OATV for strength estimations in Copenhagen Limestone

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ABSTRACT
Copenhagen Limestone is a highly variable material. The sizes of rock constituents vary, as well as the basic classification parameters of the matrix material, such as the bulk density and the degree of induration. In the usual practice, these properties are observed at a limited number of specific locations along a core, most often discontinuous due to the intrinsic nature of material as well as the effects of coring process. Application of continuous logging techniques, such as Optical and Acoustic Televiewer (OATV), enables observation of rock properties in a continuous manner. Due to the differences in applied techniques and tested domains in situ and in the laboratory, the measurements are not necessarily interchangeable, but are able to supplement each other.
The Copenhagen Limestone OATV data considered in this work is gathered within the Copenhagen Cityring project
Previous experience shows that UCS strength and bulk density are well correlated in Copenhagen Limestone. The current work extends the framework of combined interpretation of laboratory and in situ tests presented recently, see Katic & Christensen 2014 2015.
The work investigated possibilities of making continuous estimation of UCS strength along a core. The correlations between the bulk density and the formation density are used as a basis for observing material variation, using acoustic and optical televiewer. The work shows that the logarithm of the acoustic amplitude can be used to describe the vertical variation of the material along the borehole depth. Hereafter, it is showed that a match between the acoustic amplitude and the density logs can be used for continuous estimation of UCS. Finally, the use of optical televiewer results is discussed and an interpretation method is suggested.

Keywords: Copenhagen Limestone, OATV, UCS.

1 INTRODUCTION

Copenhagen Limestone is a highly variable material. The sizes of rock constituents vary, as well as the basic classification parameters of the matrix material, such as the bulk density and the degree of induration. In the usual practice, these properties are observed at specific locations along a core, most often discontinuous due to intrinsic nature of material as well as the effects of the coring process. Application of continuous logging techniques, such as Optical and Acoustic Televiewer (OATV), enables observation of rock properties in a continuous manner; see Foged et al. (2011). Due to the differences in applied techniques and tested domains in situ and in the laboratory, the measurements are not necessarily interchangeable, but are able to supplement each other.
The Copenhagen Limestone data considered in this work is gathered within the Copenhagen Cityring project. The current work extends the framework of simultaneous interpretation of laboratory and in situ tests presented recently (Katic & Christensen 2014, 2015).
The work investigates possibilities of making continuous estimation of UCS strength along the core. A hypothesis implied herein is that if the strength measured in the laboratory correlates to the sample bulk density or one of its proxies (e.g. porosity), then a similar

correlation can be seen on the geophysical proxies of strength and density, such as the amplitude of acoustic wave measured by the acoustic televiewer, and formation density, respectively. A similar hypothesis has been made earlier by prof. Foged, suggesting that the median amplitude found by the acoustic televiewer relates to the induration of the core. However, it is understood that the correlations derived from the continuous OATV and/or geophysical logs may not be as clear as the correlations derived from the laboratory measurements. These differences may stem from the properties of the rock mass, such as fracturing, disturbance due to coring as well as other technical limitations of the field methods, such as the clarity of the fluid filling the borehole (see e.g. Williams & Johnson, 2004).

Using the correlations between the parameters assessed using OATV and laboratory measurements, UCS strength can be estimated from the established correlations between the UCS strength and bulk density. The final aim of the work is hence to assess the applicability of OATV for estimating the limestone strength.

2 SELECTED LABORATORY AND FIELD TESTING

2.1 *Correlation of UCS strength and bulk density*

Previous experience shows that UCS strength and the bulk density are well correlated in Copenhagen Limestone, see e.g. Hansen & Foged 2002 and Foged et al. 2007, 2011.

Figure 1 presents the measurements carried out during the additional investigation phase of the Cityring project.

The data shows a factor of 2 to 3 between the maximum and minimum UCS strength for the same bulk density. The UCS for the strongest and the weakest samples varies by a factor of nearly 40. These findings are in good agreement with aforementioned references and other available data.

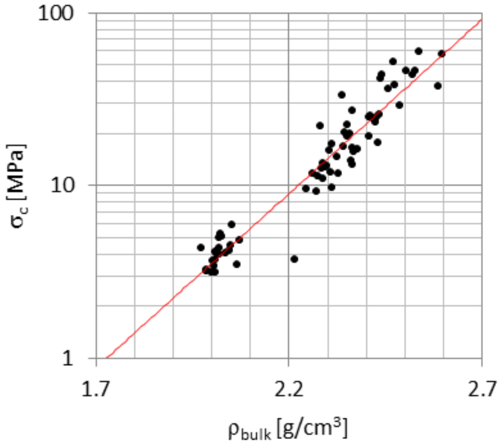

Figure 1 Correlation between UCS and bulk density of the samples on boreholes carried out in the additional investigation phase.

In terms of porosity, the semi-logarithmic plot presented in Figure 2 also shows a clear trend in agreement with previously published works (see e.g. Katić & Christensen 2015, Eberli et al. 2003).

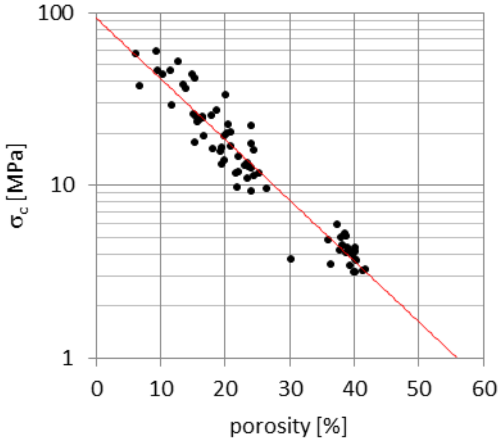

Figure 2 Correlation between UCS and porosity of the samples on boreholes carried out in additional investigation phase.

2.2 *Formation density and density of laboratory samples*

The formation density (compensated gamma-gamma density) is measured with a caesium source mounted on the probe that emits directional gamma radiation into the formation. The gamma radiation emitted from the source collides with the electrons in the formation and is scattered. The more electrons per volume unit (as in dense rocks), the larger the scattering of the gamma radiation, and the less gamma radiation is received by the sensors in the probe. The electron density is related to the density of the solid material, and the extent of the reflected radiation is inversely proportional with the formation density.

Three sensors are incorporated in the probe with an increasing distance from the source.

During logging, the probe is pressed against the borehole wall by a caliper arm. In boreholes drilled with the DTH method, the borehole diameter can vary considerably. In these situations, the contact pressure between probe and sidewall is not constant and the borehole fluid influences the measured values. In the part of the borehole with steel casing, the density log can reflect cavities behind the casing and not the exact density of the formation.

In some instances, the density log cannot be carried out due to unstable boreholes. Furthermore, the passage from the top soil drilling to the 146 mm core drilling sometimes obstructs the probes to enter the core-drilled section.

The large scattering of extensive datasets caused by the nature of the site and material is often caused by variation in technical means and conditions. This is found discouraging while seeking a correlation between parameters; namely, the parameters that are expected to correlate well based on the underlying physics show very weak to no correlation.

In this particular presentation, a choice was made to demonstrate the observations from OATV and geophysical testing on an example borehole, rather than on the whole dataset. The scattering stemming from different conditions between borings, including e.g. different ratios of Upper to Middle to Lower Copenhagen limestone, variable fracturing and positions of the flint beds due to possible inclinations of the rock mass layers, variable flow conditions etc. is minimized by focusing on a single borehole.

The same example borehole has been used for all of the following illustrations.

Figure 3 presents a correlation between the formation density and the density of laboratory UCS test specimens from the example borehole. It can be seen on Figure 3 that the formation density and bulk density of laboratory samples correlate within a tolerance.

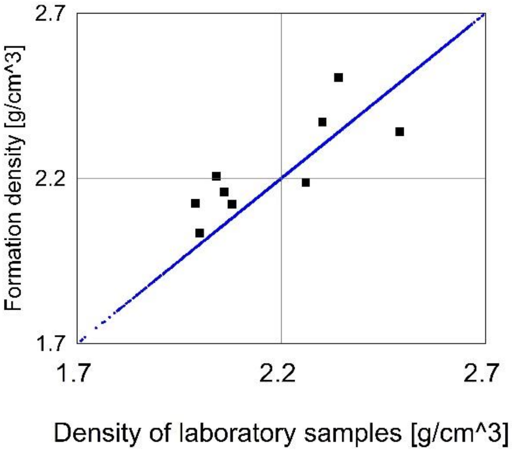

Figure 3 Correlation between the formation density and the density of UCS samples from the example borehole.

The scattering between the bulk density and the formation density stems from the difference in the way of measuring the density on laboratory samples and in situ, as well as from the difference in the volumes of material involved in a particular measurement. This is further emphasized by the fact that the values from the geophysical logs relate to a particular depth (although involving a certain volume of rock around the measurement point), whereas the bulk densities of the laboratory samples average the measurement over the height of a sample. If the formation density values are averaged over a length of the corresponding sample, the scattering can occasionally be reduced, depending on the horizontal distribution of indurations.

It is important to notice that bulk density and formation density parameters do not strictly reflect each other. While the laboratory-measured values of the bulk density reflect the core, the formation density measured in the field reflects the surrounding of the core. Given the presented variability of Copenhagen limestone, an argument can be made that these two domains are in fact as comparable as neighbouring samples and that large variations can occur. However, if the density within a core and out of the core are rather dissimilar, this information can be used for an assessment of the horizontal variability.

In line with this, points where the density measured in the laboratory is rather dissimilar from the assessed formation density, should be excluded from the set when attempting continuous estimation of correlated parameters such as UCS strength.

2.3 UCS estimates based on formation density

Figure 4 shows a combined plot between the bulk density and UCS strength (red symbols) and formation density and UCS strength (blue symbols).

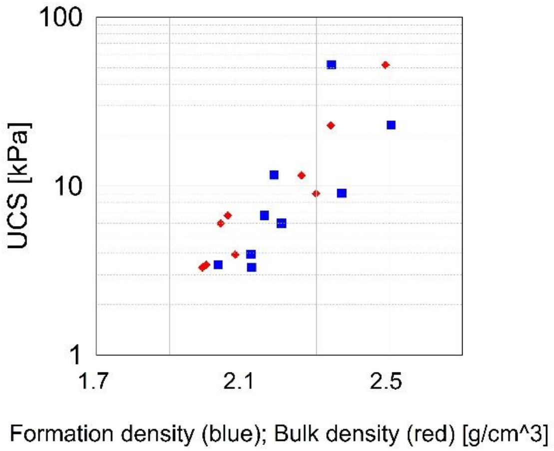

Figure 4 Correlation between the formation density and the density of UCS samples with UCS on the example borehole.

It can be seen that the trend between the UCS and density exists, whether the bulk density or formation densities are considered. This implies, although the correlation is not smooth, that an estimation of strength based solely on the formation density is possible, under condition that an appropriate pre-determined correlation between the UCS and the bulk density has been established on the samples from the same material and formation.

2.4 OATV

The Optical and Acoustic Televiewer (OATV) probes measure a continuous and orientated image (+-3 degrees) of the borehole walls. Both optical and acoustic images are oriented from the north.

The Acoustic Televiewer (ATV) probe uses a fixed acoustic transducer and a rotating acoustic mirror to scan the borehole walls with a focussed ultrasound beam. The amplitude and travel time of the reflected acoustic signal are recorded simultaneously as separate image logs. Features such as fractures reduce the reflected amplitude. Fractures appear as dark traces on the log. These traces are sinusoidal if the fractures are inclined.

The zone of passage between the top soil drilling and the 146 mm core drilling challenges the televiewer logging similarly as the density logging (see ch. 2.1).

The optical televiewer is recorded with a vertical resolution of 0.7 mm and a horizontal resolution of 720 pixels/revolution.

The acoustic televiewer is recorded with vertical resolution of 2 mm and horizontal resolution of 360 pixels/revolution.

3 CORRELATIONS OF LABORATORY TEST RESULTS AND FIELD TEST RESULTS

3.1 Amplitude of acoustic televiewer as index test

The acoustic amplitude images are believed to correlate to the degree of induration at a certain depth along the borehole. If so, the hypothesis is extended to believe that acoustic images will present a reflection of density and thereby correlate to the UCS strength.

The following analysis is carried out using statistics on the data collected around the perimeter of the example borehole. As the data is collected with different vertical raster, in the first step, the logs are statistically processed around the perimeter of the borehole at particular record depth, and thereafter reduced to the same vertical scale.

Figure 5 presents a correlation between the amplitude of acoustic televiewer (average, median, and 50% percentile), formation density, the bulk density measured on UCS samples and the UCS strength along the depth of the example borehole.

The 50% percentile of the acoustic amplitude and the density of UCS samples along the depth of the example borehole presented on

Figure 5 are isolated on Figure 6, where the presentation scale of the acoustic amplitude log is chosen to show the correlation with the density.

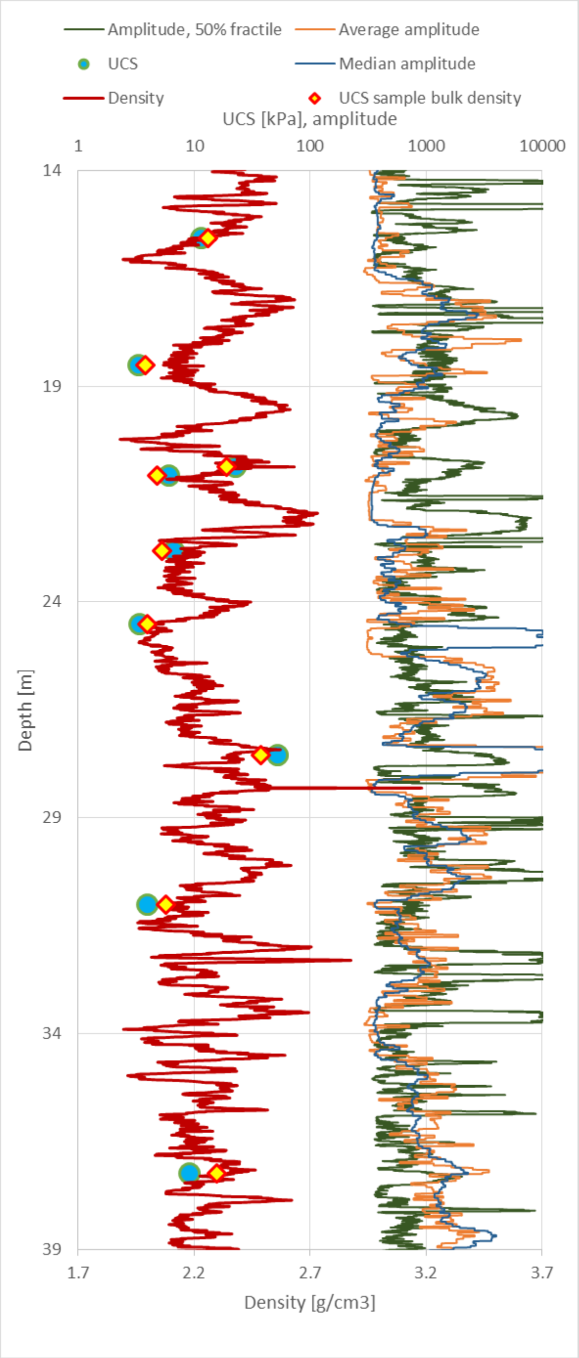

Figure 5 The formation density and the density of UCS samples with the UCS strength and the amplitude of acoustic televiewer through various statistical means along the depth of the example borehole.

Based on the results of the amplitude versus depth plot presented on Figure 6, a cross-plot of the read-out values of the logarithm of the amplitude vs. UCS, together with the plot of the bulk density vs. UCS is given on Figure 7.

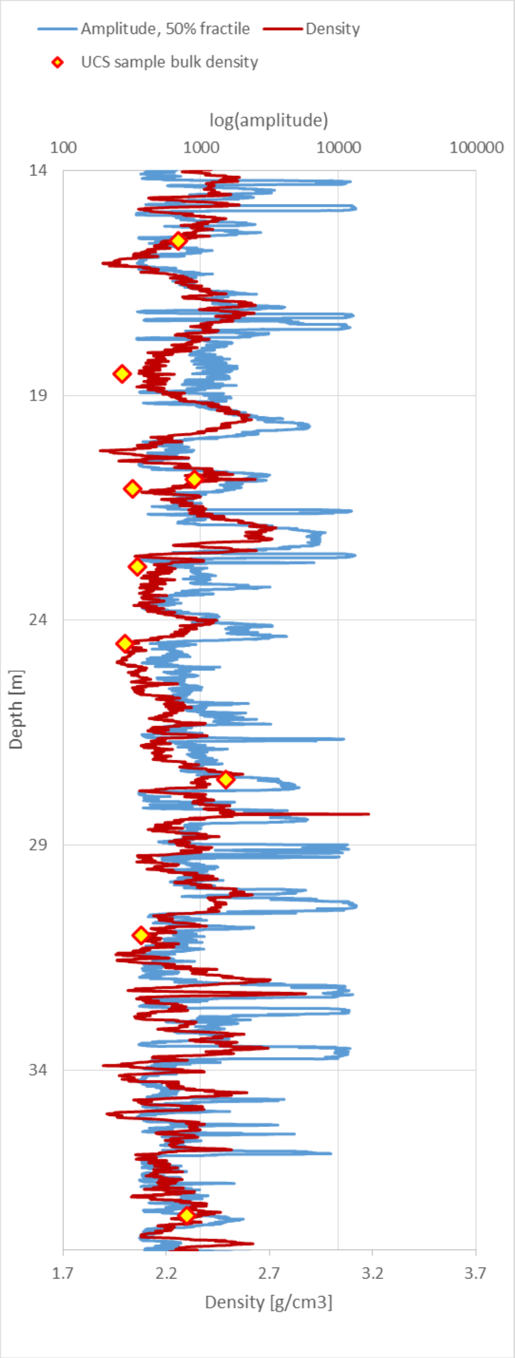

Figure 6 Correlation between the amplitude of acoustic televiewer (50% percentile), formation density and the density of UCS samples along the depth of the example borehole.

It is apparent from the presented Figure 6 & Figure 7, that a correlation between the amplitude and UCS has the trend following the correlation between the bulk density and the UCS. Discrepancies between the values seem to reflect different conditions within the core and around the borehole.

Based on the presented plots, it is concluded that a direct correlation between the UCS strength and the amplitude of the acoustic televiewer is possible in this particular case.

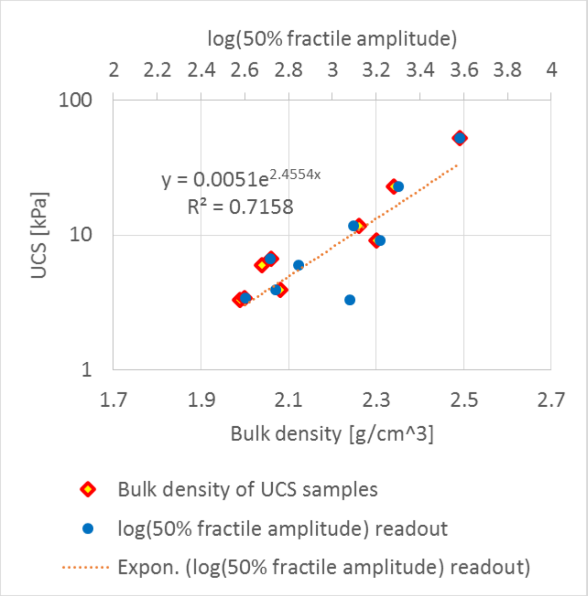

Figure 7 Cross-correlation between the amplitude of acoustic televiewer (50% percentile), formation density and the density of UCS samples on example borehole.

3.2 *Linking the optical televiewer log to acoustical and mechanical measurements*

In a common logging procedure, the optical televiewer log is recorded first, in order to provide a visual estimate of material prior to running the acoustic logging. This estimate is subjective and depends on the experience of the personnel doing the logging. An attempt to quantify such an estimation, and hence reduce the subjectivity by comparing the visual log with the other measurements, is carried out hereafter.

In order to compare the results of the optical televiewer with the other measurements presented, the full two dimensional visual log is reduced to a longitudinal log plotted versus the borehole depth in a similar way as the acoustic amplitude log.

The image of the optical televiewer is a matrix-sorted collection of points along the depth and perimeter, where each point is associated with a set of coordinates in a chosen colour system. The data processed on the particular example borehole have been presented in terms of RGB system, where each of the coordinates (Red, Green and Blue) is independent of the other two. The matrix representing the picture is therefore five-dimensional, out of which two dimensions (the depth and the angle along the perimeter measured from the north) are physical, and the other three are colour coordinates.

The range of the colour coordinates in the RGB system is from (0, 0, 0) depicting black colour, i.e. the darkest materials, to (255, 255, 255) depicting pure white colour, i.e. the brightest materials. In order to enable direct comparison with the density log, the results are presented in terms of an average colour, where the average is taken as a third of the sum of the component colours along the perimeter.

In comparison with the geophysical, acoustic and mechanical measurements, optical televiewer has the smallest penetration into the bulk of the material. In fact, it reflects only the surface of the borehole, hence the engaged volume described by the test is close to zero.

Averaging of the optical televiewer results in terms of colours is particularly influenced by the occurrence of flint and fractures, and more so than the other measurements mentioned within this study. Possible reasons for this are as follows.

The fractures are depicted by the optical televiewer as dark lines, which coincides with the dark flint – whether present in the fracture or not. Hence, the spikes in the optical televiewer log will coincide with mechanical properties of either flint or hollow space, which are on two opposite ends of the range of values. This is depicted on Figure 8.

More so, not all of the flint in Copenhagen Limestone is dark. For these reasons, it is understood that averaging of the optical televiewer results is not likely to correlate noticeably with the other measurements. However, as the fractures are generally very thin, it is expected that some notions of the trend may be visible.

Figure 8 shows that the average colour log weakly correlates with the formation density log, with a limitation in the depths including flint. The discrepancies between the logs, however, can partially be explained by the horizontal variability of the material, as well as different absolute volumes of material involved in various logs.

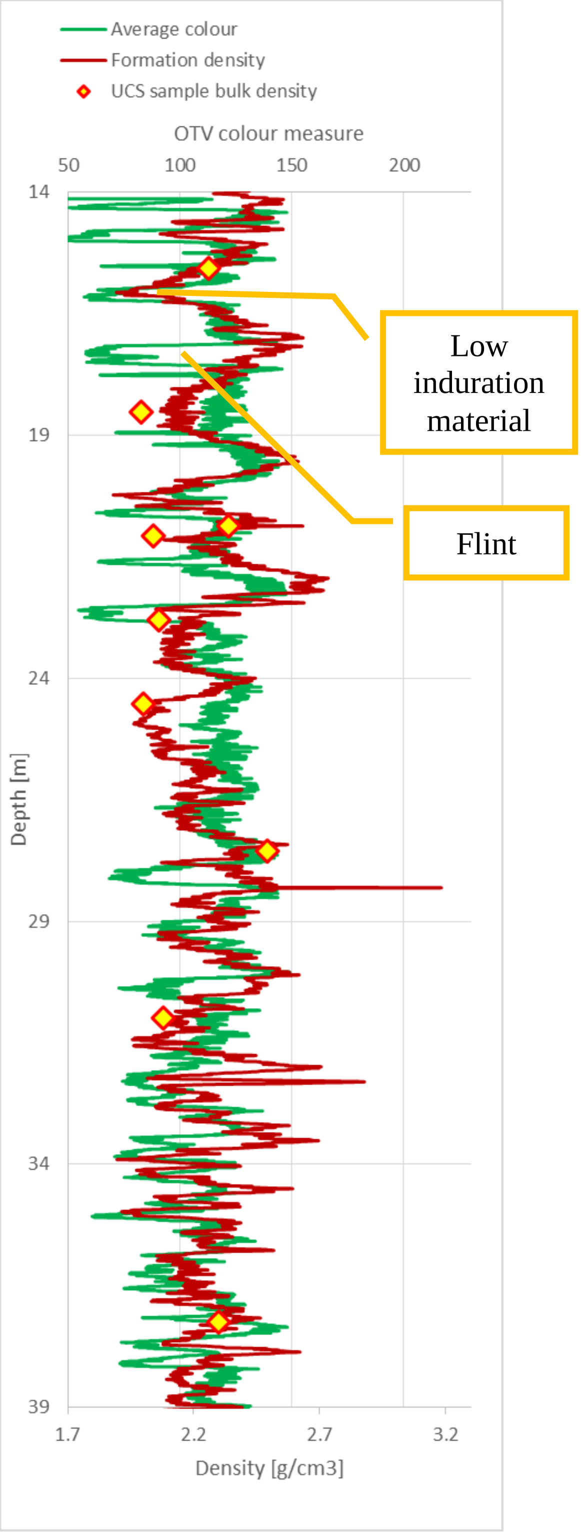

Figure 8 Formation density and UCS strength with the optical televiewer colour measure along the depth of the example borehole.

4 DISCUSSION AND CONCLUSION

The initial work presented a systematic correlation between the mechanical strength tests (UCS) carried out at certain depths along a borehole, and continuous logs of formation density. Despite the obvious difference in measuring domains, namely core material vs. the surrounding rock mass, the presented correlation is in general agreement with the previously established dependencies between UCS and the bulk density measured on the laboratory samples. Based on the observations, the differences between the formation density and the bulk density can be primarily attributed to the variation of the induration, i.e. material, within the core and in the surrounding rock mass. The differences in the actual measurement methods amplify the scattering, but seem to be secondary to the variation of material properties.

The tensorial representation of the acoustic amplitude and the colour logs makes it challenging to correlate these measurements with longitudinal logs and pointwise measurements. In order to enable a correlation, different ways of linearizing the two presented tensors are considered, including statistical measures such as percentiles, median or average.

While attempting to establish the correlation between the acoustic amplitude and density / strength measurements, average, median and 50% percentile have been visually compared. It is concluded that for this particular location the 50% percentile measure, presented herein, matches the formation density log somewhat better than the average and median values, and therefore it is presented on the Figure 6 and Figure 7. However, further investigation is needed to conclude if this is a general rule or an exclusive occurrence.

It should be noted that the scattering of the results of the acoustic amplitude is related to the scattering of the borehole radius and variable induration in the horizontal plane.

For example, if the induration close to the edge of the borehole (and possibly inside the core) is low, then the radius may be enlarged during the drilling process, by washing out some of the material. This means that the material left in the borehole, which is logged thereafter, is stronger, hence the amplitude will relate to the higher induration than what is estimated along the surface of the core, and possibly higher than within the core. On the contrary, if the material close to the surface of the boring (and possibly inside the core) is stronger, then it is possible to have it chipped from the weaker underlying material during the coring process. Consequently, in this case, the amplitude might relate to a lower induration.

These observations indicate that only measurements relating to a stable borehole wall conditions should be taken into account for establishing general trends. When establishing the relevant correlations based on the amplitude, applicable to a wider area and including several logs, the amplitude measurements need to be filtered in such a way that all the measurements relating to radii outside of certain bounds have to be disregarded. This has not been included in the present study.

The questions stemming from the acoustic televiewer analysis, namely what are the relevant bounds of radii to be included and how do they relate to the evaluation of the existing, natural, fracturing of the limestone depicted by OATV, are not discussed herein.

Although the presented processing of the optical televiewer log is merely more than an intellectual exercise, a certain overlapping of trends depicted in Figure 8 is observed.

A major obstacle with the presented analysis of the optical televiewer results is the colour match between fractures and flint, as mentioned above. However, if the average colour is understood as a “pressure-equivalent measure” of a colour log, a question can be risen if an alternative “shear-equivalent measure” representing a distance between the darkest and the brightest pixels around a perimeter, would bring an additional insight for continuous comparison. Based on this, it is concluded that while the presented optical televiewer results cannot be independently successfully used for correlations with density, and thereby strength, a direct comparison of the longitudinal logs shows how the intensity of colours correlates to the density of the samples.

Based on the presented logs, it is concluded that a continuous estimation of the strength is possible by using formation density and the amplitude of the acoustic televiewer.

5 ACKNOWLEDGEMENTS

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