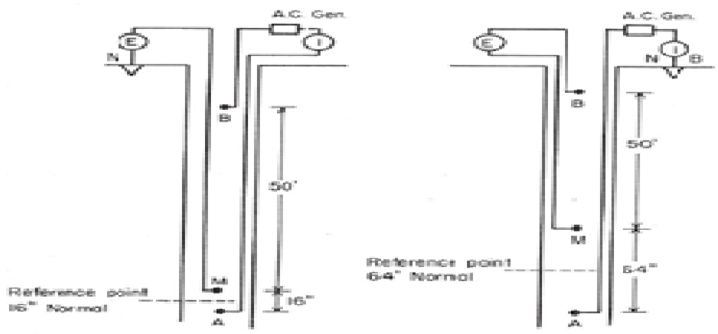

Figure 3: The configuration for the normal resistivity log (from Stefansson and Steingrimsson,1980)

Normal electric logs measure the apparent resistivity of a volume of formation surrounding the logging-probe electrodes. The depth of investigation is relative to the resistivity and bed thickness, but is considered to be twice the AM spacing. The short-normal probe is considered to measure only the mud cake and the invaded zone. The long-normal probe is considered to investigate the invaded zone and the zone where native formation water is present.

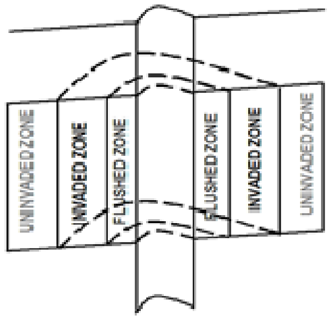

Figure 4: Flushed, invaded, and un-invaded zone around a borehole. (Phongpiyah and Dürrast, 2012)

The normal devices give poor results in highly resistive rocks and do not function at all in very saline environments. The major limitations of the long-normal resistivity log are the poor resolution in thin beds and the averaging effect in interbedded clay and sand.

The gamma ray log measures as a passive tool the natural emission of gamma rays by a formation. The emission depends on the mineral content and the amount in the rock or sediment. In particular, shale usually emits more gamma rays than other sedimentary rocks, such as sandstone, gypsum, salt, coal, dolomite, or limestone. Studies by Amjad (2000) have indicated that due to large variation in rock composition, the type and content of radioactive minerals in metamorphic and igneous rocks may vary considerably. Field and laboratory tests have indicated radio-activity and gamma radiation levels for individual metamorphic or igneous rock units. Slate and phyllites were found to have moderate gamma radiation levels; basalts and bedded tuffs may have fairly gamma radiation, while pegmatites and some granites usually have low radiation levels

ANALYSIS AND INTERPRETATION

Correlation of Geological logs and Geophysical logs

Empirical knowledge of the ground-water basin can save steps in the evaluation of the log record and can eliminate the need for some logs. Local knowledge of aquifer characteristics may lead to elimination of some geophysical-logging parameters not needed in the resolution of the immediate problem. Caution needs to be taken, however, in the elimination of any available data. Although some data may not be needed in the resolution of an immediate problem, future problems in the same area may require comparable log data. Estimation of the depth to the water table is an example of the need for the evaluation of the log record and the misleading conclusions that can be drawn as a result of too few data. Therefore, to be conclusive, most geophysical-log interpretations require two measurements that are in agreement.

The object of the geophysical logs and the geological logs is to determine which rock formation are permeable and thus productive, and which are so shaley or clayey that they can be eliminated from the search for potential aquifers. Such information is critical in the well design and the determination of the geological model of the project area. A secondary object of interpretation is to find correlations between the trace patterns of logs from different wells, so permitting the continuity and relative positions of subsurface formations to be assessed. But since the logging was conducted in few isolated boreholes which were vastly isolated the continuity of the subsurface strata could not be scientifically be established. Hence the geological model derived from the interpretation could be described as location specific.

Geophysical and Geological log (Project ID: BH2, Kogyena)

On Figure 5, the gamma-ray log shows low counts, as the probe descends to the depth of about 12m it then increases slightly below this depth to the depth of about 48m. This suggests that the materials penetrated by the borehole have very low clay content. The negative SP log however shows some changes in the nature of the rock formation at the depth of about 20 to 24m and between the depth of 40 and 48m. These portions are thus more permeable than the other parts.

A correlation with the geological log reveals that the SP deflection at 20m marks the boundary between the lateritic clay and the completely weathered hornblende schist. The SP deflections at 40m also mark the boundary between the slightly weathered hornblende schist and the completely weathered formation on top. Groundwater was found in the slightly weathered hornblende schist at the depth estimate of 32m. It is also seen that both the short and the long normal logs within the top formation are about the same. This indicates the extent of weathering of rock away from the borehole.

There is also a sharp increase in the long normal resistivity log at the junction between the highly and slight weathered hornblende schists followed by a drop to zero as groundwater is encountered in the borehole. The presence of the groundwater is also indicated by the elevated deflection of the SP log to the left. The groundwater is highly conductive.

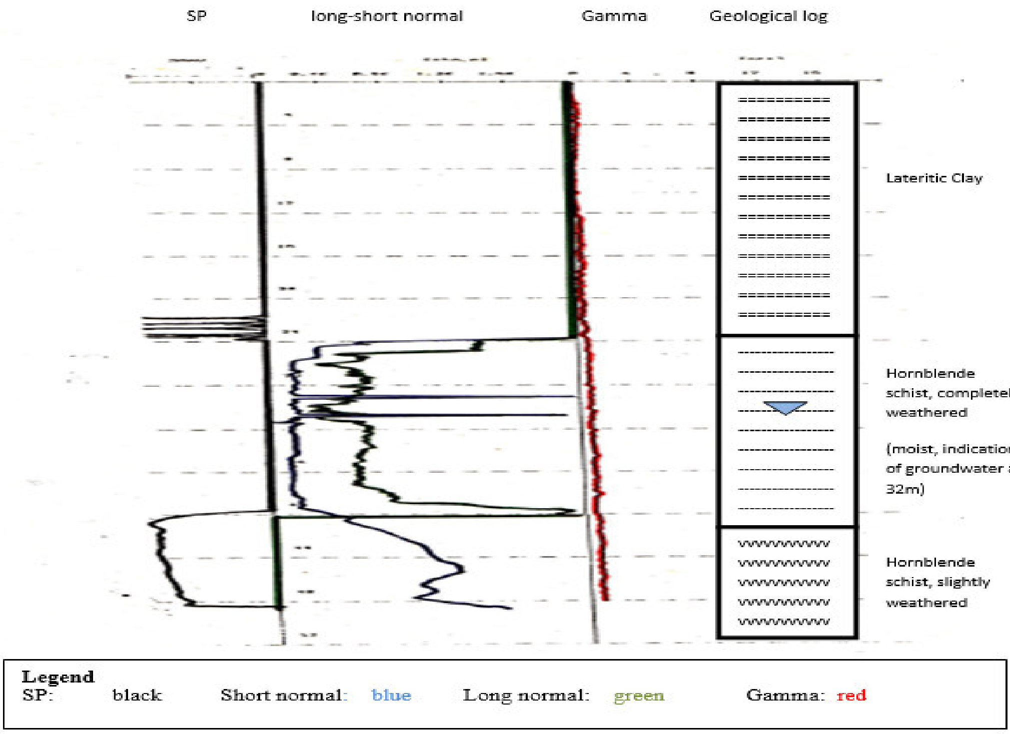

Figure 5: Geophysical and Geological log (Project ID: BH2. Depth= 49m, Kogyena)

Geophysical and Geological log (Project ID: BH3, Kwafukaar)

On Figure 6, the gamma-ray log of BH3 does not show any deflection even though the geologic log shows the presence of clayey materials in the formation from the top of the borehole to the depth of about 19m. This may be due to the compressed horizontal scale which makes any smaller deflections insignificant. Below this depth the presence of radioactive materials is apparent around 20m and 24m and from 37m to about 46m. These may coincide with weathered granitic materials rather than clay with hard stones, as indicated by the geologic log.

A careful study of geophysical log shows that the highly weathered granitic layer starts from the depth of 18m to a depth of about 30m. This is underlain by a slightly fractured fresh granitic layer to a depth of about 36m and in turn underlain by highly fractured fresh granitic layer which contains groundwater.

The SP log on the other hand, indicates the existence of a very thin layer of permeable formation from about 8m to 12m depth. Below this depth there is an indication of increasing activity to about 24m, below 38m depth, the deflection is more negative suggesting the presence of amore permeable formation which probably contains groundwater.

Four possible lithological layers are indicated by the short normal logs: a highly resistive layer from the ground surface to the depth of about 18m, followed by a low resistive layer to the depth of about 32m. Another, moderately resistive layer occurs between 32 and 40m below which a resistive formation is encountered.

The long normal indicates a highly resistive formation from the top of the borehole to a depth of about 31m. Below this depth the log shows an increase in resistivity which seems to suggest that a non-conductive formation has been penetrated. This formation extends from about 31m to 42m where there are several changes in resistivity from high to moderate values until a sharp drop where groundwater was struck in substantial quantity. The probable aquifer was therefore located between the depth of 38m and 48m which is correlated with the geologic log as fractured granitic formation, giving rise to the high apparent resistivity recorded on the long-short normal

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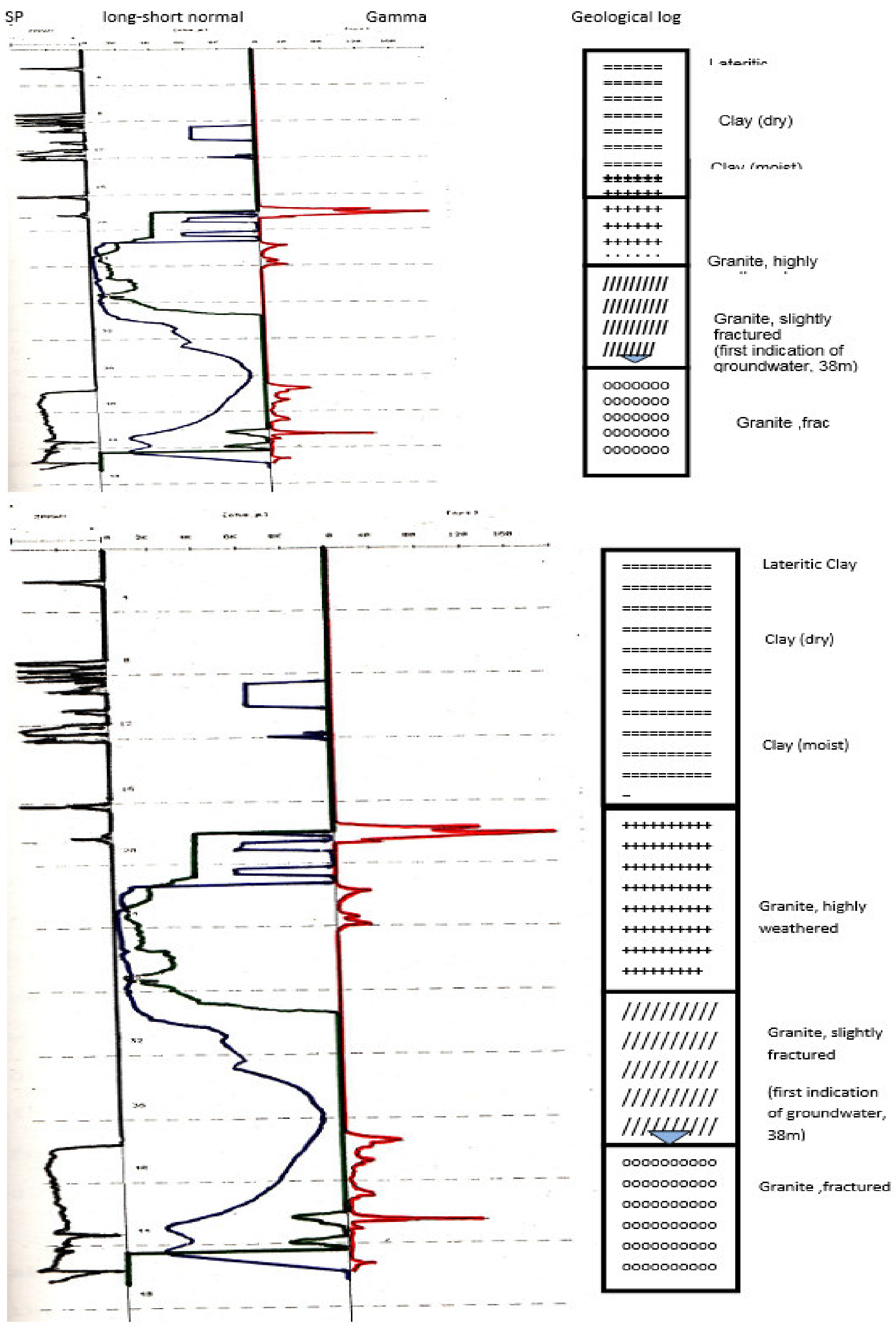

Fig 7. Geophysical and Geological log (Project ID: BH3. Depth= 46m, Kwafukaar)

Geophysical and Geological logs (Project ID BH5 at Akyeakyem)

On Figure 7, the gamma-ray log shows that the clay content within BH5 is low. The deflection is almost constant for all the formations penetrated by the borehole. The SP log however suggests the presence of a non-porous layer of clay from the ground surface to the depth of 8m and from 32m to about 44m depth.

Between 8 and 32m limits lies a porous formation as indicated by the SP log. The long normal log also shows a conductive formation below the depth of 6m. An increase in resistivity was recorded below 8m but was moderate, decreasing to low values between the depth of about 16m and 46m. The magnitude of the resistivity values suggests a low resistive formation. All the three logs suggest the presence of permeable formation of thickness about 24m and located within the weathered zone when correlated with the geological logs.

Three lithological units could be identified. A top clay layer of thickness of about 8m overlying a 24m thick completely weathered hornblende schist, which in turn is underlain by slightly weathered hornblende schist.

Groundwater yield increased as drilling depth increased to the lower part of the permeable formation indicating the presence of a thin permeable bed at the boundary between the weathered and the slightly weathered hornblende schist. Placement of perforated screen at this location in the well design could make use of this aquifer to increase groundwater flow into the borehole

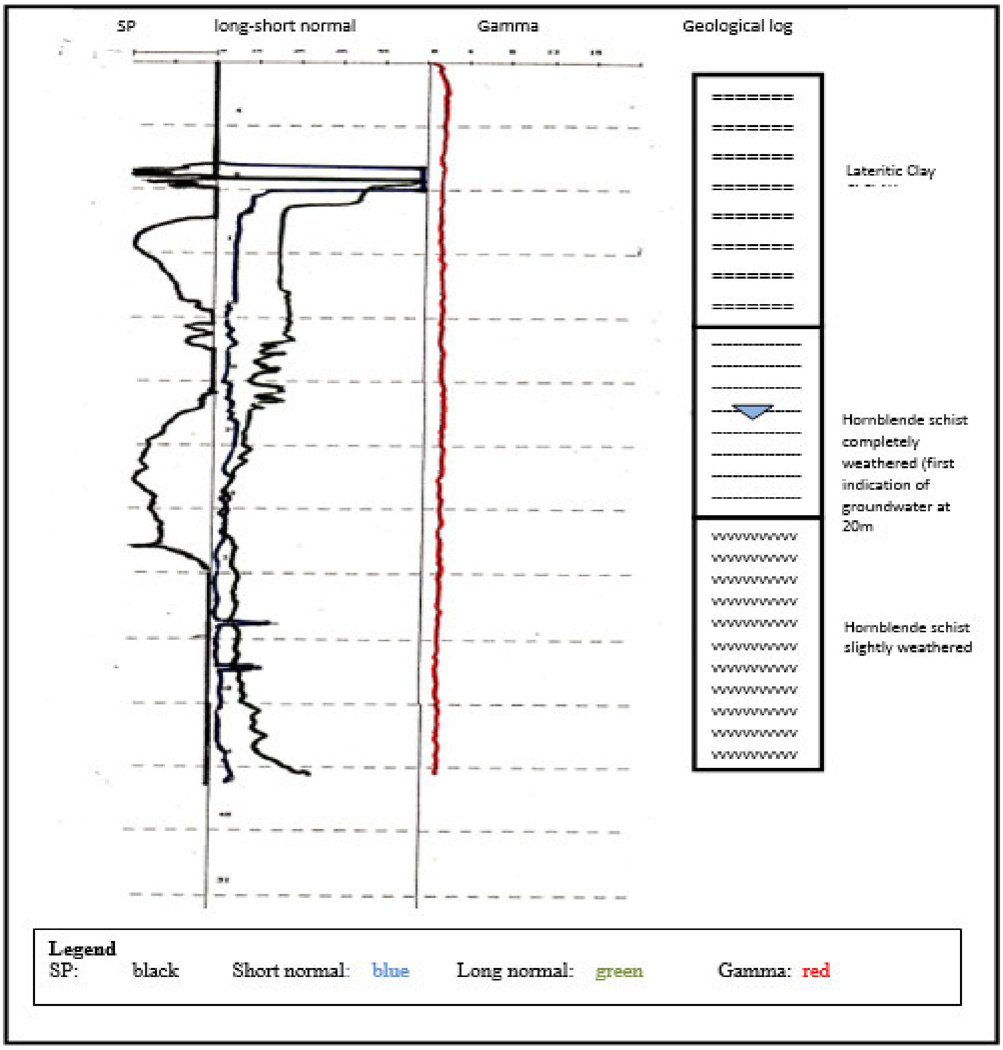

Figure 7 : Geophysical and Geological log (Project ID: BH5, Depth= 45m, Akyeakyem)

Geophysical and Geological logs (Project ID: BH6, Akyeakyem)

On Figure 8, the gamma-ray logs indicated a low clay content of almost equal concentration within the materials penetrated by the borehole. This showed up as an almost constant magnitude in the signal along the entire depth of the borehole. However, the geologic log showed that the clay was more predominant within the first 20m of the borehole length than the deeper parts of the borehole.

The SP log also showed that the formation was not permeable as the log was constantly positive to a considerable depth. From the depth of about 40m to 45m, the signal was more negative indicating, the presence of a permeable formation at that depth.

The short normal log suggested a three layer geological formation with the lithological boundaries around 24m and 28m depth respectively.

The long normal log also indicated that the area was very conductive since resistivity values were very low from the top of the borehole down to the depth of about 40m. Slight increases in resistivity were recorded around the depth of 28m and between the depth of 40m and 48m.

The aquifer position was estimated to be between 40 to 48m depth and correlated with the slightly weathered hornblende schist formation.

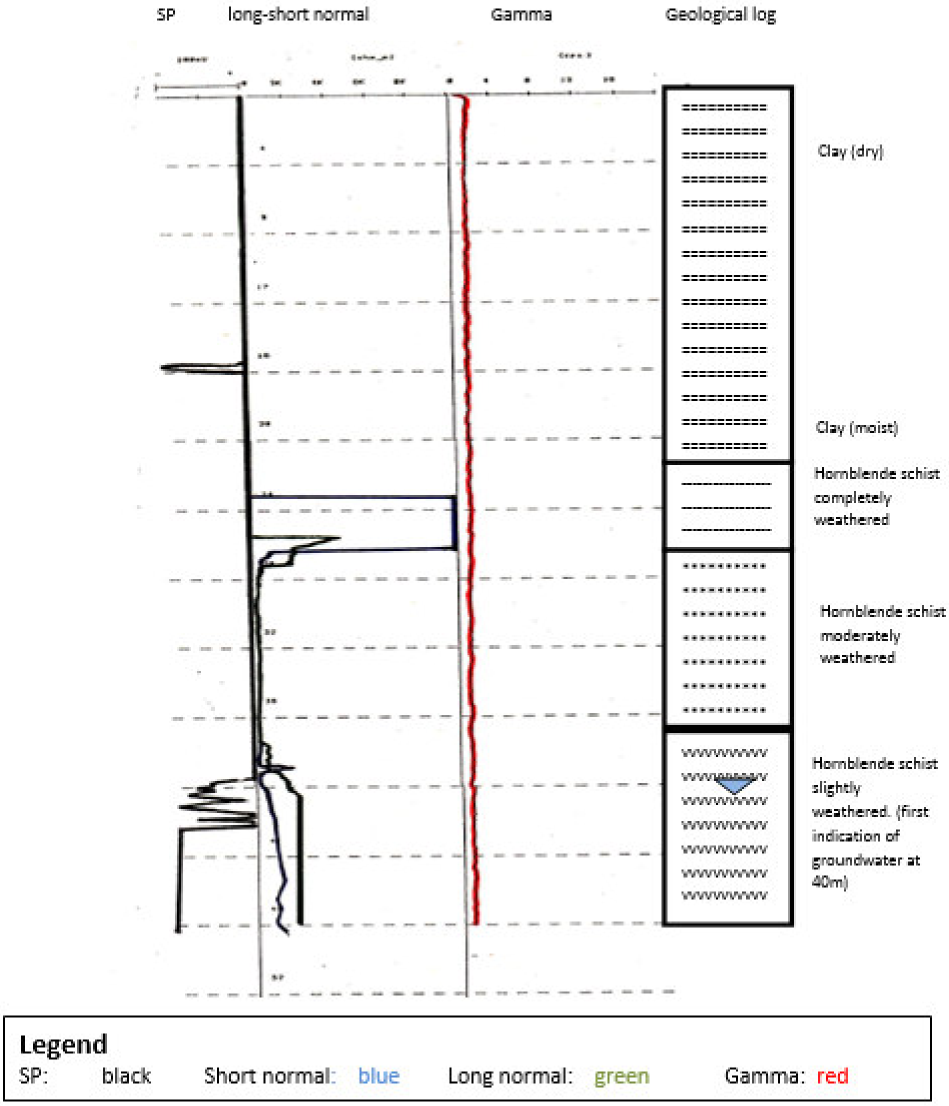

Figure 8 : Geophysical and Geological logs (Project ID: BH6. Depth= 48m, Akyeakyem)

Geophysical and Geological logs (Project ID: BH8 at Denkyemuasua)

From Figure 9, the long normal log indicated that the formations penetrated by the borehole were very resistive. Except the top 4m and 8 to 16m, where the log indicated a small decrease in resistivity, the rest correlated with high resistivity values.

This high suggested a very low prospect for striking groundwater. The short normal log indicated a four-layer subsurface geological model with boundaries estimated at the depth of 7m, 20m, and 38m respectively. Except at the depth range of about 3 to 8m, and most significantly, around the 5m depth which recorded moderately high values of gamma radiation, elsewhere the recorded values of the radiation was very low indicating that the content of radioactive element in the formation was very low. A permeable formation was encountered from the depth of about 21m to 48m indicated by the negative value of the SP log and an impermeable formation below 48m. Drilling through the permeable rock formation encountered very little water which could not be sustainably developed. The borehole was abandoned. Though an earlier EM contour map at the depth of 30m depth had shown a high conductive zone within which this borehole was sank, it was clear from a dipole-dipole sounding curve that the rock formation could not be water-bearing. This could be correlated with elevated the normal log below 16m to the end of the hole. However, the borehole was drilled to prove an important point of the necessity of geophysical investigation in groundwater exploration projects as an important cost reduction strategy.

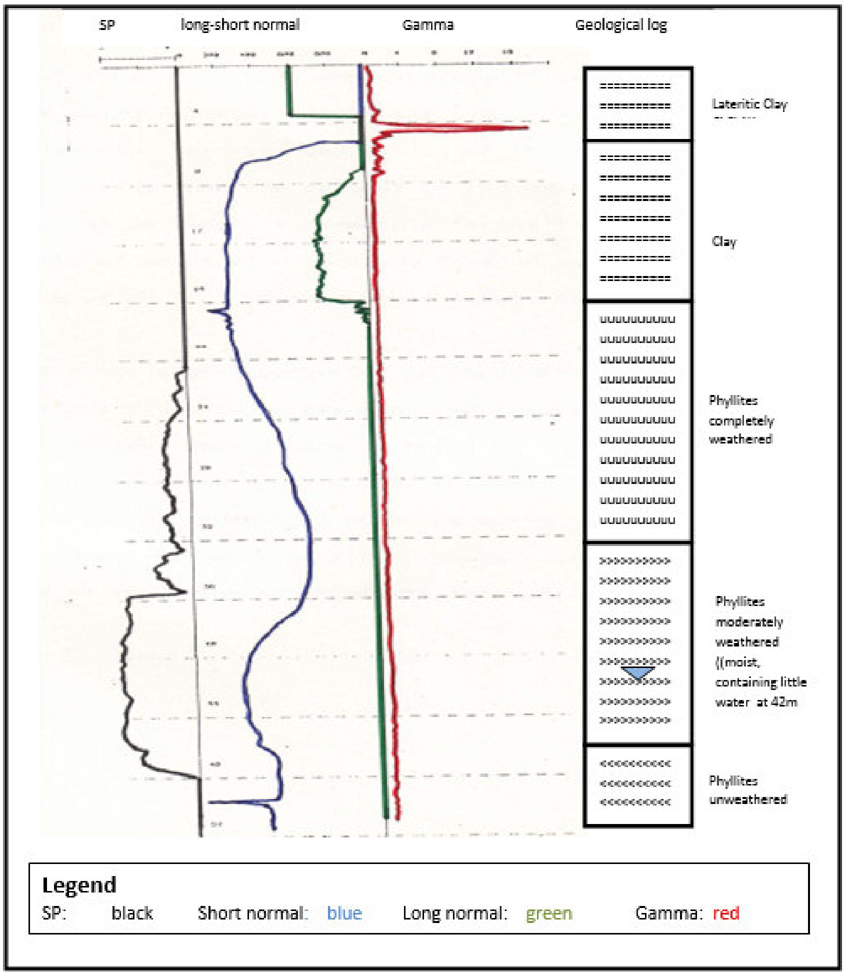

Fig 9. Geophysical and Geological logs (Project ID: BH8. Depth= 52m, Denkyemuasua)

CONCLUSION

The combined geophysical logs (SP, long short normal and the gamma) correlated with geological logs have proved very useful in the study of lithological units intersected by a well, locate contacts of adjacent beds, determine the thickness of the units and distinguish between permeable and impermeable strata. The geological logs showed three main geological layers: a thick top layer composed predominantly of lateritic clay, which was underlain by a weathered zone of variable rock composition which in turn overlay fresh basement rocks. On most of the logs recorded, impermeable could be distinguished from permeable beds because they showed lower apparent resistivity than the permeable beds. Alternatively, the gamma ray logs were used to identify the impermeable beds. The contacts between two beds were also shown by significant changes on the self-potential logs against the permeable bed. The existence of an SP deflection does show that a rock formation has a finite permeability, but it is absolutely no guarantee that the rock would be sufficiently permeable to produce groundwater. However, the SP deflection close to the basement rocks was found to indicate the presence of groundwater. In search of groundwater, it was realized that onsite data interpretation helped set screens or perforated caissons of recommended openings and placing of filtering media opposite such thin layered aquifer formations more effectively, especially in wells with lower yield where the aquifers are not immediately recognized during the drilling process (mud drilling in particular) and or from the geological logs.

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