# Utilising data science to test similarity of rock mass unit strength distributions in the Pilbara

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## Abstract

*Rio Tinto Iron Ore (Rio Tinto) undertakes diamond drilling within the Pilbara to geotechnically characterise the rock mass pertaining to proposed pit walls prior to implementation every year. Data from the diamond core is logged, tested in the field and in the laboratory; then committed to a local database and analysed for that particular pit or deposit when the need arises. Currently there is the assumption that each deposit within the Pilbara has independent strength properties and is diamond drilled extensively as a result.*

*Within the Pilbara rock masses there are a series of continuous, stratified units whose genesis are from the same depositional, folding, faulting and weathering events. This paper aims to utilise diamond core logging data to statistically verify that there are similarities of strength properties for some of the rock units across the Pilbara in neighbouring deposits. Proving this to be the case potentially will provide statistical evidence and the impetus to enable the Rio Tinto geotechnical department to reduce the metres of diamond drilling undertaken with a zero net effect on slope stability and safety in implemented slope designs.*

*A total of 39,815 test observations from 2008 to 2018 from five separate neighbouring deposits were used in this study; and were derived from three different tests including field estimated strength (FES), point load (PLT) and unconfined compressive strength (UCS) which are key parameters in slope stability design. The data was interrogated using state-of-the-art data visualisation and statistical software appropriately chosen based on the size of the samples and nature of the distribution. This research follows on from recommendations made by Maldonado & Haile (2015) applying non-parametric statistical methods to the skewed data for a more appropriate approach.*

*This study found sufficient statistical evidence that there is similarity in rock strength properties between five proximal deposits with 95% confidence in the vast majority of cases.*

**Keywords:** *drilling, statistics, optimisation*

## 1       Introduction

Planned geotechnical diamond drilling and associated laboratory testing expenditure is required to obtain data that feeds into current and future pit slope design parameters to optimise safety and productivity. Historically; there is the assumption that each deposit and pit within the Pilbara has unique rock mass unit strengths. However, the rock mass units are repeated throughout the Pilbara and have evolved through the same depositional, folding, weathering and faulting events.

Cost and productivity gains can be made if statistical analyses of rock mass strengths show evidence to accept that there are similarity of strength properties for rock units across the Pilbara region. Geotechnical diamond drilling of new deposits can be minimised essentially as a check that the strength falls within the range obtained. Maldonado & Haile (2015) investigated the similarity of rock mass strength in the Pilbara using statistical techniques appropriate for normally distributed data. This paper identifies that the data is skewed and uses an appropriate statistical technique for this case.

## 1.1      Rio Tinto Pilbara Iron Ore infrastructure

In the Pilbara of Western Australia; Rio Tinto operates a world-class integrated network of 16 iron ore mines, four independent port terminals, a 1,700 km rail network and related infrastructure as described by Rio Tinto (2019).

## 1.2      Regional and local geology

Rio Tinto's operating mines and undeveloped deposits are located regionally within the Hamersley Province or Hamersley Basin. The Hamersley group is a 2.5 km thick sequence of marine sedimentary and volcanic rocks of Late Archaen to Palaeoproterozoic age. It contains five major banded iron formation (BIF) units, which the Brockman Iron Formation and Marra Mamba are highest iron ore grade.

The Brockman Iron Formation is divided up into four members, Dales Gorge, Whaleback Shale, Joffre and Yandicoogina Shale. Dales Gorge and Joffre are predominantly mineralised and comprise interbedded shale and BIF.

The Marra Mamba iron Formation is subdivided into three members, Nammuldi, MacLeod and Mt Newman Members, and consist of interbedded chert, BIF, carbonate and shales.

The Hamersley Province has undergone three major tectonic events. From a geotechnical perspective, the Pilbara iron ore mines are challenging environments due to their structurally complex nature and anisotropy of the banded rock mass as mentioned in Green & Borden (2011) and in Figure 1.
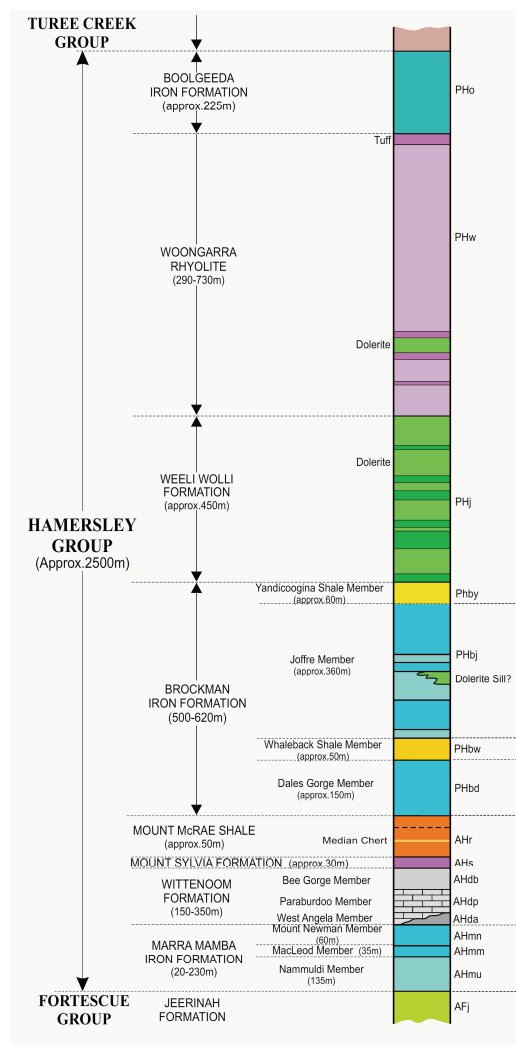


**Figure 1      Stratigraphy of the Hamersley Group (Green & Borden 2011)**

The intent of this paper is to prove that there is sufficient statistical evidence using the Mann–Whitney U test statistical technique; that there are similarities of strength properties between deposit group means; filtered by test type, weathering grade, lithology, strand and stratigraphy. In proving this, geotechnical diamond drilling metres may be able to be optimised.

## 2 Data

### 2.1 Sample dataset

'Mining Area A' was chosen as a stratified sample to trial this method of statistical inference; as it was known that there were sufficient data of generally good quality from 430 diamond drillholes; drilled from 2008 to 2018. The dataset has ~40,000 laboratory and field tests recorded in the database. Deposits have been separated into 'Deposit 1', through to 5 and occasionally 'Deposit 6' has data which was used.

### 2.2 Dataset clustering

The data was clustered by each combination of test type, lithology, strand, stratigraphy, weathering and pit.

The three types of field and laboratory testing used in this study included:

- Field estimated strength (FES).

- Point load test (PLT).

- Unconfined compressive strength (UCS) test.

The data was also grouped according to three BIF geology and mineralogy classifications arranged in descending order of magnitude; including:

- Stratigraphy; otherwise known as the Formation.

- Strand; otherwise known as the Member.

- Lithology; also known as the rock type or dominant mineralogy.

The third grouping included the weathering grades of rock and these are outlined in the table in Section 2.4.

### 2.3 Field and laboratory testing

#### 2.3.1 Field estimated strength

The manual index test of rock strength is done by striking the sample of intact rock with a geological hammer and noting the result as it fits the 'Field Identification' based on the descriptors in Brown (1981).

#### 2.3.2 Point load testing

Point Load testing in the field gives an estimate of the UCS of an intact rock sample. The diamond core sample is mounted between two pointed platens and pressure is applied until failure of the sample occurs. This load is then recorded as the peak applied load. Core can either be placed between the platens axially or diametrically in relation to the pointed platens. Testing was completed using ISRM (1985) standards.

The size corrected Point Load Strength Index (Is(50)) is 24 for BIF and 15 for Shale which are referenced from an investigation of Rio Tinto Pilbara rock samples (Donders 2009). The Strength Correlation factor (k) for Rio Tinto Pilbara Shales ranges from 9 to 13, and for BIF the k value ranges between 20 to 23 (Heslin 2014). The k value is the multiplier for deriving the UCS from the Is(50) value.
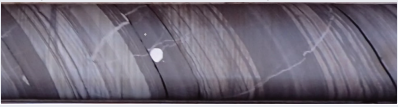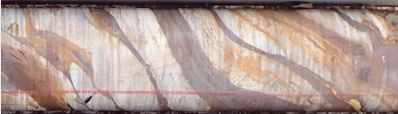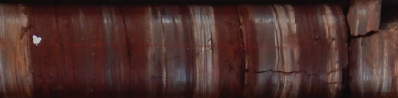
### 2.3.3 Unconfined compressive strength testing

This laboratory test subjects a diamond core sample to an axial load in a machine; between a top and a bottom plate. The bottom plate is slowly raised until an axial load is applied to the sample, and then until the sample shears.

## 2.4 Weathering

Rock weathering classifications used are described in Table 1 which is a hybrid of the ISRM convention (Brown 1981) and site-specific additions.

**Table 1 Rock weathering classification**

| Code and description | Discolouration extent | Fracture condition | Surface characteristics | Photo |
|---|---|---|---|---|
| Fresh (FR); no visible sign of rock material weathering. | None | Closed or discoloured | Unchanged | SHL (shale): <br><br> BIF (banded iron formation): |
| Slightly Weathered (SW); discolouration indicates weathering of rock material on discontinuity surfaces. Less than 5% of material altered. | <20% of fracture spacing on both sides of fracture | Discoloured, may contain thin filling | Partial discolouration | SHL: <br><br> BIF: |
| Moderately Weathered (MW); less than 50% of the rock material is decomposed and/or disintegrated to a soil. | >20% of fracture spacing on both sides of fracture | Discoloured, may contain thick filling | Partial to complete discolouration, not friable except poorly cemented rocks | SHL: <br><br> BIF: |
| Highly Weathered (HW); more than 50% of the rock material is decomposed and/or disintegrated to a soil. | Throughout | Filled with alteration minerals | Friable and possibly pitted | SHL: <br><br> BIF: |

| | | | | |
|---|---|---|---|---|
| Completely Weathered (CW); 100% of rock material is decomposed and/or disintegrated to soil. The original mass structure is still largely intact. | Throughout | Filled with alteration minerals | Resembles soil | SHL:<br><br>BIF: |
| Residual Soil (RS); all rock material is converted to soil. The mass structure and material fabric are destroyed. There may be a large change in volume, but the soil has not been significantly transported. | Throughout | N/A | Resembles soil | SHL:<br><br>BIF: |

## 2.5 Data quality and validity of testing

### 2.5.1 Field estimated strength

The number of FES observations is proportional to the duration of operation and size of the pits within the Mining Area. This dataset is considered the least accurate due to the variability in testing method employed but due to the large number of observations this inaccuracy is considered to be diminished and will converge around a central mean.

### 2.5.2 Point load tests

Only valid PLT observations were used in this investigation; and according to the criteria given by the ISRM (1985) and include duration of test between 10–60 seconds and failure mode passes through two loading points. As with the FES tests, the most abundant deposit data observations come from the deposits which have been well established over a longer time period. It is important to note that the majority of PLT observations were valid. As shown in the figure in Section 3.1.3, there is an anomalous lower UCS result for R6 as compared to R5 which may be the result of weathering classification discrepancies.

### 2.5.3 Unconfined compressive strength

The quality of UCS laboratory testing results varied; so the addition of a confidence rating dropdown menu of 0 to 3 was added to the database which gives an indication of the quality of the test data; which included:

- 0 being very low confidence (for example, no laboratory test certificate or photo able to be located).

- 1 being low confidence; laboratory has noted test is invalid- use with caution (for example, the length to diameter ratio of the sample is outside the Australian Standard guideline, AS 4133.4.2.1 (Standards Australia 2007).

- 2 being moderate confidence; laboratory has noted test is valid, Rio Tinto has noted test is invalid (for example, the test duration is outside the Australian Standard guideline, AS 4133.4.2.1 (Standards Australia 2007).

- 3 being high confidence, test is valid. Neither the laboratory nor Rio Tinto judges the test as invalid for any reason.

Only the confidence 2 and 3 rated UCS data was used in this study. UCS test durations outside 5–10 minutes were excluded from the statistical analysis. Likewise, for test specimens that did not meet the length to diameter ratio requirements as recommended by the ISRM (1979).

Other validation issues which were rectified included adding 'bulging' as a valid failure mode, the UCS value in the database differing to that on the laboratory certificate, laboratory testing photographs not able to be located and no UCS duration of test recorded in database. Only UCS tests which failed through intact rock were included in this dataset.

# 3 Methodology

## 3.1 Descriptive statistics

Numbers of observations of the Mining Area dataset classifications were as follows:

- FES: 28,789.
- PLT: 10,365.
- UCS: 661.

Initially each group of tests were plotted to gain preliminary insights into distribution of weathering, strength and stratigraphy.

It was not known at the preliminary stage what would be the most effective way of grouping data in terms of weathering and stratigraphy/strand/lithology category.

### 3.1.1 Data visualisation software

The 'Tableau Desktop' software was used to create initial visualisations of the test data to assist with choosing the correct statistical method to quantitatively assess the similarity of the individual deposit strength populations. The exported csv's of the test data were imported and manipulated to convert the data into meaningful insights.

### 3.1.2 Field estimated strength

The FES distribution of all the mining area data was skewed to the right as seen in Figure 2 (bottom histogram). The top histogram shows the number of samples within each strength grade in the dataset is a normal distribution.
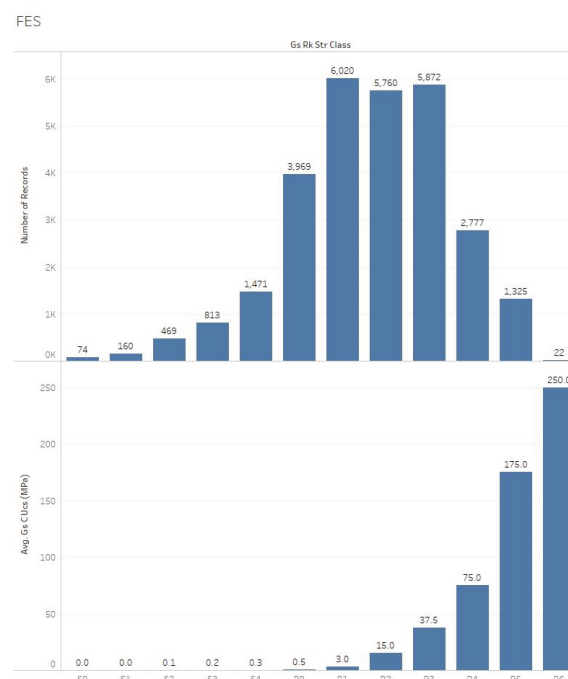


Figure 2    Field estimated strength (FES) by number of records and strength category

### 3.1.3    Point load test

The converted UCS derived from all PLT test results plotted by strength (MPa) and weathering also show a right skewness; as illustrated in Figure 3.
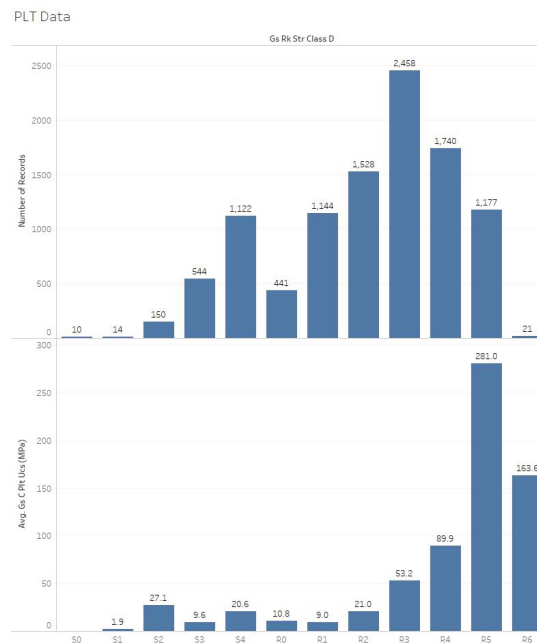


**Figure 3**      Point load test (PLT) derived average unconfined compressive strength (UCS) by number of records and strength grade

### 3.1.4    Unconfined compressive strength

Figure 4 shows that all sample data; with the samples selected are skewed to the right and there is an expected increase in UCS as the strength grades increase.
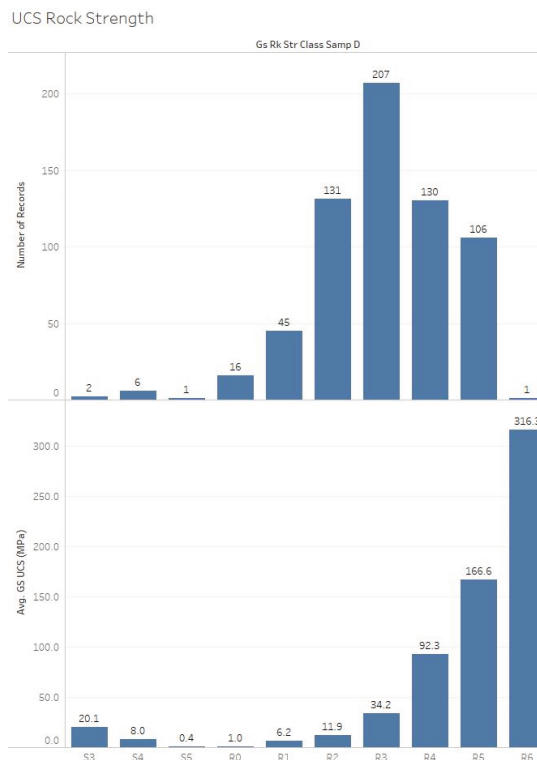


**Figure 4**      Average Unconfined compressive strength (UCS) by number of records and strength grade

## 3.2      Selection of statistical test

The previous section illustrates that none of the datasets are normally distributed; therefore, a non-parametric method is required to be sought. The variables are also a mixture of continuous (strength in MPa) and categorical (weathering and strength grade).

A Wilcoxon rank sum test or Mann–Whitney U test was decided to be most appropriate for quantifying the similarity of these datasets; as it allows for testing of equality of means of strength, comparing between two unpaired groups (deposits) at a time; and without assuming the datasets follow a normal distribution.

Additionally, the Mann–Whitney U test is robust in allowing differing sample sizes and small sample sizes (Mann & Whitney 1947).

The confidence interval was set at 95% for all tests**,** and so a two-tailed test either side of the distribution was performed. Performing a two-tailed test means that the test is for either side of the normal curve.

**The null hypothesis was:** $H_0$: The two deposits' sample sets means are equal.

**The decision rule was:** Reject $H_0$ if $p \leq 0.05$. A p-value less than 0.05 indicates strong evidence against the null hypothesis.

The minimum sample size varied over all tests; and the acceptable tolerance was calculated and is given by the below formula derived by Cochran (1963):

$$n = \frac{(1.96)^2 * \sigma^2}{E^2}$$

(1)

where:

      n    =   the required sample size.

      1.96  =   the $Z$ – value for a 95% confidence interval.

      $\sigma^2$   =   the sample variance computed from the simulation results.

      E    =   the tolerable error for the sample mean.

Dataset sample sizes that did not meet the minimum sample size were omitted from the analyses.

## 3.3      RStudio software

R is a programming language used in the open-source environment; RStudio for statistical computing and graphics. For testing multiple datasets simultaneously using the Wilcoxon rank sum test quickly and easily the RStudio Interface is well suited. A matrix of all of possible combinations of pairs of the five or six deposits' p values was generated. Several dataset plots illustrating this RStudio statistical output supported by a Tableau visualisation are shown in Figures 5 to 7 in Section 4.

# 4      Results

## 4.1      Field estimated strength

Observations of 338 separate Wilcoxon rank sum tests for FES' were run which accounted for every possible combination of weathering/stratigraphy, weathering/strand and weathering/lithology. Figure 5 shows one example of a test generated.

The p values in the matrix have been highlighted green when comparing the two deposits' FES data; $p \geq 0.05$ (the two datasets are from the same population; accept the null hypothesis) and highlighted red when $p \leq 0.05$ (the two datasets are not from the same population; reject the null hypothesis).
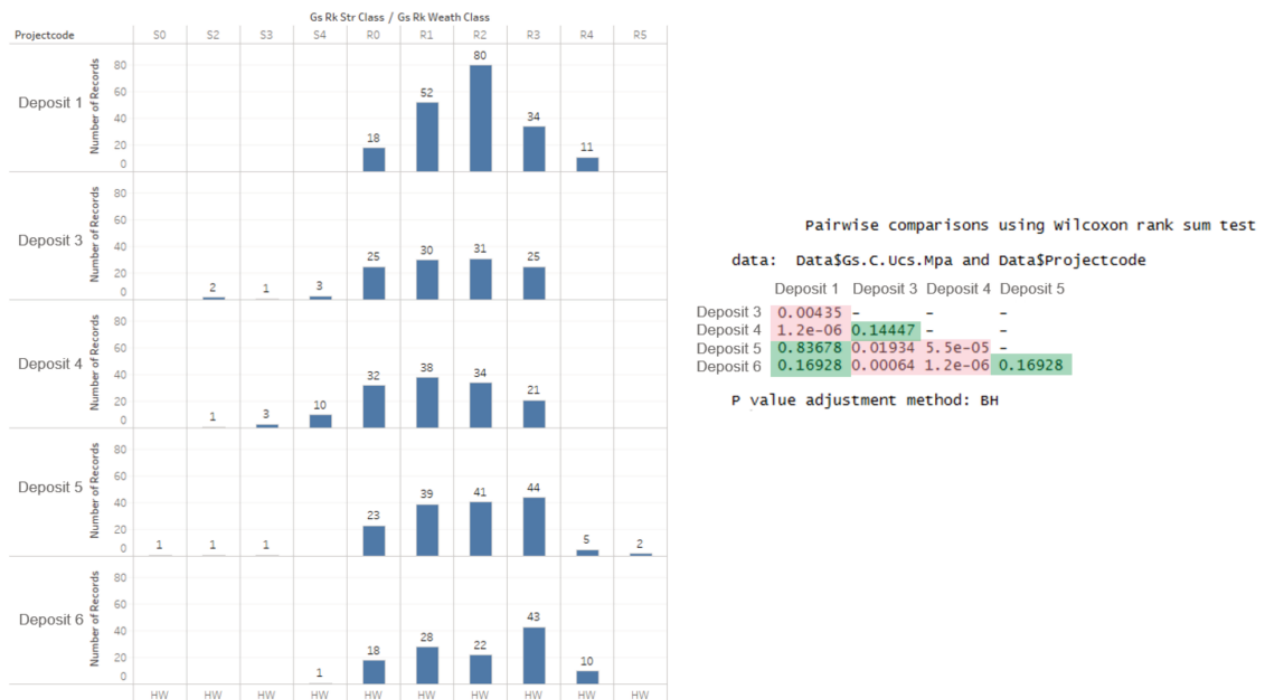
Figure 5    FES highly weathered Detritals distribution comparison and Wilcoxon rank sum test p results

## 4.2    Point load test

Observations of 99 separate Wilcoxon rank sum tests were run for PLT's which accounted for every possible combination of weathering/stratigraphy, weathering/strand and weathering/lithology. Figure 6 shows one example of a test generated.
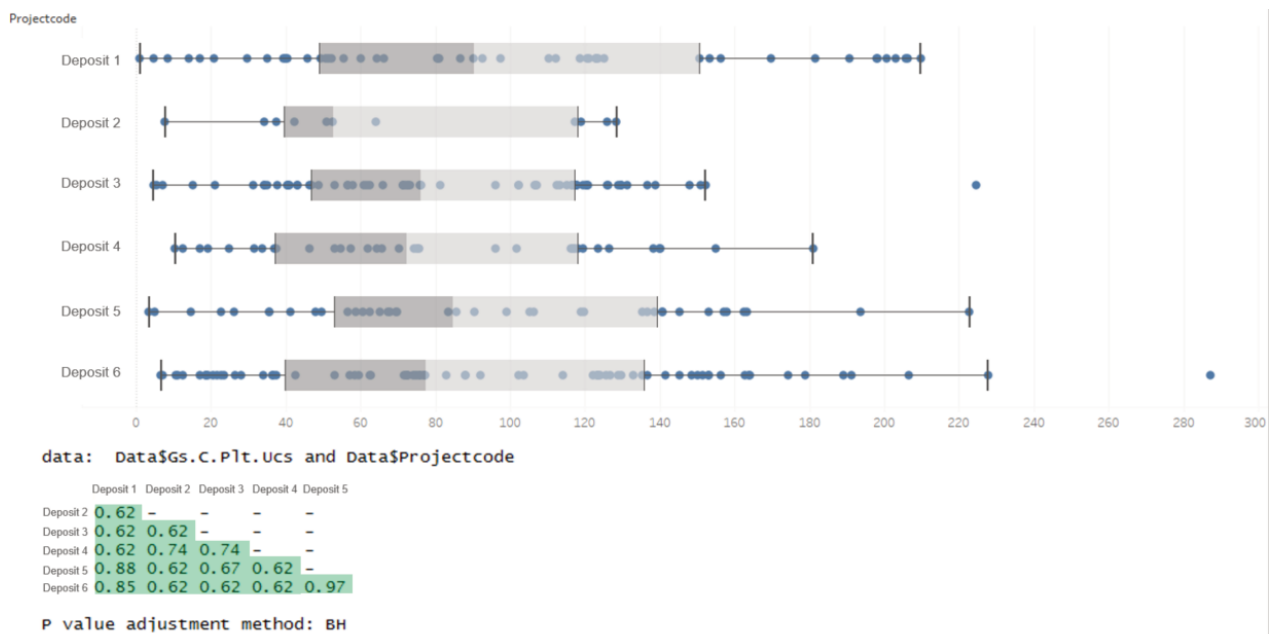


Figure 6    Field estimated strength (FES) moderately weathered Cherty Banded Iron Formation (BCT) distribution comparison and Wilcoxon rank sum test p results

## 4.3      Unconfined compressive strength

Observations of 11 separate Wilcoxon rank sum tests were run for UCS which accounted for every possible combination of weathering/stratigraphy, weathering/strand and weathering/lithology. Figure 7 shows one example of a test generated.
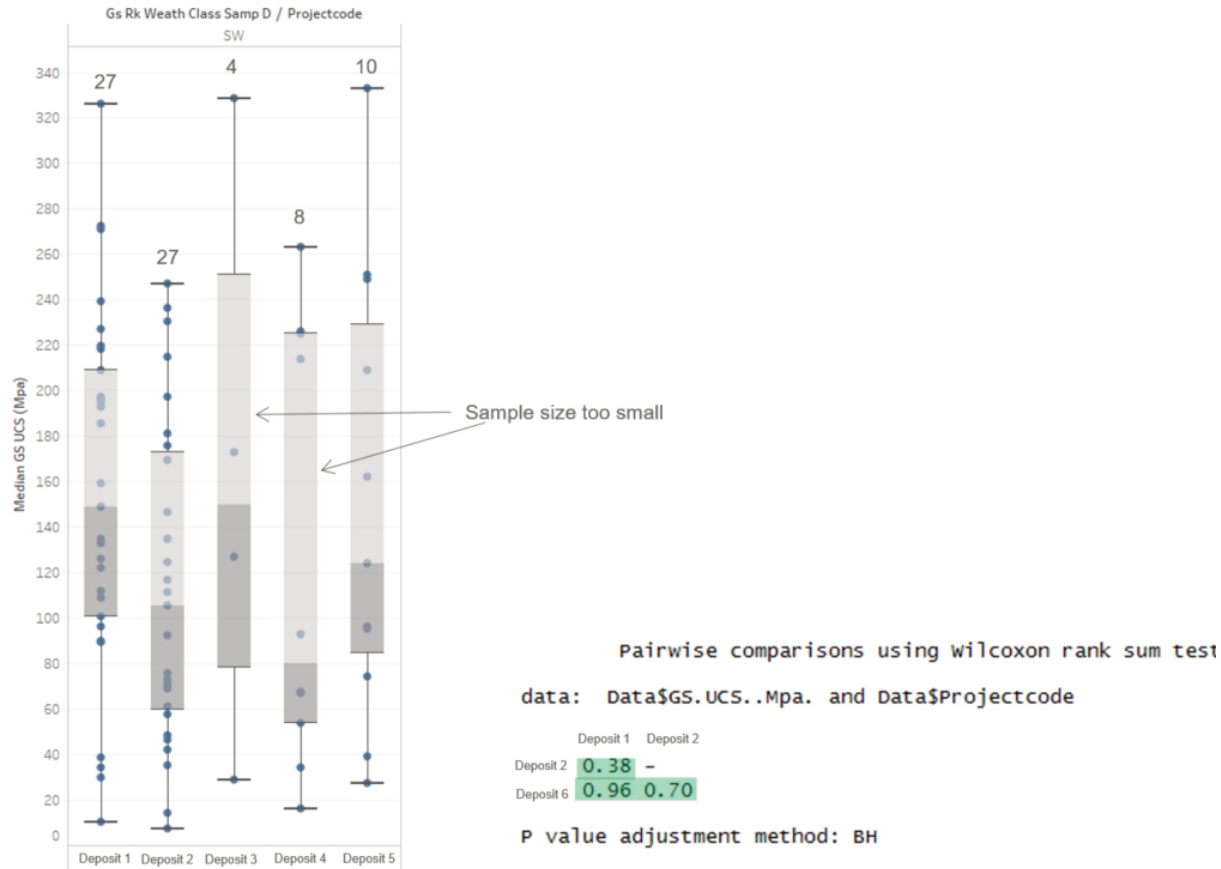


**Figure 7      Unconfined compressive strength (UCS) slightly weathered banded iron formation (BIF) distribution comparison and Wilcoxon rank sum test p results**

Using the FES data; every combination of each deposit compared to one another for each lithology and weathering grade with sufficient sample sizes had a weighted average p-value tabulated in Table 2. The weighted average was required so as to not bias the results in favour of datasets with a smaller number of deposit-to-deposit combinations. One tabulated results table is shown in Table 2, which is coloured by green: accept null hypothesis and red: reject null hypothesis.

**Table 2    FES weighted average p-value by weathering and lithology**

|     | RS | CW | HW | MW | SW | FR |
|-----|-----|-----|-----|-----|-----|-----|
| ALL | 0.44 | 0.06 | – | – | – | – |
| BCT | – | – | 0.23 | 0.20 | 0.34 | 0.00 |
| BGO | – | – | 0.23 | 0.20 | 0.07 | – |
| BHM | – | – | 0.21 | 0.28 | 0.00 | – |
| BIF | – | – | 0.15 | 0.15 | 0.37 | 0.29 |
| BLM | – | – | 0.52 | – | – | – |
| BMA | – | – | – | – | 0.10 | – |
| BPO | – | – | 0.14 | – | – | – |
| BRE | – | – | 0.08 | 0.00 | – | – |
| CAL | – | – | 0.27 | – | – | – |
| CAN | – | – | 0.50 | – | – | – |
| CLA | 0.15 | 0.11 | 0.33 | 0.18 | – | – |
| COL | 0.39 | 0.12 | – | 0.01 | – | – |
| CON | – | – | 0.64 | 0.20 | – | – |
| CTS | – | – | 0.00 | – | – | – |
| DET | 0.021 | 0.14 | 0.19 | 0.11 | – | – |
| DOF | – | – | – | – | – | 0.00 |
| DOR | – | 0.00 | 0.17 | – | – | – |
| GOE | – | 0.40 | 0.06 | 0.17 | – | – |
| GOL | – | – | 0.21 | 0.23 | – | – |
| GOV | – | – | 0.41 | 0.30 | – | – |
| HEM | – | 0.06 | 0.58 | 0.02 | – | – |
| PIS | 0.81 | 0.01 | 0.25 | – | – | – |
| SHC | – | – | – | 0.06 | – | – |
| SHF | – | 0.08 | – | – | – | – |
| SHL | 0.17 | 0.06 | 0.02 | 0.28 | 0.06 | 0.05 |
| SOL | 0.10 | – | – | – | – | – |

The combinations of deposit/lithology/weathering grade, deposit/strand/weathering grade and deposit/stratigraphy/weathering grade all tested with Wilcoxon rank sum bore the following generalised results:

- **FES:** in 81% of deposit comparisons; the population means were equal and were statistically similar. **Accept null hypothesis.**

- **PLT:** in 94% of deposit comparisons; the population means were equal and were statistically similar. **Accept null hypothesis.**

- **UCS:** in 85% of deposit comparisons; the population means were equal and were statistically similar. **Accept null hypothesis.**

These results are limited to the aforementioned deposits and cannot be extrapolated to the rest of the Pilbara mine sites or other laboratory test results. Overall numbers of samples need to be increased in future drilling programs.

# 5      Conclusion

In the large majority of hypothesis test comparison cases between deposits within the mining area; the strength properties come from the same population to a 95% confidence interval where the same lithology/stratigraphy/strand and weathering grade is compared. Generally, the finer the category of the rock mass unit, the better the statistical similarity of the test results.

# Acknowledgement

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