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Geophysical Wire-line Logging of Boreholes in Nasia River Catchment Basin

Groundwater Development and Sustainable Agriculture in White Volta Basin of Ghana

Kurt Klitten & William Agyekum

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

G E U S

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Danida Project ID 14-P02-GHA

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1. INTRODUCTION AND PURPOSE

As part of the Danida-funded groundwater resources research project (DWVP) in Nasia River Catchment Basin, the CSIR Water Research Institute (WRI) as participating partner was requested in May 2017 by Department of Earth Science, University of Ghana to conduct geophysical wire-line logging of the 10 recently drilled exploratory and monitoring boreholes located within the Nasia River Basin. These 10 boreholes are intended to augment the geological and hydrogeological information from the already existing seven monitoring boreholes, HAP 5, HAP 11, HAP 12 and HAP 14 (ref. /iv/, /v/ and /xviii/), and WVB 11&11A and WVB 12 (ref. /iii/) located within or nearby the basin.

The purpose of the geophysical wire-line logging is to verify the reported technical borehole completion (total depth, setting depths of plain pipes and of screens). Furthermore, to obtain more details on the lithology and of the weathering of the rocks encountered than obtained from the geological description of the crushed and pulverized drilling-samples (rock cuttings) airlifted and occasionally flushed up to the terrain. Other objectives are to determine magnitude and possible vertical variation of the salinity of the groundwater, and to identify the main water bearing zones (groundwater inflow zones).

HYDRONOMICS Ltd, a Ghanaian drilling company was as approved partner on the project assigned to drill the 10 monitoring boreholes. The location of the boreholes was primarily suggested by the Danish supervisors from GEUS based on their reprocessing, analysis and interpretation of existing Airborne Geophysical EM-data made available for the DWVP by Geological Survey Department of Ghana (GSD). Accordingly, the 10 boreholes were located either at some of the cross-points between flight-lines or on flight-lines. The detailed selection of drilling site was determined by the Ghanaian partners from Earth Science Department at University of Ghana, and was based on a geophysical ERT-profile conducted at each location. The length of the ERT-profile was either 400 m (at 4 locations) or 800 m (at the remaining 6 locations). The drilling site was selected at the most prominent low-resistivity anomaly, the latter thought to be an indication of more fractured and weathered rock.

The drilling activities were accomplished from 4th to 17th March, 2017. A preliminary report (ref. /i/) on the drilling works was prepared by three of the four PhD-students associated to the DWV Project (Mr. Abdul-Samed Aliou, Mr. Obed Fiifi Fynn and Miss. Millicent Obeng Addai) assisted by Mr. Richard Adams Mejida, Assistant at the Department of Earth Science, and it was submitted to DWVP late April, 2017. The authors of the report (ref. /i/) supervised the drilling activities, and conducted the pumping tests. The lithological log of the boreholes included in the report as Appendix 2, was made on the drilling site by Mr. Emmanual Mensah (ref. /xiii/), principal geologist from GSD assisted by Miss. Elikplim Abla Dzikunoo, the fourth PhD-student associated to DWVP. Pumping test for 6 hours with belonging recovery observation period was possible to conduct only in six of the ten boreholes because of lack of enough water in the remaining four boreholes. The pumping test data was presented, analysed and discussed in the same report (ref. /i/) as referred to above.

2. PREPARATORY WORK ON LOGGING SYSTEM

The wire-line logging system for digital data acquisition available at Water Research Institute (WRI) is manufactured by the British company Robertson Geo-logging Ltd., and was previously provided to WRI by Danida (Governmental Danish Development Agency) partly under its Water Sector Programme for Ghana, and partly under its ENRECA (Enhanced Research Capacity) programme. The equipment was provided stepwise as seen in the table below in order to replace components from old Robertson equipment for analogical data acquisition, also provided by Danida. The latter equipment was in year 2000 shifted from being used at a Danida Rural Water Supply project in India during 1989-1994 to be used by WRI in Ghana. Latest, a supplementary winch with 280 m four-core cable was given as a gift to WRI by GEUS in 2009.

Wire-line logging components:	**Code**	**ID No.**	**Year provided**	**Functionality as per 9th June 2017**	**Functionality as per 5th Oct. 2017**
Micro-logger for digital data acquisition			2002	OK	OK
RG winch with 500 m ***monocable***, 1/10 inch diameter (2,54 mm)			2000	Out of order	Out of order – non repairable.
Tripod with depth encoder and ***circumference 500mm wheel*** for 1/10 inch diameter cable			2000	OK	OK
Focussed resistivity probe with gamma-detector	GLOG	3888	2001	Out of order	OK
Dual Induction conductivity probe with gamma-detector	DUIN	5798	2006	OK	OK
Fluid Temp. & Conductivity probe with gamma-detector	TCGS	4164	2002	OK	OK
3-arms caliber probe without gamma-detector – renewed for digital data acquisition	3ACS	0287	2000	Out of order	Out of order – non repairable.
High resolution impeller flow-meter with gamma-detector	HRFM	3869	2000	OK	OK
RG winch with 280 m ***four core-cable***, 3/16 inch diameter (4,76 mm)	RG 500	1642	2009	Out of order	OK

Table 2.1: *Geophysical wire-line logging equipment available at WRI, year of provision and functionality status at 1st and 2nd GEUS assistance assignment in 2017.*

The system needs 12-volt power supply from a battery or from a generator via a transformer. Furthermore, the system is operated for tests and data acquisition by the software “WINLOGGER” (ref. /xv/) installed on a laptop computer. Figure 2.1 below is a photo showing wire-line logging in the test borehole on the CSIR/WRI campus in Accra.

Figure 2.1: *Equipment set-up for wire-line logging. Laptop and the Micro-logger on the table, in the middle the old RG 1/10" cable winch with electrical motor, tripod with depth encoder and wheel (500 mm circumference) above borehole, a probe partly within the borehole, and the speed controller for the winch on the wood-box.*

Obviously, the Robertson Wire-line logging system at WRI has not been used for some years, when the logging campaign for the DWV project should take place. Therefore, testing of the logging system was initiated by WRI in May 2017 in order to prepare for the logging campaign of the DWVP boreholes. Unfortunately, the system was found non-functioning, and assistance from GEUS was requested by WRI. Further details on how the problems with the equipment were solved by assistance from GEUS provided through two assignments to WRI, one from 9th to 24th June 2017 and another one from 28th September to 5th October 2017, are reported in **Annex F**.

3. GEOPHYSICAL WIRE-LINE LOGGING CAMPAIGN

The wire-line logging campaign was successfully conducted by WRI from 7th to 12th October 2017 in nine of the ten boreholes. One borehole (DWVP 03) could not be accessed due to flooding at the location. Wire-line logging in that borehole was therefore postponed to the dry season and conducted on the 4th May 2018. In Table 3.1 below are the boreholes listed with information on location, coordinates, logging date and depth, drilled well-depth, and logging tools applied. Furthermore, in those boreholes where pumping test has been conducted, the respective discharge rate (in lpm) is shown. In order to conduct the wire-line logging the WRI team had to take up the HOBO water-level recorder (pressure transducer) already installed in each borehole, and to reinstall the transducers at the same depth, when wire-line logging was completed. It was planned that the WRI team should transfer the recorded water level data from the HOBO transducer in each borehole to their logging laptop-computer. However, this was not succeeded due to insufficient instruction of the team in the procedure for data discharge from the HOBO transducer.

Borewell ID	Location	UTM X	UTM Y	Logging Date/ Month/ Year	Log. Depth (m)	Well depth (m)	TCGS probe	DUIN probe	GLOG robe	HRFM Q=0	HRFM Q=?	Pump. Test Q=lpm
DWVP 4	Kokubila	-0.8017	10.1242	07/10/17	96	100	X	X	X	No	No	12
DWVP 8	Nakpaya	-0.8553	10.1511	07/10/17	96	100	X	X	X	No	No	Dry
DWVP 9	Samene	-0.6111	10.4603	08/10/17	40	95	X	X	X	No	No	9
DWVP 1	Tamboku1	-0.4608	10.3683	09/10/17	138	150	X	X	X	No	No	22
DWVP 2	Tamboku2	-0.4806	10.3467	09/10/17	92	100	X	X	X	X	60	132
DWVP10	Salikpa	-0.1303	10.2856	10/10/17	93	100	X	X	X	No	No	Marginal
DWVP 7	Salinwia	-0.1350	10.1519	11/10/17	73	75	X	X	X	X	30	80
DWVP 5	Kpobu	-0.4178	10.1408	12/10/17	92	100	X	X	X	No	No	13
DWVP 6	Tanyeli	-0.3975	10.0297	12/10/17	96	100	X	X	X	No	No	Marginal
DWVP 3	Shienvoya	-0.5958	10.2185	04/05/18	100*	100	No	X	X	No	No	Marginal
WVB 11	BugyaPala1	-0.7448	10.2860	10/10/06	52**	56	X	02/05/18	X	X	10	9
WVB 11A	BugyaPala2	-0.7442	10.2880	20/03/07	39**	39	X	X	No	No	No	Marginal
WVB 12	Tinguri	-0.1787	9.9480	21/03/07	49**	51	X	X	No	X	60	150
HAP 12	Nakpeuk	+0.0500	10.5228	31/08/07	140**	166	X	03/05/18	X	No	No	6
HAP 11	Nalerigu	-0.3950	10.5140	01/09/07 20/10/07	130	141	X	X	X	X	20	24
HAP 5	Janga	-0.9719	10.0200	03/09/07	122	166	X 08/10/17	X	X	No	No	Dry
HAP 14	Tuuni	-0.3653	10.2980	25/11/09	120* & **	120	X	03/05/18	X	X	20	19
ZaVu1	Zangu-Vuga	-0.8628	10.3742	02/05/18	55*	55	X	X	X	No	No	?

*) The logs have been depth corrected for erroneous depth encoder setting. **) DUIN-log only was needed to be depth corrected for erroneous depth encoder setting.

Table 3.1: *Location of boreholes, depth and date (in chronological order) of logging, tools applied and discharge rate at flow-logging and at pumping test.*

This report presents and discusses the results of the geophysical wire-line logging conducted in the ten DWVP boreholes. It was found useful for the DWV project also to include reprocessing, presentation and interpretation of data (**Annex D**) from previously (2006, 2007 and 2009) conducted wire-line logging of seven earlier drilled HAP- and WVB-monitoring boreholes (ref. /iii/, /iv/ and /v/) located within or nearby the Nasia River Basin. In three of those the DUIN logging tool has not been applied, the reason why this was done by WRI during a supplementary wire-line logging campaign conducted in May 2018. The latter campaign did also include logging in DWVP 03 and of an additional borehole in the community Zangu-Vuga located Northwest of Walewale. The table 3.1 above therefore also contains information on each of the supplementary eight, but earlier drilled and investigated boreholes.

The rather late completion of the report compared to, that the wireline logging was completed in the field already in May 2018, is caused partly by the desire of having the hydrochemistry data from all the 10 DWVP boreholes included in the report for comparison with the Fluid conductivity log; partly by the Covid-19 lock-down in Denmark on the 11th March 2020; and finally in order to include possible new findings during the ongoing process of preparing a publication on the results of the wireline logging campaign. The water sampling campaign of the DWVP boreholes was conducted during July 2018. However, two boreholes were not included, DWVP 09 because of collapsed borehole from 40 m depth, and DWVP 10 because of flooding thus not accessible. Water sample was then taken from Borehole DWVP 10 in January 2019 and again in October same year, because the analysis result from the first one was erroneous. Valid hydrochemistry data from borehole DWVP 10 was received by the Authors early in January 2020.

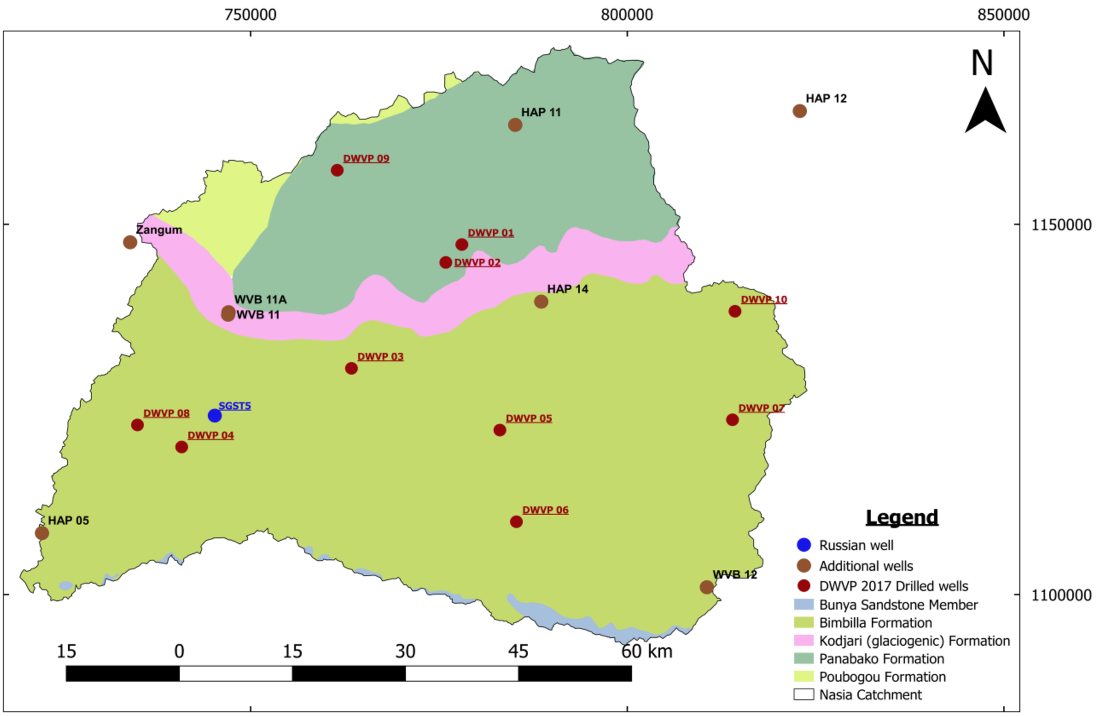

Figure 3.1: *Location of the oil-exploratory well SGST5, the ten DWVP boreholes, the five HAP and two WVB monitoring boreholes and the Zangu-Vuga well – apart from HAP 12 all are within or nearby the Nasia River catchment study area (extract of Geological Map, ref. /ix/).*

Figure 3.1 above is a section of the most recently revised geological map (ref. /ix/) and shows the location of the 10 DWVP boreholes as well as the eight additional boreholes included in this report.

Prior to commencing the geophysical wire-line logging campaign, a desk study was conducted by WRI on the information from the 10 DWVP boreholes made available by the drilling contractor (ref. /i/) and by the Geological Survey Department (ref. /xiii/). The information comprised drilled depths, geological profile encountered during drilling, air-lift yield, depth location of plain pipes and of screen sections, static water levels and of results of pumping test of six of the 10 boreholes in terms of drawdown and recovery graphs. Based on the information on the air-lift yield and pumping tests the wire-line logging field team decided to conduct flow-logging only in those two boreholes (DWVP 02 and 07) fulfilling the minimum requirement of discharge rate (20 lpm) for obtaining reliable flow-meter readings in a 6 ½ inch diameter borehole.

Borewell ID	Location	Drilling Date/ Month/ Year	Well depth (m)	Plain pipe 1 (m)	Screen 1 (m)	Plain pipe 2 (m)	Screen 2 (m)	Plain pipe 3 (m)	Total Length pipes+ screens (m)	Water level (m) b.g.l
DWVP 1	Tamboku	05/03/17	150	34	6	3	3	-	46	6.02
DWVP 2	Tamboku At river	06/03/17	100	37	3	3	6	-	49	9.55
DWVP 9	Samene	08/03/17	95	16	6	3	-	-	25	7.00
DWVP 3	Shienvoya	09/03/17	100	16	-	-	-	-	16	5.02
DWVP 8	Nakpaya	11/03/17	100	12	-	-	-	-	12	95.44?
DWVP 4	Kokubila	12/03/17	100	7	9	3	3	3	25	6.25
DWVP 5	Kpobu	14/03/17	100	21	-	-	-	-	21	8.70
DWVP 6	Tanyeli	15/03/17	100	16	-	-	-	-	16	3.40
DWVP 10	Salikpa	16/03/17	100	16	-	-	-	-	16	10.06
DWVP 7	Salinwia	16/03/17	75*	23	-	-	-	-	23	5.25

*) Might be more, but less than 80?

Table 3.2: *DWVP boreholes, date of drilling in chronological order, depth of drilling and completion details and observed water level b.g.l. as reported by driller (ref. /i/).*

The driller's borehole records (ref. /i/) indicate that the depth of the boreholes ranges between 75m and 150m, and that they were constructed as an open borehole as requested by the Client (DWVP), though with plain pipes and in some few boreholes even screen sections in the uppermost and unsteady part of the boreholes. Concerning the borehole completion details there were a lot of discrepancies between information in the field campaign report (ref. /i/), and in the driller's construction record sheets, Appendix 4 of the same report. After in January 2018 having requested the drilling company to verify the completion details, the summarizing table 3.2 above must be considered as the final completion records claimed by the drilling company.

As seen in the table 3.2 above one borehole is having one screen section installed, three boreholes are having two screen sections, whereas the remaining six have only an upper plain pipes installed. The total length of plain pipes and screens installed in each borehole varies from 12 m to 49 m, thus leaving the major part of each borehole open and thereby provide the greatest advantage of conducting geophysical wire-line logging. The length of the plain pipe which sticks up from the ground level (Fig. 3.2 below), varies between 0.51 m and 1.23 m, but is not included in the driller's record. Fortunately, this information was reported by the WRI logging team.

The table 3.2 does also include the observed water level in each borehole after its completion. The extremely deep seated water table reported in DWVP 8 seems questionable, since it was observed during the wire-line logging 6 month later to be very shallow, i.e. 0.74 m b.g.l. Bearing on the reported total drilling depth of the individual boreholes there are some doubts about the depth of borehole DWVP 7. The Appendix 3 in the report (ref. /i/) and its Appendix 4, the borehole construction data sheet, say 75 m, but the litholog description Appendix 2 in same report says 80 m?

Figure 3.2: *Completion of boreholes above ground; access protected with fence. Notice the plain pipe stick-up.*

4. LOGGING TOOLS AND PRINCIPLES OF DATA INTERPRETATION

The following three different logging tools (TCGS, GLOG and DUIN) were intended to be used on all ten DWVP boreholes, and in the order mentioned. However, unfortunately the TCGS tool went out of order during the supplementary logging of borehole DWVP 03 in May 2018, thus only two tools were used in that particular borehole. Furthermore, the High Resolution Impeller Flowmeter (HRFM) logging tool was used only in those two boreholes (DWVP 02 and 07) with sufficient yield for conducting the flow-logging. Finally, the 3 arms calliper tool (3ACS) should have been used in all boreholes, but was unfortunately not functioning and could not be repaired.

Temperature, Conductivity and Gamma (TCGS) tool is used as the first logging-run to determine magnitude and variation of respectively the fluid conductivity (mS/m = 10 µS/cm) and of fluid temperature (^{0}C) downwards in the water column in the borehole. Due to the several months period since the drilling and test pumping of the DWVP boreholes took place it is assumed that equilibrium is established between pore-/fracture water and borehole water, thus the measured fluid temperature and fluid conductivity in the open and screened section respond to the temperature of the rock and conductivity of the groundwater.

Furthermore, if a TCGS log-run downwards is also conducted below a submersible electric pump while pumping, then the variation in the fluid temperature and conductivity in the section below the pump will be different from the first log run downwards in an equilibrium water column, and thereby provide information on location of inflow zones. Unfortunately, such a log was not included in the logging campaign of the DWVP boreholes.

The TCGS tool does also contain a gamma-radiation detector for determination of natural gamma-radiation (in cps = counts per second) from soil/rocks surrounding the borehole, and thereby provide information on possible variation in the lithology. The natural gamma-radiation in most soils and rocks are mainly caused by clay-minerals or by other potassium-rich minerals (e.g. Glauconite, Mica), whereas silica-minerals or pure limestone do not contribute to natural gamma-radiation (ref. /xiv/ & /xvii/).

Focussed Guard Resistivity (GLOG) tool for determination of the rock resistivity (Ohm-m) in the open-hole section is used as the second logging-run. In sections with plain pipe and screens installed, the tool provides information indirectly on the completion of the borehole. The plain pipe sections are indicated by showing resistivity above maximum range of the tool, i.e. 13,000 Ohm-m, because the tool can't measure through the PVC-pipe. The screen sections are indicated by actually being able to measure resistivity values, however, they are far too high compared to resistivity values in the open-hole section.

It is important to notice, that the tool can't measure until it is completely below the water table (WT) within the borehole. Furthermore, because of the 10 m bridle cable and the 1 m distance between the guard-electrodes and the central current electrode on the probe, the measured resistivity will not be valid until from 11.7 m below the water table in the borehole. In most cases is the water table within the casing, which means that true formation resistivity values can't be obtained until the whole bridle cable is out of the casing pipe, i.e. 11.7 m below the end of the casing pipe (ref. /xv/). Because of these two limitations of the GLOG tool, it does not provide information on resistivity of the Saprolite (laterite and completely and partly weathered rock).

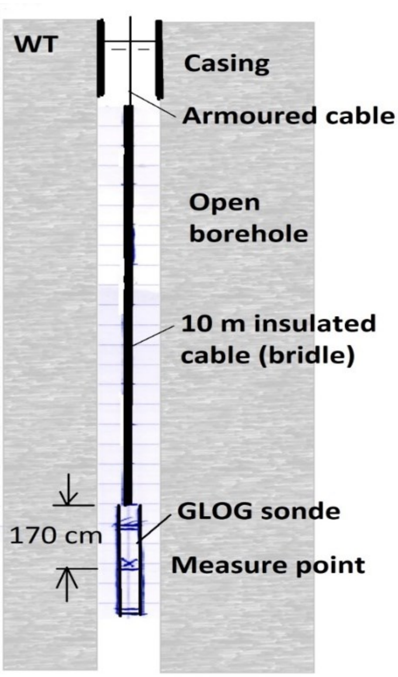

Figure 4.1: *Sketch of GLOG sonde and bridle-geometry!*

The interpretation of the resistivity log is not as simple as interpretation of the gamma-radiation log, because several factors such as clay content, water content, the salinity of the formation water and the content of metallic rock minerals are determining the magnitude of the formation resistivity (ref. /xiv/ & /xvii/). As higher content of any of these, as lower the resistivity.

Dual Induction (DUIN) tool for determination of the formation conductivity of the soil and rock (in mS/m) is used for the third logging-run. It uses one transmitter, one receiver and a number of focusing coils to give two different depths of investigation. The Long and the Short coil spacing are optimized to achieve high vertical resolution, deep radius of investigation and minimal influence from conductive fluid in the borehole. Differing from the GLOG resistivity tool, the DUIN tool does not need water for establishing contact to the formation because its measure-principle is based on induction current. Accordingly, it can measure above as well as below groundwater table, and also through the sections with PVC-plain pipes and screens as well as in the open-hole section. Therefore, this tool is essential for obtaining information on the conductivity and thereby on the resistivity of the whole borehole profile including the Saprolite.

The magnitude of the formation conductivity is determined by the same factors as controlling the resistivity (ref. /xiv/ & /xvii/), i.e. the clay content, the water content, the salinity of the formation water and the content of metallic rock minerals. The higher the content of any of these, the higher the conductivity will be.

Important for the interpretation of this type of log, i.e. for the identification of reason for a certain level or variation in conductivity, is the comparison to the variation of the gamma-radiation. Where sections of the variation of conductivity conform to variation of the gamma-log, then the conductivity as well as the gamma-radiation is controlled primarily by the clay content. On the other hand if the gamma-log shows variation which is not seen on the conductivity-log, then the gamma-radiation is mainly caused by other potassium rich minerals than clay, e.g. Glauconite, Mica, Feldspar rich sandstone (arkosic). In rare cases it can be caused by Uranium content (e.g. related to Phosphorites). If the conductivity-log shows variation which does not confirm to the gamma-log, then the conductivity is controlled by the content of water, salinity or metallic minerals.

What has been mentioned above on reasons for similarity or difference between gamma-log pattern and conductivity-log pattern is valid also for comparison of gamma-log and resistivity-log.

High Resolution Impeller Flowmeter (HRFM) logging tool provides information about inflow zones and the relative magnitude of inflow from each zone. The tool measures the actual upward vertical velocity of the water in the borehole relative to downward movement of the logging tool. This is obtained by measuring the number of impeller rotations per minutes (rpm) when running the log-tool downwards in the borehole section below the submersible electrical pump during pumping with a constant discharge rate. However, during logging while pumping the number of rotations will be determined not only by the flow of water upwards to the pump but also by the speed of the downward movement of the tool (logging speed to be kept constant between 5 to 7 m/min).

In order to distinguish at a certain depth the number of impeller rotations caused by logging speed from the number of rotations caused by actual upwards flow of water it is necessary exactly to know the logging speed and the relationship between speed and its responding impeller rotations. The speed (= cable speed) is registered continuously during logging by measuring the time between each impulse per 10 mm movement of the cable on the depth encoder wheel (see Fig. 2.1).

The relation between the logging-speed and the number of rotations of the impeller caused solely by the downward movement of the tool is determined for each borehole by running the tool downwards with different log-speed, e.g. varying stepwise from 4 m/min to 8 m/min, and without pumping (calibration of the tool). The processing of the flow-log data is further discussed in Chapter 5: “Data processing, presentation and results”**.**

3-Arm Calliper (3ACS) tool is used to provide information on borehole diameter, thus for control of the claimed technical completion in terms of installation depth of plain pipes and of screen sections. Furthermore, sudden and very local variation in diameter in the open-hole section is often an indication of weak and fissured zones.

Knowledge on the diameter through a calliper-log is conditional for proper interpretation of a flow-log. Diameter variation, e.g. when going from plain pipe or from screen section to open-hole section, or diameter change caused by change of drilling bit size, will result in effect on the flow-log conducted during pumping. A sudden decrease of diameter downwards due to change to a smaller diameter bit will be seen as an increase in impeller rotations on the flow-log during pumping. Opposite, a sudden increase of diameter downwards from plain pipe or screen pipe to open-hole will be seen as a decrease in impeller rotations. In the section without any water flowing upwards to the pump the diameter changes will not be reflected by any variation in impeller rotations unless the borehole diameter is of same magnitude as the diameter of the HRFM-tool. In such a case the water volume similar as the corpus of the HRFM-tool will be forced upwards by the downward moving tool and cause additional impeller rotations (so-called piston effect).

Unfortunately, neither the WRI calliper tool nor the GEUS calliper tool was functioning during the campaign; as such diameter-logging has not been performed in any of the DWVP boreholes. Further discussion of effects from diameter variation on the actually conducted flow-logging results can be found in the Flow-logging section in Chapter 5.

It has to be mentioned that the GLOG-, DUIN- and HRFM-tools like the TCGS-tool do have a gamma-radiation detector for determination of natural gamma-radiation from soil/rocks surrounding the borehole. Gamma-radiation unit is cps = counts per second, though the GLOG tool is calibrated into API, based on the radioactivity of a particular calibration source at the University of Houston, Texas USA having a radioactivity of 200 American Petroleum Institute (API) units. The gamma-log from each of the tools provides possibility for depth control by comparing the gamma-log from the different tools as mentioned below in section 5.1 “Logging-data processing”.

5. DATA PROCESSING, PRESENTATION AND RESULTS

5.1 Logging-data processing

The collected wire-line logging data were processed and presented for each borehole as a composite sheet containing the whole log-suite by using VIEWLOG software (ref. /xvi/). The processing steps were as follows:

- Sample intensity of one per 1 cm of all logs was re-sampled to an intensity of one per 5 cm by averaging subsequently each five samples.
- Thereafter, each set log data was edited by removing noisy readings, if needed.
- Due to the statistical nature of the gamma-ray activity, the gamma-log from all four tools (TCGS, GLOG, DUIN and HRFM) was smoothed using an 11 point 'boxcar filter' type to reduce the statistical fluctuations of the radiation.
- The conductivity-log from the TCGS tool was eventually depth shifted in order to ensure alignment between depth of water table (as reported by the logging team) and the depth to the first obtained fluid conductivity reading. If depth shifted, then the two other logs (temperature and gamma) from the TCGS-tool were similarly depth shifted.
- The gamma-logs from the other three tools were then compared to the gamma-log from the TCGS tool, and individually depth shifted if needed to ensure conformity to the TCGS gamma-log. These gamma-logs are not shown on the final presentation (as also described below). If gamma-log has to be depth shifted from any of these three tools, a similar depth shift was then conducted on the other log(s) from the respective tool (GLOG, DUIN and HRFM).
- A DUIN resistivity-log is calculated from the DUIN long spacing conductivity-log as Resistivity (Ohm-meters) = 1,000/Conductivity (mS/m) for comparison with the GLOG resistivity-log. The comparison of these two resistivity-logs is particularly important for verification of the technical completion of the construction because major difference will be due to the effect on the GLOG-resistivity from the PVC-pipe even down to 11.7 m below the end of the pipe as described above in Chapter 4, section ii. Further information, which can be obtained by the comparison of these two types of logs, is the magnitude of conductivity of the stagnant water column in the borehole. Because high fluid conductivity (>400 mS/m) of the water column will affect the GLOG-resistivity thus it will be significantly lower than the DUIN-long resistivity. This additional option for obtaining information from the DUIN-log is particularly important if the TCGS-probe is out of order, and the Fluid-conductivity can't be determined (as was the case in borehole DWVP 03, see later).

The final result of the processing of the logs is presented on two composite log-sheets for each borehole. The first composite log-sheet (**Annex A**) consists of the GLOG gamma-log, GLOG resistivity-log, the calculated DUIN L-resistivity log, the Fluid-temperature and Fluid-conductivity and the resulting Flow-log, and is primarily used for discussion of the claimed construction details. The second composite log-sheet (**Annex B**) consist of the TCGS gamma-log (and the GLOG gamma-log for comparison), the two DUIN-conductivity logs, the GLOG-resistivity log edited by deleting the erroneous part (caused by effect from PVC-pipe), the calculated DUIN L-resistivity log, and the Fluid-temperature & conductivity log, and are primarily used for discussion of the lithology, but also of the salinity of the groundwater. A third composite log-sheet (**Annex C**) is prepared for the two boreholes, DWVP 2 and DWVP 7, where flow-logging has been conducted. This particular log-sheet consists of all the logs obtained during the different steps of processing the flow-logging data as described in section 5.6: Flow-log and Inflow Distribution.

5.2 Well completion details

A summary of the results of the interpretation of the logs from composite log-sheet**, Annex A,** with respect to the verification of the claimed construction details from table 3.2 is presented in the table 5.2.1 below. The logging depth is the maximum depth below ground to which data has been measured, i.e. the maximum depth of the measuring point on the TCGS probe, which is having its measuring point close to the end of the probe (Conductivity offset = 10 cm, Temperature offset = 14 cm and Gamma offset = 37 cm). The other probes are having larger offset of measuring point (distance from end of probe), and therefore normally do not reach as far deep as the TCGS-probe irrespectively they have been run down until reaching the bottom of the borehole, or run upwards starting from the bottom.

Borewell ID (*in order of drilling date*)	Location	Well depth (m)	Log Depth* (m)	Plain pipe 1 (m)	Plain pipe above ground (m)**	Plain pipe 1 below ground (m)	Screen No 1 (m)	Plain pipe No 2 (m)	Screen No 2 (m)	Plain pipe No 3 (m)	Total Length of pipes and screens (m)
DWVP 1	Tamboku	150	140	34	1.02	(17)	6 (9)	3 (0)	3 (0)	-	46 (27)
DWVP 2	Tamboku At river	100	93	37	0.70	(16)	3 (12)	3 (0)	6 (0)	-	49 (29)
DWVP 9	Samene	95	41	16	0.93	(15)	6 (3)	3 (3)	-	-	25 (22)
DWVP 3	Shienvoya	100	100	16	0.78	(15)	-	-	-	-	16 (16)
DWVP 8	Nakpaya	100	97	12	0.51	(8.5)	- (6)	-	-	-	12 (15)
DWVP 4	Kokubila	100	97	7	1.23	(9)	9 (9)	3 (3)	3 (0)	3 (0)	25 (22)
DWVP 5	Kpobu	100	93	21	0.67	(21)	-	-	-	-	21 (22)
DWVP 6	Tanyeli	100	97	16	0.84	(13)	-	-	-	-	16 (14)
DWVP 10	Salikpa	100	94	16	0.84	(11)	-	-	-	-	16 (12)
DWVP 7	Salinwia	75 (80?)	74	23	0.54	(16)	-	-	-	-	23 (17)

**) The logging depths of the DWVP boreholes are rounded off to full meters. **) Measured by WRI field team.*

Table 5.2.1: *Completion details from drillers report (in table 3.2) compared to interpreted completion details (shown in brackets).*

As seen in table 5.2.1 above, the wire-line logging has been conducted to near the full depth of most of the boreholes. Accordingly, the silting up of the boreholes seems in general limited, 1 to 7 meters. Only in one, DWVP 09, was the logging seriously obstructed already at a depth of 41 m thus excluding logging of the lowermost 54 m. In another one, DWVP 01, the lowermost 10 m could not be reached.

When comparing the reported completion details with the completion details as interpreted primarily based on the GLOG resistivity-log, surprisingly many discrepancies are seen. Only two of the ten boreholes seem completed as reported, DWVP 05 and DWVP 03. Discrepancies are particularly significant in the four boreholes with screen sections, DWVP 01, 02, 04 and 09. One more borehole, DWVP 08, seems also to have a screen installed, which was not reported by the driller. Apart from this borehole, all are having fewer meters of plain pipes and screens installed than reported, and in some even considerable less.

The arguments for the interpreted completion details can be read in the header of the composite log-sheet for each DWVP borehole, see **Annex A**. An additional reason for focussing on the completion details in this report is the necessity of knowing which part of the GLOG resistivity-log has to be excluded from the interpretation of the lithology because of being affected by the installed plain pipes and screen.

5.3 Verification of the Geology

As already mentioned in Chapter 4 the Gamma-log, the DUIN conductivity-log and GLOG resistivity-log are the log types, which can be interpreted in terms of lithology. Though for the GLOG resistivity-log the uppermost section of the log, which is affected by plain pipe as discussed in the header of each log-sheet in **Annex A**, is deleted on the composite log-sheets **in Annex B**. The latter log-sheets contain the detailed lithological interpretation as well as the drillers and the geologist's log, and the interpreted lithology is summarized in the header of each log-sheet. The type of rock (sandstone/Panabako or siltstone/Bimbila) described in the geologist log, is maintained as the starting point for the interpretation. The more detailed lithological interpretation in terms of different siltstone or sandstone sections and of intercalations of clayey or sandy beds is based on the extent of variation in the gamma-, conductivity- and resistivity- logs and whether there is mutual conformity in the variation in between these logs. The table 5.3.1 below is summarizing for each DWVP borehole the geologist log, as well as the conformity in between the three types of wire-line log, and finally also the interpreted lithology in terms of the weathered upperpart (Laterite & Saprolite & Saprock) and the underlying fresh "mother rock".

The boreholes are in table 5.3.1 grouped in relation to the expected geological formation, i.e. boreholes located on the Gambaga Massif are penetrating into the Panabako Formation, while the other boreholes are located in areas underlain by the Bimbila Formation. Since the latter is assumed dipping towards south, the most northern of these boreholes are located on the eldest part of the Bimbila Formation, the boreholes further south are located on the expected middle part of the Bimbila Formation and finally the most southern located boreholes are suggested to represent the younger section of the Bimbila Formation. The question to discuss is whether the wire-line logs verify lithological similarities within each group of boreholes, as well as lithological differences between these groups?

DWVP No	Well depth (m)	Geology	Depths (m)	Geologist description	Log Depth (m)	Conformity between gamma- and conductivity/ resistivity logs	Interpreted supplementary lithological information from wire-line logs
01	150	Panabako Formation	0-13	Laterite & HW SS	140	Yes	Not reflected.
			13-150	SS, shifting colour and grain size, mica-and quartz content.		Yes, though resistivity log affected by extremely low conductivity in fluid to 38 m.	Different type of sandstone with several intercalations of clayey beds.
02	100		0-10	Laterite & HW SS	93	Partly	Not reflected.
			10-100	SS, shifting colour and grain size, mica-and quartz content.		Yes, though resistivity log affected by extremely low conductivity in fluid to 44 m.	Different type of sandstone with several intercalations of clayey beds.
09	95		0-4	Lateritic SS	41	Limited log section	Not reflected.
			4-95	SS, shifting colour and grain size, mica-and quartz content.		Yes, partly – but few gamma-peaks are not seen as conductivity peaks/ resistivity low.	Two type of sandstone, different from DWV1 and 2, though still intercalations of clay but also of arkosic sandstone beds.
10	100	Bimbila old	0-5	Laterite	94	No	Weathering to 8 m.
			5-100	SiS, brownish		Yes, from 30 m.	Different type of siltstone to 84 m, underlain by sandstone (later recognized to be Kodjari).
03	100		0-4	Clay above laterite	100	No	Weathering to 7 m.
			4-100	SiS, shifting colour		Not until below 80 m, where Gamma decrease conformable to conductivity decrease/ resistivity increase.	Glauconitic fine-grained sandstone followed by different type of siltstone to 88 m, underlain by sandstone (later recognized to be Kodjari).
07	75	Bimbila middle	0-10	Laterite, clay, W SiS	74	No	Weathering to 11 m.
			10-80?	SiS, greyish		Yes, from 11 m.	A rather uniform siltstone.
05	100		0-10	Laterite, W SiS	93	No	Weathering to 18 m.
			10-100	SiS, greyish-brown		Yes, from 18 m.	A rather uniform siltstone, though a boundary at 36 m.
08	100	Bimbila young	0-10	Laterite and clay and W SiS	97	No	Weathering to 10 m.
			10-100	SiS, greyish		Yes, from 10 m.	Different type of siltstones, and with several intercalations of sandstone beds.
04	100		0-10	Laterite on clay	97	No	Weathering to 13 m.
			10-100	SiS, greyish		Yes, from 13 m.	Different type of siltstones, and with some few sandstone sections.
06	100		0-5	Laterite and clay	97	No	Weathering to 10 m.
			5-100	SiS, greyish		Yes, from 16 m.	A feldspar rich siltstone to 16 m, followed by different siltstone, some sandy, and with intercalations of clay.

Abbreviations: SS = Sandstone; SiS = Siltstone. HW = Highly weathered; W = Weathered.

Table 5.3.1: *Expected geological formation, geologist log, conformity between gamma- and conductivity-/resistivity-log, supplementary lithological information from wire-line logs.*

5.3.1 Identification of weathered zone (Residual + Saprolite + Saprock)

In order to evaluate to which extent the weathering is reflected by the Gamma- and DUIN conductivity-log it might be useful to recall the general character of the lithology of the tropical weathered profile of hardrocks as illustrated in the Fig. 5.3.1.1 below. It is also important for this evaluation to recall, that the gamma-radiation is mainly caused by clay minerals and feldspar content, and that the formation conductivity similarly is caused by content of clay minerals but also of the content of pore-water and the salinity of the latter. Furthermore, content of metallic minerals like iron-oxides in laterite will also have an impact on the formation conductivity.

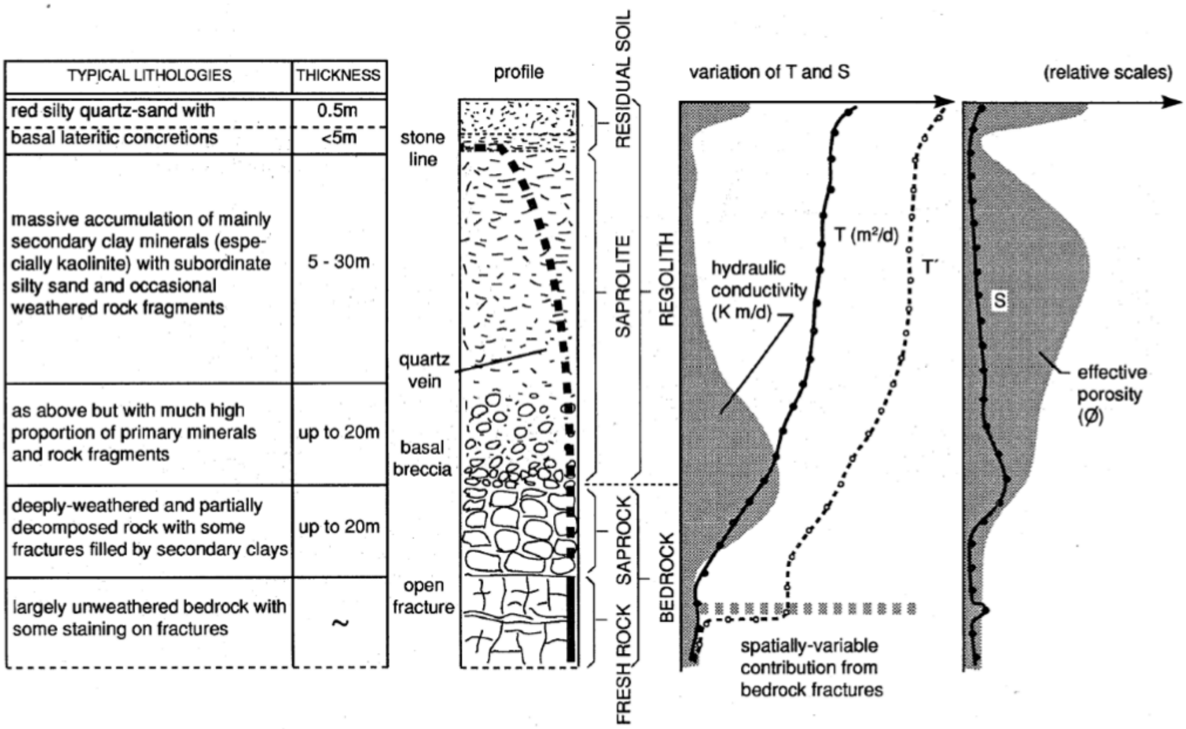

Figure 5.3.1.1: *Generalized lithology of tropical weathered profile of hardrock and the relative variation of the corresponding hydraulic parameters (ref. /x/).*

Interesting differences occur between the boreholes in the Panabako sandstones and the boreholes in the Bimbila formation on the mutual pattern of the two types of wireline-logs as seen on Figure 5.3.2.1 below. In all the Bimbila boreholes there is no conformity between the gamma-log and the DUIN-conductivity log in the uppermost 7 to 18 m, where only the conductivity-log shows higher values than in the underlying host rock. Thus the weathering in the Bimbila formation is reflected by higher conductivity but not by higher gamma-radiation. Accordingly, if the weathering of rocks belonging to Bimbila formation might have resulted in higher clay content than in the host rock, the content of potassium remains the same as it was in the host rock (its content of feldspar). The higher clay content, and the higher porosity and water content in the weathered part of Bimbila rocks obviously are reflected by increased conductivity compared to the fresh rock. The depth to which the conductivity is higher than in the host rock varies from 7 to 18 m, i.e. the depth of weathering. Thus, as seen in the table 5.3.1 above, the depth of weathering in nearly all the seven boreholes in the Bimbila formation is greater than observed by the geologist.

The weathered section in the three boreholes in the Panabako sandstone is neither reflected by higher gamma-radiation nor by higher DUIN-conductivity. Obviously, the weathering of sandstone normally does not result in clayey Saprolite, and therefore the gamma-radiation is not higher than in the host rock. However, the weathering of the sandstones most probably has resulted in increased porosity but because the water table is not very shallow, the water saturation in the Saprolite is low, which might be the explanation why the weathering is not reflected by a higher conductivity than in the host rock.

5.3.2 Lithological differences between and similarities within Formations

There is as expected a significant difference in the general log-pattern of the Panabako sandstone compared to the Bimbila Formation. All three type of wire-line logs show in the three boreholes in Panabako Formation much more variation and with higher amplitudes (difference between low and high values) than in the seven boreholes in Bimbila Formation as seen on Fig.5.3.2.1 below. Notice that GLOG-resistivity logs are not included on Fig. 5.3.2.1, partly in order to make it easier to overview, and partly because the upper part of the GLOG-resistivity logs are affected by plain pipe and screen, thus not valid until 11.7 m below bottom of plain pipe & screen (top open hole).

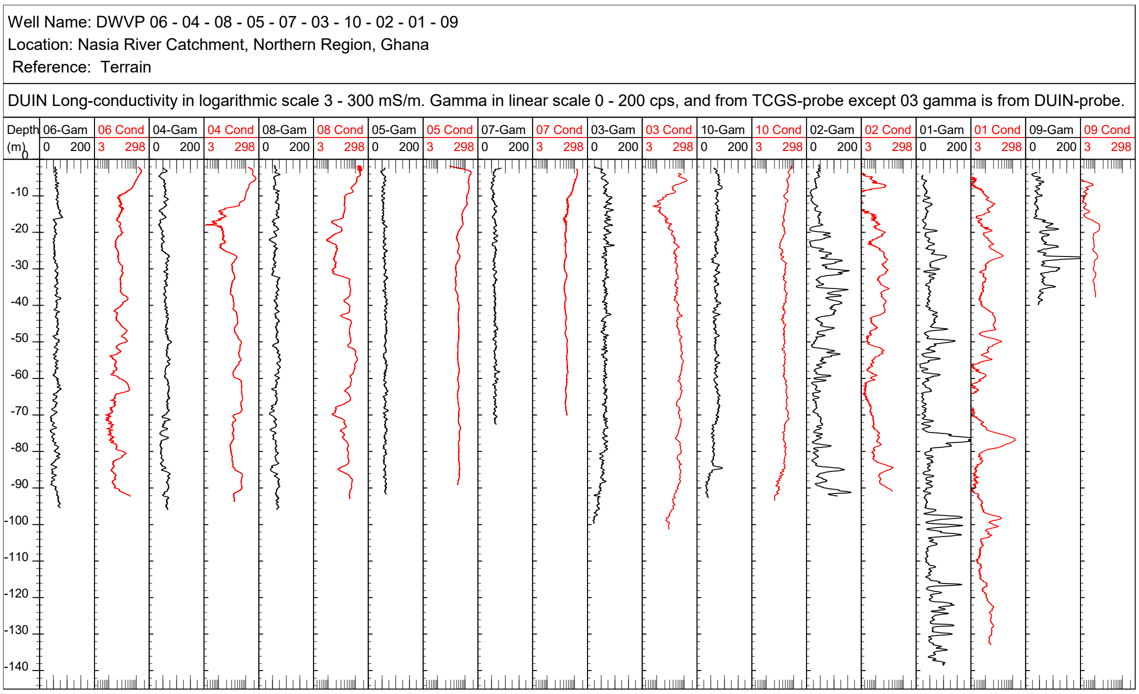

Figure 5.3.2.1: *TCGS Gamma-logs and DUIN Long-conductivity logs from the 10 DWVP boreholes presented in the order from left to wright: DWVP 6 – 4 – 8 – 5 – 7 – 3 – 10 (Bimbila formation) and DWVP 2 – 1 – 9 (Panabako formation). Gamma-logs (black colour) in linear scale 0-200 cps, and DUIN conductivity logs (red colour) shown in logarithmic scale 3-300 mS/m.*

Furthermore, the general or average level of the DUIN L-conductivity is as expected significantly lower in the Panabako Formation (5-15 mS/m) than in the Bimbila Formation (25-70 mS/m). Oppositely to the Bimbila Formation it is not possible to make an assessment of the general or average level of the Gamma-radiation in the Panabako formation due to its frequent and huge variation. The Gamma-radiation in the Bimbila formation varies mainly between 50-70 cps whereas it comes as low as to 20 cps and as high as to 200 cps in the Panabako Formation (Gamma measured with the TCGS probe in all boreholes).

Even though both type of logs show general similarities between the boreholes within each of the two Formations they also indicate certain differences between the boreholes in the same formation, thus reflect different litho-stratigraphical sections of the respective formation. As seen from Fig. 5.3.2.1 the Conductivity-logs and the Gamma-logs generally show more variation in the three boreholes DWVP 06, 04 and 08 than in the four other and more Northern located boreholes in the Bimbila formation, DWVP 05, 07, 03 and 10.

5.3.3 Lithology of the Panabako Formation

The three boreholes from the Gambaga Massif are discussed in the order of expected relative age, i.e. from eldest in the northern to youngest in the most southern borehole. The discussion is based on the composite log-sheet B of each respective borehole as seen in **Annex B**.

DWVP 9 (Annex B9): Surprisingly, the drillers log describes a siltstone all the way through the 95 m deep borehole, though with internal boundaries at 20 m, 55 m and 80 m, whereas the geologist log describes sandstone only, the latter with varying colour and varying grain size. Unfortunately, the wire-line logging could be conducted to 40 m depth only. The gamma- and the conductivity-logs indicate one type of sandstone to 16 m depth underlain by another type of sandstone. The upper one seems rather uniform with low gamma-radiation and low conductivity. The underlying one has generally a higher gamma-radiation and higher conductivity. Furthermore, conformable gamma- and conductivity-peaks indicate intercalation of clayey beds, and gamma-peaks without conformable conductivity-peaks indicate intercalation of arkosic beds.

Weathering is noticed only by the drillers log saying slightly weathered to 3 m, and clayey to 12 m. None of the wire-line logs indicate any such weathering or clay.

DWVP 1 (Annex B1): The drillers log and the geologist log are both describing sandstone throughout the 150 m deep borehole. The driller has noticed micaceous sandstone from 40 to 80 m, whereas the geologist has observed micaceous sandstone from 26 to 51 m. The geologist log is much more detailed than the drillers log by illustrating variation in colours and grain size. The gamma- and the conductivity-log show frequent and conformable variation indicating that certain sections of the sandstone contains several intercalations of claystone.

Weathering is noticed by driller and by geologist. The first one describes highly weathering to 18 m and moderately weathered to 40 m, whereas the geologist has noticed highly weathered to 13 m. Although it is present from field observations, neither the gamma- nor the conductivity-log reflects the weathering.

DWVP 2 (Annex B2): The drillers log describes the uppermost 20 m as sandstone underlain by siltstone right to the bottom at 100 m, though with boundaries at 55 m and at 80 m (suspiciously the same as in DWVP 09). The geologist describes the whole 100 m as sandstone varying in colour and grain size, though certain sections as micaceous and from

50 m generally also quartzose. The gamma- and the conductivity-log show frequent and conformable variation as in borehole DWVP 01. Conclusively, clay content and clayey beds are similarly common in the sandstone as in borehole DWVP 01.

Weathering is noticed by driller and by geologist. The first one describes weathering to 12 m, whereas the geologist has noticed weathering to 10 m. Like in the two boreholes just discussed above neither gamma- nor the conductivity-log provides basis for predicting or classifying the weathering. Probable reasons for that are explained in section 5.3.1.

The litho-stratigraphy of Panabako Formation

The litho-stratigraphy of the three boreholes in Panabako Formation can be summarized as follows: The wire-line logs verify that the penetrated sections in the three DWVP boreholes represent sandstone sections, but with different thickness and with different frequency of intercalations of clayey beds. Comparison of the wire-line logs in the three boreholes, see Figure 5.3.3.1 below, might encourage correlation of the log-pattern in the uppermost 40 m of DWVP 09 with the lowermost 40 m of DWVP 01, and furthermore to correlate the uppermost 25 m in DWVP 01 to the lowermost 25 m in DWVP 02. Thereby, it seems verified what was expected that the three boreholes represent different sequences of the Panabako formation with DWVP 09 as an elder sequence than in DWVP 01 and with DWVP 02 as a younger sequence than DWVP 01.

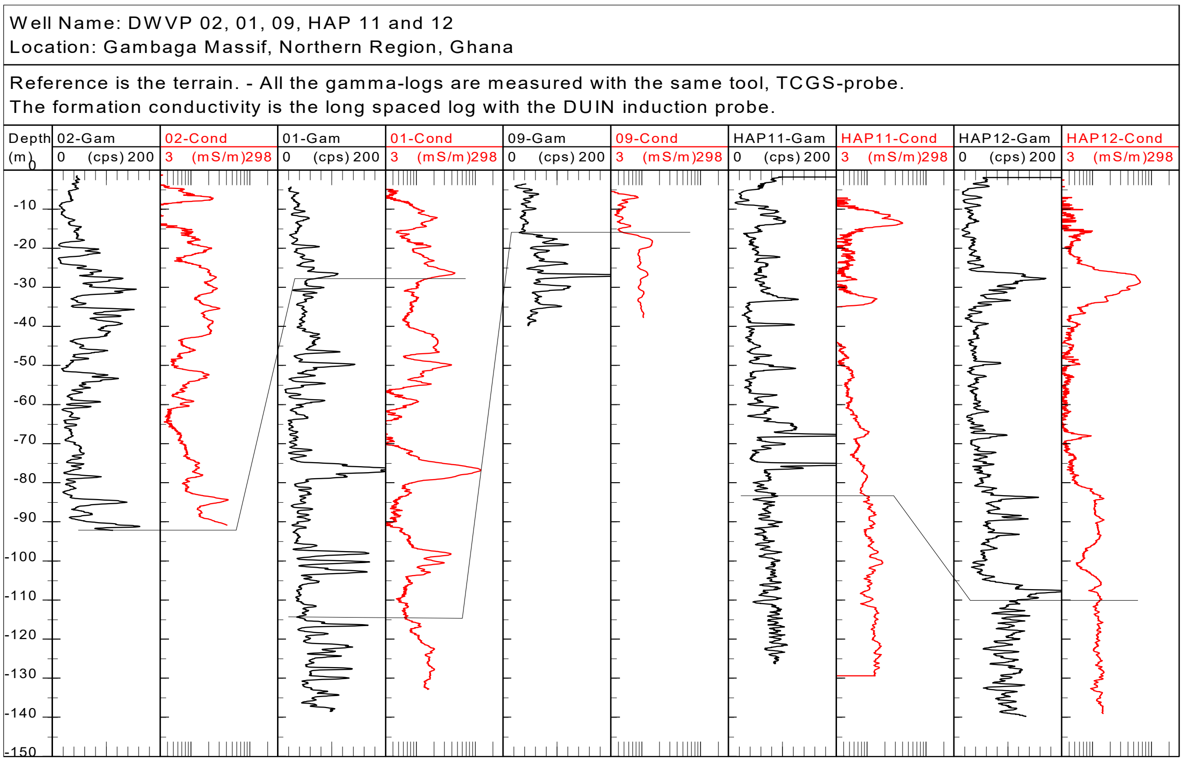

Figure 5.3.3.1: *TCGS Gamma- and DUIN Long-conductivity logs from the three DWVP boreholes and from the two HAP boreholes in the Gambaga Massif presented in the order from left to wright: DWVP 02, 01, 09, HAP 11 and HAP12. Gamma-logs (black colour) are shown in linear scale 0-200 cps, and DUIN conductivity logs (red colour) in logarithmic scale 3-300 mS/m. They are all penetrating into the Panabako formation, and HAP11 and HAP12 probably even further into the Poubogou formation at respectively 83 m and 110 m depth.*

However, with reference to Carney *et al.*, *2010* (ref. /ix/) the rocks of the Panabako Formation are believed to have been formed in deltaic and nearshore environments reflected by a cyclical mode of deposition. The latter seems illustrated by the pattern of the gamma- as well as of the DUIN conductivity-log, see Figure 5.3.3.1 above, indicating that the Panabako Formation consists of 10-30 m thick sandstone sequences separated by individual or sequences of clay beds. When considering the sedimentological environment the detailed correlation of the geophysical logs suggested above and shown on Fig. 5.3.3.1 seems questionable also in view of the several kilometre distances between these boreholes.

When including the boreholes HAP 11 and 12 (**Annex D2 and D3**), both also located within the Gambaga Massif, see figure 3.1, in the comparison of the gamma- and of the DUIN conductivity-logs, none of the log-patterns in these two HAP-boreholes can be recognized in any of the three DWVP-boreholes, as seen on the figure 5.3.3.1 above. Furthermore, the logs in these two HAP boreholes indicate that they both have reached generally more homogeneous and fine grained rocks (siltstone and mudstone with frequent thin intercalations of sandstone) at a depth of respectively ca. 83 m and 110 m, and which most probably represent the Poubogou Formation.

5.3.4 Lithology of the Bimbila Formation

The seven boreholes located within the Bimbla Formation are discussed in the order of the expected relative age from eldest in the northern to youngest in the most southern borehole. The discussion is based on the composite log-sheet B of each respective borehole seen in **Annex B**.

DWVP 10 (Annex B10): The drillers log describes the uppermost 80 m of the 100 m deep borehole as siltstone, and the lowermost 20 m without any lithology described. The geologist describes the whole 100 m as brownish siltstone. None of the two descriptions have any particular details other than the driller has noticed the light grey colour on the section from 20 m to 55 m. The gamma- and the conductivity-log show from 21 m depth and downwards quite a conformable pattern which indicate that clay minerals determine the gamma-radiation as well as the conductivity of the rock. The quite variable conductivity and lack of conformity to the more uniform gamma-radiation in the uppermost 21 m indicates variation in porosity (weathering) or content of metallic minerals (ferruginous). Based on the pattern of the two wire-line logs the penetrated rock sequence was subdivided into five different siltstones underlain from 84 m by sandstone. Later this interpretation was revised by PhD-student E. A. Dzikunoo based on correlation with the wire-line logs from borehole HAP 14, **Annex D4** (see below under "The litho-stratigraphy of the Bimbila Formation"), i.e. the lowermost siltstone section from 72 m as being Kodjari silexites (Darebe tuff) followed from 84 m by Kodjari limestone (Buipe) as shown on Annex B10.

Slight weathering was noticed by driller to 3 m depth, whereas the geologist observed lateritic materials to 5 m. As already mentioned the gradual increase in conductivity from 18 m and upwards and the lack of conformity to the gamma-log indicate weathering, which gradually decreases from top towards 18 m depth.

DWVP 3 (Annex B3): The drillers log describes siltstone right to the bottom at 100 m, though with boundaries between different type of siltstone at 20 m, 55 m and 80m, i.e. suspiciously the same boundary depths as reported by driller in DWVP 02, DWVP 09 and DWVP 10 above as well as in DWVP 05, DWVP 06 and DWVP 08 as described below. The geologist describes the whole penetrated section as siltstone, though with boundaries between shifting colours as greenish grey, brownish, greenish brown, brownish, greenish brown, brownish at 20 m, 30 m, 45 m, 55 m and 90 m. The quite variable conductivity and lack of conformity to the more uniform gamma-radiation in the section from 45 m down to 80 m depth indicates variation in porosity or in content of metallic minerals (ferruginous) of that particular siltstone section. Based on the pattern of the two wire-line logs the penetrated rock sequence can be subdivided into six different siltstone sections underlain from 90 m by sandstone. The latter indicated by a significant decrease in gamma-radiation as well as in conductivity. This interpretation was later revised by PhD-student E. A. Dzikunoo based on correlation to the wire-line logs from borehole HAP 14 (see below under "The litho-stratigraphy of the Bimbila Formation"), i.e. the lowermost siltstone section from 80 m interpreted as being Kodjari silexites (Darebe tuff) followed from 89 m by Kodjari limestone (Buipe) as shown on Annex B3.

Weathering is noticed by driller and by geologist. Both observed Laterite to respectively 3 and 4 m depth, though the geologist describes the uppermost 1 m as clay. The general increase in conductivity from 7 m and upwards and the lack of conformity to the gamma-log indicate weathering. It is notable that the gamma-radiation in the weathered section, e.g. to 7 m depth is slightly less than otherwise in the siltstone.

DWVP 7 (Annex B7): The drillers log describes siltstone right to the bottom at 75 m, though with boundaries between different type of siltstone at 20 m and 40 m. The geologist describes also like in boreholes DWVP 05 and 06 the whole penetrated section as siltstone, in this case just greyish. Apart from the uppermost 11 m the gamma- and the conductivity-log on Annex B7 show conformable and quite uniform pattern thus verifying the geologist's description, i.e. a rather uniform siltstone without significant lithological variation.

Weathering is noticed by the driller as being clayey laterite to 5 m depth and highly weathered and clayey to 9 m depth. The geologist describes the uppermost 5 m as Laterite and clay, and weathering in the siltstone to 10 m depth. The gradual increase in conductivity from 11 m and upwards and the lack of conformity to the gamma-log indicate weathering, which gradually decrease from top towards 11 m depth. It is notable that the gamma-radiation in the major part of the weathered section, e.g. to 11 m depth is slightly less than otherwise in the siltstone.

DWVP 5 (Annex B5): The drillers log describes siltstone right to the bottom at 100 m, though with boundaries between different type of siltstone at 20 m and 55 m, thus similarly as in borehole DWVP 6. The geologist describes also like in borehole DWVP 06 and 07 the whole 100 m as siltstone, though greyish-brown instead of just greyish. Apart from the uppermost 18 m the gamma- and the conductivity-log on Annex B5 show conformable and quite uniform pattern thus verifying the geologist's description, i.e. a rather uniform siltstone without significant lithological variation other than the upper siltstone to 36 m depth which has a slightly lower and more varying conductivity.

Weathering is noticed by the driller as being laterite above highly weathered sandstone to 5 m depth and moderately weathering to 20 m depth in the underlying siltstone. The geologist describes the uppermost 5 m as Laterite, and weathering in the siltstone only to 10 m depth. The gradual increase in conductivity from 18 m and upwards and the lack of conformity to the gamma-log indicate weathering, which gradually decreases from top towards 18 m depth. It is notable that the gamma-radiation in the major part of the weathered section, e.g. to 18 m depth is slightly less than otherwise in the siltstone.

DWVP 8 (Annex B8): The drillers log describes siltstone right to the bottom at 100 m, though with boundaries between different type of siltstone at the debatable depths of 20 m, 55 m and 80 m. The geologist describes the whole 100 m as greyish siltstone. Apart from the uppermost 9 m the gamma- and the conductivity-log on Annex B8 show a conformable but quite varying pattern which indicate that clay minerals determine the gamma-radiation as well as the conductivity of the rock, and that different type of siltstone occur with several intercalations of sandstone beds.

Weathering is noticed by the driller only as being slightly to 3 m depth, whereas the geologist has observed laterite and clay to 5 m and weathering to 10 m depth. The gradual increase in conductivity from 9 m and upwards and the lack of conformity to the gamma-log indicate weathering, which gradually decreases from top towards 9 m depth.

DWVP 4 (Annex B4): The drillers log describes siltstone right to the bottom at 100 m, though with boundaries between different type of siltstone again at the debatable depths of 20 m, 55 m and 80m, thus similarly as in borehole DWVP 08. The geologist describes also like in borehole DWVP 08 the whole 100 m as greyish siltstone. Apart from the uppermost 13 m the gamma- and the conductivity-log on Annex B4 show conformable but quite varying pattern thus indicating not only much more lithological variation than observed by the driller and geologist, but also that clay minerals determine the gamma-radiation as well as the conductivity of the rock. There are even two sections in the siltstone with rather low gamma-radiation as well as low conductivity, which might indicate fine grained sandstone.

The driller noticed slightly weathered siltstone to 3 m depth underlain by clayey material to 12 m. Similarly, the geologist has observed laterite to 5 m and clay to 10m (not described as weathering but assumed to be Saprolite). The gradual increase in conductivity from 13 m and upwards and the lack of conformity to the gamma-log indicate weathering, which gradually decreases from top towards 13 m depth.

DWVP 6 (Annex B6): The drillers log describes siltstone right to the bottom at 100 m, though with boundaries between different type of siltstone at 20 m and 55 m. The geologist describes the whole 100 m just as greyish siltstone. Apart from the uppermost 16 m the gamma- and the conductivity-log show a conformable but quite varying pattern, which indicates that clay minerals determine the gamma-radiation as well as the conductivity of the rock, and that different type of siltstone occur with several intercalations of claystone beds. The different pattern of gamma-log compared to the DUIN conductivity-log in the section from 10 to 16 m with increase downwards in Gamma-radiation without similar variation in conductivity indicate downward increasing feldspar content in this section (arkosic).

Weathering to 5 m depth is noticed by the driller and by the geologist. The first one describes highly weathered lateritic sandstone, whereas the geologist has observed laterite and clay. The gradual increase in conductivity from 10 m and upwards and the lack of conformity to the gamma-log indicate weathering, which gradually decreases from top towards 10 m depth.

The litho-stratigraphy of the Bimbila Formation

Conclusively, the litho-stratigraphy of the seven boreholes in the Bimbila Formation can be summarized as follows: Comparison of respectively the gamma-logs and the DUIN Conductivity-logs in the seven boreholes as seen on Figure 5.3.4.1 below allows correlation of a 10-15 m section in the upper part of borehole 04 and 08 and of another 15 m section between the lower part of 04 and 06, though the latter correlation being debatable. Furthermore, correlation is obvious between the lower section of borehole 03 and of borehole 10. The log-patterns in the two remaining boreholes, 05 and 07, have hardly any variation thus no characteristic anomalies and are therefore difficult to correlate otherwise than indicating same lithology.

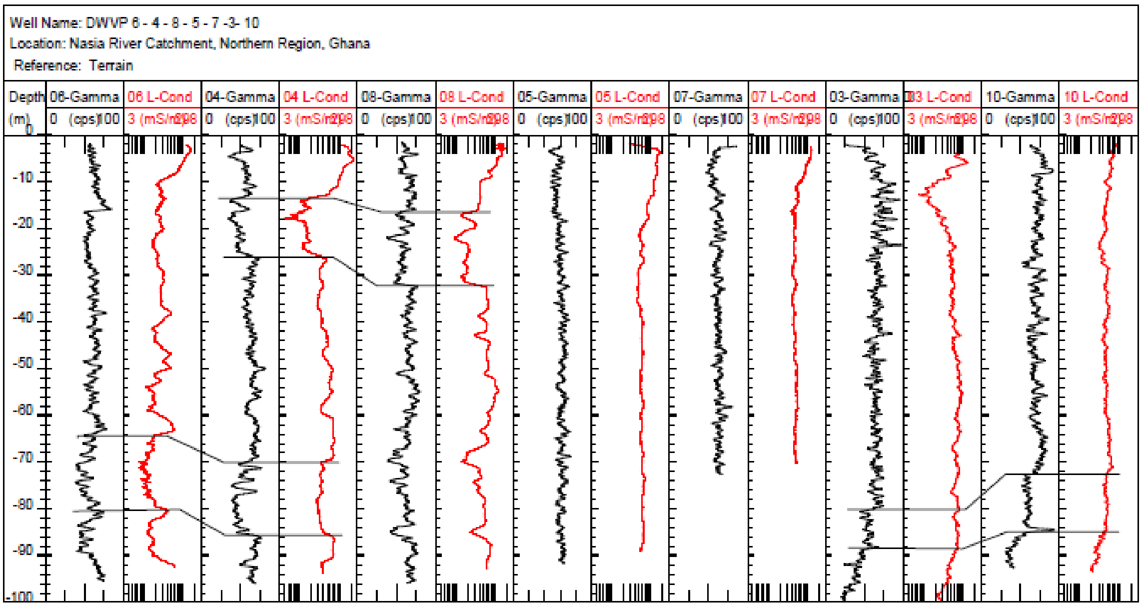

Figure 5.3.4.1: *Gamma- and DUIN Long-conductivity logs from the seven DWVP boreholes penetrating into the Bimbila formation, and presented in the order from left to right: DWVP 06, 04, 08, 05, 07, 03 and 10. Gamma-logs (black colour) are shown in linear scale 0-100 cps, and DUIN conductivity logs (red colour) in logarithmic scale 3-300 mS/m.*

The seven boreholes can be grouped into three with significantly different log patterns representing three different litho-stratigraphical sections:

- The most southern located boreholes 08, 04 and 06, where both types of log show significant and conformable variation apart from the uppermost section reflecting the weathered zone. Furthermore, correlation between the boreholes seems possible for certain sections of the logs as shown on Fig. 5.3.4.1.

- The more northern located boreholes 05 and 07, where both types of log show very limited variation apart from the uppermost section which reflects the weathered zone.
- The most northern boreholes 10 and 03, where both types of log are slightly varying and correlation possible between the two boreholes for the lowermost 20 m as shown on Fig. 5.3.4.1 (i.e. the section with Kodjari formation as discussed below).

This conclusive grouping seems to reflect the expected relative chrono-stratigraphy in terms of boreholes 10 and 03 representing the eldest section of the Bimbila Formation in contact with the underlying Kodjari formation, boreholes 05 and 07 representing a middle section of the Bimbila Formation, and finally boreholes 08, 04 and 06 representing younger sequences of the Bimbila Formation.

The interpretation by PhD-student E. A. Dzikunoo of the lowermost 20 m log-pattern in boreholes 03 and 10 as being part of the Kodjari Formation was justified by her correlation, see Fig. 5.3.4.2 below, to the logs from previously conducted wire-line logging of the bore-hole HAP 14 (ref./v/). The latter having been reprocessed and re-interpreted as part of the work with this report, see **Annex D4,** whereby the characteristics of the resistivity and of the gamma-radiation of the Kodjari triad has been revealed: The Buipe limestone having a generally higher resistivity and lower gamma-radiation than the underlying tillite and the overlaying Darebe tuff. Furthermore, the variation in the gamma-radiation and in the resis-tivity does also indicate the tillite as being the most heterogeneous rock of the triad.

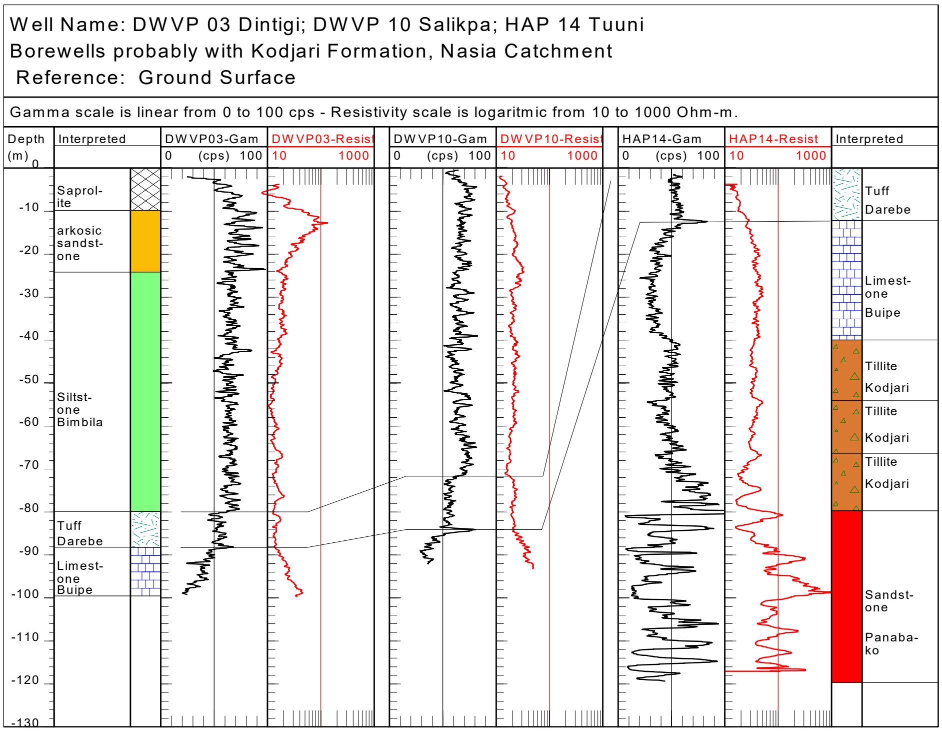

Figure 5.3.4.2: *Gamma- and DUIN Long-resistivity logs from the two DWVP boreholes 03 and 10 correlated by E. A. Dzikunoo to similar logs from borehole HAP 14 after the latter was re-processed and re-interpreted compared to ref. /v/. Gamma-logs (black colour) are shown in linear scale 0-100 cps and DUIN resistivity logs (red colour) in logarithmic scale 10-1,000 Ohm-m. Reference line 50 cps and 100 Ohm-m is shown for respectively gamma- and resistivity-logs.*

5.4 Fluid Temperature Logs

The magnitude and variation of the fluid temperature in the DWVP boreholes vary both vertically within each borehole and from borehole to borehole as seen on Figure 5.4.1 below. The fluid temperature and conductivity were in each borehole measured during non-pumping condition, and as the very first logging run. Since the DWVP boreholes were drilled several months before the wire-line logging was conducted, the stagnant water in the borehole is assumed to be in equilibrium with pore-/fracture water, thus the measured fluid temperature and fluid conductivity in the open and screened section responds to the temperature of the rock and conductivity of the groundwater. Though, possible internal flow between different water-bearing fractures caused by differences in hydraulic pressure might disturb the equilibrium. Such cases with internal flow from one fracture to another one can be identified as a section having completely constant Fluid temperature and Fluid conductivity, as seen in borehole DWVP 02 under the section 5.5 Fluid Conductivity Logs.

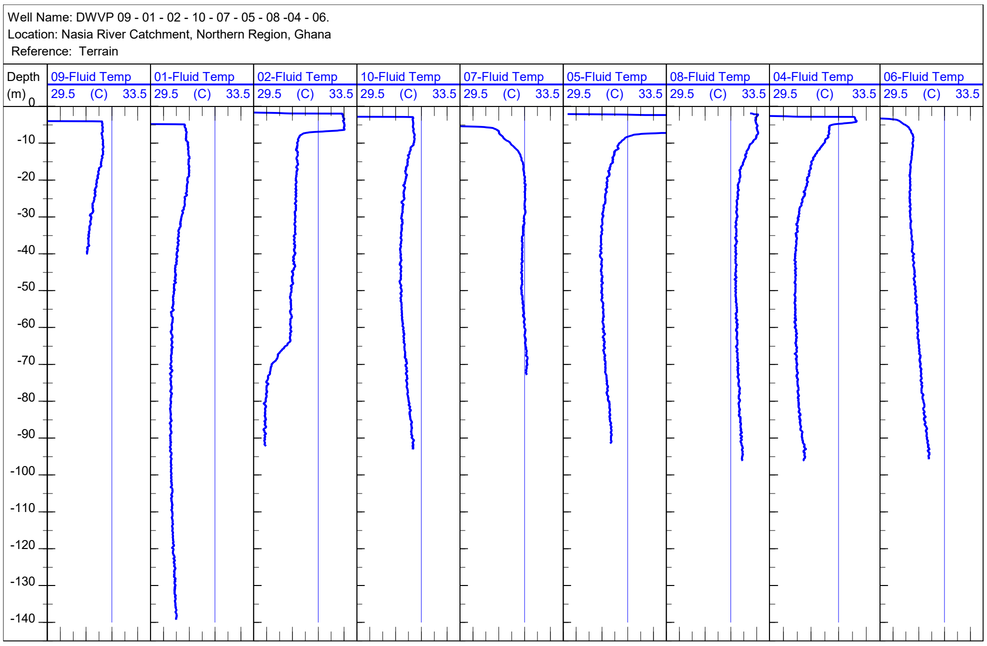

Figure 5.4.1: *Fluid-temperature logs from nine of the ten DWVP boreholes shown in the order of northern towards southern thus geologically eldest towards youngest – and linear scale from 29.5 to 33.5 ^{0}C. A reference-line of 32 ^{0}C is shown on each log.*

The table 5.4.1 below summarizes the magnitude and variation of the observed Fluid temperature in the DWVP boreholes. The temperature of the borehole water is of the magnitude 29.9 °C to 33.0 °C, though within the individual boreholes is the difference between lowest and highest temperature only 0.6 °C to maximum 1.5 °C. There is no relation between depth of the borehole and the magnitude of the variation. The temperature can in most cases be described as highest at the water table caused by a high air-temperature (from 31.6 °C to 36.3 °C), then rather constant within the casing pipe and then decreasing downwards in the screen or/and in the open section until a depth of 30 to 60 m followed by an increase towards bottom. Though, in three of the boreholes (DWVP 01, 06 and 07) the temperature in the air above the water table was relatively low (25.0 °C to 28.0 °C), with the consequence that the Fluid temperature variation started low at the water table followed by increase, decrease and increase.

BoreWell	Geology	Tempera-ture in water (°C)	Δ °C	Depth (m)	Downwards variation type	**Variation characteristics (**See Fluid Temp logs on Annex B – though for control of the air-temp see Fluid Temp logs on Annex A)
09	Pan.	31.0 – 31.6	0.6	40	High – low	Highest and constant within 15m top casing. – Air-temp. as uppermost water 31.6 °C
01	Pan.	30.2 – 31.0	0.8	140	Low - high – low – higher	Slightly increasing downwards within the 17m top casing. – Low air-temp. 25.0 °C
02	Pan.	29.9 – 31.2	1.3	92	High – lower – low	Highest and constant within 16m top casing, weak decrease downwards to 44, further constant to 64 m depth followed by sudden decrease. - Air-temp 33.0 °C thus higher than uppermost water.
03	Bi-old	No log	-	-	-	-
10	Bi-old	31.1 – 31.7	0.6	93	High – low – higher	Highest and constant within 10 m top casing. – Air-temp. as uppermost water 31.6 °C
07	Bi-mid	30.7 – 32.2	1.5	72	Low – higher – low – high	Lowest and increasing within 16 m top casing. – Low air-temp. 27.8 °C
05	Bi-mid	30.9 – 32.0	1.1	92	High – low – higher	Highest and decreasing within 21 m top casing. – High air-temp. 36.3 °C
08	Bi-y	32.2 – 33.0	0.8	96	High – low – higher	Highest and constant within 9 m top casing. – No measurement above water.
04	Bi-y	30.4 – 31.6	1.2	96	High – low – higher	Highest and constant within 9 m top casing. – Air-temp. 32.7 °C thus higher than uppermost water.
06	Bi-y	30.6 – 31.4	0.8	96	Low – higher – low – high	Lowest at top and increasing within 13 m top casing – highest at bottom. – Air-temp. 28.0 °C thus lower than uppermost water.

Table 5.4.1: *Fluid temperature and its variation downwards in the DWVP boreholes as observed from wire-line log.*

It is notable that the Fluid temperature in the two most water bearing boreholes, DWVP 02 and DWVP 07, are showing some particular characteristics compared to the other boreholes. E.g. in DWVP 02 is the temperature variation completely different from the general variation pattern described above. The temperature is constant between 44 m and 63 m depth, i.e. between the two water bearing fractures (see later section on Flow-logs), and a sudden and significant decrease below 63 m depth results at bottom in the lowest temperature observed in any of the boreholes, 29.9 °C. In DWVP 07 varies the Fluid temperature in accordance to the general pattern described above, but ends with second highest temperature at bottom, 32.2 °C, in spite of not being as deep (75 m) as the other boreholes. One could expect the highest bottom temperature in the deepest borehole, DWVP 01 (150 m), but that is not the case (30.5 °C only).

Summarizing, there is need for further research on reasons for the observed difference in variations and magnitudes of the temperature, thus for clarification of to which extent hydrogeological important information can be drawn from such temperature logs.

5.5 Fluid Conductivity Logs

The magnitude and variation of the fluid conductivity in the DWVP boreholes vary quite a lot both vertically within each borehole and from borehole to borehole as seen on Figure 5.5.1 below. The variation of the Fluid conductivity is in all the boreholes increasing from being lowest at the top to being highest at bottom. The lowest being 10 mS/m or less as seen in the three boreholes in the Panabako formation (DWVP 09, 01 and 02) and in one borehole in Bimbila formation (DWVP 07). The highest Fluid conductivity 2,300 mS/m occurs in the deeper part of DWVP 10. In two other boreholes, DWVP 02 and 04 the Fluid conductivity is relatively high, 300-400 mS/m towards bottom. As expected the Fluid conductivity is not exceeding 100 mS/m in the two shallowest boreholes, DWVP 09 and 07. More surprisingly the same is seen in the deepest borehole, DWVP 01. In the remaining three boreholes, DWVP 05, 08 and 06, the Fluid conductivity in the deeper parts ranges 150-200 mS/m.

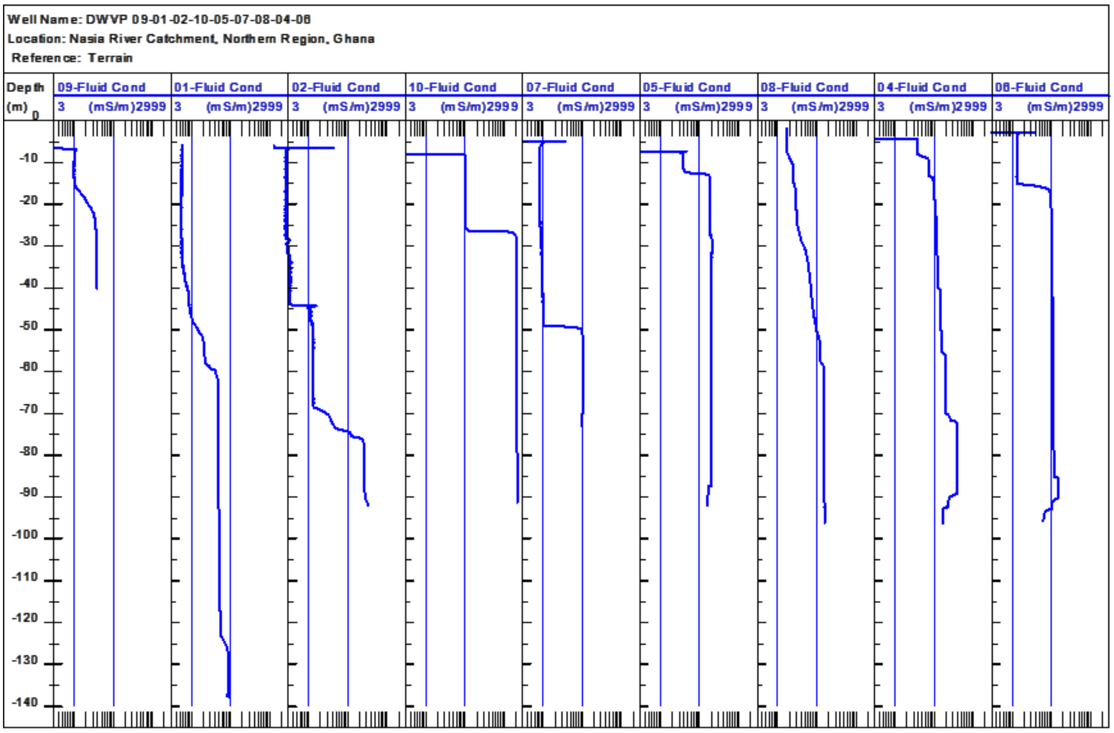

Figure 5.5.1: *Fluid-conductivity logs from nine of the ten DWVP boreholes shown in the order of northern towards southern thus geologically eldest towards youngest – and mS/m in logarithmic scale from 3 to 3,000. The reference-lines of 10 and of 100 mS/m are shown at each borehole. All logs start at the water table.*

It is noteworthy that most of the Fluid conductivity logs are characterized by having sections with rather constant conductivity and with sudden shift from section to section. Considering that the DWVP boreholes were drilled several months before the wire-line logging was conducted, and that the Fluid Temperature- and Conductivity log was the first log-run in each borehole, then as already mentioned the water in the borehole is assumed to be in equilibrium with pore-/fracture water. However, a variation as described above normally indicates internal upwards flow of water from the bottom section with high conductivity, the latter lowered by inflow at different fractures of water with lower conductivity thus causing the sudden shifts. Though, since the Temperature-logs apart from a certain section in borehole DWVP 02 do not show similar constant temperature, the internal flow upwards from deep seated fractures to more shallow fractures must be extremely slow, thereby the flowing water will be in temperature equilibrium with the surrounding rock. The extremely fresh water observed in the upperpart of boreholes 01, 02 and 07 indicates infiltration of surface water.

Many different quality classification systems do occur based on threshold values of either total weight salinity (TDS) or of fluid conductivity (EC^{25C}). A modified version from ref. /xii/ is preferred and shown in Table 5.5.1 below. The threshold values for TDS in mg/l are transformed to fluid conductivity at 31°C, the average temperature during logging, by using the equation: EC^{25} (uS/cm) = 1.54 * TDS (mg/l), thus EC^{31} (mS/m) = 0.1 * EC^{25} * 1.1303 = 0.1 * 1.54 * TDS * 1.1303 = 0.2 * TDS. The resulting conductivity values are finally transformed to equivalent Cl^- concentrations for the different quality classifications by using the equation:

$$Cl^- \text{ (mg/l)} = 8/3 * EC^{25} \text{ (uS/cm)} = 8/3 * EC^{31C} / (1.1303) = 2.36 * EC^{31C}.$$

The equation is based on the assumption that Cl^- concentration in mg/l is equal to 4 * EC at 10 ^{0}C in uS/cm (ref. /vii/), and that EC at 25 ^{0}C is equal to 3/2 * EC^{10C} (ref. /vii/) i.e. EC^{25}= (3/2) * EC^{10} = (3/2) * (1/4) * Cl^- = (3/8) * Cl^-. Furthermore, since EC^t= EC^{25} * (0.47 + 0.0213 * t) then EC^{31C} = EC^{25} * (0.47+0.0213 * 31) = EC^{25} * (1.1303).

Classification	TDS (mg/l)	EC^{31C} (mS/m)	Equivalent Cl^- (mg/l)
Extremely fresh	<50	<10	<25
Fresh	50 – 500	10 – 100	25 – 250
Influenced marginally	500 – 1,000	100 – 200	250 – 500
Brackish	1,000 – 5,000	200 – 1,000	500 – 2,500
Saline	5,000 – 25,000	1,000 – 5,000	2,500 – 12,500
Highly saline	>25,000	>5,000	>12,500

Table 5.5.1: *Water quality classification modified after Mayer et al., 2005 (ref. /xii/) based on TDS threshold values with related fluid conductivity at 31^{0}C and equivalent Cl^- content.*

The above listed threshold values in Table 5.5.1 for EC^{31C} has then been applied for the quality classification in Table 5.5.2 below of the different sections of water column in each borehole based on their respective fluid conductivity-log.

The actual quality of the water in the boreholes was determined by hydrochemistry analysis of water samples taken in a campaign in July 2018, **Annex E**. However, borehole DWVP 10 could not be accessed due to flooding. Therefore, sample from this borehole was taken in January 2019 and again in October 2019. The conductivity of the water samples could unfortunately neither be determined in the field nor in the lab. Therefore, it had to be calculated by the hydrochemistry lab. by using EC(µS/cm) = 1.54 * TDS(mg/l), where the TDS being the total amount of the major ions from the hydrochemistry analyses (Na, Ca, Mg, Fe, HCO_3, SO_4, Cl, SiO_2).

Borehole ID / Geology	Depth section (m)	Fluid cond. (mS/m)	Quality* of water evaluated from Fluid cond.:	Conductivity/ quality of water sample (mS/m)	Evaluated main inflow represented by water sample
DWVP 9/ Panabako	7-16 16-26 26-40	10 10-40 40	Extremely fresh Fresh Fresh	No sample	No sample
DWVP 1/ Panabako	5-46 46-59 59-124 124-137	5-10 10-30 45-55 85	Extremely fresh Fresh Fresh Fresh	13/ fresh	From 59 m and above
DWVP 2/ Panabako	7-44 44-68 68-74 74-76 76-90	2.5-3.5 13 15-100 100-200 250-300	Extremely fresh Fresh Fresh Influenced Brackish.	6/ extremely fresh	From 68 m and above
DWVP 3/ Bimbila old		No log	Evaluated from DUIN- versus GLOG-log based on experi-ence from DWVP 10: *Fresh above 33 m* *Saline below 33 m*	1,275/ saline	From below 33 m
DWVP 10/ Bimbila old	8-26 26-78 78-90	100 2,000 2,300	Fresh Saline Saline	2,080/ saline	From below 26 m
DWVP 5/ Bimbila middle	7-12 12-27 27-87	35 180 200	Fresh Influenced Influenced	174/ influenced	From 27 m and above
DWVP 7/ Bimbila middle	5-49 49-70	10 105	Extremely fresh Fresh	17/ fresh	From 49 m and above
DWVP 8/ Bimbila young	1-30 30-50 50-58 58-90	15-50 50-100 100-120 155	Fresh Fresh Influenced Influenced	46/ fresh	From 30 m and above
DWVP 4/ Bimbila young	4-13 13-50 50-70 70-90	40-80 100-150 160-200 400	Fresh Influenced Influenced Brackish	49/ fresh	From 13 m and above
DWVP 6/ Bimbila young	3-15 15-80 80-90	15 110 120-160	Fresh Influenced Influenced	16/ fresh	From 15 m and above

*): Extremely fresh (<10 mS/m) – fresh (10-100 mS/m) – influenced (100-200 mS/m) – brackish (200-1,000 mS/m) – saline (1,000–5,000 mS/m) - highly saline (>5,000 mS/m).

Table 5.5.2: *Vertical variation of water quality evaluated from fluid conductivity log, water sample conductivity and inflow location which was thought to contribute to the water sample.*

On basis of comparison of the vertical variation of the fluid conductivity and the conductivity of the water sample it has been evaluated for each borehole as shown in the Table 5.5.2 above, which depth section with main inflow is thought to be represented by the water sample. The latter taken in each borehole after that water being discharged by a submersible pump has shown constant conductivity and temperature (mostly after 20-30 min.).

As already mentioned there was no Fluid Temperature and Conductivity log conducted in borehole DWVP 03. However, as shown in the table 5.5.2 (above) the quality of the water in this borehole is expected from a certain depth (33 m) to be as saline as observed in DWVP 10. This expectation is based on the similarity and proportion between the GLOG resistivity-log and the Calculated DUIN-L resistivity-log in borehole DWVP 03 and 10 as seen on the Figure 5.5.2 below.

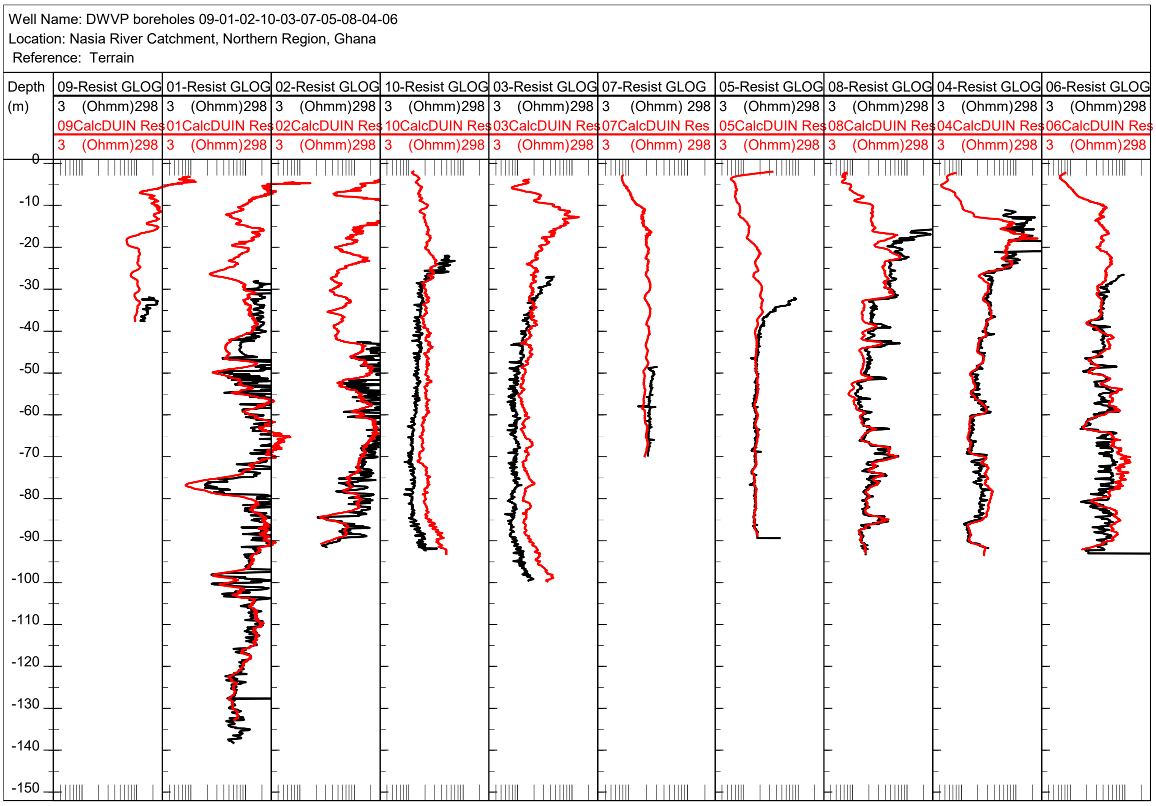

Figure 5.5.2: *GLOG resistivity-log (black colour) and Calculated DUIN-L resistivity-log (red colour) from the ten DWVP boreholes shown in the order of northern towards southern thus geologically eldest towards youngest. Logarithmic scale: 3 to 300 Ohm-m.*

As illustrated on Figure 5.5.2 the GLOG resistivity and the Calculated DUIN-L resistivity show quite similar values in eight of the ten boreholes. Conversely, in DWVP 03 and 10 the GLOG Resistivity from a certain depth is significantly lower than the DUIN-L resistivity. From the DWVP 10 (**Annex B10**) it is seen that the depth from where the GLOG resistivity goes below the DUIN-L resistivity, is at the same depth, where the Fluid conductivity suddenly increases, i.e. the water quality shifts from fresh to saline. Obviously, the GLOG resistivity probe is more affected by the saline water in the borehole than the DUIN induction probe. Since DWVP 03 has the same relation between GLOG Resistivity and Calculated DUIN-L resistivity as DWVP 10, the water could similarly be expected to be saline in borehole DWVP 03. The latter was verified by the water sample, which shows a Fluid conductivity of 1,275 mS/m (see **Annex E**). However, that the water in DWVP 10 was similar saline was not verified until a valid water sample could be taken in October 2019 showing a Fluid conductivity of 2,080 mS/m (see **Annex E**).

5.6 Flow-log and Inflow Distribution

The distribution of the inflow zones and the relative magnitude of the inflow in each zone are determined by a downwards run with a High Resolution Impeller Probe (HRFM) during pumping from the borehole with constant discharge rate. Even that this probe is quite sensitive, the minimum flow velocity required for obtaining reliable and steady measurements of rotations is 1 cm/sec, which means 20 lpm in average for a 6 ½" diameter borehole. The processing of the data from a flow-log respectively without pumping (Q=0 lpm) and with pumping (Q=? lpm) is rather cumbersome compared to all other log-types, but can be summarized as follows:

Depth control: The HRFM tool has a gamma-radiation detector like all the other tools applied. By comparing the gamma-log of the two HRFM runs (without and with pumping) with the TCGS-gamma log it can be detected whether a depth shift is needed for any of the two HRFM-gamma logs. If so, the same depth shift has to be performed on the accompanying flow- and cable-speed logs.

Transformation of recorded times of rotation: The flow-log without as well as with pumping is recorded as Time in mSec of ¼ rotation of the impeller, shown on the logs with header *RD Slow Q=0 lpm (mSec)* and *RD Slow Q=discharge lpm (mSec)*, which shall both be transformed to number of rotations per minutes (= 60*1,000/4*Time) and thereafter shown on the logs with header respectively *Flow Q=0 lpm (RPM)* and *Flow Q=discharge lpm (RPM)*.

Transformation of recorded time of 10 mm cable movement: The cable speed without and with pumping is recorded as Time per sample (taken per 10 mm) in 0,1 mSec, shown on the logs with header *Time p.S. Q=0 lpm (0.1 mSec)* and *Time p.S. Q=discharge lpm (=0.1 mSec)*, which shall both be transformed to log speed in m per minutes (=60*100/Time p. S.) and thereafter shown on the logs with header respectively *Log speed Q=0 lpm (m/min)* and *Log speed Q=discharge lpm (m/min)*.

Relationship between tool movement and impeller rotation: Corresponding pair of sample values on *Log speed Q=0 lpm (m/min)* and of *Flow Q=0 lpm (RPM)* at different depths are selected and are plotted, and the linear regression coefficients 'a' and 'b' are obtained from the relation:

Flow Q_0 = a * Speed Q_0 + b,

where

Flow Q_0 = non-pumping flow in rotations/min due to tool movement only.

Speed Q_0 = Cable Speed in m/min during the non-pumping log run.

Part of the recorded flow-log during pumping is caused by tool movement: Next step in the processing of the data is to calculate the Flow-log representing the impeller rotations caused solely by the downward movement of the tool during pumping by using the equation above under step d: Speed Flow $Q_?$ = a * Speed $Q_?$ + b

where

Speed Flow Q? = flow in rotations/min during pumping (with discharge?) but caused solely by the tool movement.
Speed Q? = log run speed in m/min during pumping (with discharge?).

Remaining part of the recorded flow-log during pumping is caused by actual water flow: The actual vertical water flow, shown with the header *Flow Q=? corr (rpm)*, is the difference between the *Speed Flow Q?(rpm)* from step e) and the *Flow Q=? lpm (rpm)* from step b), thus calculated by reducing the total measured flow during pumping, *Flow Q=? lpm in (rpm)*, by the number of impeller rotations, *Speed Flow Q? in (rpm)*, caused solely by the down movement of the tool using the formula:
Flow Q? corr. = *Flow Q?* - *Speed Flow Q?* = *Flow Q?* - (a* *Speed Q?* + b),
Where:
Flow Q? corr. = actual water flow during pumping (rpm)
Flow Q? = total measured flow during pumping (rpm)
Speed Flow Q? = calculated flow caused solely by tool movement during pumping (rpm)
Speed Q? = actual logging speed (= cable speed) during pumping (m/min)
'a' and 'b' = linear regression coefficients determined from the non-pumping flow-log data.

The actual water flow distribution in percentage: Finally, the computed actual flow-log, *Flow Q? corr.,* is re-calculated into relative flow distribution in percentage by assuming the number of rotations at the uppermost part of the flow-log just below the pump is representing 100 % of the discharge. The relative inflow distribution is normally presented as the last column of the composite log suite for those boreholes on which HRFM logging was conducted.

Location of inflow zones and their respective inflow: Based on the resulting distribution graph the actual inflow zones and their respective in-flow in percentage can be determined.

HRFM logging was conducted on two of the DWVP boreholes (Table 3.1), whose safe yield was evaluated from the previous pumping test to be higher than the required minimum yield of 20 lpm, i.e. DWVP 02 and DWVP 07. The different steps in the processing of the Flow-log data as described above are illustrated in respectively **Annex C2 and C7**. The pump setting depth (20 m in both boreholes) as well as the discharge rate (respectively 60 lpm and 30 lpm) were selected in order to ensure, that the water table will not be lowered down to the suction head of the submersible pump during the run of the flow-log. The latter is normally conducted with a speed of 6 m/minutes, i.e. it takes 10 to 15 minutes for running 60 to 90 m logging. A centraliser was installed around the flow-meter tool to ensure a smooth downwards moving during logging. A summary of the detected inflow zones and the relative magnitude of inflow in percentages at each inflow zone are shown in the Table 5.6.1 below.

The resulting flow-log from borehole DWVP 02, **Annex C2,** actually shows upwards increasing impeller rotation at each of the depths 27 m, 44 m, 62 m and 74 m, and still rotations at 92 m depth where the logging was to stop in order to avoid the possible mud at bottom of the borehole. However, considering the fact that the diameter changed at the depth of 27 m from 5" in the screen pipe to 6.5" in the open-hole section below, the change in impeller rotation at that depth is caused by the diameter shift. E.g. a change from 6.5" to

5” is equal to a change in area from 214 cm^2 to 127 cm^2, i.e. a change to 60% of the flow-area, which will result in 40% higher impeller rotation in the 5” screen compared with the 6.5” open hole. It is exactly what can be seen on the apparent flow-graph, where the accumulated flow upwards is 100% in the screen and 60% in the uppermost part of the open-hole section. Therefore, the correct Flow-graph is calculated by neglecting the rotations in the screen pipe and instead using the average impeller rotation level in the section below the screen pipe as representing 100% flow, thus adjusting impeller rotation level in the other sections below accordingly.

Location	BH ID. / Discharge on flow-log	Yield estimated from pumping test	Drillers’s water zones: Cumulative yield (lpm) / Depth (m)	Depth to inflow zones on flow-log (m)	Inflow (%)
Tamboku – near river	DWVP 02/ 60 lpm	130 lpm	6/18 60/36 100/46	44 62 74 >92	25 55 5 15
Saliwia	DWVP 07/ 30 lpm	85 lpm	134/63 45/70 45/75	48	100

Table 5.6.1: *Identified inflow zones and their relative inflow (% of discharge) compared to driller’s water zones (ref. /i/ - Appendix 4).*

The resulting distribution in DWVP 02 of respectively 25 %, 55%, 5 % and 15 % inflow from respectively 44 m, 62 m, 74 m and below 92 m fits well with the interpretation of the fluid conductivity log compared to the conductivity of the water sample as shown in Table 5.5.2, i.e. that the water sample mainly represents inflow from zones above 68 m depth. Contrary, the inflow distribution determined by flow-logging does not agree with the information on water zones and related cumulative yield during drilling from driller’s record as shown in the table 5.6.1 especially since the driller has not observed any further inflow zones below 46 m depth.

The resulting flow-log from borehole DWVP 07, **Annex C7**, shows 100 % inflow at 48 m depth, i.e. far below the blind pipe. Accordingly, this increase is not caused by any diameter change, but reflects that the borehole has only one inflow zone. This result is in accordance with the interpretation of the fluid conductivity log compared to the conductivity of the water sample as shown in Table 5.5.2, i.e. that the water sample represents inflow above 49 m depth. Like in borehole DWVP 02 the inflow situation in DWVP 07 is not consistent with the driller’s observation, in this case of no water inflow until a depth of 63 m.

6. SUMMARY OF RESULTS

6.1 Borehole completion, lithology and groundwater classification

The advantage of geophysical wire-line logging of boreholes for control of the driller's completion report as well as of the geologist's log has once again been illustrated. When comparing the completion details of the ten DWVP boreholes as reported by the driller with the completion details as interpreted primarily based on the GLOG resistivity-log (because the Calliper-probe was out of order), many discrepancies are seen. Only two of the ten boreholes seem completed as reported, DWVP 05 and 03. The discrepancies are significant, particularly in the four boreholes with claimed screen sections, DWVP 01, 02, 04 and 09, which all have fewer meters of plain pipes and screens installed than reported, and considerable much less in 01 and 02. Contrarily, the DWVP 08 has a screen installed without being reported by the driller. The remaining three boreholes, DWVP 06, 07 and 10 without screens have 2 to 6 m shorter plain pipes installed than claimed by the driller.

When it comes to the geology the driller's log seems in most cases to differ quite significantly from what was interpreted. The geologist's log is very detailed in the three boreholes penetrating into the Panabako sandstones. However, did neither notice the many clayey beds identified by the gamma- and conductivity logs nor the cyclic architecture of the formation, which consists of 10-30 m thick sandstone sequences separated by individual or groups of clay beds. The geologist's log of the seven boreholes penetrating into the Bimbila formation only describes it as a siltstone, though with certain variation in colour. The intercalations of sandstone and clayey beds identified in the siltstone by gamma- and conductivity logs in the three boreholes DWVP 04, 06 and 08 were obviously not observed. Furthermore, neither the Darebe silexites nor the Buipe limestone identified in the lowermost part of borehole DWVP 03 and 10 by correlation of gamma- and conductivity log with borehole HAP 14, were noticed in the geologist's log.

The fluid temperature-log has revealed major differences in the vertical variation as well as in the magnitude of the temperature of the water column of the nine boreholes with TCGS-log. However, more research is needed in order to draw conclusions on the reasons for the observed differences between the boreholes, thus also in terms of extracting possible hydrogeological valuable information.

The fluid conductivity-log being the first wireline-log conducted (together with the temperature-log) in each borehole has in most of the ten DWVP boreholes indicated internal upwards flow of high conductivity water from the bottom section stepwise being mixed at different fractures with inflow of water with lower conductivity. However, since the Temperature-logs did not show similar constant and stepwise shift as the fluid-conductivity log, the internal flow upwards from deep seated fractures to more shallow fractures must be extremely slow, thus allowing the flowing water to be in temperature equilibrium with the surrounding rock. Summarizing, the fluid-conductivity log has indicated infiltration of extremely fresh surface water (<10 mS/m) into the upper 40-50 m of the rock at boreholes DWVP 01, 02 and 07. This extremely fresh upper groundwater has in those three boreholes obviously been the main contributor to the water sample, which has a conductivity of respectively 13 mS/m, 6 mS/m and 17 mS/m. Marginally influenced groundwater (100-200 mS/m) was observed below the freshwater (<100 mS/m) upper zone in DWVP 04, 05, 06 and 08 and even brackish groundwater (400 mS/m) at bottom of 04. However, only in DWVP 05 it seems to have contributed to the water sample showing a conductivity of 175 mS/m. In the remaining boreholes only the fresh upper groundwater has contributed to the sample. Saline groundwater (1,000-5,000 mS/m) was observed below the freshwater (<100 mS/m) upper zone from respectively 33 m and 26 m depth in boreholes DWVP 03 and 10. In both boreholes the saline groundwater has contributed heavily to the sample, which showed a conductivity of respectively 1,275 mS/m and 2,080 mS/m. In this way it is illustrated, that comparison of the fluid conductivity-log to the conductivity of a water sample taken after sufficient time of discharge provides basis for evaluating which depth section has contributed with water inflow to the sample, even that the fluid conductivity-log was not conducted during discharge of water from the borehole.

However, a combined fluid temperature- and conductivity-log conducted during discharge would provide more detailed information on the water quality to be expected from exploitation of the borehole. Furthermore, such a log makes it possible to identify the individual zones with inflow of water with conductivity or temperature being different from the conductivity or temperature of the water flowing upwards from inflow zones below. Therefore, TCGS-logging during pumping is recommendable even in boreholes with expected yield as low as 10 lpm, though conditional to adjustment of the pump discharge accordingly. Examples on this type of logging from the previous logging campaign are seen in **Annex D2, D4, D5 and D6**.

With regards to the flow-logging, only two of the ten DWVP boreholes comply with the minimum requirement on yield of 20 lpm for obtaining a reliable flow-log in a 6 ½” diameter borehole. The flow-log in the 100 m deep borehole DWVP 02 shows four inflow zones at depths of 44 m, 62 m, 74 m and below 92 m with the one at 62 m as the main inflow zone contributing with 55 %. The flow-log in the 75 m deep borehole DWVP 07 shows only one inflow zone, i.e. 100 % inflow at the depth of 48 m. In both cases the inflow distribution does not align with the driller’s observation of water zones, but was in rather good agreement to the collected water sample in terms of the depth section contributing to the sample. The latter evaluated on basis of the fluid-conductivity log compared to the conductivity of the water sample.

Finally, the supplementary results obtained by including and reprocessing the data from previously conducted geophysical wire-line logging of eight additional boreholes in or nearby the Nasia River basin are shown in **Annex D**, but can be summarized as follows:

- The two HAP boreholes on Gambaga Massif, HAP 11 and HAP 12 (**Annex D2 and D3**), seem to represent respectively 80 and 110 m of the lowermost part of the Panabako formation and have entered respectively 40 and 30 m into the Poubogou formation. In HAP 12 the groundwater is extremely fresh (<10 mS/m) in the upper part of the sandstone, but the fluid conductivity increases gradually towards depth but is still fresh (<100 mS/m) in the Poubogou formation even at 140 m depth. It is generally the same situation at HAP 11, though without extremely fresh groundwater in the upper part of the sandstone.

- Borehole Hap14 (**Annex D4**) is seen on the geological map, Figure 3.1, to be located just south of the Kodjari Formation, which renders the interpretation, that all the three members of the Kodjari Formation are present and overlying the Panabako Formation from 68 m depth, very probable. Thus, it seems characteristic for the Kodjari that the Buipe limestone has a generally higher resistivity and lower gamma-radiation than the underlying tillite and the overlying Darebe tuff. Furthermore, the two geophysical logs indicate that the tillite is the most heterogeneous rock of the triad. The groundwater seems brackish (400-700 mS/m) without indications of freshwater occurrence even at shallow depth.
- Borehole HAP 05 (**Annex D1**) is seen on the geological map, Figure 3.1, to be located more close to the outcropping Bunya Formation, thus more close to the axis of the westerly extended Daka syncline (ref. /ix/) than any of the seven DWVP boreholes within the Bimbila Formation. Therefore, it would be obvious to conclude its 120 m quite homogeneous mudstone as belonging to the youngest sequence of the Bimbila Formation. Though, since it has quite similar gamma- and resistivity-log pattern as the two boreholes DWVP 05 and 07 apart from the uppermost 19 m, most probably they all belong to the same stratigraphical sequence, i.e. the younger part of the Middle section of the Bimbila Formation. Most of the lithological more variable Upper Bimbila sequence, represented in DWVP 06 and in WVB 12 (see below), seems removed by erosion at the low-laying HAP 05 leaving 19 m alluvium on top of the homogeneous mudstone belonging to the middle section of Bimbila formation. A new Fluid-conductivity log run in 2017 showed remarkably higher values than the one from the 2007 logging campaign, i.e. from being fresh to influenced water (<200 mS/m) in 2007 to be saline (1,400-1,500 mS/m) in 2017 apart from the uppermost 26 m, where several freshwater inflow is seen as stepwise decrease of slowly up-flowing saline water.
- Borehole WVB 12 (**Annex D5**) is similarly located close to the outcropping Bunya Formation as DWVP 06, and its gamma- and resistivity-log pattern reflects like the latter a slightly more variable lithology than just a shale as described by the driller's log. The groundwater seems slightly influenced by having fluid conductivity of 110 mS/m from the lowermost screen and 95-100 mS/m in the inflow to the upper screen.
- The two boreholes in Bugya Pala, WVB 11 and Bugya Pala 2 (**Annex D6 and D7**), are both located within the Kodjari on the geological map, Figure 3.1, which justifies the interpretation of occurrence of tillite underlain by Panabako sandstones in both. However, in Bugya Pala 2 located 400 m north of WVB 11 the tillite overlain by a rock with unusual high conductivity, which neither is caused by clay nor by saline groundwater, and suggested to be Darebe tuff with major content of highly conductive minerals. In both boreholes the groundwater is fresh, and in WVB 11 with sandstone as the dominant rock it is even extremely fresher (<10 mS/m).
- The Zangu-Vuga borehole (**Annex D8**) is also located within the Kodjari formation on the geological map, Figure 3.1, but further Northwest of Bugya Pala, where the Neoproterozoic palaeo-valley cuts into the Bombouaka Group between the Gambaga Massif and the Damango Massif leaving the Poubogou formation as the substratum for the Kodjari formation. The Gamma- as well as the DUIN conductivity/resistivity log clearly indicates the occurrence of the Poubogou formation from 28 m depth. The overlying rock with very variable Gamma-radiation and occasionally

high resistivity is interpreted as tillite with associated sandy diamictons or calcitic diamictite. The fluid conductivity-log shows, the groundwater in the Poubogou formation is saline (900-1,200 mS/m) and seems to become brackish upwards and even fresh in the upperpart of the tillite.

Only two of the eight additional boreholes fulfil the minimum requirement for flow-logging, i.e. yield of 20 lpm, and both boreholes were fully constructed with plain pipes and two screen sections. In borehole HAP 11 (**Annex D2**) the whole inflow seems to come into the upperpart of the upper screen, thus from above 30 m depth, whereas in borehole WVB 12 (**Annex D5**) there was inflow to both screens being 80 % into the upper screen thus 20 % into the lower screen. In the latter borehole a fluid-conductivity log was also conducted during pumping and by combining the information from the two types of log it is possible to calculate the fluid conductivity of each inflow as shown in the header section of **Annex D5.**

6.2 Log-stratigraphy

Figure 6.2.1 below summarises the interpretation of the wireline logs regarding the stratigraphic units suggested to be present in the ten boreholes located in the Bimbila formation area. It illustrates the characteristic pattern of the gamma- and resistivity-log of at least four different stratigraphic sequences, which in total constitute about 400 m of the maybe 1,000 m thick Bimbila formation. Though, the stratigraphic depth is relative, and the thickness of the gaps between the different sequences is unknown. Furthermore, the log-stratigraphical column on Figure 6.2.1 does also contain the characteristic gamma- and resistivity-log pattern of the Kodjari Triad, suggested to be present in borehole HAP 14 as 10 m Darebe tuff, 25 m Buipe limestone and 40 m tillite above approximately 40 m Panabako formation.

However, the gamma- and resistivity-log patterns of the Bimbila section overlying the Kodjari Group in the two boreholes DWVP 03 and 10 are showing some differences, i.e. slightly higher gamma-radiation as well as resistivity in DWVP 10 compared to 03. This might indicate different Bimbila sections present in the two boreholes, thus an unconformity between the Kodjari formation and the Bimbila formation as also stated by Affaton, 2008 (ref. /ii/). Accordingly, five different stratigraphic sequences of the Bimbila formation are covered by gamma- and resistivity-logs, thus might represent about 500 m of this formation with the section in borehole 03 most probably being elder than the section in the more easterly located borehole 10.

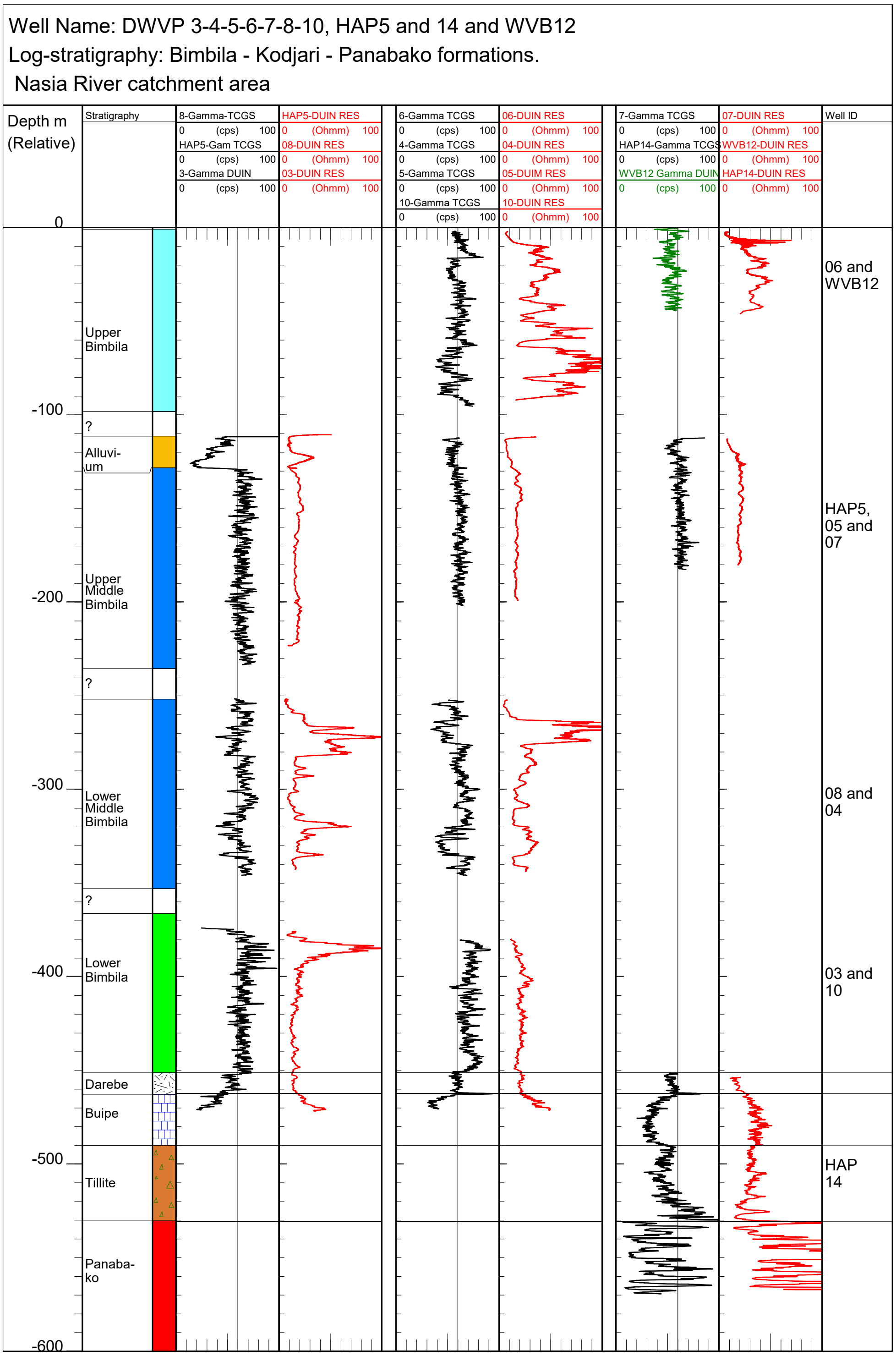

Figure 6.2.1: *TCGS Gamma-log (black colour - linear scale 100 cps) and DUIN-L resistivity-log (red colour – linear scale 100 Ohm-m) from ten boreholes located within the Bimbila formation area, shown in relative stratigraphic order. A reference-line of 60 cps is shown on Gamma-logs.*

The earlier presented Figure 5.3.3 illustrates the characteristic pattern of the TCGS gamma- and DUIN-L conductivity-logs from the five boreholes located within the Panabako Formation. In the Figure 6.2.2 below are the TCGS gamma- and DUIN-L resistivity-logs of these five boreholes shown in relation to the stratigraphic unit thought to be present in the respective boreholes, i.e. as a log-stratigraphic column with relative depth. The two HAP-boreholes are representing the lowermost section of the Panabako formation since they have penetrated into the upper part of the underlying Poubogou formation. The interpreted boundary between the two formations in both HAP-boreholes is kept at the same relative depth of 260 m in the log-stratigraphic column, Figure 6.2.2. The two DWVP boreholes, 01 and 02, most probably represent younger sections of Panabako than is present in HAP 11 and 12, partly because they are located more southwards within the Gambaga Massif, and partly because there seems neither to be any correlative overlap between upper parts of the HAP boreholes and lower parts of borehole DWVP 01 nor 02. Accordingly, they are shown above HAP 11 and 12 in the stratigraphic column and with unknown thickness of gap between the lower and the upper Panabako units.

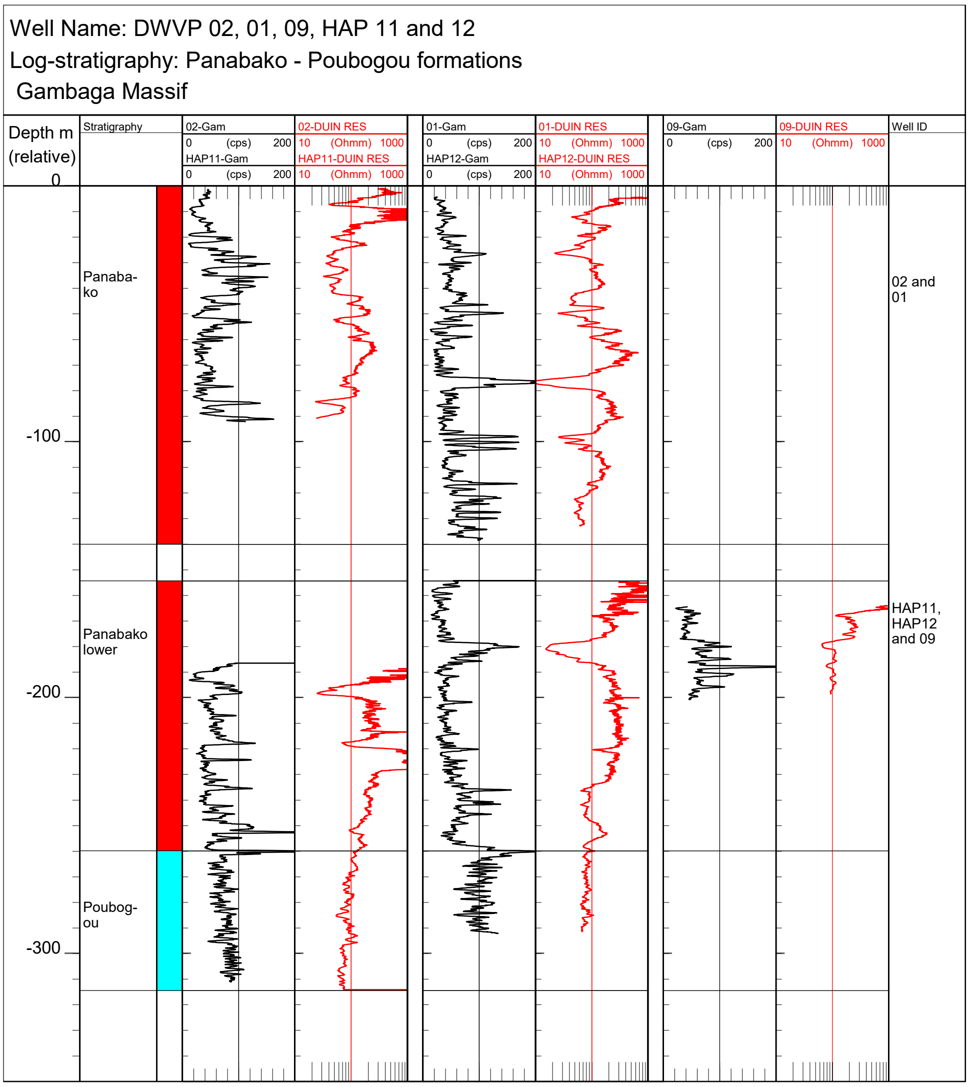

Figure 6.2.2: *TCGS Gamma-log (black colour - linear scale 200 cps) and DUIN-L resistivity-log (red colour – logarithmic scale 10-1,000 Ohm-m) from five boreholes located within the Gambaga Massif, shown in relative stratigraphic order. Reference-lines of 100 cps and 100 Ohm-m are shown on respectively Gamma- and Resistivity-logs.*

When it comes to the rather limited section (37 m) in borehole DWVP 09 with gamma- and resistivity-logs, this is suggested to represent a certain section of the lower part of the

Panabako formation because of DWVP 09's close location to the northern escarpment of the Gambaga Massif, where the Poubogou formation is observed to be covered by only 65 m of the Panabako formation (ref. /viii/). Though, DWVP 09 was drilled to 95 m depth without reaching the Poubogou formation (ref. /xiii/), why the top of its log-section is placed 95 m above the Poubogou formation on the stratigraphic column, Figure 6.2.2. It is noteworthy that this results in the same depth of a significant boundary between a sandstone and clayey section within the Panabako formation in DWVP 09 as in HAP 12.

6.3 Resistivity and gamma-radiation of stratigraphic units

The Table 6.3.1 below summarises the interpretation of the wireline logs regarding the stratigraphic units suggested to be present in each of the 18 boreholes. It illustrates a more complex stratigraphy at the two localities Bugya Pala and Zangu-Vuga, i.e. Darebe suggested to lie on tillite in Bugya Pala 2 and tillite lying on the Poubogou in Zangu-Vuga. The characteristic average resistivity of each stratigraphic unit is shown. For some units it seems obvious to assign two average values, one for the upper part (excluding the saprolite) and one for the lower part. In borehole DWVP 02 three average values are needed for characterization of the resistivity of the sections of the Panabako formation encountered.

Borehole ID (log depth in m) Stratigraphy	DWVP 06 (96)	WVB 12 (49)	HAP 05 (122)	DWVP 05 (92)	DWVP 07 (73)	DWVP 08 (96)	DWVP 04 (96)	DWVP 03 (100)	HAP 14 (120)	DWVP 10 (93)	WVB 11=BP1 (52)	Bugya Pala 2 (39)	Zanga Vuga (55)	DWVP 02 (92)	DWVP 01 (138)	DWVP 09 (40)	HAP 11 (130)	HAP 12 (140)
Upper Bimbila	50	**30** **50**																
Upper Middle Bimbila			20	15	20													
Lower Middle Bimbila						50 20	70 30											
Lower Bimbila								20 15		20								
Kodjari-Darebe								15	20	25		4						
Kodjari-Buipe								40	40	40								
Kodjari-Tillite									30		50	10	30 1,000					
Panabako									80			>100		60 200 100	200 100			
Panabako Lower											200 500					200 100	200	300 100
Poubogou											<100		30 10				70	80

Table 6.3.1: *Borehole depths, stratigraphic units encountered, average resistivity and groundwater salinity (yellow shading = brackish, grey shading = saline).*

Even though the units can be distinguished by difference in the general magnitude of resistivity, it is worth noting that none of the units can be unambiguously classified only by its resistivity. One reason being that the conductivity of the groundwater affects the resistivity particularly, when it is brackish (200-1,000 mS/m) or saline (1,000-5,000 mS/m) as observed in some of the boreholes (marked in the table 6.3.1 with light grey or grey shading). Notice in the Zanga-Vuga borehole the groundwater is saline only in the Poubogou formation (Annex D8).

With relation to geological interpretation of the airborne time-domain electromagnetic data (AIR-TEM) available from the Voltaian area it is important to note that the resistivity of the Panabako formation present in the two HAP boreholes 11 and 12 seems generally higher than in the two DWVP boreholes 01 and 02, which seems to oppose an occurrence of an Upper Panabako sandstone with higher resistivity than a Lower Panabako sandstone.

Table 6.3.2 below is similar to Table 6.3.1, but summarises the characteristic Gamma-radiation (in cps) of each stratigraphic unit instead of the average resistivity. For some few units it is reasonable to give an average value, but in most cases the Gamma-radiation varies and a variation range must be applied.

Borehole ID (log depth in m) / Stratigraphy	DWVP 06 (96)	WVB 12 (49)	HAP 05 (122)	DWVP 05 (92)	DWVP 07 (73)	DWVP 08 (96)	DWVP 04 (96)	DWVP 03 (100)	HAP 14 (120)	DWVP 10 (93)	WVB 11=BP1 (52)	Bugya Pala 2 (39)	Zanga Vuga (55)	DWVP 02 (92)	DWVP 01 (138)	DWVP 09 (40)	HAP 11 (130)	HAP 12 (140)
Upper Bimbila	40-80	**45-60**																
Upper Middle Bimbila			65	65	65													
Lower Middle Bimbila						40-80	40-75											
Lower Bimbila								60-100		60-80								
Kodjari-Darebe								55	55	60		45						
Kodjari-Buipe								20-40	30-50	30-50								
Kodjari-Tillite									40-100		40-100	50	40-120					
Panabako									80			10-40		30-200	40-200			
Panabako Lower											20-60					40 60-120	25-100	30-100
Poubogou											100		100				70-90	100

Table 6.3.2: *Borehole depths and stratigraphic units encountered, gamma-radiation in cps (conditional to 6 1/2" diameter borehole and same tool).*

The table 6.3.2 illustrates that for characterization, i.e. for identification of the stratigraphic unit, the pattern of the Gamma-radiation log is more important than the absolute magnitude of the Gamma-radiation, whereas the latter is most important for a detailed description of the lithology.

7. ACKNOWLEDGEMENT

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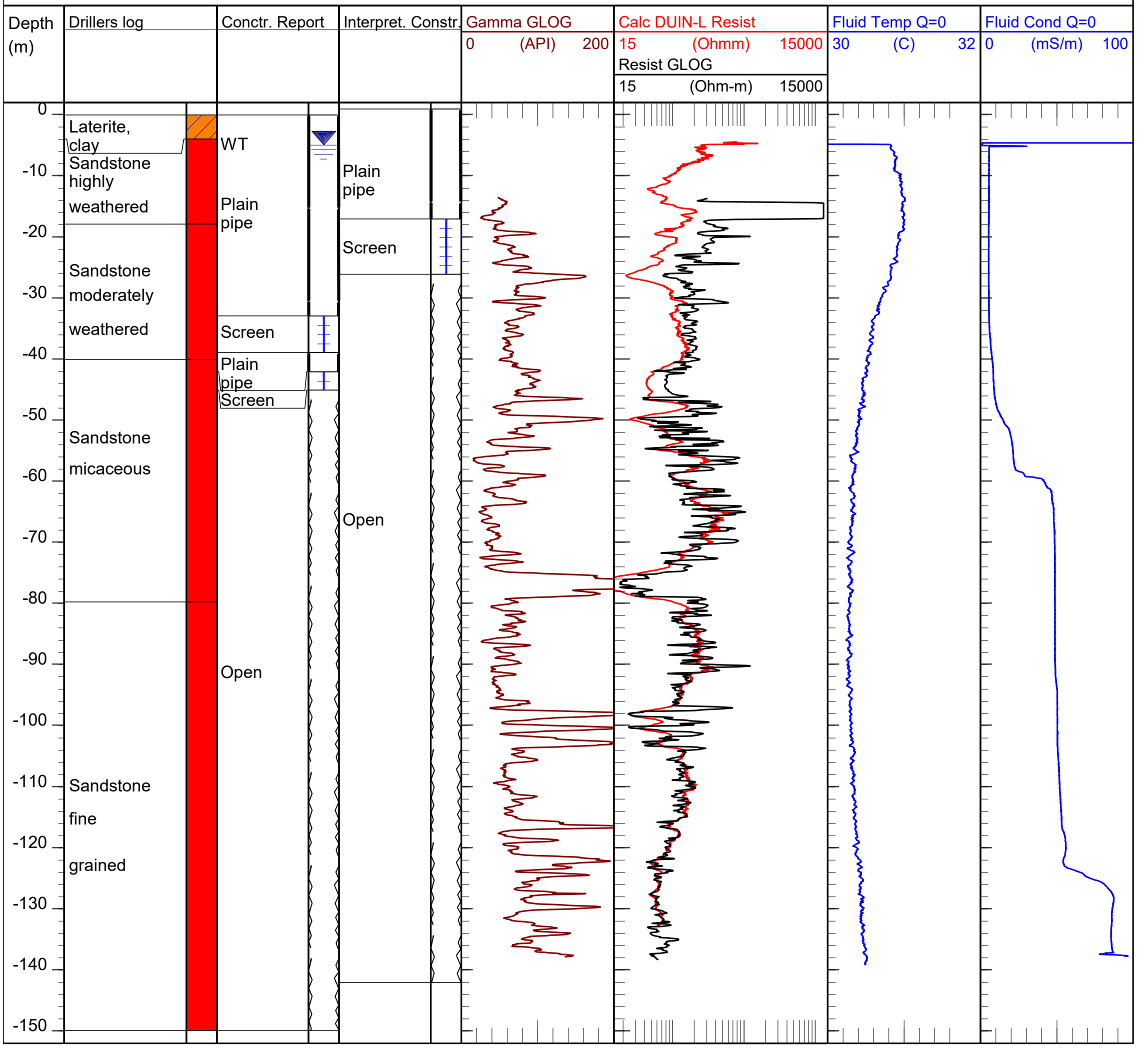
9. ANNEX A: BOREHOLE COMPLETION FROM WIRE-LINE LOGS

Annex A1: DWVP 01 –	Tamboku	(Panabako fm.)
Annex A2: DWVP 02 –	Tamboku river	(Panabako fm.)
Annex A3: DWVP 03 –	Dintigi	(Bimbila and Kodjari fm.)
Annex A4: DWVP 04 –	Kokubila	(Bimbila fm.)
Annex A5: DWVP 05 –	Kpobu	(Bimbila fm.)
Annex A6: DWVP 06 –	Tonyeli	(Bimbila fm.)
Annex A7: DWVP 07 –	Saliwia	(Bimbila fm.)
Annex A8: DWVP 08 –	Nakpaya	(Bimbila fm.)
Annex A9: DWVP 09 –	Samene	(Panabako fm.)
Annex A10: DWVP 10 –	Salikpa	(Bimbila and Kodjari fm.)

Annex A1

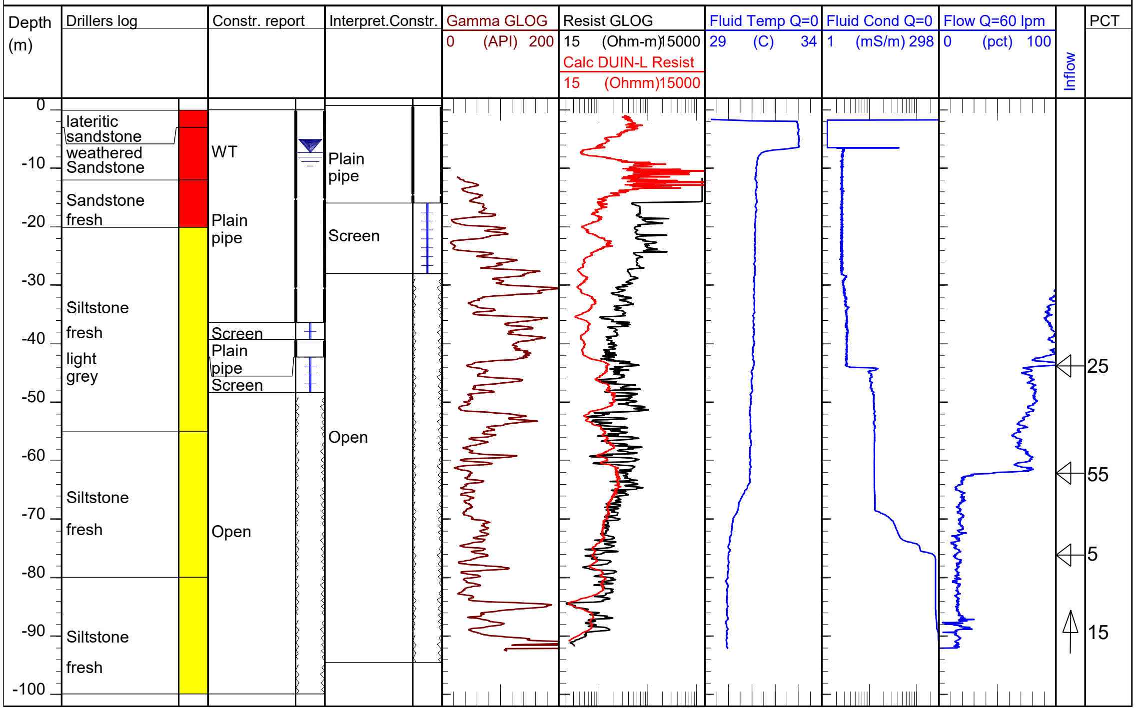
Well Name: DWVP 1 (10* 22' 06" N - 0* 27' 39" W)
Location: Tamboku,Nasia River Catchment, Northern Region, Ghana
Reference: Terrain

Wireline logging 9. Oct. 2017 by Water Research Institute, WRI Ghana. - Water table: 5.07 m b.g. Casing stick-out 1 m.
Data processing & interpretation: K. Klitten, GEUS Denmark, July 2018. - Resistivity (GLOG) can not be measured until below 17 m depth, i.e. plain pipe to 17 m. From 17 m and to 26 m the GLOG-resistivity is too high and only partly conformable to Calculated DUIN-resistivity, e.g. with suspicious peaks thus indicating installed screen to 26 m depth (9 m screen).



Well Name: DWVP 2 (10* 20' 48" N - 0* 28' 50" W)
Location: Tamboku-near river,Nasia River Catchment, Northern Region, G
Reference: Terrain

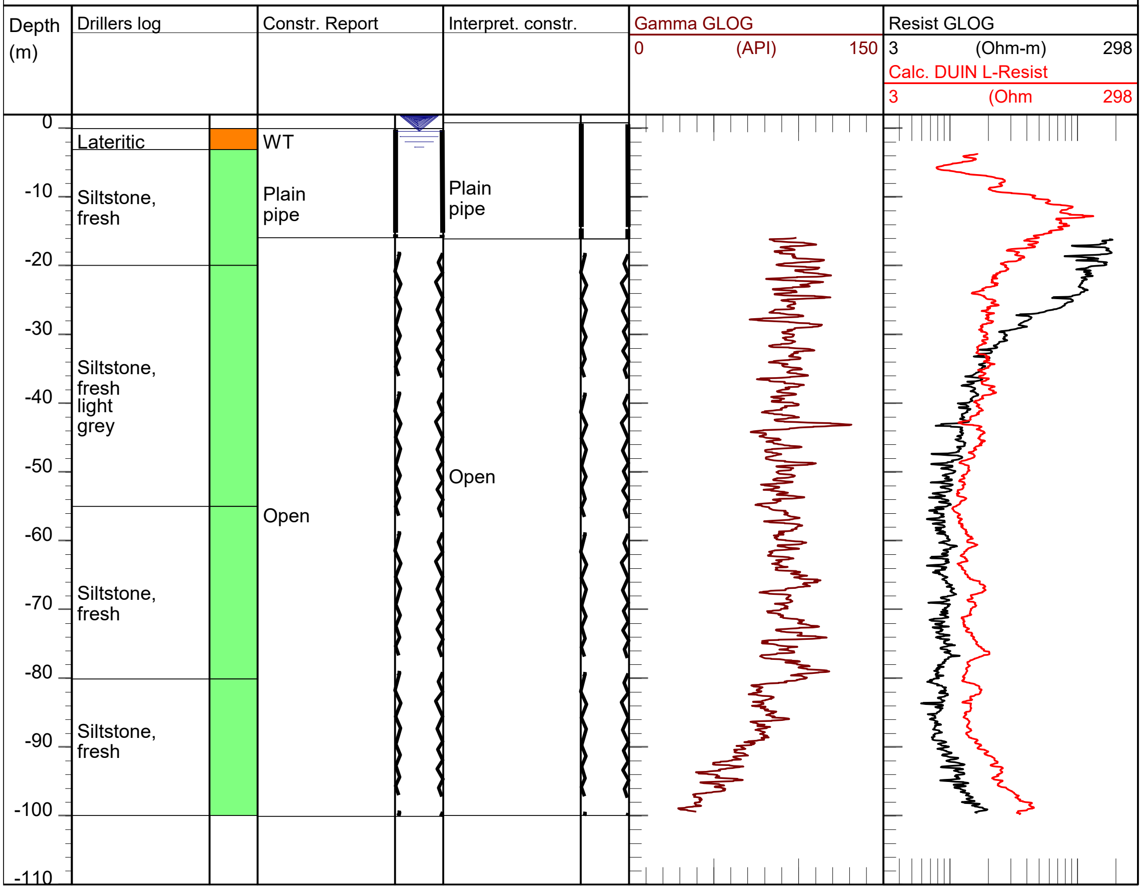
Wireline logging 9. Oct. 2017 by Water Research Institute, WRI Ghana - Water table: 7.26 m b.g. Casing stick-out 0.7 m.
Data processing & interpretation: K. Klitten, GEUS Denmark, July 2018.
Resistivity (GLOG) can be measured from 16 m depth and downwards, therefore plain pipe to 16 m depth only. However, the Resistivity (GLOG) is conformable to calculated DUIN-resistivity not until from 28 m depth and downwards, thus indicating screen from 16 to 28 m (verified by Fluid Cond.-log).
The generally higher GLOG-resistivity compared to calculated DUIN-resistivity to 43 m depth is partly caused by the 11 m bridle cable (to 11+16=27 m below plain pipe) but also due to the extremely low Fluid conductivity (<5 mS/m) to 43 m depth, which affect the GLOG-resistivity tool but not the DUIN-induction tool.



Annex A3

Well Name: DWVP 3 (10* 13' 07" N - 0* 35' 45" W)
Location: Dintigi, Nasia River Catchment, Northern Region, Ghana
Reference: Terrain

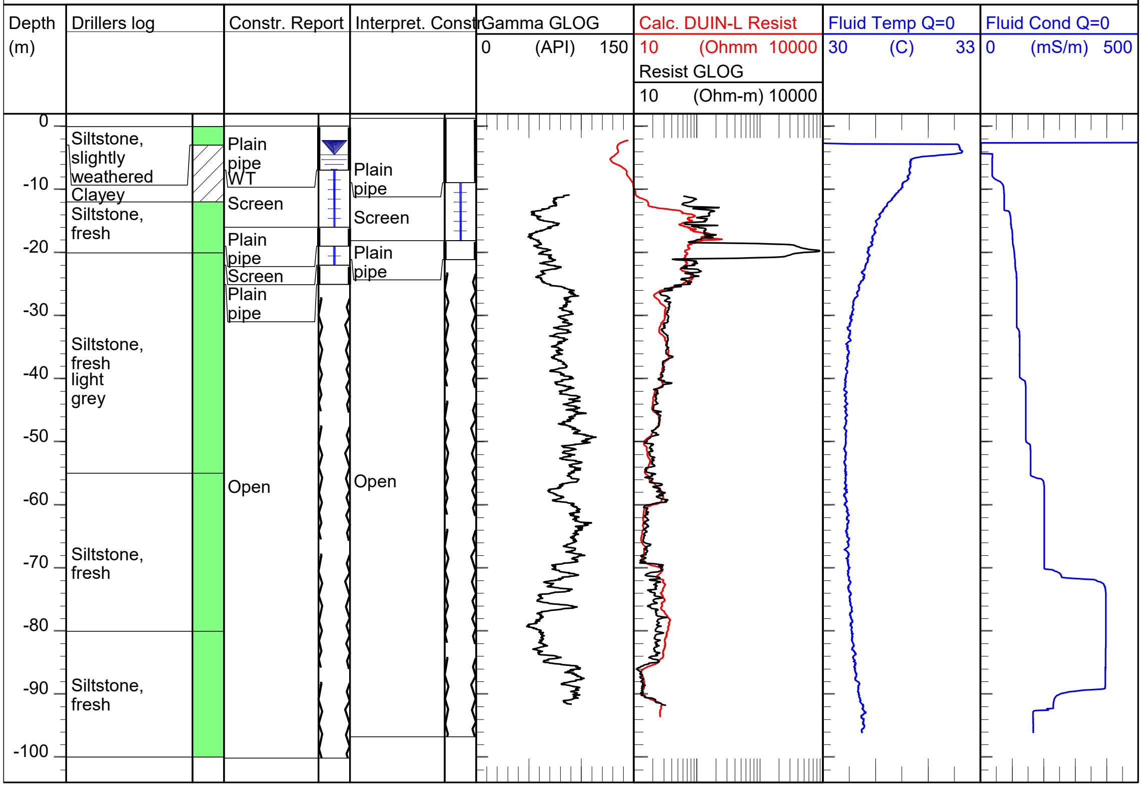
Wireline logging 04. May 2018 by Water Research Institute, WRI Ghana - Water table: 0.44 m b.g.l. - Casing stick-out 0.78 m.
Data processing and interpretation: K. Klitten, GEUS Denmark, June 2018.
Resistivity (GLOG sonde) was run upwards but unfortunately stopped at 16 m. Therefore, plain pipe was not directly verified.
However, the far too high GLOG-resistivities seen above 27 m depth indicate plain pipe 11 m (bridle) above 27 m, i.e. at 16 m depth.
Notice: The TCGS probe went out of order, thus no Fluid temperature & conductivity log was run. Though, the generally lower GLOG resistivity compared to DUIN resistivity below 36 m depth indicates high Fluid-conductivity (>400 mS/m).



Annex A4

Well Name: DWVP 4 (10* 07' 27" N - 0* 48' 06" W)
Location: Kokubila,Nasia River Catchment, Northern Region, Ghana
Reference: Terrain

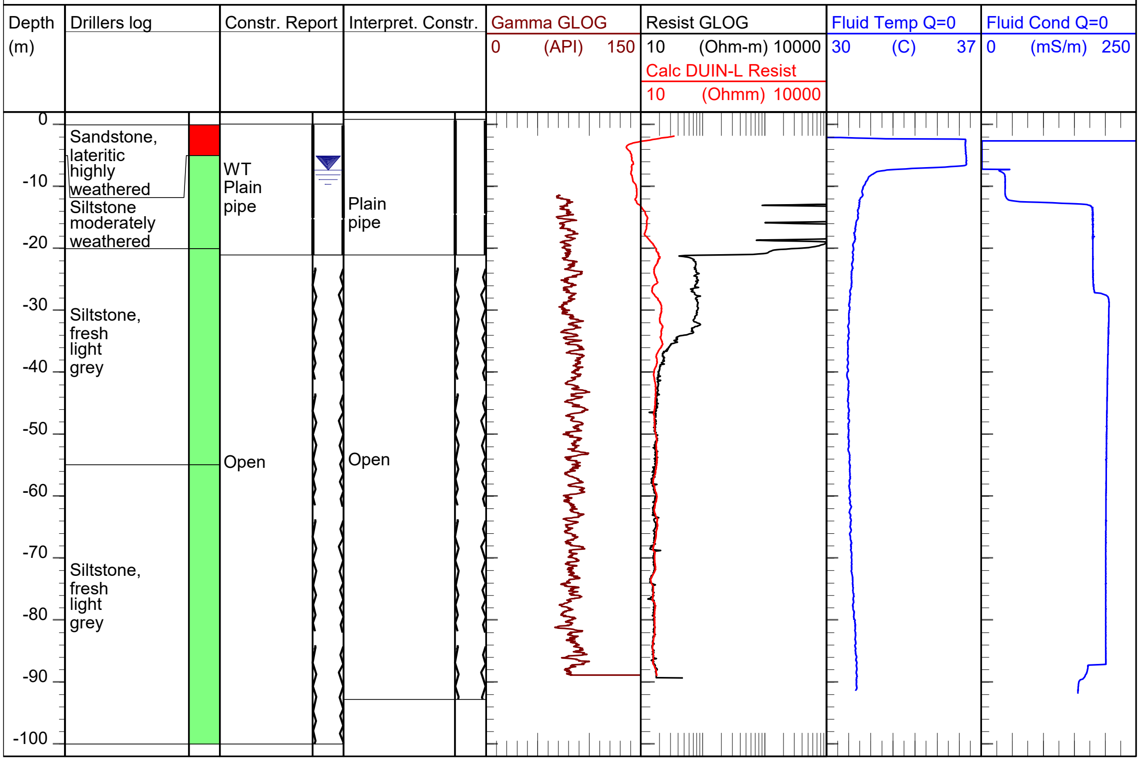
Wireline logging 7. Oct. 2017 by Water Research Institute, WRI Ghana - Water table: 4.47 m b.g. - Casing stick-out 1.25 m.
Data processing & interpretation: K. Klitten, GEUS Denmark, June 2018. - Resistivity-GLOG was run upwards and stopped at 11 m depth.
Therefore, the upper plain pipe was not directly verified. Resistivity (GLOG) can be measured and is conformable to calculated DUIN-resistivity not until from 21 m depth and downwards, i.e. open hole from 21 m depth. Though resistivity (GLOG) measured also in section 11-18 m, but too high compared to DUIN resistivity, i.e. screen at section 11-18 m and lower plain pipe at 18-21 m.
Fluid temperature drop and Fluid conductivity increase at 9 m depth indicate screen already from 9 m depth, thus upper plain pipe to 9 m depth.



Annex A5

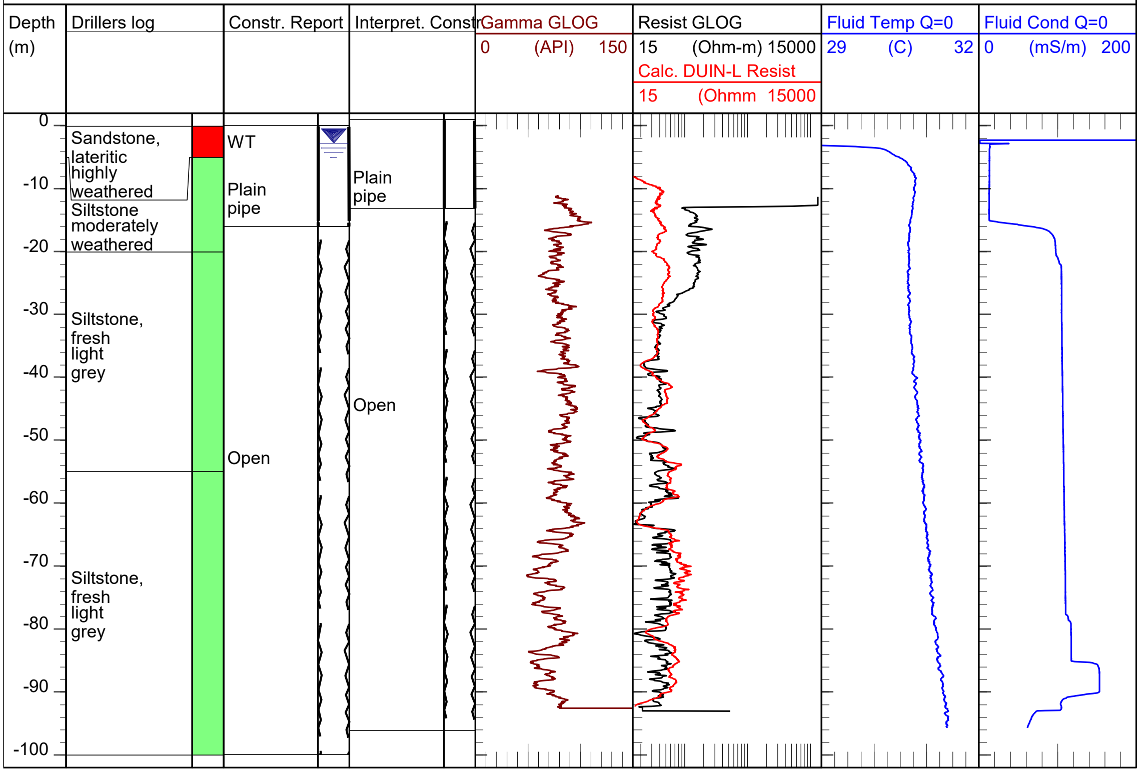
Well Name: DWVP 5 (10* 08' 27" N - 0* 25' 04" W)
Location: Kpobu, Nasia River Catchment, Northern Region, Ghana
Reference: Terrain

Wireline logging 12 Oct. 2017 by Water Research Institute, WRI Ghana - Water table: 7.40 m b.g.l. - Casing stick-out 0.70 m.
Data processing & interpretation: K. Klitten, GEUS Denmark, June 2018. Resistivity (GLOG) was run upwards and stopped at 11 m.
The plain pipe is directly verified by extremely high resistivities above 21 m. The GLOG-resistivity from 21 to 33 m are conformable to calculated DUIN resistivity thus verifying open hole, but is too high due to the effect of the 11 m bridle cable.



Well Name: DWVP 6 (10* 01' 47" N - 0* 23' 51" W)
Location: Tonyeli, Nasia River Catchment, Northern Region, Ghana
Reference: Terrain

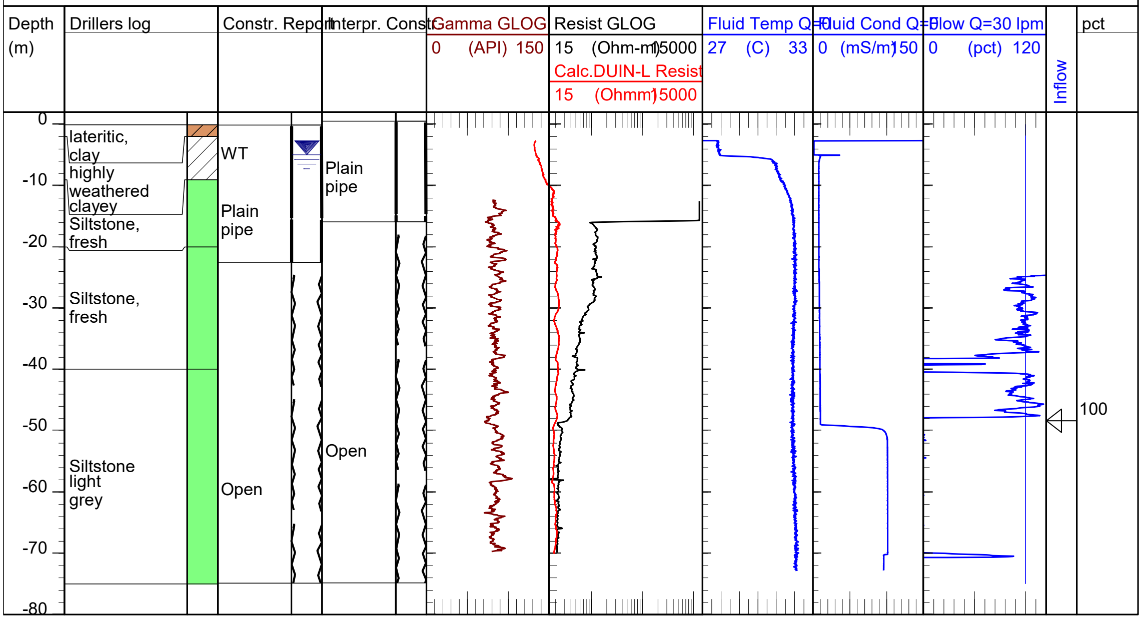
Wireline logging 12. Oct. 2017 by Water Research Institute, WRI Ghana - Water table: 2.75 m b.g.l. - Casing stick-out: 0.85 m.
Data processing and interpretation: K. Klitten, GEUS Denmark, June 2018.
Resistivity (GLOG sonde) was run upwards and stopped at 11 m. The plain pipe is directly verified by extremely high resistivities above 13 m.
The GLOG-resistivities seen from 13 to 25 m are conformable to calculated DUIN-resistivity thus verifying open hole,
but the GLOG-resistivity is too high due to the effect of the 10 m bridle cable.



Annex A7

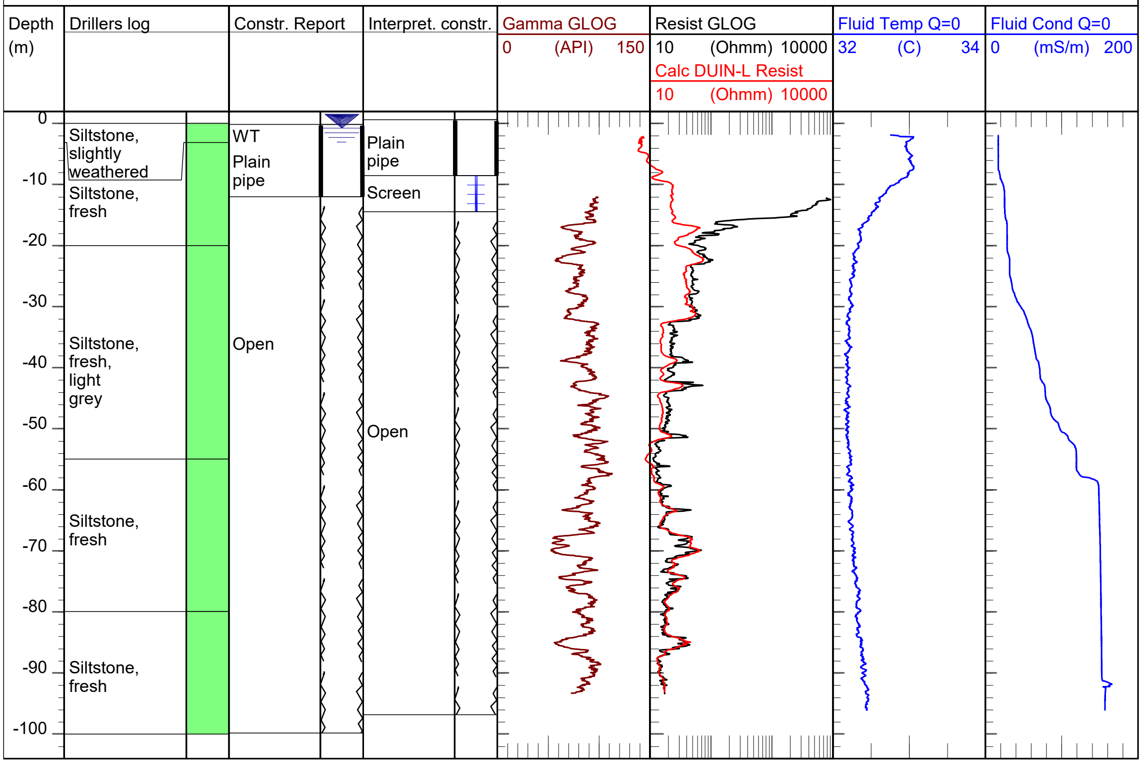
Well Name: DWVP 7 (10* 09' 07" N - 0* 08' 06" W)
Location: Saliwia, Nasia River Catchment, Northern Region, Ghana
Reference: Terrain

Wireline logging 11. Oct. 2017 by Water Research Institute, WRI Ghana- Water table: 5.00 m b.g.l. - Casing stick-out 0.55 m.
Data processing & interpretation: K. Klitten, GEUS Denmark, June 2018. - Resistivity (GLOG sonde) was run upwards and stopped at 12 m.
The plain pipe is directly verified by extremely high resistivities above 16 m. The GLOG-resistivities seen from 16 to 28 m are conformable to calculated DUIN-resistivity thus verifying open hole, but the GLOG-resistivity is too high due to the effect of the 10 m bridle cable.
From 28 to 49 m is the GLOG resistivity still too high compared to DUIN-resistivity, which is caused by the occurence of extremely low fluid conductivity (<10 mS/m) to 49 m depth. Accordingly, GLOG-resistivity is valid below 49 m depth only.



Well Name: DWVP 8 (10* 09´04" N - 0* 51´19" W)
Location: Nakpaya, Nasia River Catchment, Northern Region, Ghana
Reference: Terrain

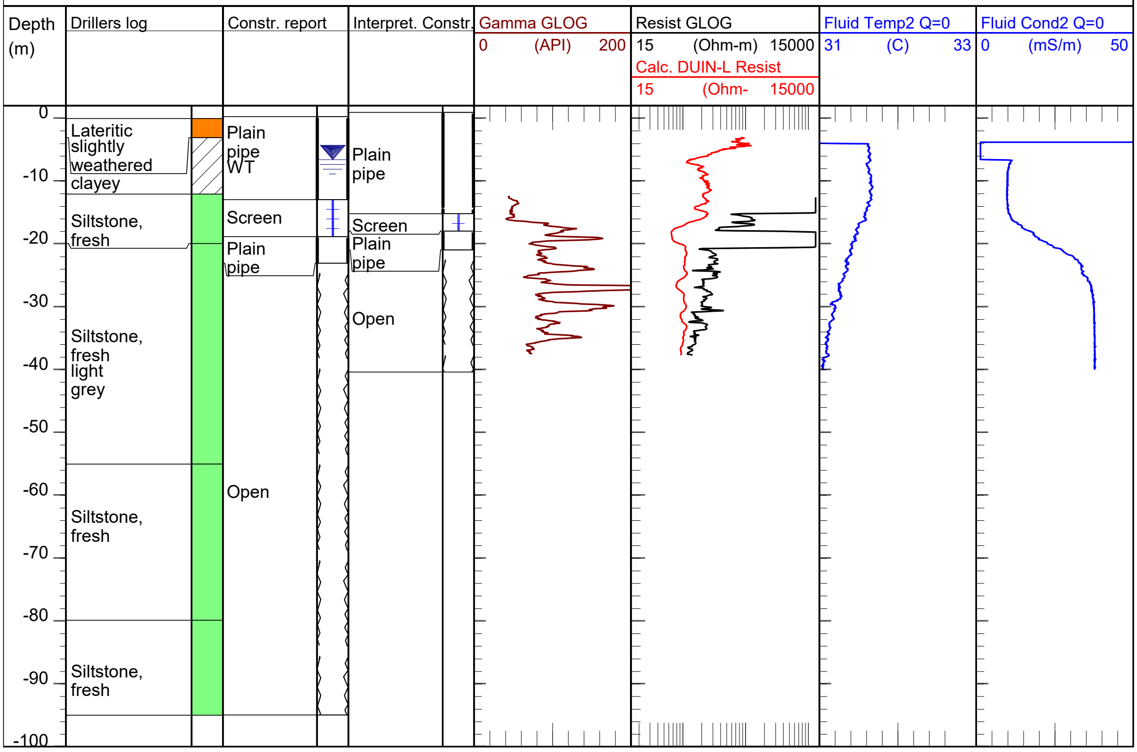
Wireline logging 7. Oct. 2017 by Water Research Institute, WRI Ghana - Water table: 0.74 m b.g.l. - Casing stick-out: 0.50 m.
Data processing & interpretation: K. Klitten, GEUS Denmark, June 2018.
GLOG-Resistivity was run upwards and stopped at 12 m. Therefore, the upper plain pipe was not directly verified.
Resistivity (GLOG) can be measured up to 12 m depth, but is unconformable to DUIN-resistivity from 12 m to 15 m, i.e. screen at section 12-15 m. Fluid temperature drop and Fluid conductivity increase at 9 m depth indicate screen from 9 m depth, thus upper plain pipe to 9 m depth. GLOG-resistivity too high to 11 m below plain pipe, i.e. valid below 20 m depth only.



Annex A9

Well Name: DWVP 9 (10* 27' 37" N - 0* 36' 40" W)
Location: Samene, Nasia River Catchment, Northern Region, Ghana
Reference: Terrain

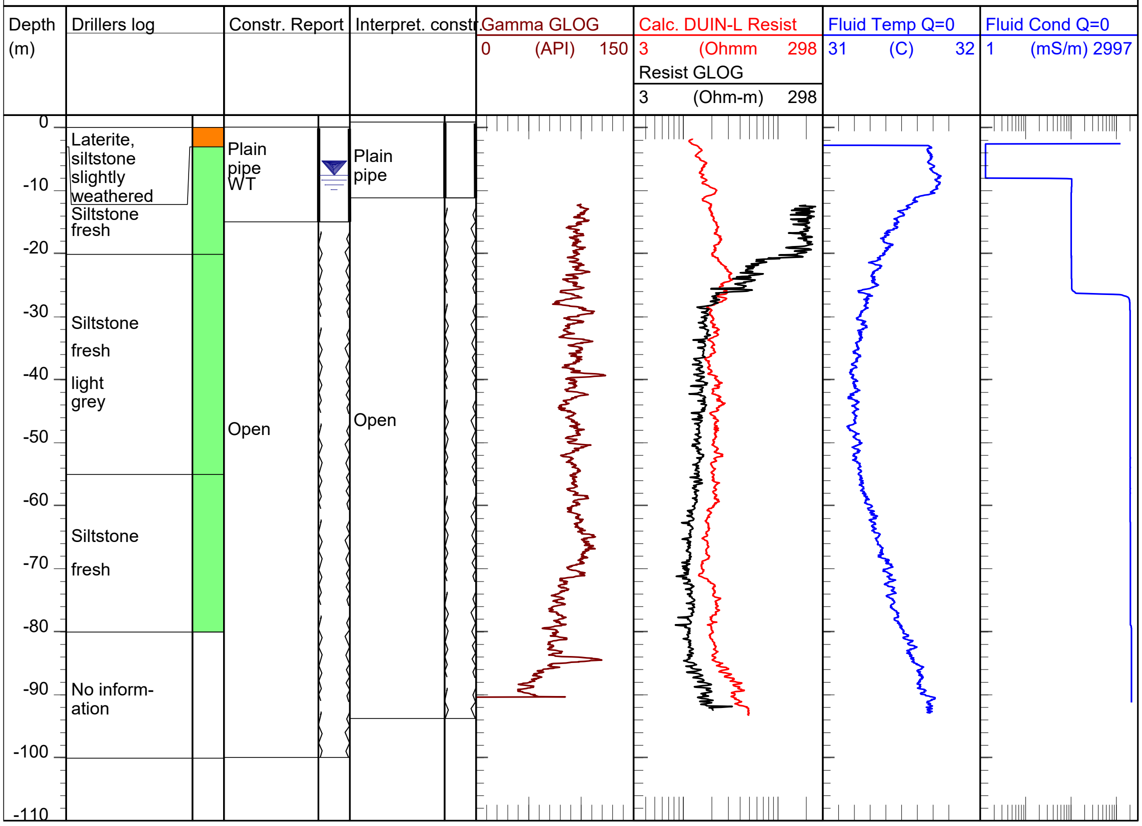
Wireline logging 8. Oct. 2017 by Water Research Institute, WRI Ghana - Water table: 6.61 m b.g.l. - Casing stick-out 0.95 m.
Data processing & interpretation: K. Klitten, GEUS Denmark, July 2018. None of the logging tools could pass a blocking at 40 m depth.
Resistivity (GLOG) measurable and is conformable to calculated DUIN-resistivity not until from below 21 m, i.e. open hole from 21 m depth.
Though resistivity measured also in section 15-18 m, but unconformable to DUIN resistivity, i.e. screen at section 15-18 m.
Resistivity (GLOG) too high to 11 m below plain pipe, i.e. valid below 32 m depth.



Annex A10

Well Name: DWVP 10 (10* 17' 08" N - 00* 07' 49" W)
Location: Salikpa, Nasia River Catchment, Northern Region, Ghana
Reference: Terrain

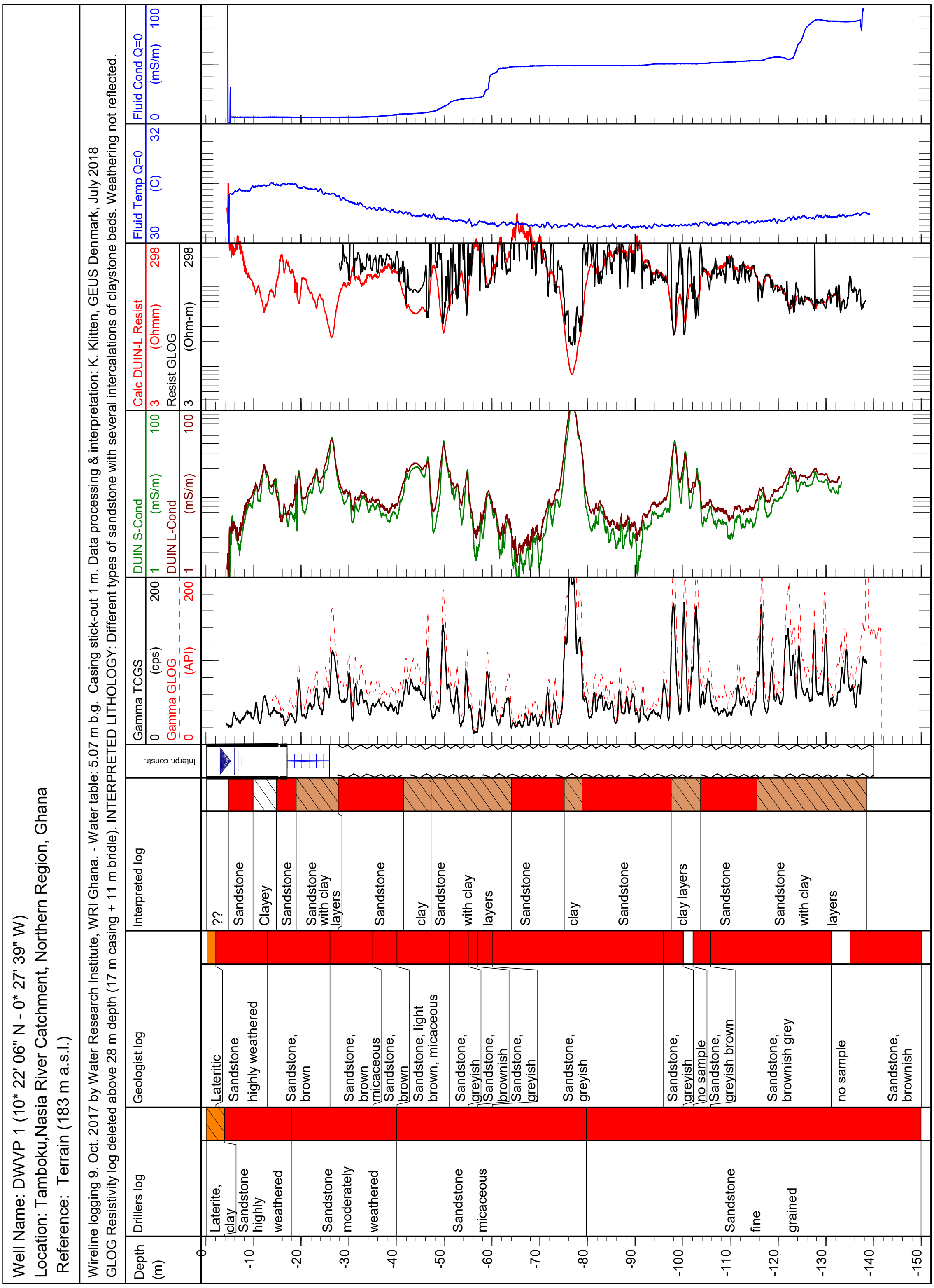
Wire-line logging 10. Oct. 2017 by Water Research Institute, WRI Ghana - Water table: 8.13 m b.g.l. - Casing stick-out 0.85 m.
Data processing & interpretation: K. Klitten, GEUS Denmark, June 2018.
GLOG-Resistivity was run upwards to 12 m depth only. Therefore, the plain pipe was not directly verified.
However, Fluid temperature drop at 11 m depth does indicate plain pipe to 11 m below terrain only.
Measurable but too high GLOG-resistivity from below 12 m indicates open hole, but resistivity values affected to 20 m, i.e. until the 11.7 m bridle cable and probe is fully below the water table at 8.1 m. Further affected to 23 m depth, thus also verifying that the plain pipe ends at 11 m.
Notice, the extremely high Fluid conductivity below 26 m depth is affecting particularly the GLOG-resistivity tool, why it shows lower resistivity values than the DUIN-resistivity.



10. ANNEX B: LITHOLOGY FROM WIRE-LINE LOGS

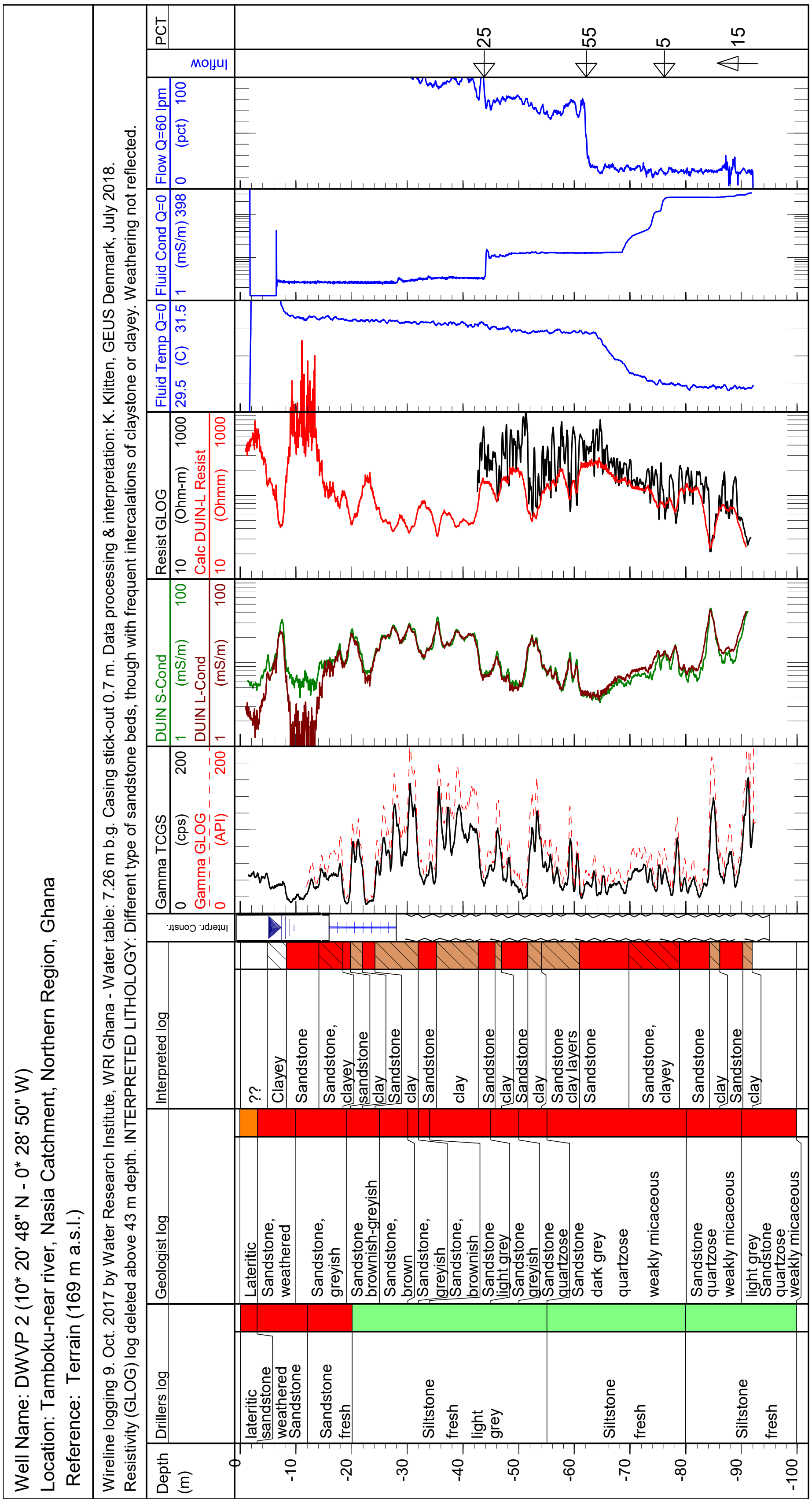
Annex B1: DWVP 01 –	Tamboku	(Panabako fm.)
Annex B2: DWVP 02 –	Tamboku river	(Panabako fm.)
Annex B3: DWVP 03 –	Dintigi	(Bimbila and Kodjari fm.)
Annex B4: DWVP 04 –	Kokubila	(Bimbila fm.)
Annex B5: DWVP 05 –	Kpobu	(Bimbila fm.)
Annex B6: DWVP 06 –	Tonyeli	(Bimbila fm.)
Annex B7: DWVP 07 –	Saliwia	(Bimbila fm.)
Annex B8: DWVP 08 –	Nakpaya	(Bimbila fm.)
Annex B9: DWVP 09 –	Samene	(Panabako fm.)
Annex B10: DWVP 10 –	Salikpa	(Bimbila and Kodjari fm.)

Annex B1



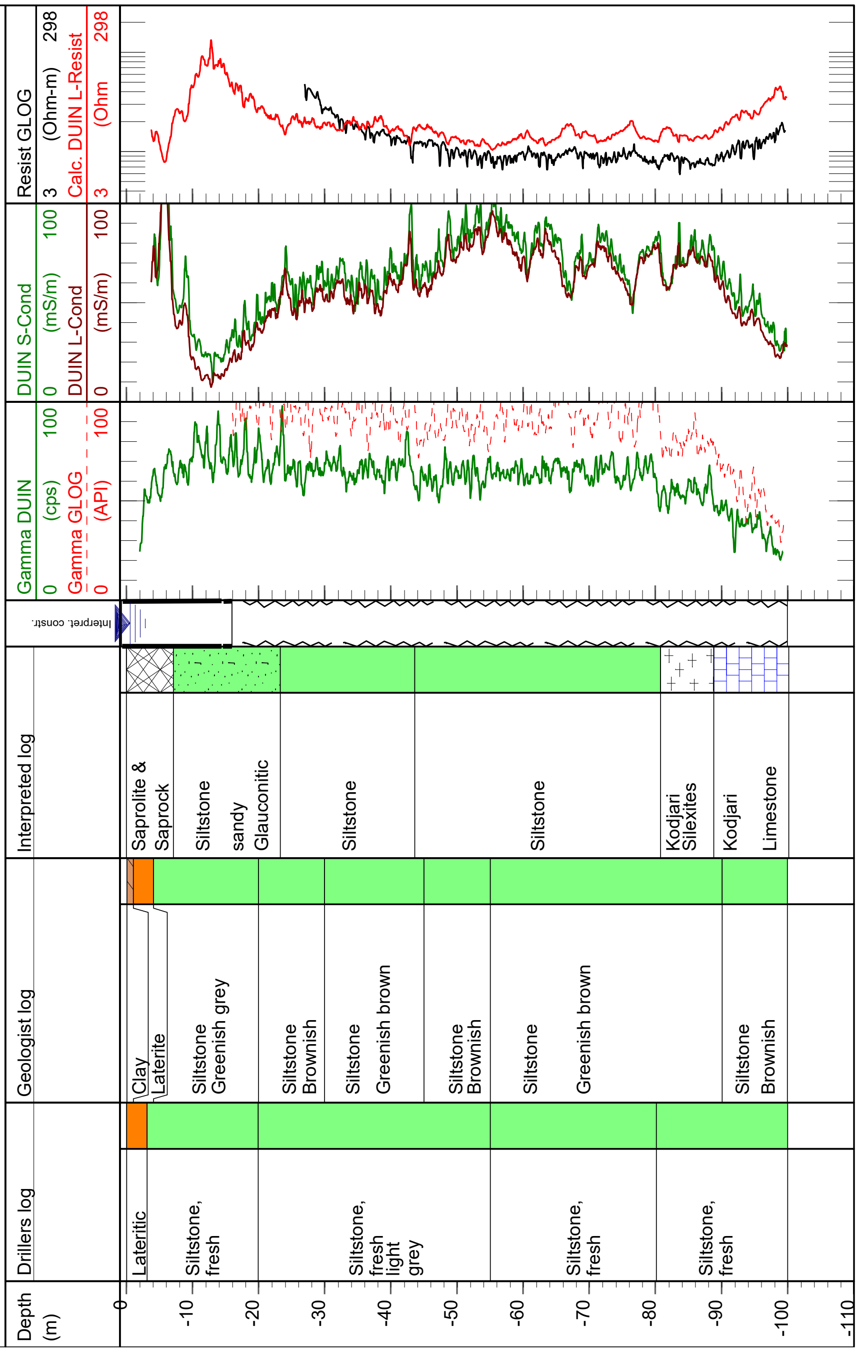
Well Name: DWVP 1 (10* 22' 06'' N - 0* 27' 39'' W)
Location: Tamboku,Nasia River Catchment, Northern Region, Ghana
Reference: Terrain (183 m a.s.l.)
Wireline logging 9. Oct. 2017 by Water Research Institute, WRI Ghana. - Water table: 5.07 m b.g. Casing stick-out 1 m. Data processing & interpretation: K. Klitten, GEUS Denmark, July 2018
GLOG Resistivity log deleted above 28 m depth (17 m casing + 11 m bridle). INTERPRETED LITHOLOGY: Different types of sandstone with several intercalations of claystone beds. Weathering not reflected.
Depth (m)
Drillers log
Geologist log
Interpreted log
Interpr. constr.
Gamma TCGS 0 (cps) 200
Gamma GLOG 0 (API) 200
DUIN S-Cond 1 (mS/m) 100
DUIN L-Cond 1 (mS/m) 100
Calc DUIN-L Resist 3 (Ohmm) 298
Resist GLOG 3 (Ohm-m) 298
Fluid Temp Q=0 30 (C) 32
Fluid Cond Q=0 0 (mS/m) 100
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
Laterite, clay
Sandstone highly weathered
Sandstone moderately weathered
Sandstone micaceous
Sandstone fine grained
Lateritic
Sandstone highly weathered
Sandstone, brown
Sandstone, brown micaceous
Sandstone, brown
Sandstone, light brown, micaceous
Sandstone, greyish
Sandstone, brownish
Sandstone, greyish
Sandstone, greyish
Sandstone, greyish
no sample
Sandstone, greyish brown
Sandstone, brownish grey
no sample
Sandstone, brownish
??
Sandstone
Clayey
Sandstone
Sandstone with clay layers
Sandstone
clay
Sandstone with clay layers
Sandstone
clay
Sandstone
clay layers
Sandstone
Sandstone with clay layers

Annex B2


Well Name: DWVP 2 (10* 20' 48" N - 0* 28' 50" W)
Location: Tamboku-near river, Nasia Catchment, Northern Region, Ghana
Reference: Terrain (169 m a.s.l.)
Wireline logging 9. Oct. 2017 by Water Research Institute, WRI Ghana - Water table: 7.26 m b.g. Casing stick-out 0.7 m. Data processing & interpretation: K. Klitten, GEUS Denmark, July 2018.
Resistivity (GLOG) log deleted above 43 m depth. INTERPRETED LITHOLOGY: Different type of sandstone beds, though with frequent intercalations of claystone or clayey. Weathering not reflected.
Depth (m)
Drillers log
Geologist log
Interpreted log
Interpr. Constr.
Gamma TCGS (cps) 0 200
Gamma GLOG (API) 0 200
DUIN S-Cond (mS/m) 1 100
DUIN L-Cond (mS/m) 1 100
Resist GLOG (Ohm-m) 10 1000
Calc DUIN-L Resist (Ohmm) 10 1000
Fluid Temp Q=0 (C) 29.5 31.5
Fluid Cond Q=0 (mS/m) 1 398
Flow Q=60 lpm (pct) 0 100
Inflow
PCT
25
55
5
15
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
lateritic sandstone
weathered Sandstone
Sandstone fresh
Siltstone fresh light grey
Siltstone fresh
Siltstone fresh
Lateritic
Sandstone, weathered
Sandstone, greyish
Sandstone brownish-greyish
Sandstone, brown
Sandstone, greyish
Sandstone, brownish
Sandstone light grey
Sandstone greyish
Sandstone quartzose
Sandstone dark grey quartzose weakly micaceous
Sandstone quartzose weakly micaceous
light grey Sandstone quartzose weakly micaceous
??
Clayey
Sandstone
Sandstone, clayey
sandstone
clay
Sandstone
clay
Sandstone
clay
Sandstone
clay
Sandstone
clay
Sandstone
clay layers
Sandstone
Sandstone, clayey
Sandstone
clay
Sandstone
clay

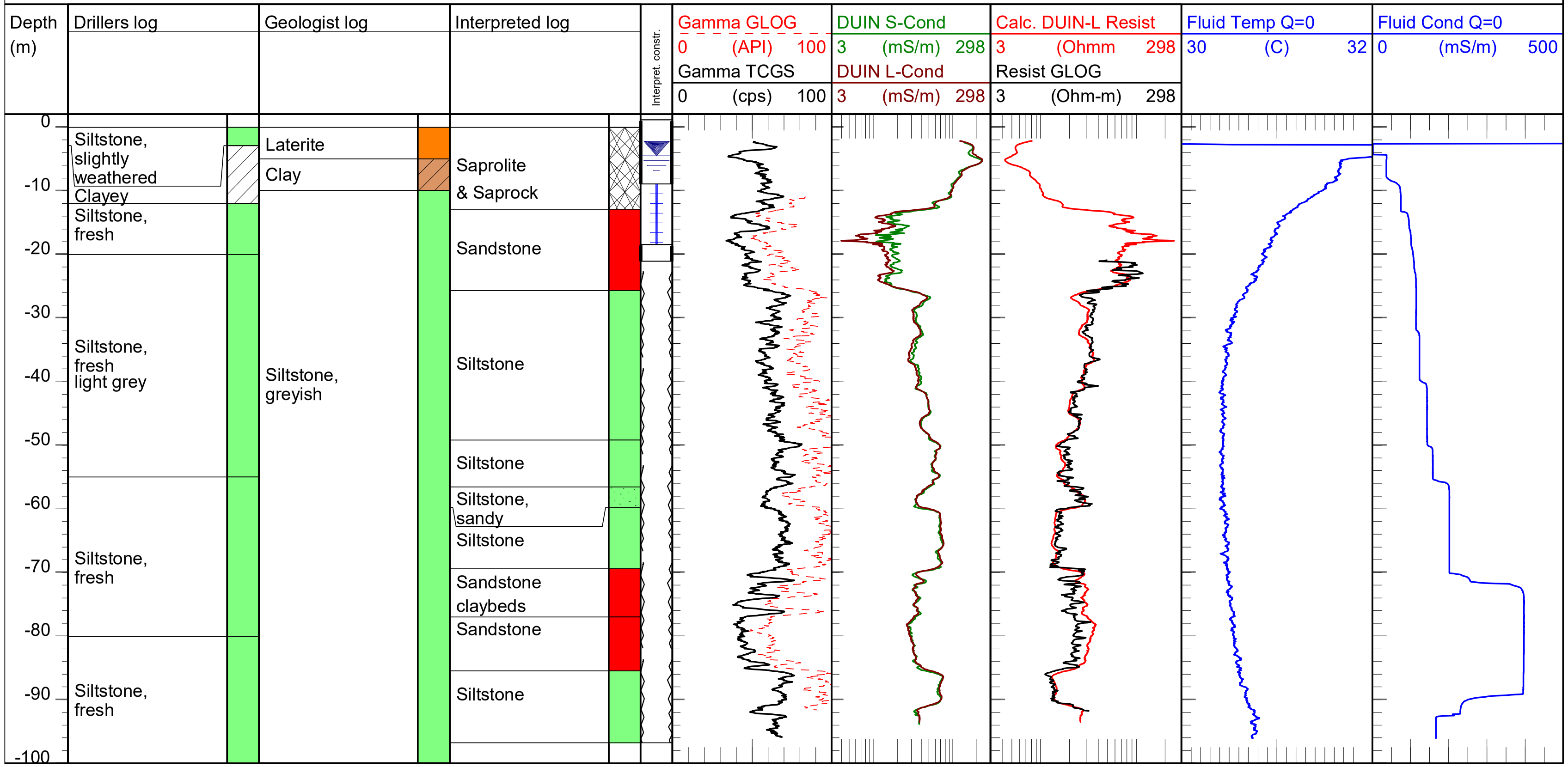
Well Name: DWVP 3 (10* 13' 07" N - 0* 35' 45" W)
Location: Dintigi, Nasia River Catchment, Northern Region, Ghana
Reference: Terrain (140 m a.s.l.)

Wireline logging 04. May 2018 by Water Research Institute, WRI Ghana - Water table: 0.44 m b.g.l. - Casing stick-out 0.78 m.
Data processing and interpretation: K. Klitten, GEUS Denmark, June 2018. Resistivity log (GLOG) deleted to 27 m depth.
INTERPRETED LITHOLOGY: Different type of siltstones, sandy and glauconitic at top, and with Kodjari silexites and limestone at bottom.
The Kodjari was identified by PhD-student Elikplim A. Dzikunoo. - The TCGS probe went out of order. Like in DWVP 10 the GLOG resistivity varies conformable to DUIN resistivity, though with generally lower values than DUIN resistivity, thus indicating similar high Fluid conductivity as in DWVP 10.
Decreasing weathering downwards from terrain to 7 m indicated by decreasing DUIN-conductivity.



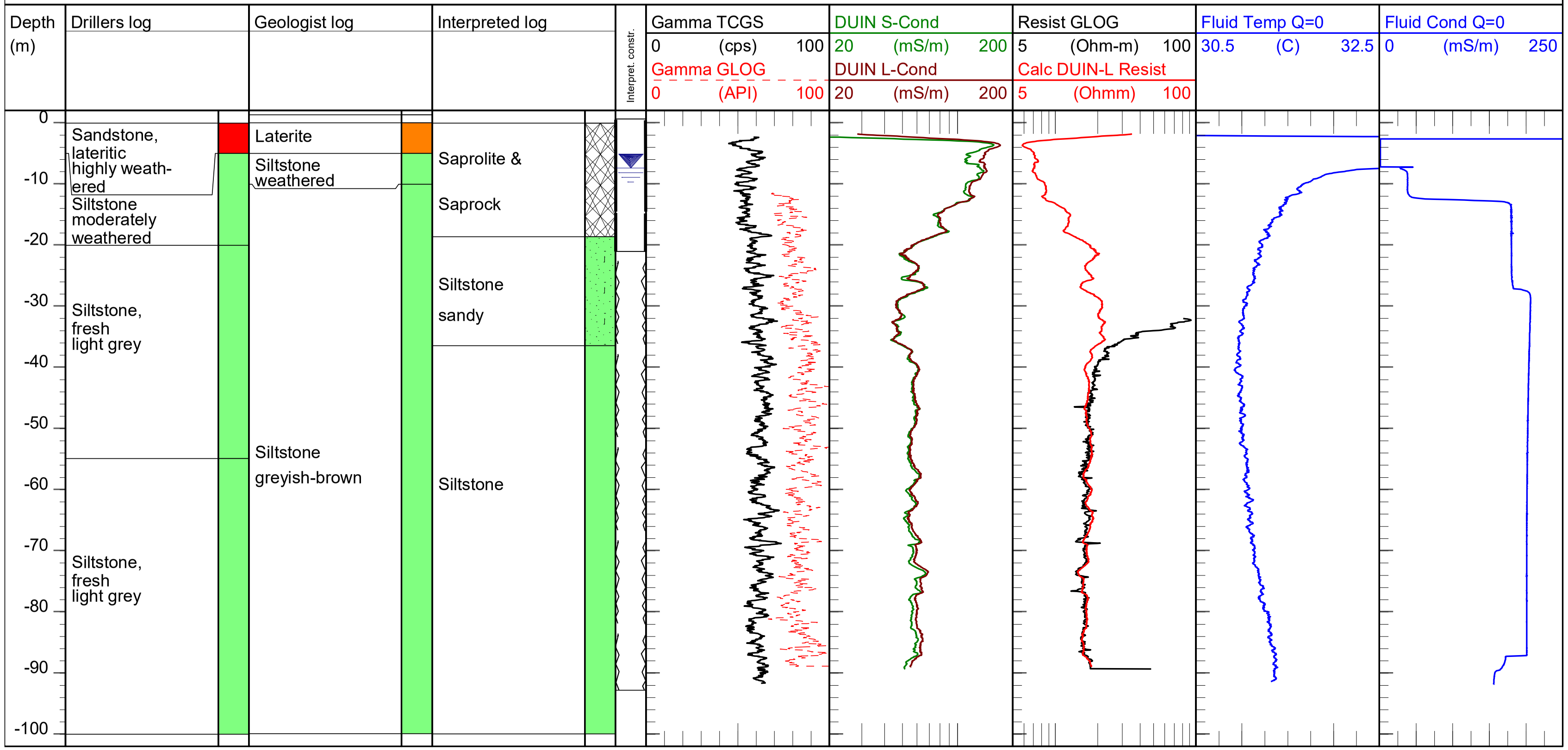
Well Name: DWVP 04 (10* 07' 27" N - 0* 48' 06" W)
Location: Kokubila,Nasia River Catchment, Northern Region, Ghana
Reference: Terrain (119 m a.s.l.)

Wireline logging 7. Oct. 2017 by Water Research Institute, WRI Ghana - Water table: 4.47 m b.g. - Casing stick-out 1.25 m. Data processing & interpretation: K. Klitten, GEUS Denmark, June 2018. Resistivity (GLOG) above 21 m depth is not valid and therefore deleted. INTERPRETED LITHOLOGY: At least two sections with sandstone within the siltstone. Decreasing weathering downwards from terrain to 13 m indicated by decreasing DUIN-conductivity.



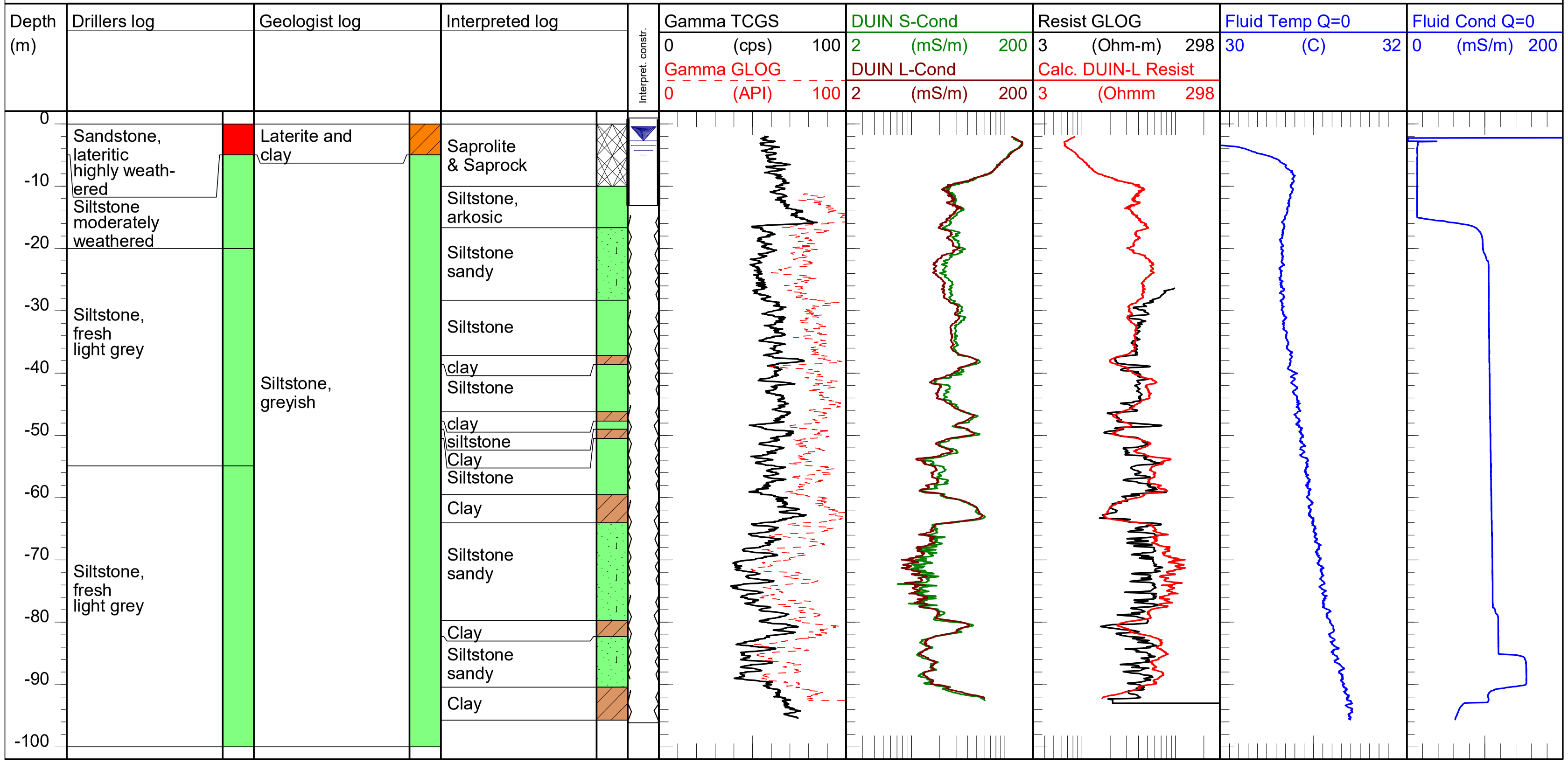
Well Name: DWVP 5 (10* 08' 27" N - 0* 25' 04" W)
Location: Kpobu, Nasia River Catchment, Northern Region, Ghana
Reference: Terrain (127 m a.s.l.)

Wireline logging 12 Oct. 2017 by Water Research Institute, WRI Ghana - Water table: 7.40 m b.g.l. - Casing stick-out 0.70 m.
Data processing & interpretation: K. Klitten, GEUS Denmark, June 2018. - Resistivity log (GLOG) is deleted to 11 m below casing pipe, thus to 32 m depth.
INTERPRETED LITHOLOGY: Uniform siltstone, though with a boundary at 36 m depth between an upper section with slightly lower gamma-radiation and conductivity than the lower section. Decreasing weathering downwards from terrain to 18 m depth indicated by decreasing DUIN-conductivity.



Well Name: DWVP 6 (10* 01' 47" N - 0* 23' 51" W)
Location: Tonyeli, Nasia River Catchment, Northern Region, Ghana
Reference: Terrain (156 m a.s.l.)

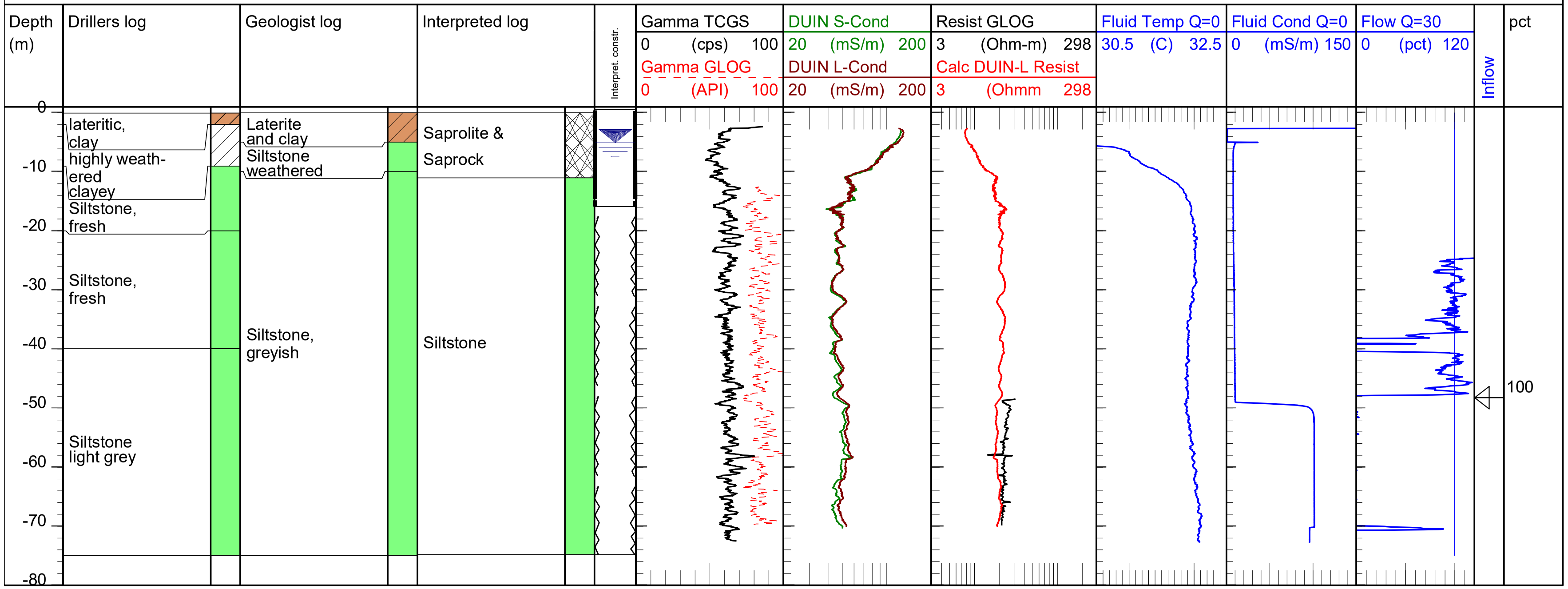
Wireline logging 12. Oct. 2017 by Water Research Institute, WRI Ghana - Water table: 2.75 m b.g.l. - Casing stick-out: 0.85 m. Data processing & interpretation: K. Klitten, GEUS Denmark, June 2018. GLOG-resistivity above 25 m (11.7 m below plain pipe) is not valid, and therefore deleted. INTERPRETED LITHOLOGY: Siltstone, arkosic in the upper part, otherwise with sandy sections as well as with claystone intercalations. Decreasing weathering downwards from terrain to 10 m depth indicated by decreasing DUIN-conductivity.



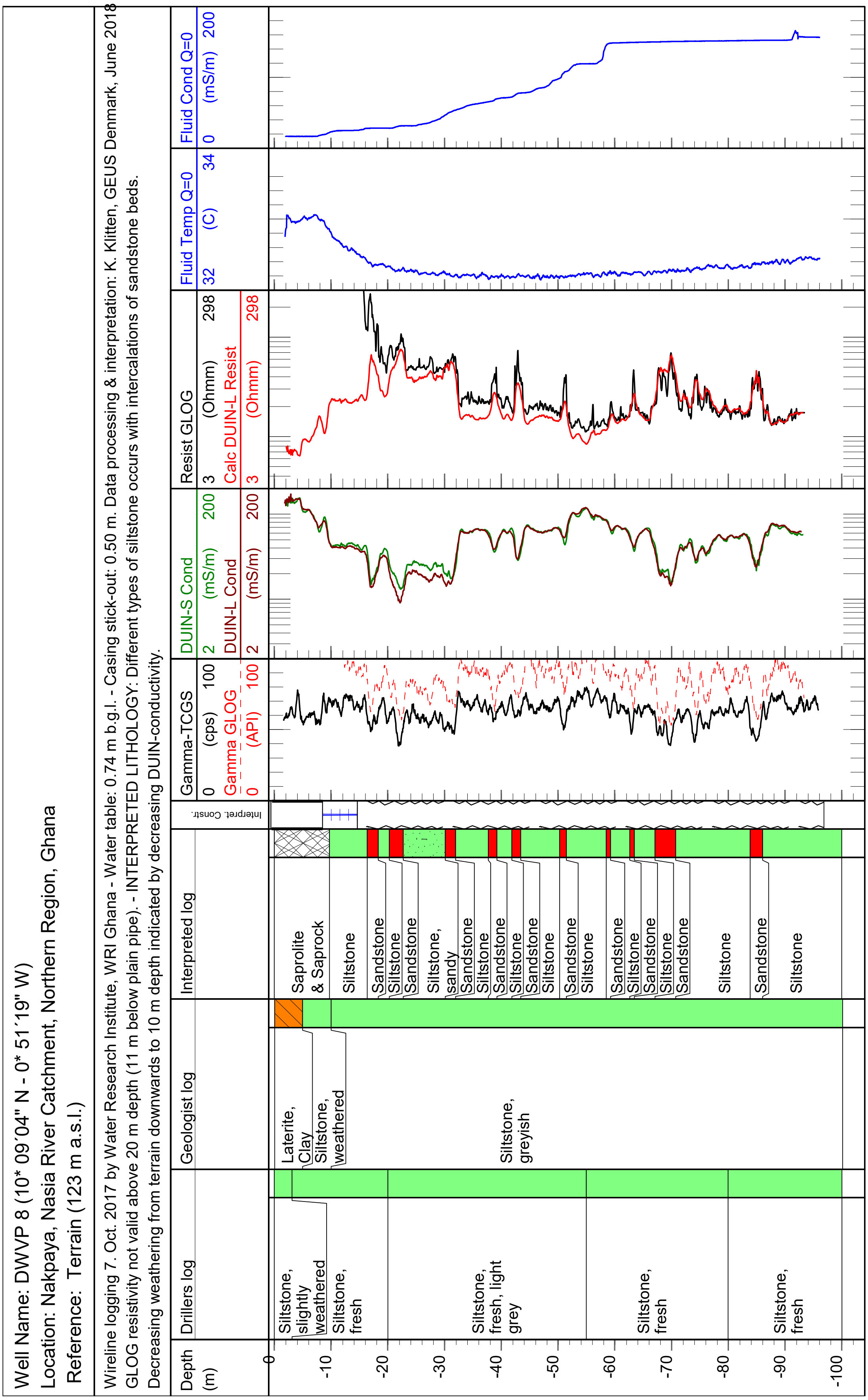
Annex B7

Well Name: DWVP 7 (10* 09' 07" N - 0* 08' 06" W)
Location: Saliwia, Nasia River Catchment, Northern Region, Ghana
Reference: Terrain (166 m a.s.l.)

Wireline logging 11. Oct. 2017 by Water Research Institute, WRI Ghana- Water table: 5.00 m b.g.l. - Casing stick-out 0.55 m. Data processing & interpretation: K. Klitten, GEUS Denmark, June 2018.
Resistivity log (GLOG) is deleted to 49 m depth. INTERPRETED LITHOLOGY: Uniform siltstone. Decreasing weathering downwards from terrain to 11 m depth indicated by decreasing DUIN-conductivity.



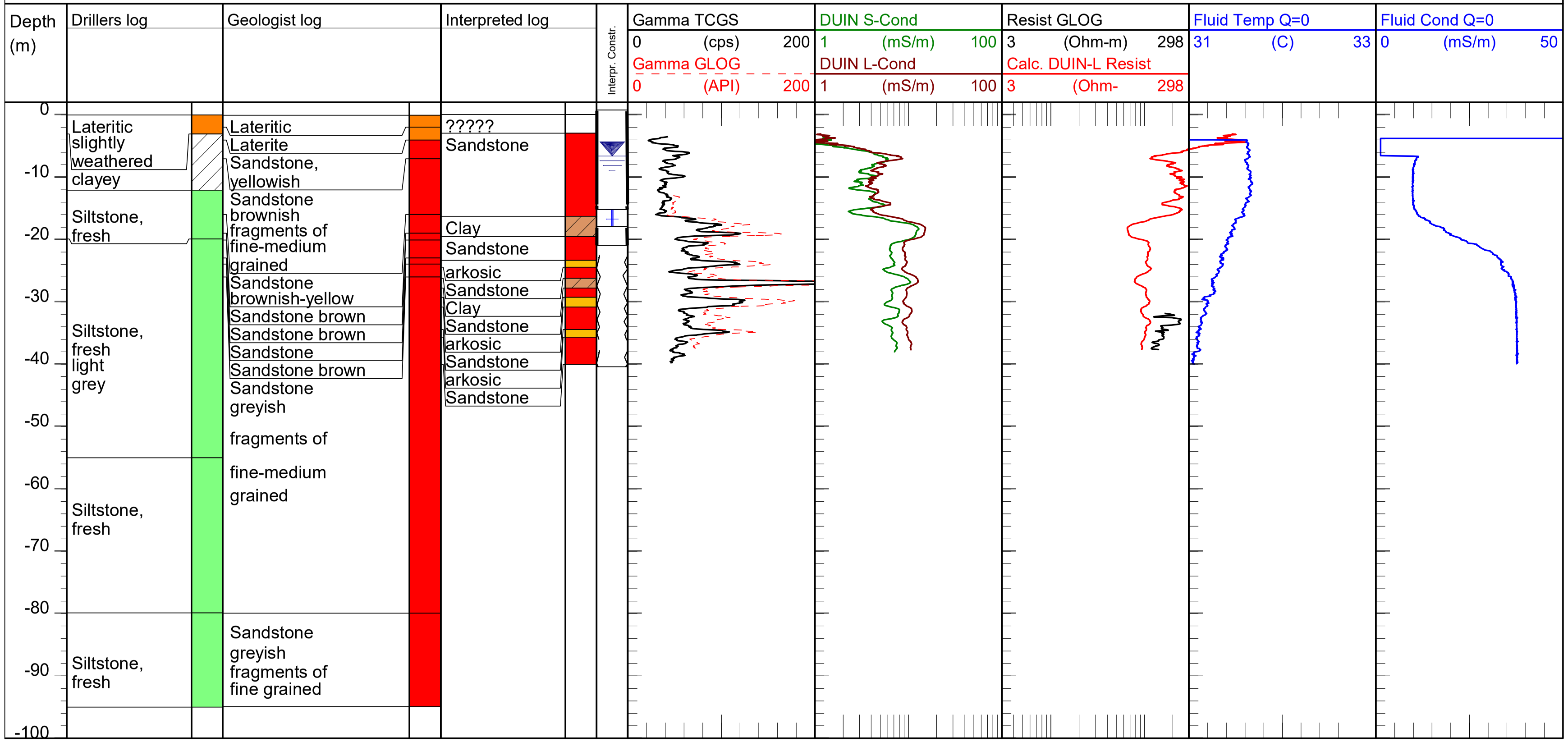
Annex B8



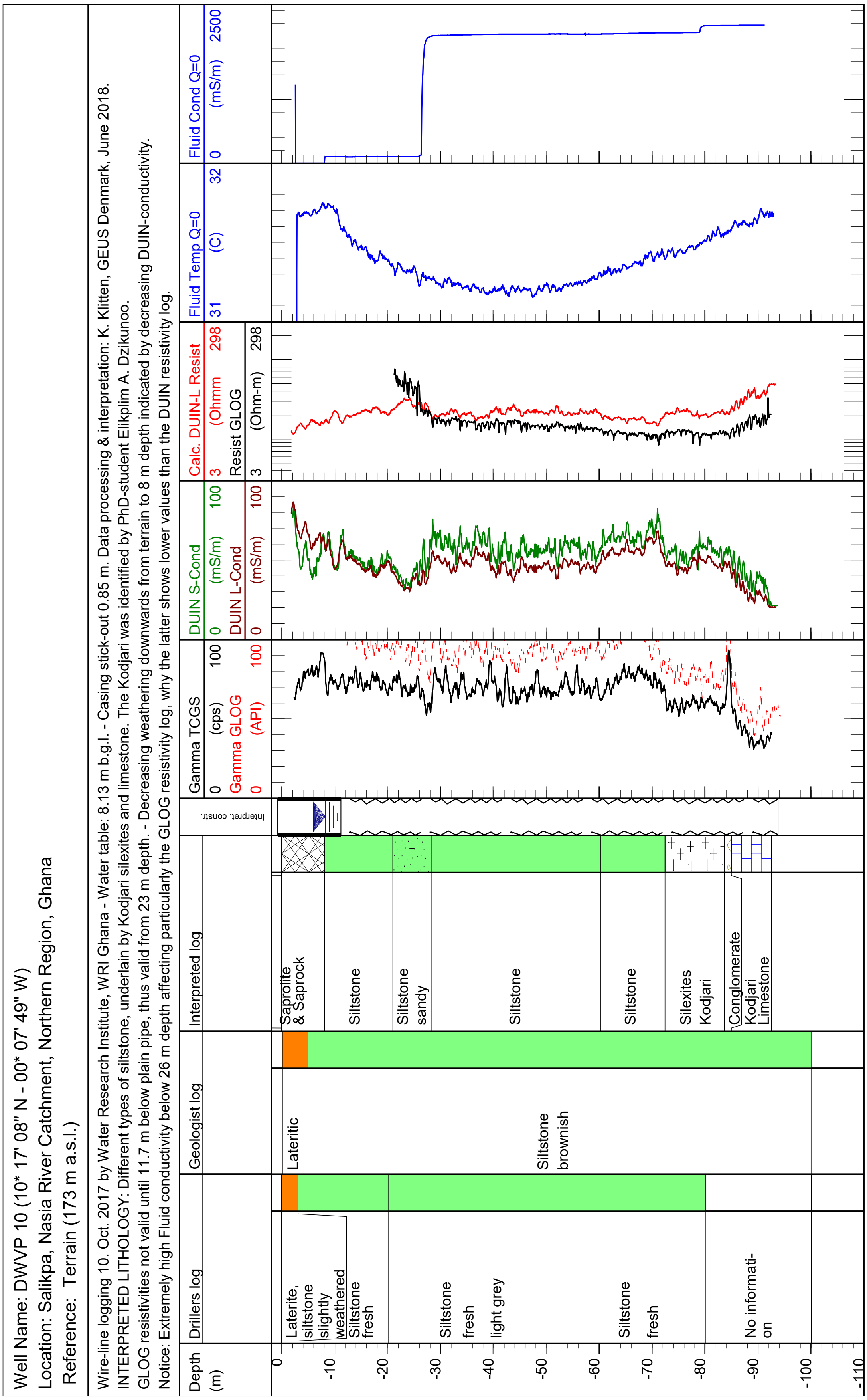
Well Name: DWVP 8 (10* 09´04" N - 0* 51´19" W)
Location: Nakpaya, Nasia River Catchment, Northern Region, Ghana
Reference: Terrain (123 m a.s.l.)
Wireline logging 7. Oct. 2017 by Water Research Institute, WRI Ghana - Water table: 0.74 m b.g.l. - Casing stick-out: 0.50 m. Data processing & interpretation: K. Klitten, GEUS Denmark, June 2018
GLOG resistivity not valid above 20 m depth (11 m below plain pipe). - INTERPRETED LITHOLOGY: Different types of siltstone occurs with intercalations of sandstone beds.
Decreasing weathering from terrain downwards to 10 m depth indicated by decreasing DUIN-conductivity.
Depth (m)
Drillers log
Geologist log
Interpreted log
Interpret. Const.
Gamma-TCGS
0 (cps) 100
Gamma GLOG
0 (API) 100
DUIN-S Cond
2 (mS/m) 200
DUIN-L Cond
2 (mS/m) 200
Resist GLOG
3 (Ohmm) 298
Calc DUIN-L Resist
3 (Ohmm) 298
Fluid Temp Q=0
32 (C) 34
Fluid Cond Q=0
0 (mS/m) 200
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
Siltstone, slightly weathered
Siltstone, fresh
Siltstone, fresh, light grey
Siltstone, fresh
Siltstone, fresh
Laterite, Clay
Siltstone, weathered
Siltstone, greyish
Saprolite & Saprock
Siltstone
Sandstone
Siltstone
Sandstone
Siltstone, sandy
Sandstone
Siltstone
Sandstone
Siltstone
Sandstone
Siltstone
Sandstone
Siltstone
Sandstone
Siltstone
Sandstone
Siltstone
Sandstone
Siltstone
Sandstone
Siltstone

Well Name: DWVP 9 (10* 27' 37" N - 0* 36' 40" W)
Location: Samene, Nasia River Catchment, Northern Region, Ghana
Reference: Terrain (308 m a.s.l.)

Wireline logging 8. Oct. 2017 by Water Research Institute, WRI Ghana - Water table: 6.61 m b.g.l. - Casing stick-out 0.95 m. - Data processing & interpretation: K. Klitten, GEUS Denmark, July 2018.
Resistivity log (GLOG) not valid until 11.7 m below plain pipe due to the bridle cable effect, and therefore deteted above 32 m depth. - INTERPRETED LITHOLOGY: Sandstone.
High gamma-radiation and DUIN conductivity indicate clay, whereas high gamma without high DUIN conductivity indicate arkosic sandstone or phosphorites. Weathering is not reflected.



Annex B10

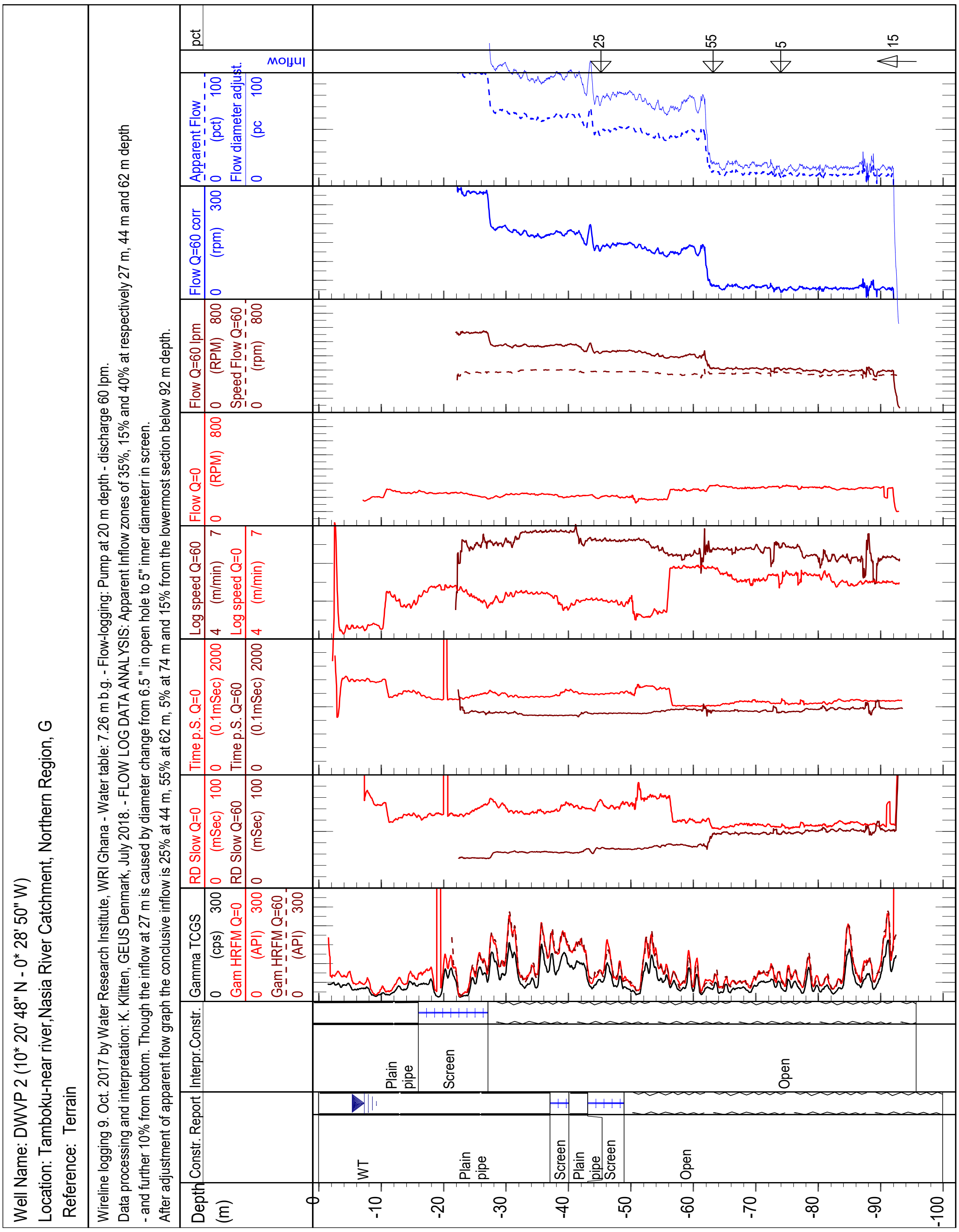


Well Name: DWVP 10 (10* 17' 08" N - 00* 07' 49" W)
Location: Salikpa, Nasia River Catchment, Northern Region, Ghana
Reference: Terrain (173 m a.s.l.)
Wire-line logging 10. Oct. 2017 by Water Research Institute, WRI Ghana - Water table: 8.13 m b.g.l. - Casing stick-out 0.85 m. Data processing & interpretation: K. Klitten, GEUS Denmark, June 2018.
INTERPRETED LITHOLOGY: Different types of siltstone, underlain by Kodjari silexites and limestone. The Kodjari was identified by PhD-student Elikplim A. Dzikunoo.
GLOG resistivities not valid until 11.7 m below plain pipe, thus valid from 23 m depth. - Decreasing weathering downwards from terrain to 8 m depth indicated by decreasing DUIN-conductivity.
Notice: Extremely high Fluid conductivity below 26 m depth affecting particularly the GLOG resistivity log, why the latter shows lower values than the DUIN resistivity log.
Depth (m)
Drillers log
Laterite, siltstone slightly weathered
Siltstone fresh
Siltstone fresh light grey
Siltstone fresh
No informati-on
Geologist log
Lateritic
Siltstone brownish
Interpreted log
Saprolite & Saprock
Siltstone
Siltstone sandy
Siltstone
Siltstone
Silexites Kodjari
Conglomerate Kodjari Limestone
Interpret. constr.
Gamma TCGS 0 (cps) 100
Gamma GLOG 0 (API) 100
DUIN S-Cond 0 (mS/m) 100
DUIN L-Cond 0 (mS/m) 100
Calc. DUIN-L Resist 3 (Ohmm 298
Resist GLOG 3 (Ohm-m) 298
Fluid Temp Q=0 31 (C) 32
Fluid Cond Q=0 0 (mS/m) 2500
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110

11. ANNEX C: PROCESSING OF FLOW-LOG

Annex C2: DWVP 02 –	Tamboku	(Panabako formation)
Annex C7: DWVP 07 –	Saliwia	(Bimbila formation)

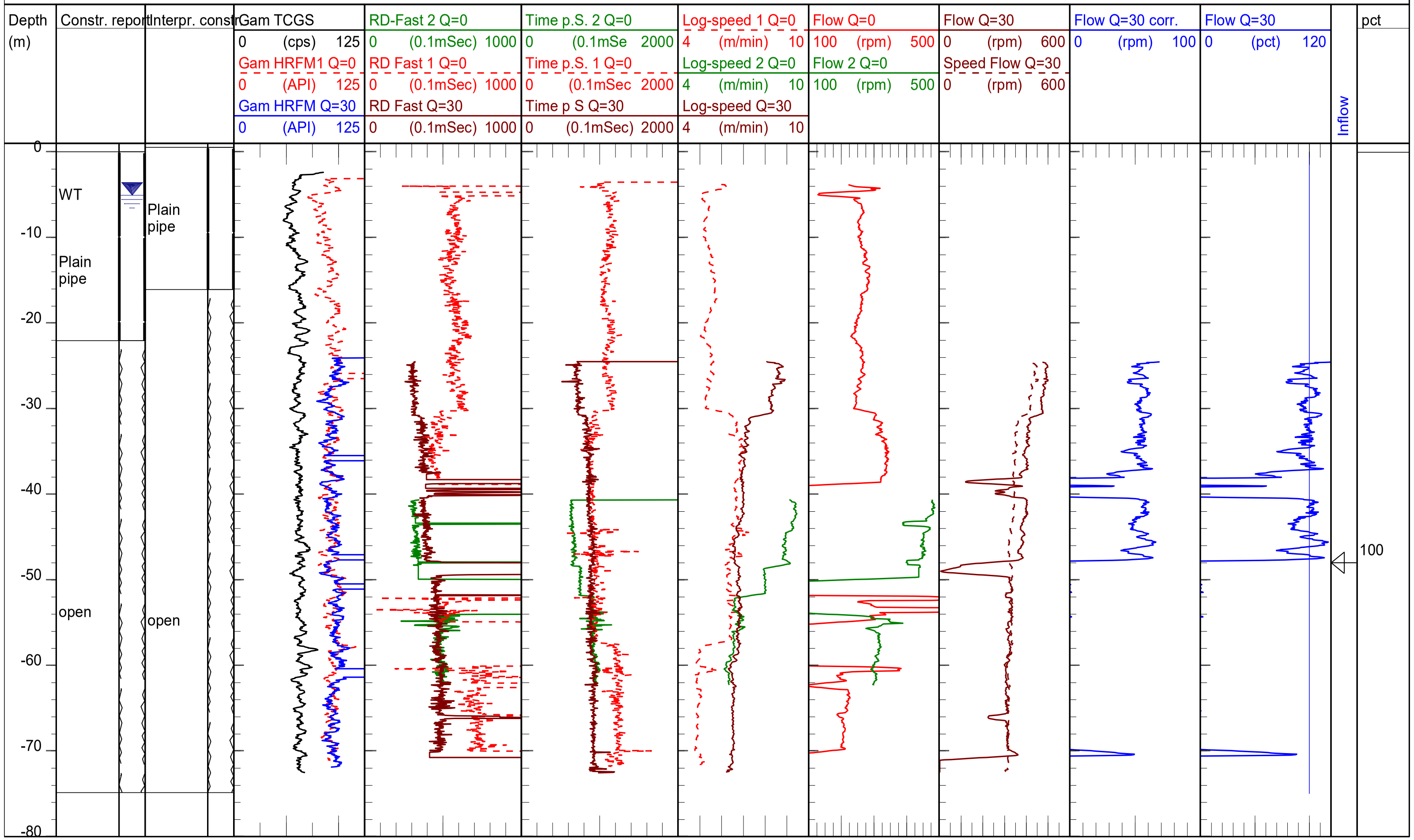
Annex C2



Well Name: DWVP 2 (10* 20' 48" N - 0* 28' 50" W)
Location: Tamboku-near river,Nasia River Catchment, Northern Region, G
Reference: Terrain
Wireline logging 9. Oct. 2017 by Water Research Institute, WRI Ghana - Water table: 7.26 m b.g. - Flow-logging: Pump at 20 m depth - discharge 60 lpm.
Data processing and interpretation: K. Klitten, GEUS Denmark, July 2018. - FLOW LOG DATA ANALYSIS: Apparent Inflow zones of 35%, 15% and 40% at respectively 27 m, 44 m and 62 m depth
- and further 10% from bottom. Though the inflow at 27 m is caused by diameter change from 6.5 " in open hole to 5" inner diameterr in screen.
After adjustment of apparent flow graph the conclusive inflow is 25% at 44 m, 55% at 62 m, 5% at 74 m and 15% from the lowermost section below 92 m depth.
Depth (m)
Constr. Report
Interpr.Constr.
Gamma TCGS 0 (cps) 300
Gam HRFM Q=0 0 (API) 300
Gam HRFM Q=60 0 (API) 300
RD Slow Q=0 0 (mSec) 100
RD Slow Q=60 0 (mSec) 100
Time p.S. Q=0 0 (0.1mSec) 2000
Time p.S. Q=60 0 (0.1mSec) 2000
Log speed Q=60 4 (m/min) 7
Log speed Q=0 4 (m/min) 7
Flow Q=0 0 (RPM) 800
Flow Q=60 lpm 0 (RPM) 800
Speed Flow Q=60 0 (rpm) 800
Flow Q=60 corr 0 (rpm) 300
Apparent Flow 0 (pct) 100
Flow diameter adjust. 0 (pc 100
Inflow pct
25
55
5
15
WT
Plain pipe
Screen
Plain pipe
Screen
Open
Plain pipe
Screen
Open
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100

Well Name: DWVP 7 (10* 09' 07" N - 0* 08' 06" W)
Location: Saliwia, Nasia River Catchment, Northern Region, Ghana
Reference: Terrain

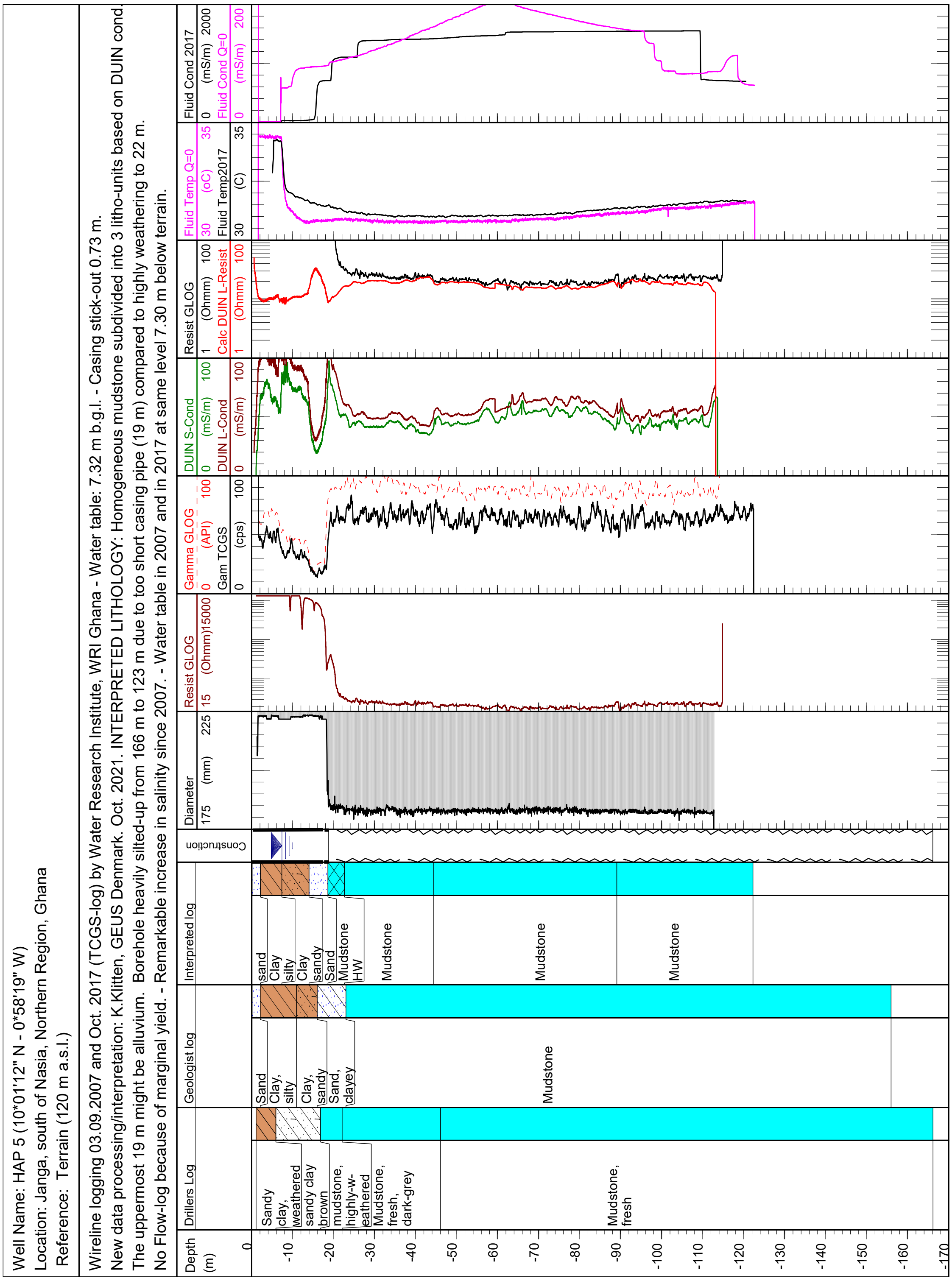
Wireline logging 11. Oct. 2017 by Water Research Institute, WRI Ghana - Water table: 5.00 m b.g.l. - Flow-logging: pump at 20 m depth - discharge 30 lpm.
Data processing and interpretation: K. Klitten, GEUS Denmark, June 2018. - Additional flow-log without pumping (Q=0) was run from 40 m to 63 m because of partial data fall-out during first run.
FLOW LOG DATA ANALYSIS: Only one major inflow zone, and located at 48 m depth.



12. ANNEX D: WIRE-LINE LOGS FROM 8 OTHER BOREHOLES

Annex D1: HAP 05 –	Janga	(Bimbila formation)
Annex D2: HAP 11 –	Nalerigu	(Panabako and Poubogou fm.)
Annex D3: HAP 12 –	Nakpeuk	(Panabako and Poubogou fm.)
Annex D4: HAP 14 –	Tuuni	(Kodjari fm. and Panabako fm.)
Annex D5: WVB 12 –	Tinguri	(Bimbila formation)
Annex D6: WVB 11 –	Bugya Pala 1	(Kodjari and Panabako fm.)
Annex D7: CWSA –	Bugya Pala 2	(Kodjari and Panabako fm.)
Annex D8:	Zangu-Vuga	(Kodjari and Poubogou fm.)

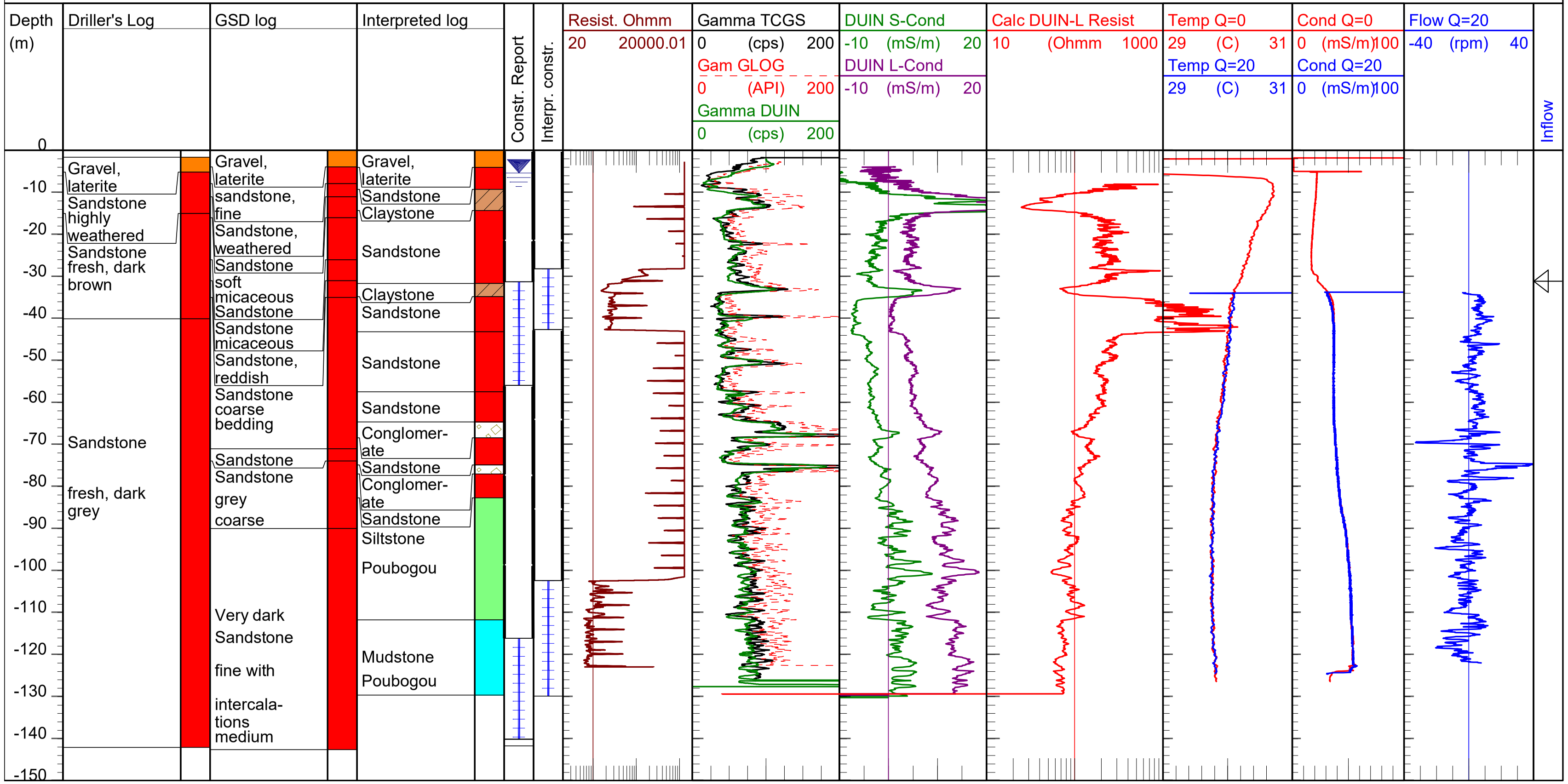
Annex D1



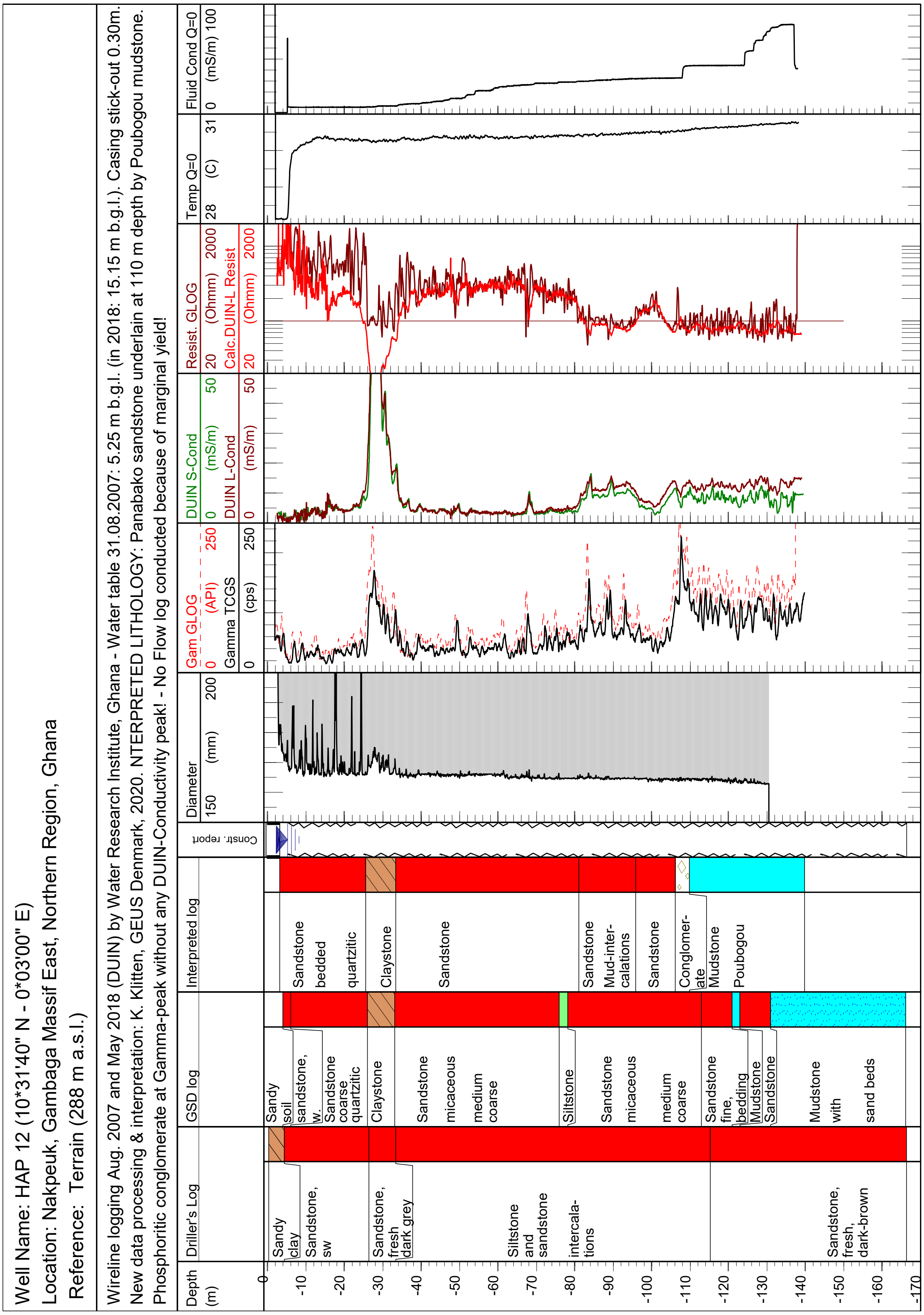
Well Name: HAP 5 (10*01'12" N - 0*58'19" W)
Location: Janga, south of Nasia, Northern Region, Ghana
Reference: Terrain (120 m a.s.l.)
Wireline logging 03.09.2007 and Oct. 2017 (TCGS-log) by Water Research Institute, WRI Ghana - Water table: 7.32 m b.g.l. - Casing stick-out 0.73 m.
New data processing/interpretation: K.Klitten, GEUS Denmark. Oct. 2021. INTERPRETED LITHOLOGY: Homogeneous mudstone subdivided into 3 litho-units based on DUIN cond.
The uppermost 19 m might be alluvium. Borehole heavily silted-up from 166 m to 123 m due to too short casing pipe (19 m) compared to highly weathering to 22 m.
No Flow-log because of marginal yield. - Remarkable increase in salinity since 2007. - Water table in 2007 and in 2017 at same level 7.30 m below terrain.
Depth (m)
Drillers Log
Geologist log
Interpreted log
Construction
Diameter 175 (mm) 225
Resist GLOG 15 (Ohmm) 15000
Gamma GLOG 0 (API) 100
Gam TCGS 0 (cps) 100
DUIN S-Cond 0 (mS/m) 100
DUIN L-Cond 0 (mS/m) 100
Resist GLOG 1 (Ohmm) 100
Calc DUIN L-Resist 1 (Ohmm) 100
Fluid Temp Q=0 30 (oC) 35
Fluid Temp2017 30 (C) 35
Fluid Cond 2017 0 (mS/m) 2000
Fluid Cond Q=0 0 (mS/m) 200
Sandy clay, weathered sandy clay brown
mudstone, highly-weathered
Mudstone, fresh, dark-grey
Mudstone, fresh
Sand
Clay, silty
Clay, sandy
Sand, clayey
Mudstone
sand
Clay silty
Clay sandy
Sand
Mudstone HW
Mudstone
Mudstone
Mudstone
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
-170

Well Name: HAP 11 (10*30'50" N - 0*23'42" W)
Location: Nalerigu, Nasia River catchment, Northern Region, Ghana
Reference: Terrain (355 m a.s.l.)

Wireline logging 01.09 and 20.10.2007 (GLOG-log) by Water Research Institute, WRI Ghana - Water table 5.30 m b.g.l.- Casing stick-out 0.62 m.
- New data processing and interpretation: K. Klitten, GEUS Denmark, 2020. - Flow-log downwards from 34 m depth with discharge 20 lpm. It does not show any unambiguous inflow into any of the two screens. This is verified by the lack of difference between respectively temperature-log with and without pumping and between fluid conductivity log with and without pumping. Accordingly, inflow occurs above 34 m, i.e. in the upperpart of the upper screen. - INTERPRETED LITHOLOGY: Panabako sandstones with two intercalations of phosphoritic conglomerate (Gamma-peak without corresponding DUIN-conductivity peak) above Poubogou silt- and mudstone.



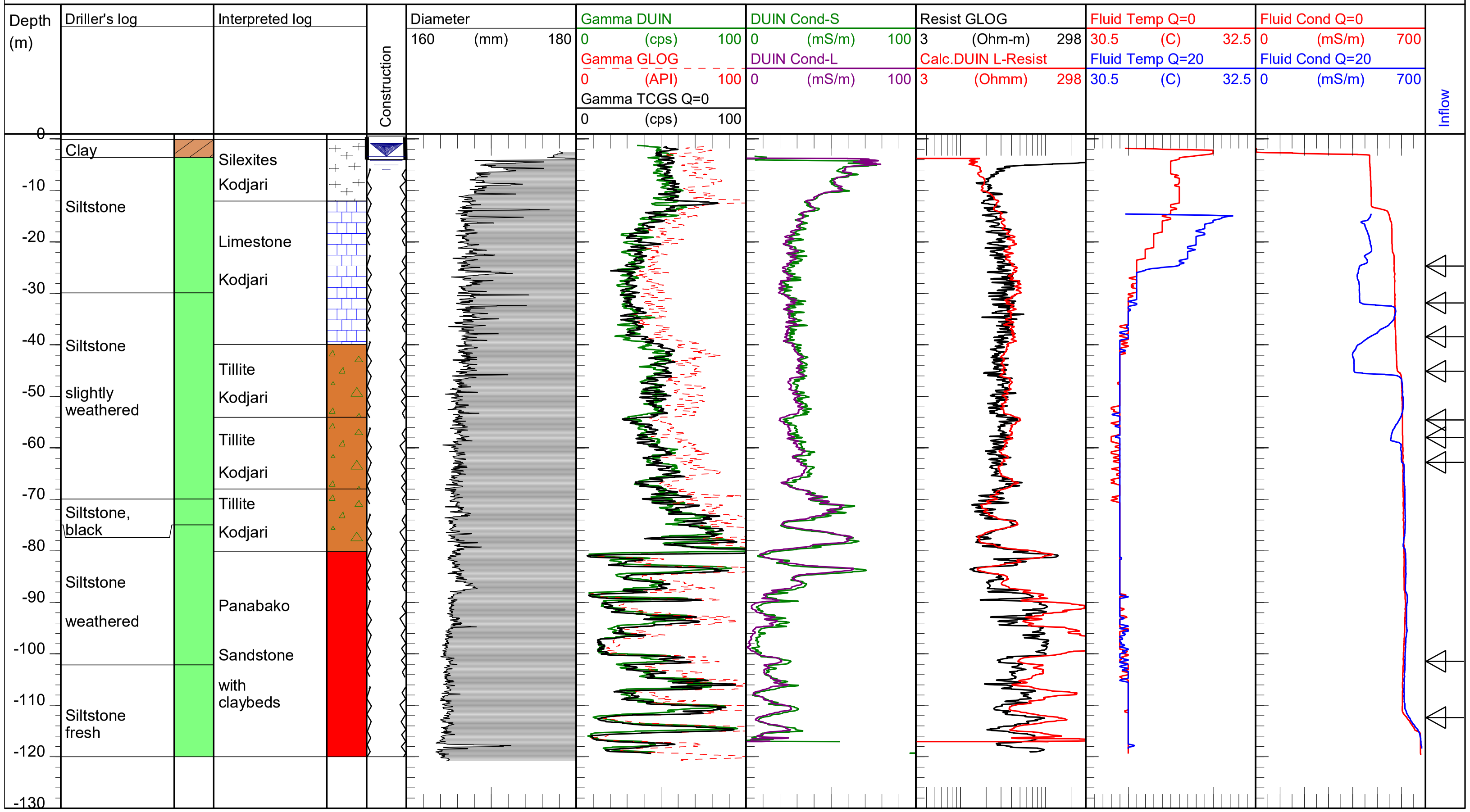
Annex D3


Well Name: HAP 12 (10*31'40" N - 0*03'00" E)
Location: Nakpeuk, Gambaga Massif East, Northern Region, Ghana
Reference: Terrain (288 m a.s.l.)
Wireline logging Aug. 2007 and May 2018 (DUIN) by Water Research Institute, Ghana - Water table 31.08.2007: 5.25 m b.g.l. (in 2018: 15.15 m b.g.l.). Casing stick-out 0.30m.
New data processing & interpretation: K. Klitten, GEUS Denmark, 2020. NTERPRETED LITHOLOGY: Panabako sandstone underlain at 110 m depth by Poubogou mudstone.
Phosphoritic conglomerate at Gamma-peak without any DUIN-Conductivity peak! - No Flow log conducted because of marginal yield!
Depth (m)
Driller's Log
GSD log
Interpreted log
Constr. report
Diameter 150 (mm) 200
Gam GLOG 0 (API) 250
Gamma TCGS 0 (cps) 250
DUIN S-Cond 0 (mS/m) 50
DUIN L-Cond 0 (mS/m) 50
Resist. GLOG 20 (Ohmm) 2000
Calc.DUIN-L Resist 20 (Ohmm) 2000
Temp Q=0 28 (C) 31
Fluid Cond Q=0 0 (mS/m) 100
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
-160
-170
Sandy clay
Sandstone, sw
Sandstone, fresh dark grey
Siltstone and sandstone
intercala-tions
Sandstone, fresh, dark-brown
Sandy soil
sandstone, w.
Sandstone coarse quartzitic
Claystone
Sandstone
micaceous
medium coarse
Siltstone
Sandstone
micaceous
medium coarse
Sandstone fine, bedding
Mudstone
Sandstone
Mudstone
with
sand beds
Sandstone
bedded
quartzitic
Claystone
Sandstone
Sandstone Mud-inter-calations
Sandstone
Conglomer-ate
Mudstone
Poubogou

Annex D4

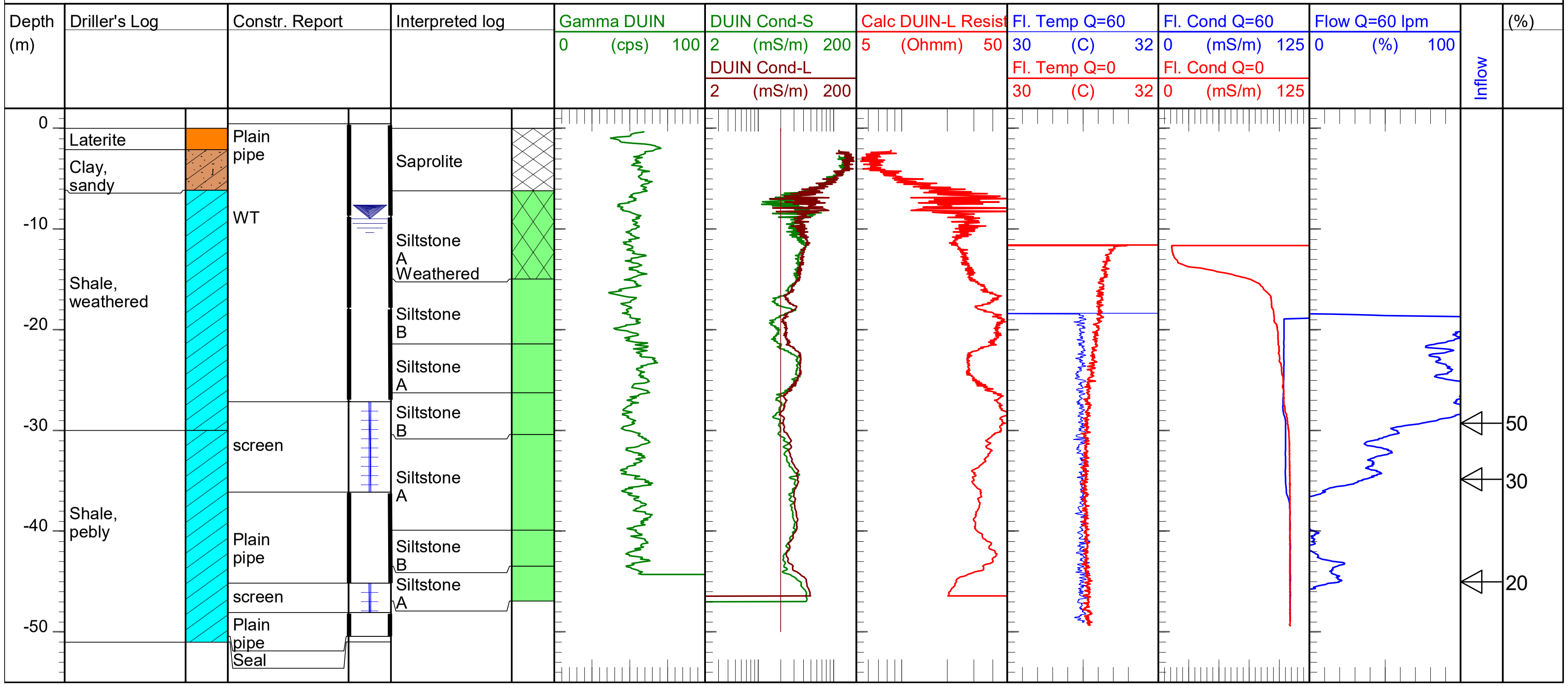
Well Name: HAP 14 (10* 17' 53" N - 0* 21' 55" W)
Location: Tuuni, Nasia River Catchment, Northern Region, Ghana
Reference: Terrain (157 m a.s.l.)

Wireline logging 25. Nov. 2009 and 3. May 2018 by Water Research Institute, WRI Ghana - Water table: 2.72 m (2009) and 3.24 m b.g.l. (2018). - Casing stic-out 0.79 m. Data processing and interpretation: K. Klitten, GEUS Denmark, 2020. - Interpreted Lithology: The 3 members of Kodjari, i.e. Darebe silexites, Buipe limestone and tillites underlain at 80 m depth by the Panabako sandstone with claybeds. - The Kodjari was identified by PhD-student Elikplim A. Dzikunoo through correlation to logs in boreholes DWVP 03 and 10. - Inflow zones are identified by sudden changes either on fluid temp. - or on conductivity log during discharge Q= 20 lpm.



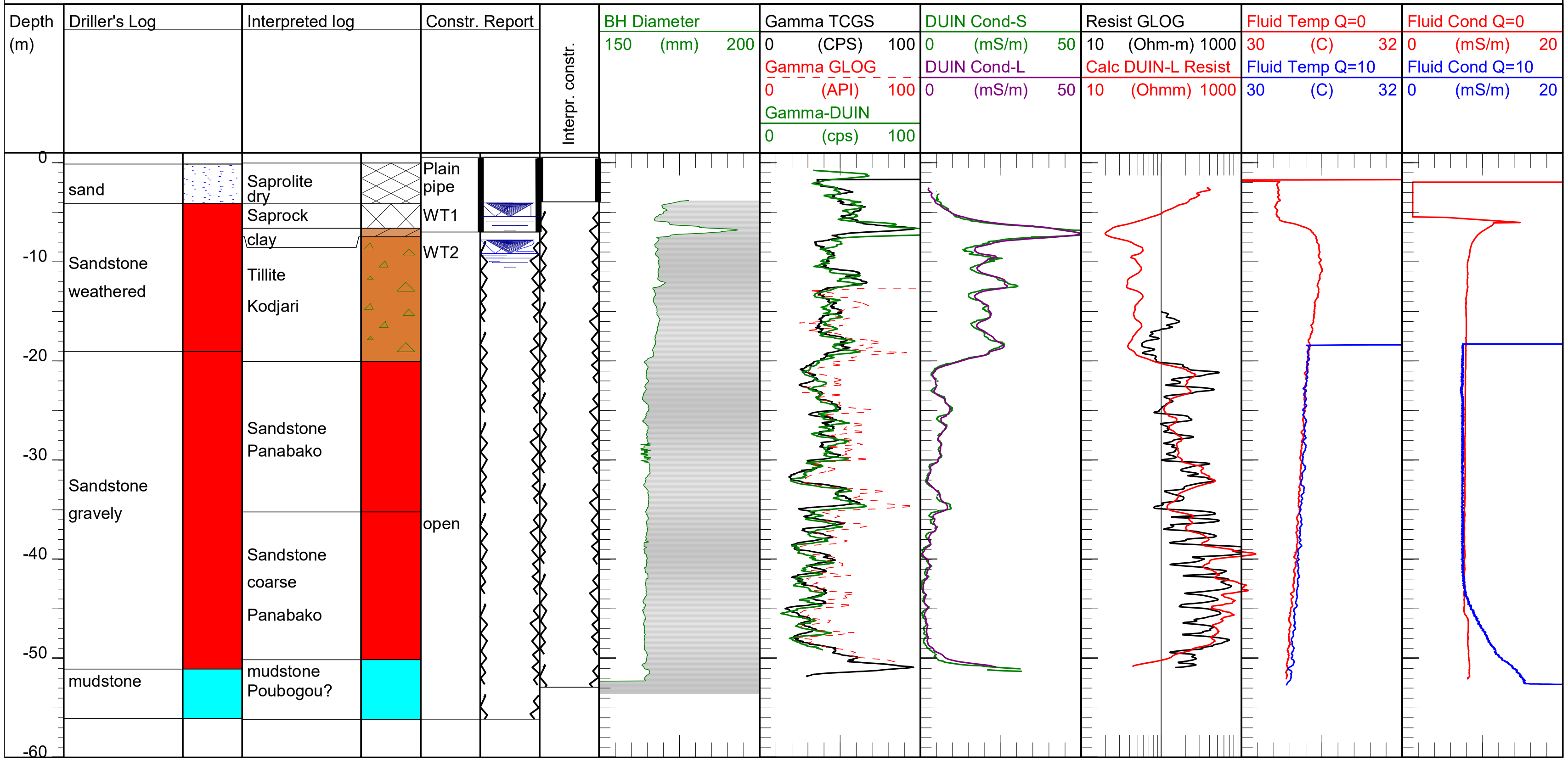
Well Name: WVB12 (9*56'53" N - 0*10'04" W)
Location: Tinguri, Nasia River catchment, Northern Region, Ghana
Reference: Terrain (193 m a.s.l.)

Wireline logging 21. March 2007 by Water Research Institute, WRI Ghana - Water table: 9.00 m b.g.l. - Data processing and interpretation: K. Klitten, GEUS Denmark, 2021. Neither Caliper-log nor GLOG-resistivity log is conducted, why the construction details could not be verified. However, the Flow-log shows 3 inflow zones out of which two are at the upper screen section, and one is at the top of the lower screen section. - INTERPRETED LITHOLOGY: The level of Gamma-radiation (in average 55 cps), and formation-conductivity/resistivity indicate siltstone, which is subdivided into Saprolite, weathered siltstone and 6 sub-units based on DUIN conductivity/resistivity variation. The Fluid conductivity of each of the 3 inflow is calculated by combining inflow with the fluid conductivity log: 20 % x 110 + 30 % x X2=50 % x 105 thus X2=100 mS/m. 100 % x 100=50 % x X3 + 30 % x X2 + 20 % x X1, where X1=110 mS/m and X2=100 mS/m gives X3=96 mS/m.



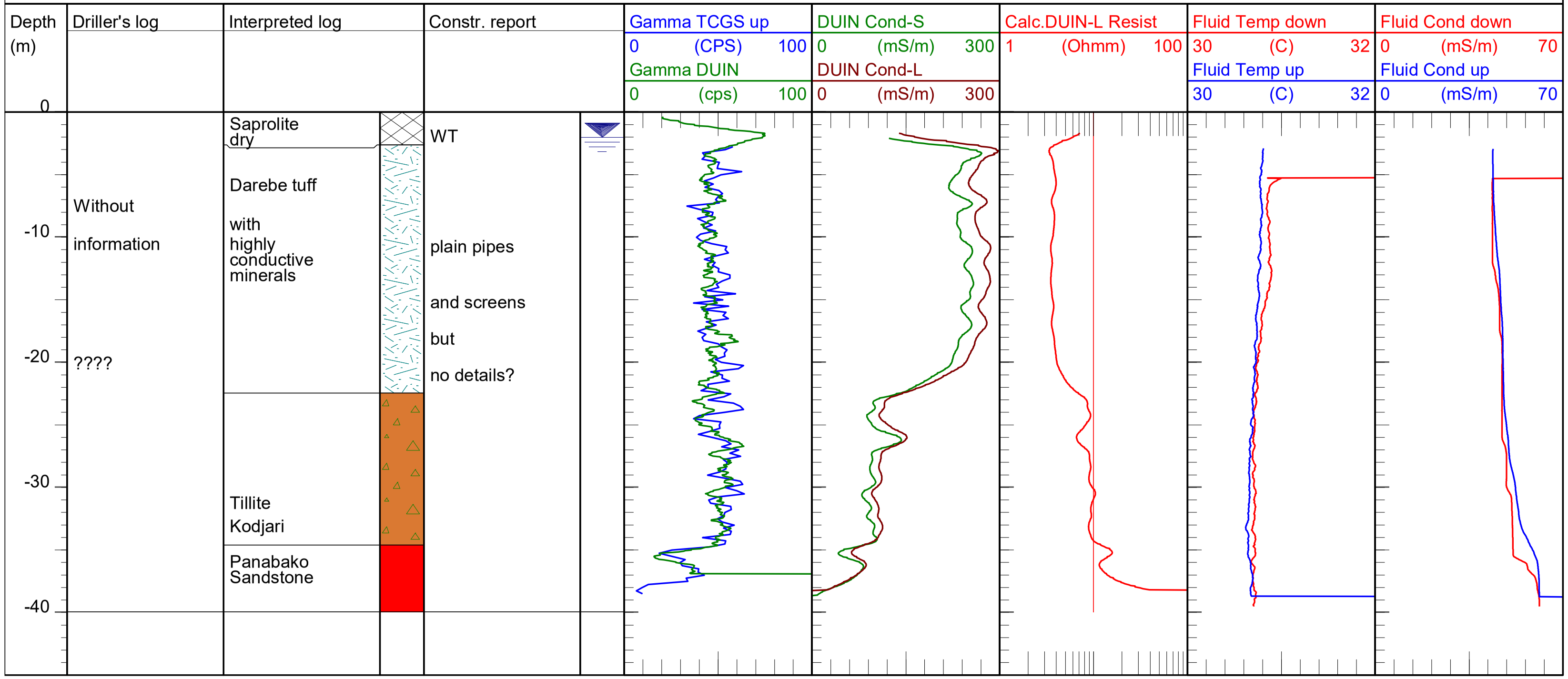
Well Name: WVB11 = Bugya-Pala 1 (10*17'06" N - 0*44'41" W)
Location: Bugya Pala, Nasia River Catchment, Northern Region, Ghana
Reference: Terrain (138 m a.s.l.)

Wireline logging 10. Oct. 2006, 24. July 2007 (TCGS-log with flow) and 2. May 2018 (DUIN-log) by Water Research Institute, WRI Ghana
- Water table: 5.40 (2006) and 9.13 m b.g.l. (2018). - Data reprocessed and reinterpreted: K. Klitten, GEUS Denmark, November 2020.
LITHOLOGY INTERPRETATION: Saprolite & Saprock to 8 m depth underlain by 11 m weathered sandy claystone (Kodjari tillite), followed by two types of bedded sandstone (Panabako?) and terminating in mudstone (Poubogou?). - Flow-log downwards (not shown) from 18 m with discharge 10 lpm only (marginal yield), and shows no inflow in accordance to the lack of difference between respectively Fluid Temp.and Fluid Conductivity logs during and without pumping. Conclusion: Inflow from above 18 m depth.



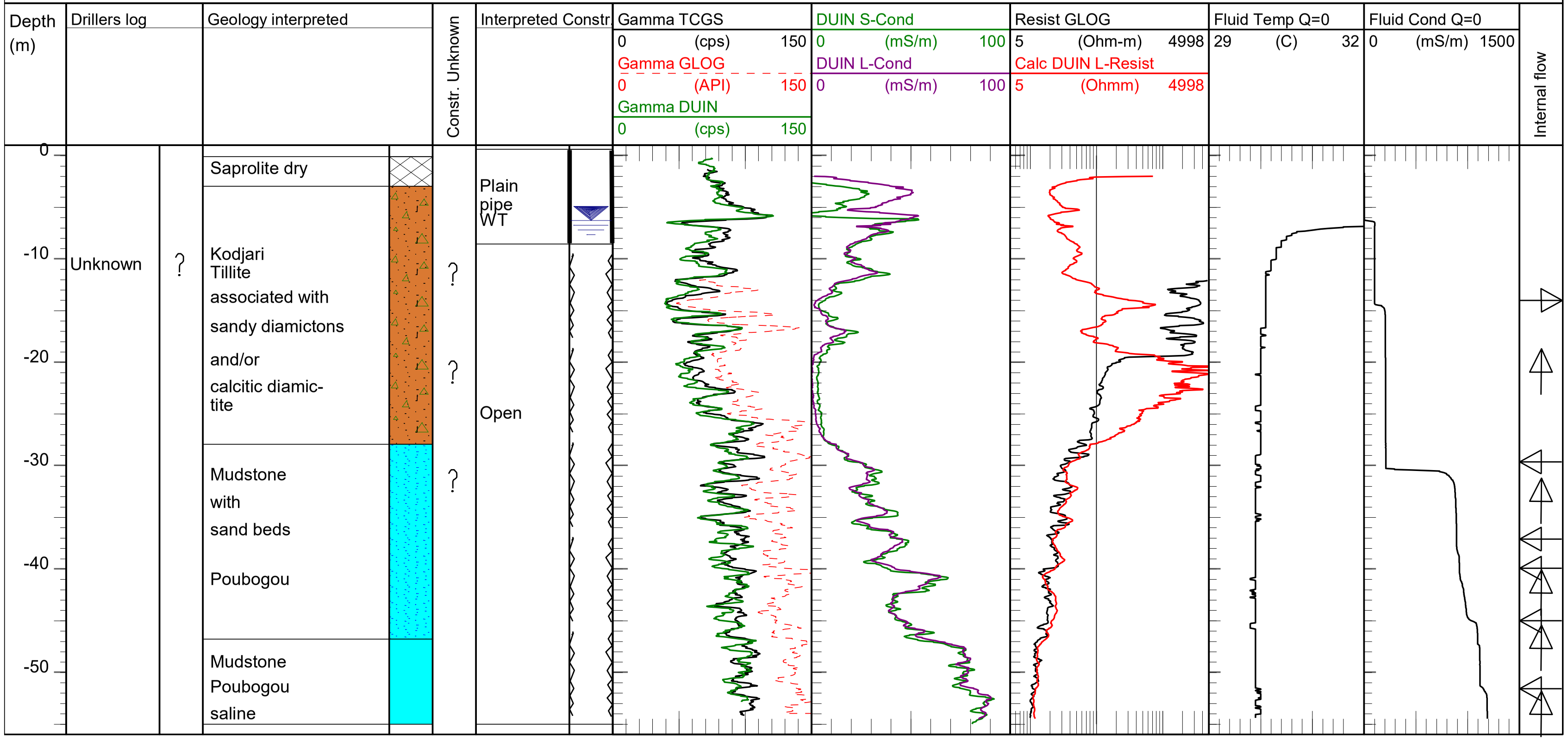
Well Name: Bugya-Pala 2 (10*17'17" N - 0*44'39" W) 400 m north of WVB11
Location: Bugya Pala, Nasia River Catchment, Northern Region, Ghana
Reference: Terrain (138 m a.s.l.)

Wireline logging: March 2007 by Water Research Institute, Ghana - Water table: 2.00 m b.g.l.- New data processing/ interpretation: K. Klitten, GEUS Denmark, 2020. The DUIN conductivity in the upper 22 m is unusually high and even much higher than the Fluid conductivity. Furthermore, without similar higher and conformable gamma radiation it indicates content of very conductive minerals, probably Darebe tuff with magnetic pyrites, iron oxides, limonite, ferrosilites?
- Underlain by Tillite on Panabako sandstone at bottom as also suggested at borehole Bugya-Pala 1 located 400 m south. - Yield during drilling marginal (<10 lpm).



Well Name: ZANGUM-VUGA (10*22'27" N - 0*51'46" W)
Location: Northwest of Walewale, Northern Region, Ghana
Reference: Terrain (175 m a.s.l.)

Wireline logging May 2018 by Water Research Institute, Ghana - Water table: 6.24 m b.g.l. - Casing stick-out 0.61 m. - Data processing and interpretation: K. Klitten, GEUS Denmark, Nov. 2020. - CONSTRUCTION INTERPRETED: Open hole from 8.4 m depth because Resist-GLOG shows too high values above 20 m, i.e. to 11.7 m below end of pipe. LITHOLOGY INTERPRETATION: Probably Saprolite (dry) to 3 m followed by Tillite to 28 m depth, then underlain by clay- or mudstone with sand-intercalations (Poubogou fm.). The very high resistivity in sections of the Tillite might be associates of sandy diamictons and/or calcitic diamictite.
FLUID CONDUCTIVITY INTERPRETED: Several small inflow from the Poubogou fm. of saline water, though less saline than at bottom, and upflow and outflow at about 15 m in the Tillite. - Flow-log was not conducted of unknown reasons.



13. ANNEX E: HYDROCHEMISTRY OF DWVP BOREHOLES

HYDROCHEMISTRY OF DWVP BOREHOLES

SAMPLE ID	pH	EC calculated from TDS(µS/cm)	TDS calculated from major ions(mg/L)	Temp (°C)	Na (mg/L)	K (mg/L)	Alkalinity as CaCo3 (mg/L)	HCO3 (mg/L)	Ca (mg/L)	Mg (mg/L)	CO3 (mg/L)	SO4 (mg/L)	Cl (mg/L)
DWVP 01	5,82	27	17,5	32,0	0,6	2,5	8,2	10	1,76	0,873	0	<1.00	1,79
DWVP 02	6,58	56	36,6	29,2	4,9	2,1	13,0	15,9	1,04	2,96	0	5,75	3,97
DWVP 03	7,55	12754	8290	28,0	3000	4,2	19,4	23,67	343	44,8	0	5,38	4869
DWVP 04	7,78	463	301	32,3	62,0	2,2	71,6	87,4	21,9	12,0	0	19,5	95,9
DWVP 05	7,53	1719	1117	31,5	330	1,2	380,0	463	20,3	4,64	0	58,9	239
DWVP 06	7,08	129	84	31,3	6,6	1,5	31,6	38,6	4,57	2,62	0	27,9	2,08
DWVP 07	7,73	150	97	31,4	16,2	1,4	46,6	56,9	5,13	3,88	0	11,3	2,68
DWVP 08	8,45	674	438	33,5	75,0	1,0	149,0	182	4,89	4,17	0	9,9	12
DWVP 10-1*	7,76	1324	700		100	6,8	485	591,3	31,6	31,22	0	32	177,3
DWVP 10-2**	7,36	19160	11496		4100	5,2	18	22	357	325	0	20	8705

SAMPLE ID	NO3 (mg/L)	F (mg/L)	PO4 (mg/L)	SiO2 (mg/L)	Fe (mg/L)	Mn (mg/L)	Zn (mg/L)	Cu (mg/L)	Pb (mg/L)	Co (mg/L)	Ni (mg/L)	As (mg/L)	Al (mg/L)	Cation-anion balance (% diff.)
DWVP 01	1,07	<0.005	0,116	52,3	15,7	0,265	0,052	<0.010	<0.005	<0.010	<0.010	0,035	3,11	3,76
DWVP 02	1,76	<0.005	0,068	2,1	0,402	0,012	<0.005	<0.010	<0.005	<0.010	<0.010	0,002	<0.010	3,55
DWVP 03	0,006	1,09	0,081	4,49	0,131	0,579	<0.005	0,0220	<0.005	<0.010	<0.010	0,006	0,067	4,74
DWVP 04	0,104	0,33	0,047	11,8	5,42	0,125	0,106	<0.010	<0.005	0,0100	<0.010	0,021	1,57	3,11
DWVP 05	0,017	0,7530	0,019	12,3	0,878	0,023	0,009	<0.010	<0.005	<0.010	<0.010	0,009	0,71	0,72
DWVP 06	0,251	<0.005	0,326	15,4	3,18	0,537	<0.005	<0.010	<0.005	<0.010	<0.010	0,001	1,85	24,8
DWVP 07	0,556	<0.005	0,288	10,8	0,715	0,070	<0.005	<0.010	<0.005	<0.010	<0.010	0,002	0,328	2,47
DWVP 08	0,214	0,604	0,318	8,26	4,49	0,122	0,041	<0.010	<0.005	<0.010	<0.010	0,069	1,81	4,63
DWVP 10-1*	0,25	0,25	0,33		1,826	0,635	<0.001	0,612	<0.001			0,002	0,009	27,8
DWVP 10-2**	0,003	1,2	0,098		1,88	1,13	0,158	<0,020	<0,005	<0,010	<0,010	0,021	0,38	4,91

SAMPLE ID	EC calculated from TDS(µS/cm)	TDS calculated from major ions(mg/L)	EC/TDS	Water sampling campaign	TDS as reported from Lab. (mg/L)	TDS when including all major ions (mg/L)	Difference (mg/L)	Parameters not included as probable reason for difference	EC calc. from total TDS (µS/cm)
DWVP 01	27	18	1,54	July 2018	17,5	83	66	SiO2 and Fe	128
DWVP 02	56	37	1,54	July 2018	36,6	37	0		57
DWVP 03	12754	8290	1,54	July 2018	8290	8290	0		12755
DWVP 04	463	301	1,54	July 2018	301	316	15	SiO2 and Fe	486
DWVP 05	1719	1117	1,54	July 2018	1117	1129	12	SiO2 and Fe	1737
DWVP 06	129	84	1,54	July 2018	84	101	17	SiO2 and Fe	155
DWVP 07	150	97	1,54	July 2018	97	108	10	SiO2 and Fe	166
DWVP 08	674	438	1,54	July 2018	438	301	-137	Not explainable!	463
DWVP 10-1 *	1324	700	1,89	January 2019	700	965	265	Not explainable!	1484
DWVP 10-2**	19160	11496	1,67	October 2019	11496	13531	2035	Not explainable!	20817

*) Hydrochemistry analysis conducted by ECOLAB - all other analysis conducted by WRI-CSIR lab in Accra.

Information from Professor Mark Yidana Sandow: EC and TDS were not measured in the laboratory but were computed from the hydrochemistry data:

EC, pH, TDS, are usually measured onsite and used to check results from the laboratory. Unfortunately, the probe stoped working in the field and reliable results could not be achieved.

For DWVP 10-1 the ECOLAB used a probe to measure TDS and EC directly in the water sample. However, as seen on the data, TDS can't explain the parameters well as they do not add up.

**)In the case of DWVP 10-2 the WRI-LAB determined TDS and EC in the Lab. Thus not calculated.

14. ANNEX F: GEUS ASSISTANCE TO WATER RESEARCH INSTITUTE

1st GEUS assistance assignment:

In order to identify and rectify the actual problems and get the system running GEUS provided assistance to WRI by the visits of Technician Mr. Per Jensen (9th – 18th June 2017) and Emeritus Senior Scientist Mr. Kurt Klitten (11th – 24th June 2017). They brought with them a Caliber logging probe and a Focused Resistivity logging probe, since the similar WRI probes were reported out of order. Furthermore, shortly after their arrival to WRI they requested GEUS to send to Ghana a logging cable-winch because both the two cable-winches available at WRI turned out to have different kind of technical errors thus were also not functioning.

The problems and their solutions are summarized as follows:

- The problem with the WRI GLOG probe was found to be caused by a damaged plug-in connector on its bridle cable. The latter is used only for this type of probe with the purpose to force the measuring current from the central electrode on the GLOG probe as deep as possible into the surrounding rock. The problem with the plug-in connector was temporarily solved by using the bridle cable belonging to the GEUS GLOG probe, and it was finally solved by repairing the WRI bridle cable at GEUS in Denmark after this first assignment.
- Winch problems – As already experienced during the PhD-study of William Agyekum (2006-09) the old WRI winch has a problem with its gear, why it is difficult to keep the logging speed sufficiently low and steady. Therefore, focus was given to solve the problem with the WRI winch II, which turned out to be caused by non-functioning speed controller due to a spoiled fuse. The latter was not available in Ghana. Therefore a temporary solution was to install the speed controller from the old WRI winch on the WRI winch II.
- Signal communication was neither possible with any of the WRI probes, nor with the two brought-in GEUS probes. This problem was thought to be caused by damage, moisture or erroneous connection through the cable head, which therefore was dismantled, cleaned and reassembled, however without any positive effect on the missing signal. After communication with Roberson Geologging Ltd it was concluded that the missing signal communication with probes might be caused by coating on the sliding contact on the winch II after not having been used for several years. In order to clean the coating from the sliding contact the winch was intensively moved/rolled for many minutes on the 14th June, after which voltage, power consumption and signal communication finally was obtained with all the five WRI-probes (TCGS, GLOG, DUIN, HRFM and 3ARC) as well as with the 2 GEUS probes (3ARC and GLOG). Though, the WRI caliper probe (3ARC) was still not functioning in terms of getting the arms to move. Instead the GEUS caliper probe should be used.

The planned return to Denmark of Per Jensen was then changed from 16th to 18th June, allowing him to leave Accra for Tamale together with Kurt Klitten on the 15th June and participate on the start-up of the logging campaign on the 16th June at borehole DWVP-6 at Tanyili located north of Karaga town.

During the wire-line logging of borehole DWVP-6 north of Karaga town on the 16th June a very good signal communication was obtained to the 4 WRI tools, but the error message “No current record” occurred when preparing log run by creating “New log file” on menu “log settings”. Obviously, this new problem was caused by erroneous or missing sonde text-files in the Winlogger software system setup on the WRI logging laptop. – Furthermore, the arms on the GEUS caliper probe like on the WRI caliper probe could also not open (el-motor not possible to activate)!

All sort of attempts using other copies of sonde text-files, cleaning up of the sonde-database folder on the WRI laptop and re-installing sonde text-files were tried as means of rectifying the problem of not being able to initiate recording of logging data, irrespectively having good signal communication with the individual probes. But after having spent most of the 17th June still without solving the problem it was decided to return to Accra, also because steady internet communication with Robertson was needed for getting further advice, which was difficult to establish from Tamale.

After the return of the field team to Accra on the 18th June a lot of efforts were spent the following days on reorganizing and reinstall the Winlogger software on the WRI logging laptop in accordance to guidance from Robertson on the sonde text-file issues.

Finally, after having received new sonde text-files from Robertson a successful test logging was conducted with three of the five WRI probes on the 22nd June in the test borehole at the WRI campus. The WRI caliper probe was still not functioning and could not be repaired, and the text file received from Robertson for the DUIN probe was either erroneous or wrongly installed.

Further efforts were spent the whole 23rd on the DUIN probe problem, including further communication with Robertson, but without succeeding to make any DUIN-log in the WRI test borehole.

Due to the importance of having the DUIN-log as a part of the log suite it was decided to postpone initialization of the logging campaign until Kurt after his return to Denmark on the 24th June had sought further advice from Robertson on how to solve the problem of not being able to prepare data file for recording with the DUIN5798 probe. The two GEUS probes (GLOG and 3ARC) were brought back to Denmark by Kurt, the first probe due to that the WRI GLOG probe was now functioning, the latter GEUS probe because of not being operational, i.e. el-motor could not be activated, e.g. like the WRI caliper probe.

2nd GEUS assistance assignment:
After several fruitless attempts by WRI in the period July and August to reinstall Winlogger software and different versions of the text-file for the DUIN5798 probe, thus still not be able to run logging with the DUIN probe, Kurt Klitten went on his 2nd logging assistance assignment to WRI on the 28th September. He brought with him the repaired GLOG bridle/cable, new fuses for the speed controller to the WRI winch II (an earlier GEUS winch), and one

GEUS induction probe as replacement for the WRI DUIN probe. Furthermore, he also brought with him the GEUS logging laptop on which the WINLOGGER software including the sonde-database was functioning.

After a full day of intense tests it was concluded on the 30th September, that logging was possible with 3 of the WRI probes (TCGS, GLOG and HRFM), but it would not be possible to make logging with the DUIN probe if the WRI logging laptop was to be used. The DUIN Sonde import might have corrupted the WINLOGGER database. Furthermore, the WRI laptop showed erroneous functionality, i.e. part of its keyboard was not functioning, and difficulties occurred when deleting files. Accordingly, the logging program with the four WRI probes (HRFM, TCGS, GLOG and DUIN) had to be done by using the GEUS laptop, which would be available in Ghana until the departure of Kurt on the 19th October.

Therefore, the whole week from 1st to 5th October was used for a critical review of the respective sonde-text files and calibration-files for WRI probes, based on which some editing revisions of the files were done in accordance to communication with Robertson. Afterwards these files were installed on the GEUS laptop. Furthermore, the WINLOGGER software on the GEUS laptop was reorganized thus making it easier for the WRI team to operate it. Finally, the WRI DUIN probe was re-calibrated, and test logging with all four WRI probes (excluding the non-functioning caliper-probe) was successfully conducted in the test borehole at the WRI campus. Thereby, the necessary training of the WRI field team was obtained at the same time.