

## Downhole wireline density versus drill core density measurements in porous and vuggy rocks

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### ABSTRACT

The determination of *in situ* rock density is an important process in most opencast mining operations where an accurate estimate of total resource tonnage allows forecasting of metal production and life-of-mine. At the Skorpion zinc mine in Namibia, various techniques have been tried to improve density measurements, which are used to estimate mined tonnage and predict ore recovery based on laboratory measurements of ore yield per rock mass. Hitherto, the Archimedean submersion technique has been the basis of measurement. Downhole wireline density logging was put forward as a technology that could assist in getting accurate density determinations, particularly in the porous and vuggy arkose host rock.

A borehole logging trial was conducted where a dual spaced gamma-gamma density sonde and other complementary downhole measurements, such as the photo electric density and optical televiewer, were surveyed for comparison with core density measurements. The wireline logs were run successfully in both wet and dry borehole conditions and a high degree of precision was achieved. The accuracy of the logs was based on industry standard calibration and borehole compensation with some quality assurance using core data in non-porous sections of the borehole sample.

Results showed good agreement between core and wireline density in the non-porous rocks, but the wireline logs measured somewhat higher density in porous and vuggy zones. Analysis of the Archimedean technique used at Skorpion showed that the precision achieved was good, but accuracy was compromised by unsaturated and unmeasurable drill core porosity. The extreme geological environment and predominantly dry boreholes highlights the limitations of the gamma-gamma density measurement and demonstrates the critical requirement for sound data quality control and adherence to rigorous calibration standards. The availability of complementary measurements is found to be important to developing the right understanding of the wireline density response in an unfamiliar geological environment.

Skorpion mine has recognised the differences in density measured by the Archimedean and the wireline logging techniques, particularly in porous and vuggy formations and supports further test work for quantitative calibration of the response. Following the successful outcome of that work, the wireline method could be deployed on an ongoing basis to supplement and enhance the accuracy of the core-based measurements.

**Key words:** Borehole, Wireline Geophysical Logging, Density, Archimedes, Porosity, Vugs, Skorpion Zinc Mine

### INTRODUCTION

Skorpion mine, located ~40 km north of the Orange River, the border between Namibia and South Africa, mines a zinc oxide ore body, the main ore being sauconite. The host rock is folded, metamorphosed arkose, interbedded with tuff and underlain by a non-mineralised limestone (Borg *et al*, 2003). The ore is accessed via an opencast pit.

Formation density is strategically important to the mine because an accurate measure of total resource tonnage allows forecasting of metal production and life-of-mine. The mine had adopted a core-based Archimedean method of density estimation as the basis for resource tonnage estimates. The dry bulk density is calculated from the mass of the sample weighed dry (in air) and saturated (both suspended in water and in air). Due to

the vuggy and porous nature of the arkose host rock, accurate densities are difficult to obtain in more weathered or oxidised portions of the drill core. In such cases, it is possible that the Archimedean densities could be over- or under-estimated if water runs out of the pores before weighing the saturated mass in air, or if samples are not fully saturated in water before weighing them in water, respectively. In addition to implementing more rigorous controls, it was recommended that a number of alternative methods of measuring density, including downhole wireline logging, be investigated to test this perception and quantify the extent of any possible error.

A previous downhole wireline geophysical survey in 2000 had been partially successful, but there were some problems encountered then due to borehole caving and collapse. The logs had been run in reverse circulation (RC) percussion boreholes that did not offer the best environment for experimental work.

Seven diamond-drilled core boreholes were logged during June 2008 with a compensated gamma-gamma density sonde. Other borehole geophysical tools were mobilised to provide supporting data and a second density system (a different design) was run for quality assurance purposes. This additional density sonde also included photoelectric absorption as a measurement parameter. Approximately 1,000 m of density data were captured.

The density logs run during the trial at Skorpion were calibrated and borehole compensated. Special problems associated with unusual borehole conditions had to be overcome. Vugs and caving compromised the data in some zones. The use of other, secondary log measurements, such as gamma ray, caliper and optical televiewer, assisted in the understanding of the various log perturbations.

Ultimately, the density logs were considered accurate, within acceptable tolerances, over most of the accessible borehole metreage. Some correction of the long-spaced density log was required. Inaccurate sections of log could be flagged and either ignored or manually enhanced.

The conclusion of the trial was that the drill core system of density measurement had returned somewhat lower formation density in some sections of the porous arkose. The downhole wireline data sample in the porous arkose orebody is however small and more logging work is required to quantify the observed difference and to establish which of the two methods yields the more correct densities in such intersections.

## METHODOLOGY

The main objective of the logging trial was to capture accurate *in situ* density data in a range of lithologies, in

order to improve tonnage predictions. The following minimum goals were listed:

1. Measure *in situ* dry density using downhole geophysics (gamma-gamma dual density sonde);
2. Describe the correlation between density and ore grade (if any).

This paper reports on the first of these goals. Three sondes were run in order to assess the performance of the wireline technique. Table 1 lists the respective sondes and the different measurements obtained off each.

**Table 1: Tool suite deployed for the density study**

Sonde	Orientation	Speed	Logs included
1. Dual Receiver Gamma-Gamma Density			
DD6	Side-walled	6m/min	GRDE – Natural Gamma
			CADE – 1-Arm Caliper
			DENB - Short density
			DENL - Long density
			CODE - Comp density
2. Photo-Electric Density (PE)			
PE1	Side-walled	4m/min	DESS – Short density
			PDPE - PE density
			CAPE - caliper
3. Optical Televiewer (OTV)			
OTV	Centralised	1m/min	OTVM – Optical image
			TILT – Borehole tilt
			AZIM – Borehole azim

The sondes were calibrated at base prior to mobilisation to Namibia. On-site calibration verification was applied and all measurements were quality assured by a post-log calibration on return to base. Repeat runs were logged in selected boreholes to monitor measurement precision and electronic drift. For production logging, a calibration or test borehole is recommended to quantify measurement precision over time (Fullagar *et al*, 2005; Turner, 2002), but was not available for this test. For comparison, the PE1 density sonde has a similar 15 cm short-spaced gamma-gamma density measurement (DESS) to that on the DD6 density sonde. The PE1 tool, however, has a larger collimator radius and a marginally better front-to-back ratio (shielding).

**Natural gamma ray:** The natural gamma log represents total gamma ray counts occurring naturally in the rock

formations and is related primarily to the presence of radioactive uranium (U), thorium (Th) and potassium (K). It has an effective resolution of about 50 cm in narrow boreholes. At Skorpion, previous trials with a spectral gamma logging system indicated that the total count included all three common natural isotopes. The presence or otherwise of any particular isotope did not correlate well with rock type or mineralisation however. The general rule is that limestone emits low gamma radiation counts and any clay minerals or feldspar grains associated with the arkose, a higher count rate.

**Gamma-gamma density:** The density logs measured by the DD6 sonde (long- and short-spaced receivers) are a measure of electron abundance, which, for the major rock types, is inversely proportional to bulk density. The logging tool counts the concentration of medium energy gamma rays (emitted by a Cesium<sup>137</sup> source) scattered in the formation by interaction with electrons. The higher the density, the higher the electron concentration and the greater the moderation of the total gamma count rate at the detectors on the sonde. A low count rate then means high density.

The density measurement is very accurate in good borehole conditions. Borehole caving, variations in borehole diameter, high natural gamma counts, the fluid level and the fluid weight will all affect the density log and must be compensated for.

The logs will be perturbed by severe caving, especially in a dry borehole environment. Since the sonde provides two independent measurements (long- and short-spaced), the effect of caving will be different on each. The extent of separation of the otherwise overlaid logs is a measure of the severity of caving. A derived log, CODE, uses this difference to deduce some extra mathematical compensation that is applied to the long-spaced log. The log is an estimation of the density of the borehole sidewall where the volume being measured comprises the rock matrix (including mineralisation), pore spaces within the rock volume and air gaps between the sonde and the matrix (caving or exposed vugs). The compensated density log attempts to overcome distortions caused by the disproportionate effect of air-filled vugs and provide an *in situ* density log of weight per total volume. It will not succeed in severe vug-induced caving but will be a good estimate in most of the borehole.

**Photo-electric density:** The PE log represents the low energy part of the induced gamma ray spectrum measured by a sonde. Low energy gamma rays are emitted by an atom as a result of an incident gamma ray being absorbed. When gamma rays bombard the formation, both elastic scattering and absorption take place. The two interactions can be measured separately. Since absorption is more likely where target atoms have a higher mass, the PE log is sensitive to atomic number. It is most often used as a lithology discriminator and,

like the gamma ray log, is not much affected by borehole caving and porosity (including vugginess).

**Optical televiewer:** A centralised sonde floods the borehole wall with light and measures the intensity and colour of the light reflected off the borehole sidewall. The result is a continuous image of the borehole wall, which is, basically, a photograph without perspective. Log quality is reduced by dust and, below the water table, by muddy water.

During the Skorpion survey, some borehole accessibility problems resulted in reduced metreage, but sufficient data were captured for the purposes of the trial. Table 2 lists the boreholes logged and the depth range accessed by the downhole surveys in each. The boreholes at Skorpion were diamond-drilled to 200 m on average, at an angle of over 20° from vertical. The initial outside diameter of the boreholes was 96 mm (HQ) and changed to 76 mm (NQ) at depth when drilling conditions became too difficult to maintain the larger borehole size. The boreholes were generally dry but some intersected groundwater below 150 m. For the purposes of the trial, the dry borehole section was considered the primary logging target. The OTV was run in just three boreholes.

**Table 2: Trial Downhole Survey Boreholes**

Borehole	Drill depth (m)	Log depth (m)	Angle from vertical	Fluid level (m)
42	217	215	24	142
44	210	168	25	153
39	217	158	29	124
38	151	149	25	130
41	172	171	25	Dry
40	188	187	25	Dry
35	198	197	25	Dry

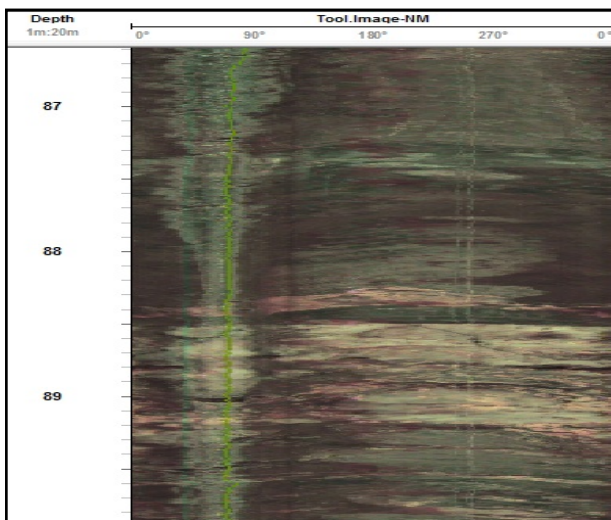
Data was quality-checked and processed on site and analysed later (off site) for density log assessment and reporting. The quality of the OTV image was variable but fit for purpose. All other logs were of good quality.

## LOG PRECISION AND ACCURACY

Like drill core measurements, wireline density logging, if done properly with good quality equipment, is a proven technique (Hallenberg, 1997; Rider, 1996; Firth, 1994, Samworth, 1992). Calibration and data quality procedures are established and have been documented (for example: Zhou and Esterle, 2008; Fullagar *et al*, 2005; Turner, 2002, Theys, 1999; Samworth, 1992). Generally, there are few problems associated with logging density in a 76 mm diameter cored borehole logged through competent rocks in a water-filled environment. Accuracy of better than +/-0.02 gm/cc is routinely achieved.

In the Skorpion study data, measurement precision is generally good but borehole caving is a cause of inaccuracy. The problem is made worse by dry borehole conditions where air presents a greater contrast with the rock density than water. It is important that the factors influencing the density response of the gamma-gamma sonde are understood and taken into account if the data are to deliver the correct and quantitative values for use in grade control systems.

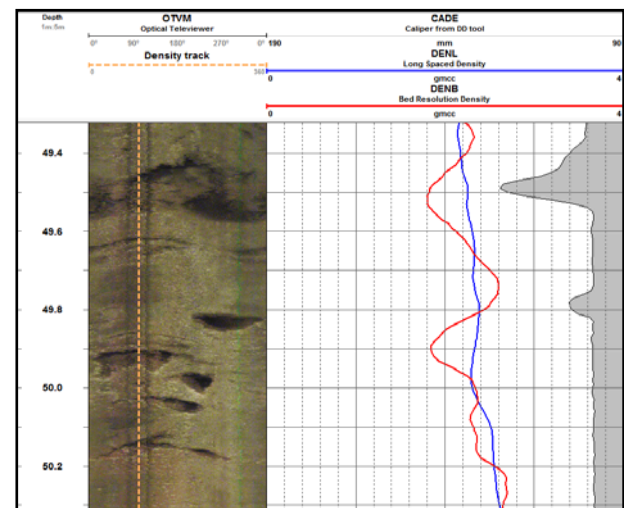
**Low-side wetting:** At Skorpion, some uncertainty is caused by water flowing down the low-side of the angled boreholes. The density sonde always looks downwards with its caliper arm projecting upwards. This might result in the sonde logging partially wet density rather than dry density. The optical televiewer image in Figure 1 shows water flowing down the borehole sidewall (thick white vertical feature on left side of the image). The location of the flow corresponds with the low-side of the borehole.



**Figure 1: Fluid flowing down the low side of the borehole captured on an oriented optical televiewer (photographic) borehole image**

The indicated flow is not strong and covers just 11% of the borehole circumference. Permeability must be low, or the flow would not be contained by the borehole. The measurement volume of the sonde is greater than the low-side of the borehole, in particular that of the long-spaced receiver. The maximum effect of saturation in 15% porosity will be +0.15 gm/cc (dry to wet density). In partial saturation, the long- and short-spaced logs should separate due to their different measurement volumes. It is difficult to quantify this wetting effect but, due to no visible separation of the logs, low apparent permeability and the large measurement volume, the increase in estimated dry density is expected to be much less than for full saturation. No compensation was applied to the Skorpion density logs.

**Vugginess:** The vugginess at Skorpion varies in cross section from a few millimetres to tens of centimetres. The vugs intersected by the survey trial boreholes were mostly small, elongated and orientated with the bedding or layering. Examples can be seen on the optical televiewer image in Figure 2. Since the image is orientated and the trajectory of the borehole is known, the paths of the density windows and the caliper arm on the opposite side of the sonde are also known. These are marked on the image (the yellow line is the density window and the green line the caliper tip). The density curves and caliper log (grey shaded) are displayed on the right of the log and confirm this orientation. The short-spaced density (DENB, red curve) moves left (lower density) as the window crosses the vugs. The long-spaced density log (DENL, blue curve) is less affected and the compensated density (CODE, black curve) describes a slightly higher density due to the calculated caving compensation.



**Figure 2: Vugginess and density**

The compensated curve (CODE) attempts to cope with vugginess. It is a mathematical correction (Equation 1) of the long-spaced density (DENL) based on the expectation that the short-spaced density (DENB) will be proportionately more affected by caving and vugs.

$$\text{CODE} = (1.2 * \{\text{DENL}\}) + ((-0.2) * \{\text{DENB}\}) \quad (1)$$

The compensation relies on DENL and DENB being properly calibrated and borehole compensated. They should overlay in good borehole cross-section. In fact, during the trial, it was noticed that DENL was describing a higher density than DENB in the arkose. The difference was +0.06 gm/cc in good borehole conditions. There was no calibration error. The contractor confirmed that there is a small systematic error in the DENL measurement due to a recent tool design change. On that basis, a minor shift was applied to the DENL log to agree with DENB (in good borehole conditions), before the extra compensation algorithm was applied. The shift was based on both the short-

spaced density logs and a correction factor supplied by the contractor.

For the density study, compensation for vugginess is not required because the desired measurement is an *in situ* bulk density. However, compensation is required for the disproportionate effect of air gaps and voids close to the detectors, which is due to caving caused by vugs. In Figure 2, the true intact rock density is described by the short-spaced (DENB) density curve (red curve) between the vugs. The compensated density (CODE) is thus measuring a lower density and including some vugginess effect.

The log of borehole 44 in Figure 3 shows the borehole caliper log with a picture of the density sonde superimposed (to scale) and the various density logs. Arkose (ARK in tan on the lithology column) is shown, as expected, to have a lower density than the dolomitised limestone (LST in blue). A second short-spaced gamma-gamma density log is captured on the PE density sonde. It was found to agree to within +/- 0.03 gm/cc with the short-spaced density log from the DD6 sonde. Note that the short-spaced density log has a similar resolution to the standard drill core lengths, 15 cm and 20 cm respectively.

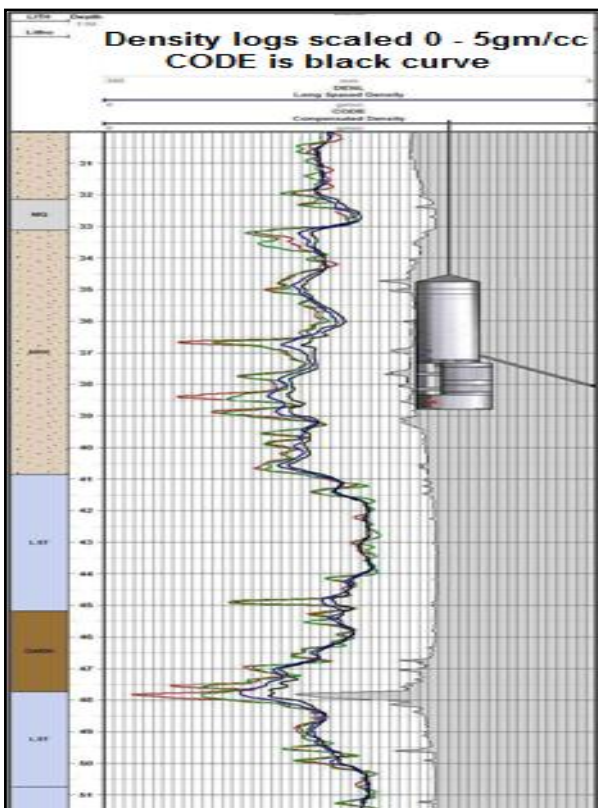


Figure 3: Vugs and the compensated density log

Overall, the three independent density logs stay within a range of approximately 0.1 gm/cc throughout, regardless of caving or vugginess. This is illustrated in the unmodified log section in Figure 4.

**Z/A correction:** The gamma-gamma density log measures the abundance of electrons in the formation, i.e. a measure of electron density ( $\rho_e$ ). Electron density is related to the true bulk density ( $\rho_b$ ) of the formation by the following equation:

$$\rho_e = 2 Z / A \rho_b \quad (2)$$

where Z/A is the ratio of the atomic number (Z) to atomic mass (A), which is typically 0.5 for common rocks and minerals (Samworth, 1992).

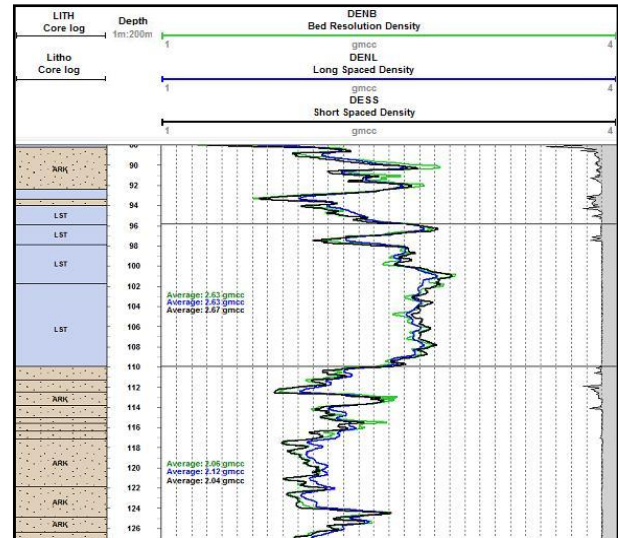


Figure 4: Wireline density variation – comparison of independent downhole density measures

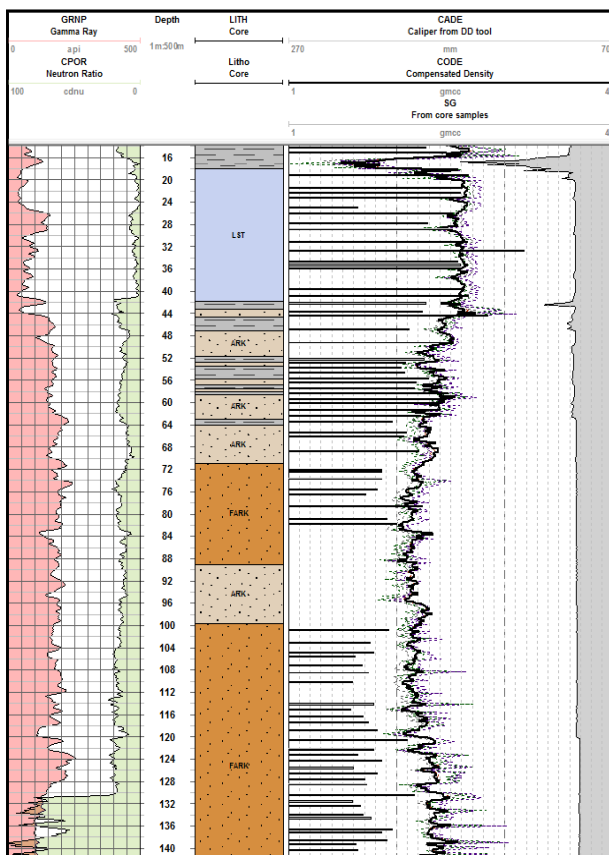
For a Z/A of 0.5 there must be the same number of protons and neutrons in the nucleus, so the number of electrons is equivalent to half the particles (nucleons) therein. An important exception is water, where H has no neutron, with a Z/A of 1.555 or an electron density of 1.11 gm/cc. Base metal elements with atomic numbers greater than 20 have an increased proportion of neutrons within their atomic nuclei. In this case, Z/A is less than 0.5 (e.g. Z/A for Zn is 0.459). There are several base metal ores present in the arkose rocks at Skorpion mine and their Z/A ratio can be averaged to 0.475. That would mean that, in an orebody containing oxides of zinc, iron, copper and manganese, with a total concentration of 25%, the log would understate density by about 1.25% since it would not be counting the extra neutrons. That represents about 0.035 gm/cc at Skorpion mine. Because typical concentrations of all metals are, on average, less than 25%, the understatement is expected to be between zero and 0.03 gm/cc.

Overall, the wetting effect of water running down the borehole will result in a slight overstatement of density and this will be partially cancelled out by the Z/A shift. Neither factor is quantifiable but their combined effect on accuracy will be in the order of +/-2%. The presence

of large vugs will perturb the density log and zones of severe vugginess in the dry borehole environment should be flagged as unreliable. Some correction for the Z/A shift is possible using the photoelectric log, but is not attempted here.

**PROCESSED RESULTS**

Figure 5 shows a depth section of logs captured within the ore-bearing arkose formation intersected by borehole 38. The drill core density measurements are included as a bar (interval) plot at the same scale as the compensated density log. The short-spaced and long-spaced density logs are plotted as well (dotted lines, underlying the compensated log) for QA. The core-based and wireline density logs show good agreement in the non-porous dolomitised limestone (LST) (Figure 5). Lower down the log, in arkose (ARK) and ferruginous arkose (FARK), the wireline logs describe a higher density than the drill core log. The difference is up to +0.5 gm/cc in certain sections of the core and averages +0.2 gm/cc for other arkose and ferruginous arkose intersections.



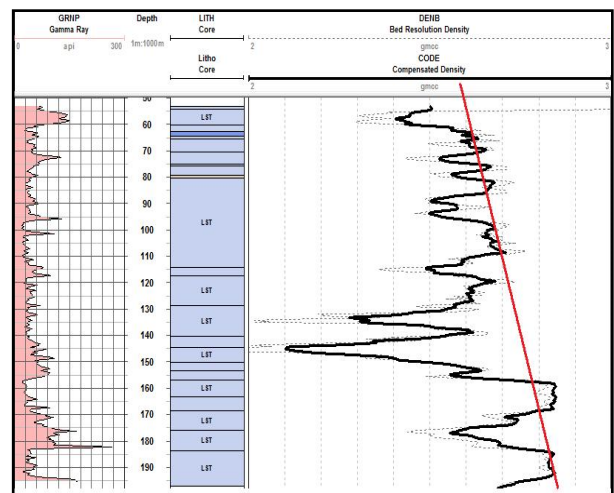
**Figure 5: Borehole 38 core v wireline density comparison**

Most of the survey boreholes intersected limestone. The wireline log and drill core densities in limestone correlate throughout. Where there are minor differences, the wireline log describes higher densities. The drill core measurements do not exhibit higher density than the wireline logs (apart from some

outliers), regardless of rock type. Where the wireline logs are consistently higher (denser) than the drill core measurements, these tend to occur in the lower half of the boreholes.

The expectation prior to the downhole logging surveys was that there is general increase in density with depth, but decreases (along with grade) with depth in the mineralised units (pers. comm.). The wireline logs describe a general increase in limestone density with depth as illustrated in Figure 6.

There are however no trends evident in the arkose (mineralised) units. The small number of arkose intersections logged in the test boreholes, allied with the variable vugginess typical of this unit, precluded evidence of any trends with depth in the arkose. Similarly, no discernible density trend with ore grade was observed due to the small sample of data.



**Figure 6: LST density increasing with depth**

It is noticeable that the wireline logs, regardless of absolute values, tend to be more consistent than the drill core measurements and reflects difficulties posed by the porosity and discrete sampling of core-based methods. The wireline logs also provide a continuous sample over the whole borehole depth range; note for example a 20 m depth zone (80 m – 100 m) in borehole 38 (Figure 5), where there is no drill core information.

Table 3 gives the average variance between wireline log and core densities for the main lithologies intersected above water level in the test survey boreholes. The large difference in borehole 38 (Figure 5) is the exception in the data sample studied. It is also the only borehole where significant intersection of ferruginous arkose is encountered above the water table. In general, the highest ore grades are encountered in ferruginous arkose, which also displays the most dominant occurrence of vuggy porosity. In borehole 38, the zones of arkose have a drill core density that is relatively close to that measured by the wireline logs. In the lower section of borehole 44, displayed in Figure 8, the wireline log describes rocks that are denser, on average,

than the drill core data, but only by 0.20 gm/cc. There are no significant differences between wireline and drill core measurements in limestone intersections in any of the survey boreholes, which, based on its density, has a very low porosity.

**Table 3: Variance between drill core and wireline log density for major lithological units above the water level**

Positive differences between core and wireline densities (gm/cc)				
BH NO.	LST	ARK	FARK	Comment
42	0.00	0.00	+0.20	
44	0.00	+0.20	N/A	
39	+0.20	N/A	N/A	No arkose
38	0.00	+0.10	+0.50	
41	0.00	N/A	N/A	No arkose
40	0.00	N/A <td N/A	No arkose	
35	+0.10	N/A	N/A	No arkose

LST = limestone; ARK = Arkose, FARK = ferruginous arkose

## CONCLUSIONS

Wireline logs captured at Skorpion Zinc Mine in 2008 provided a measure of *in situ* rock density as an alternative to the drill core based density measurements currently employed. The drill core (Archimedean) technique may suffer from inaccuracy or at least inconsistency in application in parts of the ore body that are highly porous and vuggy.

The downhole wireline density logs are also perturbed by severe vugginess, but the objective nature of the logs allows some compensation for this. Despite problems caused by borehole conditions and the nature of metallic ores, the logs could be used (after solving the long-spaced density problem) without correction or manipulation.

The logs infer that the Archimedean drill core density measurement could understate density in the vuggy arkose and particularly in the ferruginous arkose units. Since measurements in the non-porous limestones agree well, there seems to be confirmation that porosity or vugginess is the cause of the inaccuracy of the core-based method of density measurement. However, more data needs to be collected to confirm this observation. If the wireline technique proves to be a better measurement of formation dry density in vuggy or porous ore bodies, this method could have potential applications in other similar environments, e.g. nickel laterites.

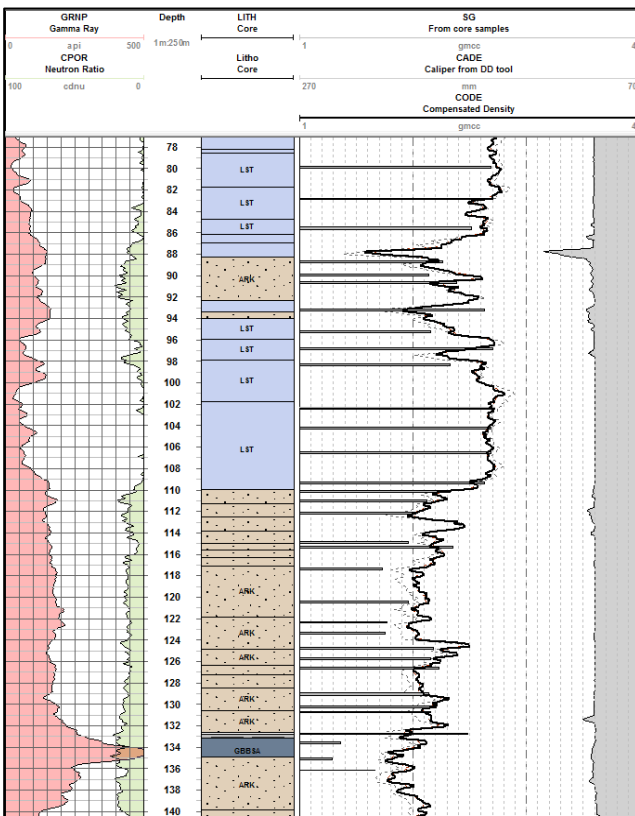
A drawback of downhole nuclear logging techniques is the hazard associated with the use of chemical radioactive sources in the borehole, in particular the risk of getting the probe and source stuck or lost down a borehole. While technical studies such as this are able to indicate the potential of the methodology, the practical application will rest with the acceptance and management of the attendant risks, or the development of alternative techniques for measuring density *in situ*. In this regard, the design of downhole electronic sources such as neutron generators, although not commercially viable at present, is encouraging.

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**Figure 8: Borehole 44 density comparison**

If vugginess and porosity are the cause of errors in the drill core measurement, the samples must be under-saturated during immersion. This indicates high porosity, particularly in the ferruginous arkose, but low permeability.

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