



Casing correction of slimline density logs for iron ore exploration

Jim Wordsworth

Weatherford

2000 St James Place, Houston, USA

Jim.Wordsworth@weatherford.com

Fredy Giraldo

Weatherford

Padre Mariano 82 504, Santiago, Chile

Fredy.Giraldo@la.weatherford.com

Julian Morales

Weatherford

Cra 72 #71–52 18B, Bogotá, Colombia

Julian.Morales@la.weatherford.com

SUMMARY

Slimline geophysical logs are frequently used worldwide in iron ore exploration because they provide key data for ore evaluation. Application can be limited by the fact that many formations associated with iron ore deposits are friable, increasing the occurrence of borehole collapse before geophysical logs can be obtained. A cased-hole correction scheme for density logs based on an existing technique developed for oil and gas (C–thru) has been developed. The technique enables accurate and reliable near-spaced density measurements in a cased-hole (or through-rods) environment by recharacterising the response equations of the density tool to account for the casing or rods. The method effectively treats the casing or rods as part of a “modified” density tool. The method means that it is possible to obtain quantitative data when the logging tools are run inside the drilling rods. The application of this technique minimizes the risks associated with logging unstable open holes in iron ores, and can reduce costs and operation times.

Key words: Iron Ore, Slimline, Density Logging, Cased–Hole, Open–Hole. Through rods, c–thru.

INTRODUCTION

Slimline logging is widely used in mining exploration campaigns worldwide. In the specific case of iron ores, slimline logs provide key information for the characterization of lithological units, and for the estimation of grade (quality) and reserves (tonnage). The main geophysical measurements for iron exploration are formation density, magnetic susceptibility, structural logs (acoustic and optical viewers, four arm dipmeter), and compensated sonic travel times (for geomechanical characterization of rock masses). One of the major difficulties for comprehensive logging in these materials is associated with the friable nature and low mechanical strength of some formations, which cause frequent borehole collapses. This condition limits the acquisition of complete open-hole logs and can increase the risk of entrapment of tools in some circumstances.

Logging through casing is a well-known challenge in the oil and gas industry, and several techniques have been developed to obtain open-hole values for some variables using cased-hole logs. In the case of iron ore exploration a slightly different approach is required, considering that the boreholes are

temporary, casing is not cemented, and that the density of the formations usually exceeds the typical values of sedimentary rocks. An adaptation of the oil and gas C–thru cased-hole processing technique (Elkington *et al.*, 2006) is used to obtain formation densities in iron ores using logs recorded through the drilling rods.

The recharacterisation stage of this technique requires both open-hole and cased-hole logs from a single borehole in order to properly adjust the density response functions of the standard density tool.

The magnitude of the differences between the open-hole and through-rods density logs in validation boreholes show that it is possible to obtain accurate and repeatable quantitative density measurements through the drilling rods, reducing the logging problems associated with borehole collapse.

METHODOLOGY AND RESULTS

The relationship between count rates, I , and formation density, ρ , is given by the response equation of the density tool for a single detector (Samworth, 1992):

$$I = E \cdot \rho \cdot e^{-k \cdot \rho} + F \cdot (c - t) \cdot (\rho_m \cdot e^{-k \cdot \rho_m} - \rho \cdot e^{-k \cdot \rho}) + G$$

Where;

ρ_m is the mud density,
 c is the borehole diameter (caliper),
 t is the effective tool diameter,
and E , F , G and k are constants.

The first term on the right side of the equation is related to the formation density, while the other two terms are contributions to the count rates associated with the borehole geometry and source activity, respectively. The values of E , F and G for open-hole environments are adequately known, and have been evaluated by measurements made in a set of well characterized test holes and pits including the Callisto facility in East Leake, UK.

The value of the exponent k is related to the spacing between the source and the detector (tool geometry), and to the mass–absorption coefficient of the source.

In many formations a compensated density log can be obtained by combining information from two detectors with different spacing from the source, each of them following a particular response equation with its own values of E , F , G and k . This compensation technique is not always available in iron ore environments - the relatively high density of the rocks and consequent attenuation of the gamma rays from the source can cause count rates at the far-spaced detector to be low with consequentially high statistical uncertainty.

Without the availability of a calculated compensated density curve, the challenge is to produce an accurate near-spaced density log which accounts for the effects of being acquired through the drilling rods.

The general effect of the steel rods is a reduction of the count rates recorded at the detector. Because of this effect it is necessary to determine a new set of values for E , F and G . That is the basis of the C–thru processing technique (Elkington *et al*, 2006), which states that the new values of the constants are controlled mainly by the nature and thickness of the casing (or in this case, the free-standing drilling rods). Therefore, a different set of E , F and G values will be required for each casing diameter.

There are no changes in the tool geometry or in the radioactive source so the value of k will remain constant.

The application of the C–thru technique requires a single borehole to be logged for both open-hole and through-rods measurements. Using the recorded count rates it is possible to recharacterise the response equation, by considering the drilling rods as part of a “modified” tool. New values of E , F and G for a given rod diameter are calculated by minimizing the root mean square errors (RMSE) between the open-hole and through-rods density logs. Those new values are then integrated into the acquisition software, allowing the correction for the effects of the rods and the determination of the equivalent open-hole densities directly in the field for subsequent through-rods logging.

Each application of the technique applies to a single type of drilling rods and assumes reasonable homogeneity along the entire length of the string. In this study, HQ drilling rods were used throughout the program.

Figure 1 shows the caliper, near-spaced density and far-spaced density logs for a characterisation borehole (HQ diameter) from the iron ore exploration project in Brazil. The red curves in that figure correspond to the original open-hole logged values, while the black curves are the values obtained from the through-rods log, with a set of constants E , F and G that minimizes the RMSE between the two logs. There is a very good fit between open-hole and through-rods densities for the entire borehole, with the larger differences associated with caves and narrow zones. For the far-spaced density the through-rods log is not continuous, because the combination of steel casing and high density rock prevents the recording of meaningful count rates at the far detector in some sections of the borehole.

The fit between open-hole and through-rods near-spaced densities is very good through the entire range of formation density values (from 2 to 4 g/cm³), showing that the modified response equation constants are effective for the different rock types present in the zone.

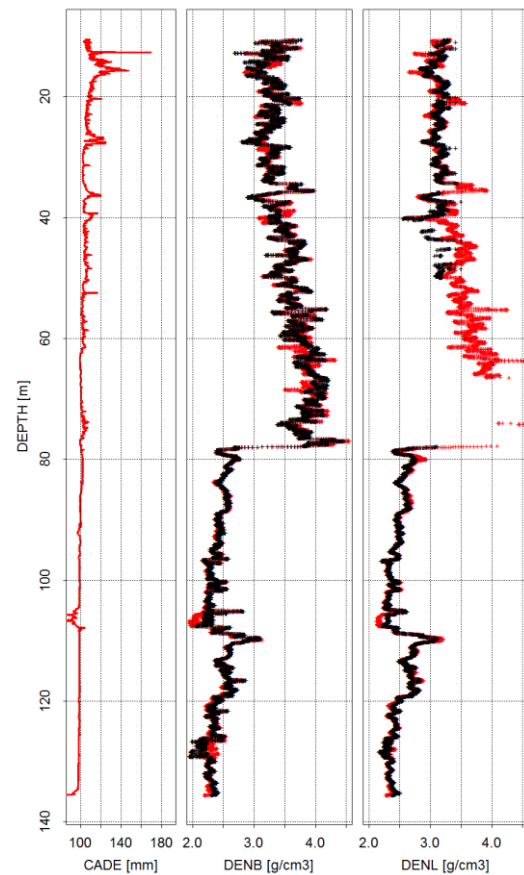


Figure 1. Open-hole (red) and through-rods (black) logs for the characterisation borehole. Caliper (CADE), near-spaced density (DENB) and far-spaced density (DENL) are shown in separate tracks.

Table 1 summarizes the residuals and percentage errors between open-hole and through-rods densities for the characterisation borehole. For both near-spaced and far-spaced curves, the mean of the residuals and errors is close to zero. A high proportion of both logs exhibits residuals lower than 0.1 g/cm³, as shown by the percentiles P10 and P90 in the table. Maximum and minimum percentage differences are close to 13% (less than open-hole logged density) and 16.5% (more than open-hole logged density) respectively for near-spaced densities, and close to 17.5% and 14% for far-spaced density. The distribution of the residuals for both densities is approximately normal and with mean close to zero, which suggests that the recharacterisation is well-behaved in statistical terms; i.e. the residuals do not contain any additional structure that is not accounted for in the model.

	DENB		DENL	
	Residual (g/cm ³)	% difference	Residual (g/cm ³)	% difference
min	−0.562	16.505	−0.384	13.953
P10	−0.070	2.432	−0.074	2.659
mean	0.002	0.012	0.007	0.150
P90	0.098	2.837	0.082	2.803
max	0.441	13.441	0.561	17.526

Table 1. Residuals and percentage errors for near-spaced density (DENB) and far-spaced density (DENL) in the characterisation borehole.

After the tool has been recharacterised and the response equation adjusted in the software, it is necessary to perform a validation of the technique in another borehole with open-hole and through-rods logs. Figure 2 shows the results of this process for a second HQ well from the same project in Brazil, and Table 2 summarizes the residuals and percentage errors obtained. There is a good match between open-hole and through-rods near-spaced densities at all depths within the borehole. The existence of caves causes a tendency towards underestimation of the bulk density values. The mean percentage errors for this variable are low (close to 3.5%), and for the majority of the log, between the percentiles P10 and P90, lies within acceptable ranges [from 1.3% (more than open-hole logged density) to 9.8% (less than open-hole logged density)]. In the validation borehole the far-spaced through-rods density is discontinuous, especially in the lower section where there is a marked increase in formation densities. The far-space through-rods density also exhibits a tendency towards underestimation, in particular in the zone between 0 m and 70 m deep where the frequency of caving is high.

The results from the characterisation and validation boreholes indicate that the main source of error in the through-rods logs is the existence of caves and narrow zones. In order to reduce as much as possible the existence of caves and narrow zones, the exploration drilling program was able to be modified to allow for all holes to be logged immediately after completion, and before the rods are ever tripped out of the hole. There are additional steps which can be taken to improve the hole conditions behind the drilling rods to ensure the best possible through-rods density results.

The implied improvement of the through-rods log is difficult to measure against any subsequent open-hole log, since the act of removing the drilling rods from the hole immediately changes the hole conditions. There are several techniques being investigated to solve the problem of the discontinuity of the far-spaced through-rods density log.

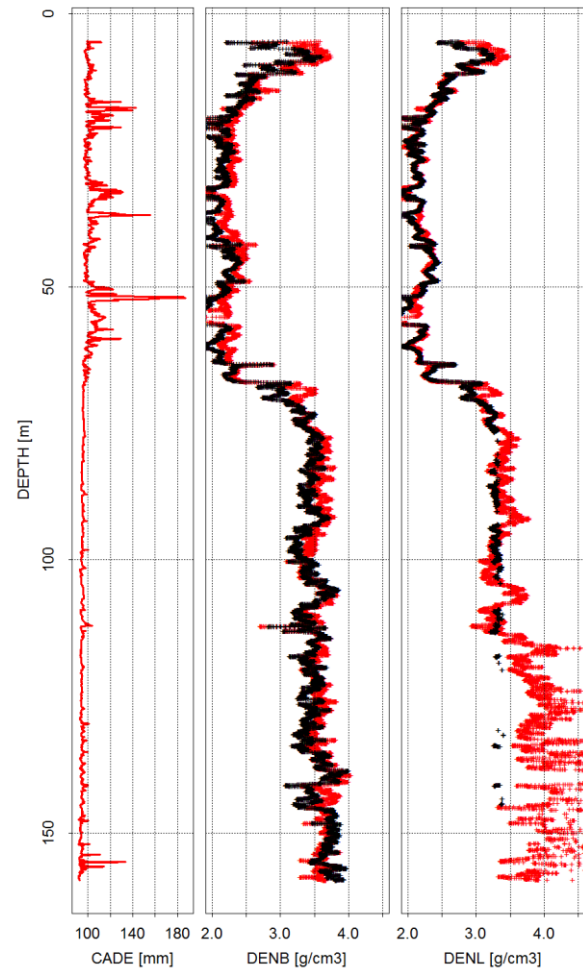


Figure 2. Open-hole (red) and through-rods (black) logs for the validation borehole. Caliper (CADE), near-spaced density (DENB) and far-spaced density (DENL) are shown in separate tracks.

	DENB		DENL	
	Residual (g/cm ³)	% difference	Residual (g/cm ³)	% difference
min	-0.326	48.083	-0.254	44.483
P10	-0.044	1.303	-0.077	2.959
mean	0.113	3.476	0.032	1.619
P90	0.274	9.753	0.187	6.992
max	0.931	41.786	0.609	27.987

Table 2. Residuals and percentage errors for near-spaced density (DENB) and far-spaced density (DENL) in the validation borehole.

CONCLUSIONS

An adaptation of a casing correction technique from the oil & gas industry was implemented, seeking to produce quantitative reliable near-spaced through drilling rods density logs in iron ores. The technique requires boreholes with open-hole and cased-hole data for the recharacterisation of the response equation of the tool, and for the validation of that recharacterisation.

Good agreement between open-hole logged and through-rods logged near-spaced density values was achieved in both characterisation and validation boreholes. The residuals and errors lie within reasonable ranges, and show that the methodology can be used for iron ore exploration, obtaining formation bulk density values directly in the field from logs run inside the drilling rods.

The main source of differences between open-hole and through-rods near-spaced densities is the existence of caves and narrow zones along the boreholes. The implemented technique allows the acquisition of logs through the drilling rods before extraction, minimizing the damage to the borehole walls and increasing the accuracy of the reconstructed values. With this solution, the risk of entrapment of logging tools is

reduced in an environment where friable formations are frequent. There is also an associated reduction in costs and operational times.

ACKNOWLEDGMENTS

The authors are grateful to WEATHERFORD's Wireline Technology Center at East Leake, UK, in particular with Mr. Roger Samworth, for his guidance during the implementation of this methodology. Productive discussions were sustained with VALE DO RIO DOCE Geophysicists, Mr. Dionisio Carlos and Mr. Wanderson Pereira. VALE authorized and encouraged the publication of this paper.

REFERENCES

Elkington, P.A.S., Pereira, C.A., and Samworth, J.R., 2006, A Novel Cased Hole Density–Neutron Log – Characteristics and Interpretation: SPE Asia Pacific Oil & Gas Conference and Exhibition, Australia.

Samworth, J.R., 1992, The Dual–spaced Density Log – Characteristics, Calibration, and Compensation: The Log Analyst, 33, 42–49