Rock Compressive Strength: A Correlation from Formation Evaluation Data for the Niger Delta*

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Search and Discovery Article #30488 (2017)**
Posted February 20, 2017

*Adapted from oral presentation given at AAPG/SPE 2016 Africa Energy and Technology Conference, Nairobi City, Kenya, December 5-7, 2016

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Abstract

The purpose of this paper is to study the strength of rocks by determining their Unconfined Compressive Strength (UCS), correlate the determined strength to physical properties of rocks that can be measured from formation evaluation data and derive an equation that can be used to derive rock strength from formation evaluation measurements. The scope of this work is limited to the Niger Delta basin from which core samples were taken. The method used for this research was to collect data of existing core samples at different depths and in various fields in the Niger Delta, then determine the strength of each sample by unconfined compressive tests. The derived strength was then analyzed with corresponding formation evaluation data utilizing regression analysis. Then, comparisons were drawn between the correlations derived and other existing correlations in the industry to check whether any of the existing correlations fits the Niger Delta region. The result is a model that takes formation evaluation data (Slowness, Young's Modulus, and Poisson's ratio) as input in order to provide rock compressive strength for the Niger Delta region. It was also observed that correlations built for other regions of the world do not yield accurate results when used for the Niger Delta region due to factors such as formation characteristics type of regression method, various sample collection conditions and so on.

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Objective

To develop a **correlation** for the **Niger Delta** & regions with similar lithology & depositional environments that can be used to derive **rock compressive strength** from **formation evaluation** measurements.

Background

- Importance of understanding rock strength
- Impact of rock strength on well operations
  - Bit selection
  - Wellbore Stability Modelling
  - Reservoir Compaction Modelling
  - And much more

The Niger Delta

- The Niger Delta continues to be a key contributor to the world's hydrocarbon supply.
- Sample spread
  - Land 50%
  - Swamp 34%
  - Shallow Offshore 16%

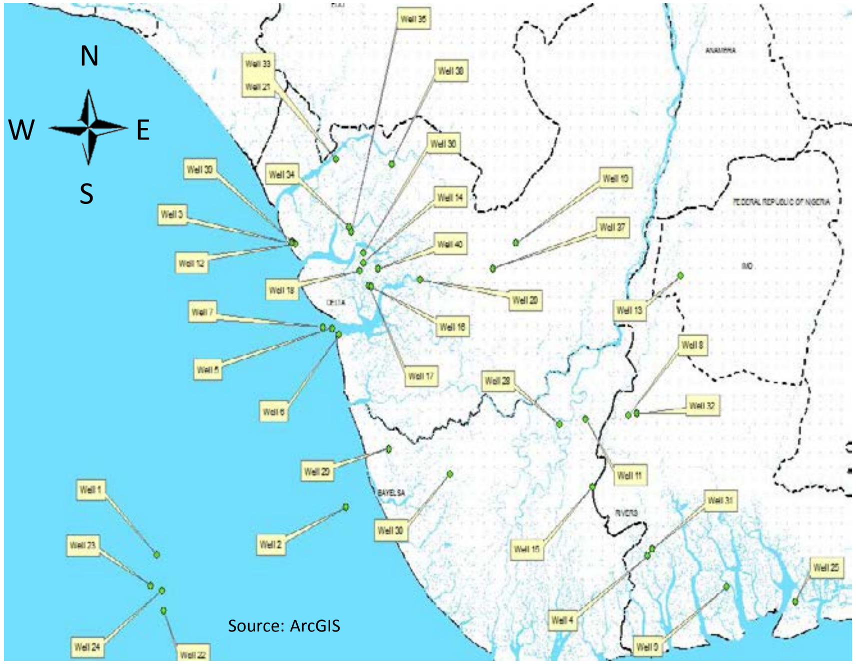
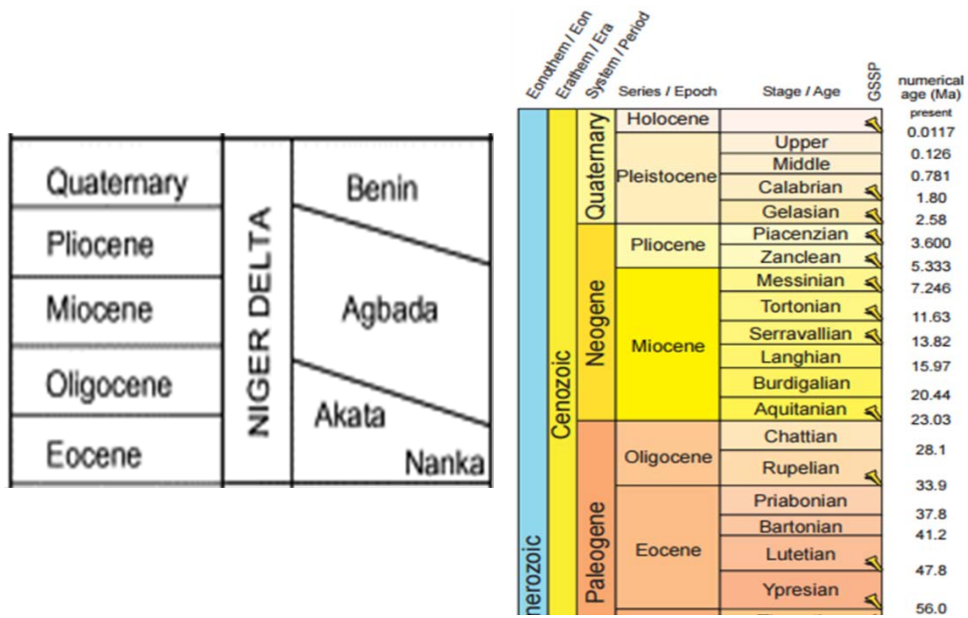


Figure 1: Map showing area studied

Niger Delta Formations

- Benin (28% of samples)
- Agbada
  - Upper Agbada (48%)
  - Lower Agbada (28%)
- Akata (Not available)
- 100% Shale Samples



Source: Wikipedia

Figure 2: Chrono-stratigraphic Chart & Stratigraphic succession in the Niger Delta

Rock Compressive Strength Correlation

- A lot of work has been done on rock strength correlations for other regions
- But no specific investigation has been published for the Niger-Delta

Table 1: Worldwide UCS models for Shales

Equation	Model & Reference	Comment
$UCS = \left[\frac{1.00}{0.0013(\Delta t_c - 50)}\right] - 2.66$	DT – Onyia (Nygaard and Hareland 2007)	Formations in Continental USA
$UCS = 0.77\left[\frac{304.8}{\Delta t}\right]^{2.93}$	DT – Hursrud (Horsrud 2001)	North Sea high porosity shales
$UCS = 0.43\left[\frac{304.8}{\Delta t}\right]^{3.2}$	DT – GoM (Chang et al 2006)	Pliocene epoch and younger
$UCS = 1.35\left[\frac{304.8}{\Delta t}\right]^{2.6}$	DT - Global(Chang et al 2006)	Applicable globally
$UCS = 0.5\left[\frac{304.8}{\Delta t}\right]^{3}$	DT - Cubed(Chang et al 2006)	Applicable in GoM
$UCS = 10\left[\frac{304.8}{\Delta t - 1}\right]$	DT – Lal (Lal 1999)	For high porosity tertiary shales
$UCS = 7.97E^{0.91}$	E - Hursrud (Horsrud 2001)	North Sea high porosity shales
$UCS = 7.22E^{0.712}$	E – Chang (Chang et al 2006)	Strong and compacted shales
$UCS = 8.48e^{4.89\rho_b} * 10^{-5}$	Rho - Khaksar(Khaksar et al. 2009)	Developed from published data for $\rho_b < 2.4$ g/cc

Figure 3: Worldwide UCS models for shales

Source: Chang, C., Zoback, M.D. and Khaksar, A., 2006. Empirical relations between rock strength and physical properties in sedimentary rocks. Journal of Petroleum Science and Engineering, 51(3)

Methodology

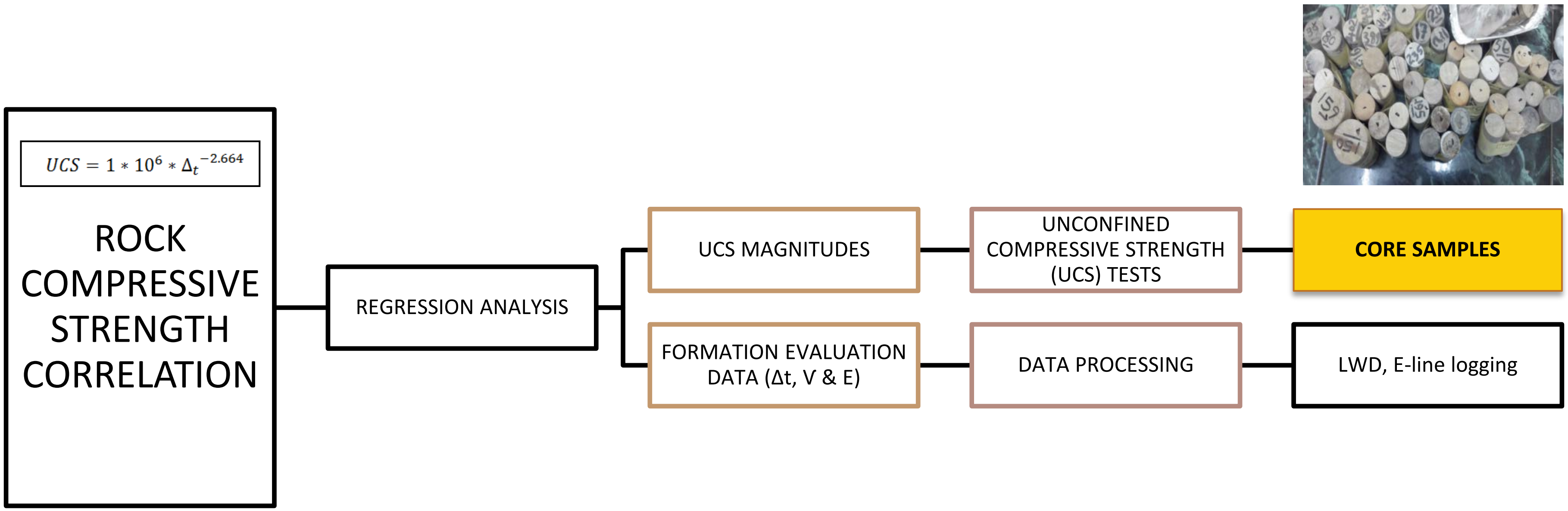
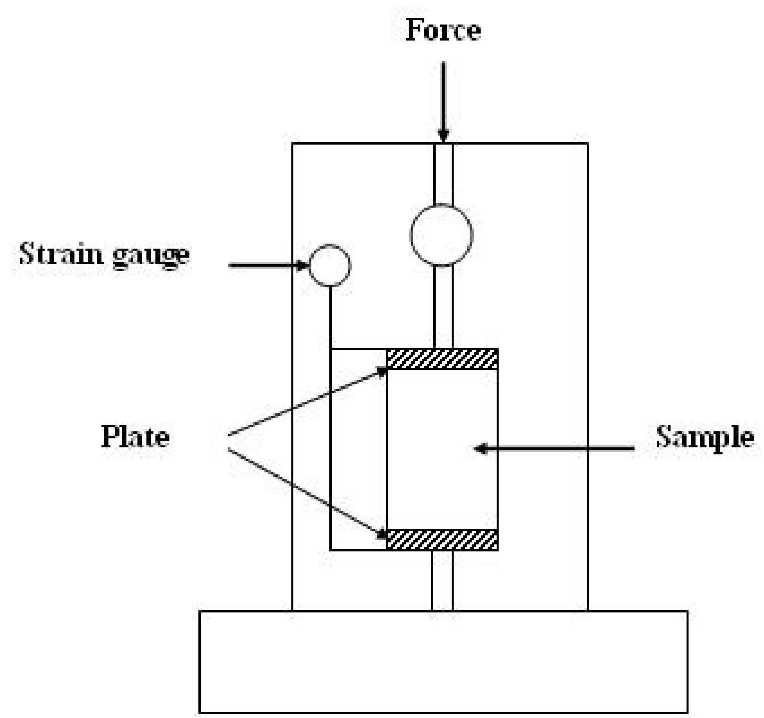


Figure 4: Process flow to derive correlation

Unconfined Compressive Strength Test

- Sample positioned between the plates

- Axial load is applied uniformly and continuously without shock until the maximum load (F) is reached where the sample fails



Source: http://osp.mans.edu.eg/geotechnical/Ch1C.htm

Figure 5: Unconfined Compressive Strength test

Results - UCS Magnitudes

- UCS generally increases with depth
- There is a marked departure from the trend in the Lower Agbada formations.
- Deviation could be for a number of reasons – Not enough data to conclude

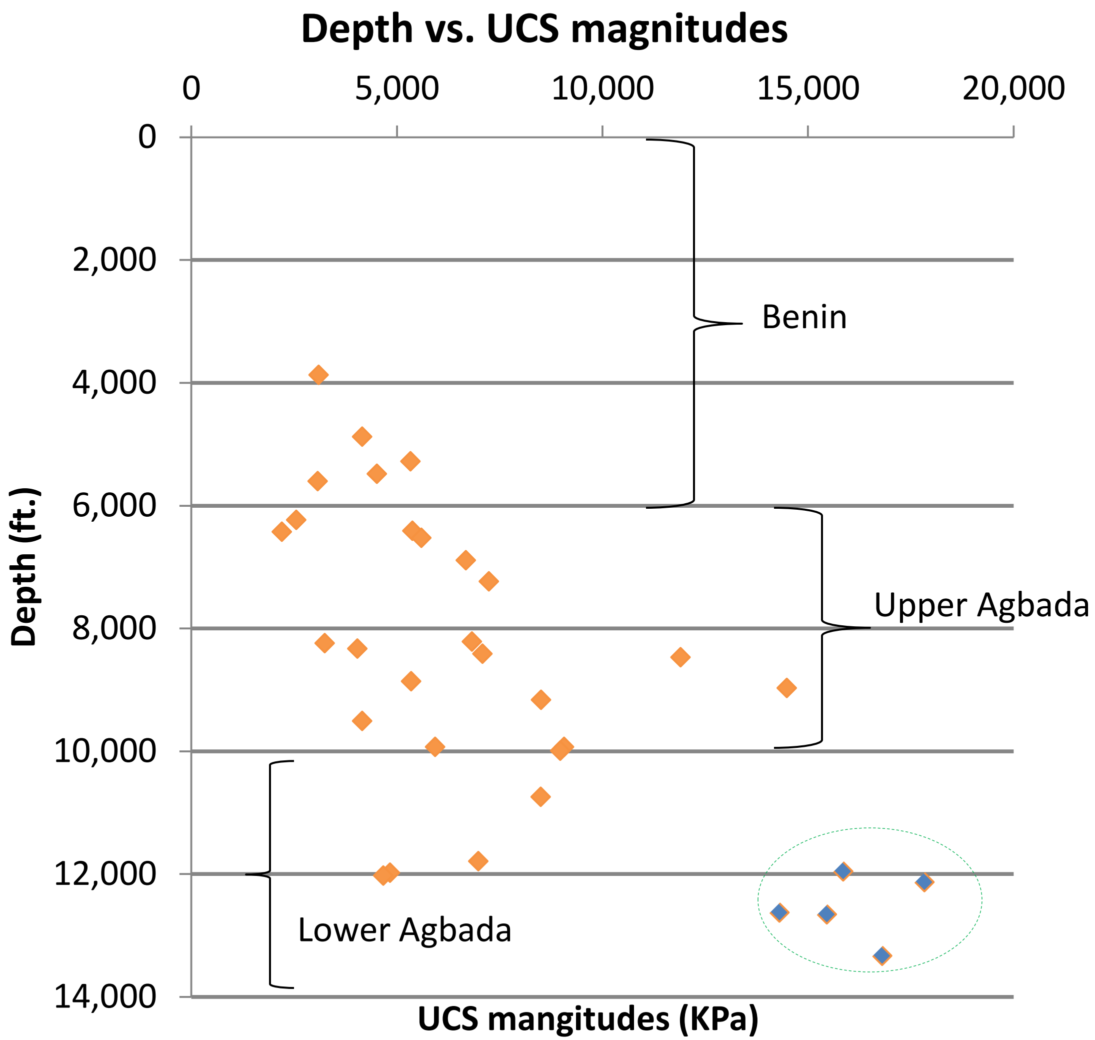


Figure 6: UCS magnitudes vs. depth

Analysis

ROCK COMPRESSIVE STRENGTH CORRELATION

$$UCS = 1 * 10^6 * \Delta_t^{-2.664}$$

REGRESSION ANALYSIS

UCS MAGNITUDES

FORMATION EVALUATION DATA (Δt, V & E)

valid?

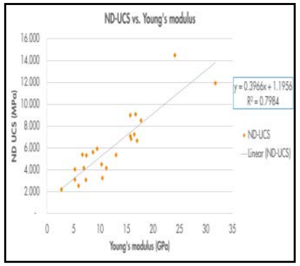


Figure 7: Process flow for Correlation

Niger-Delta UCS vs. Slowness

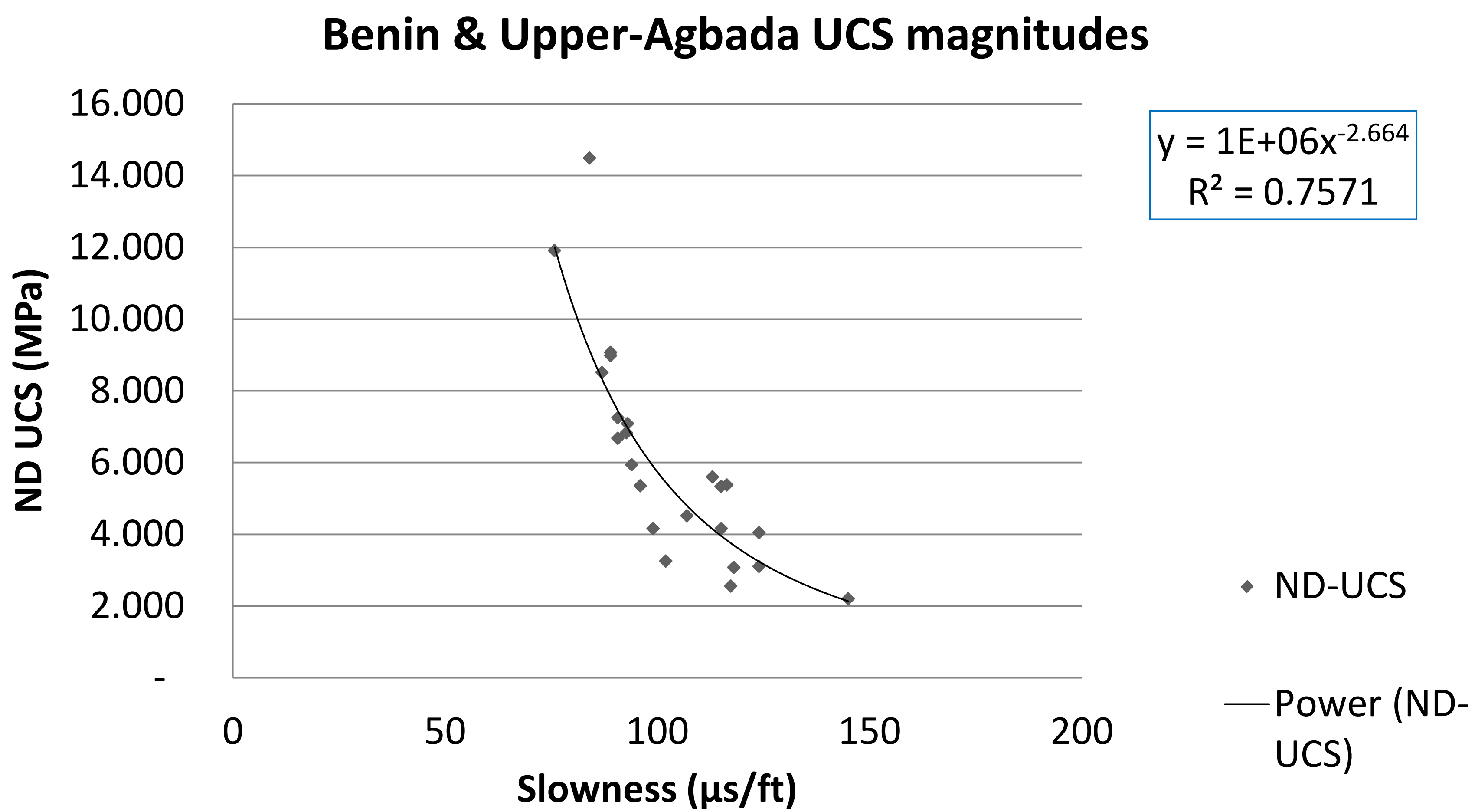


Chart 3: Benin & Upper Agbada UCS vs. Slowness

Niger-Delta UCS vs. Young's Modulus

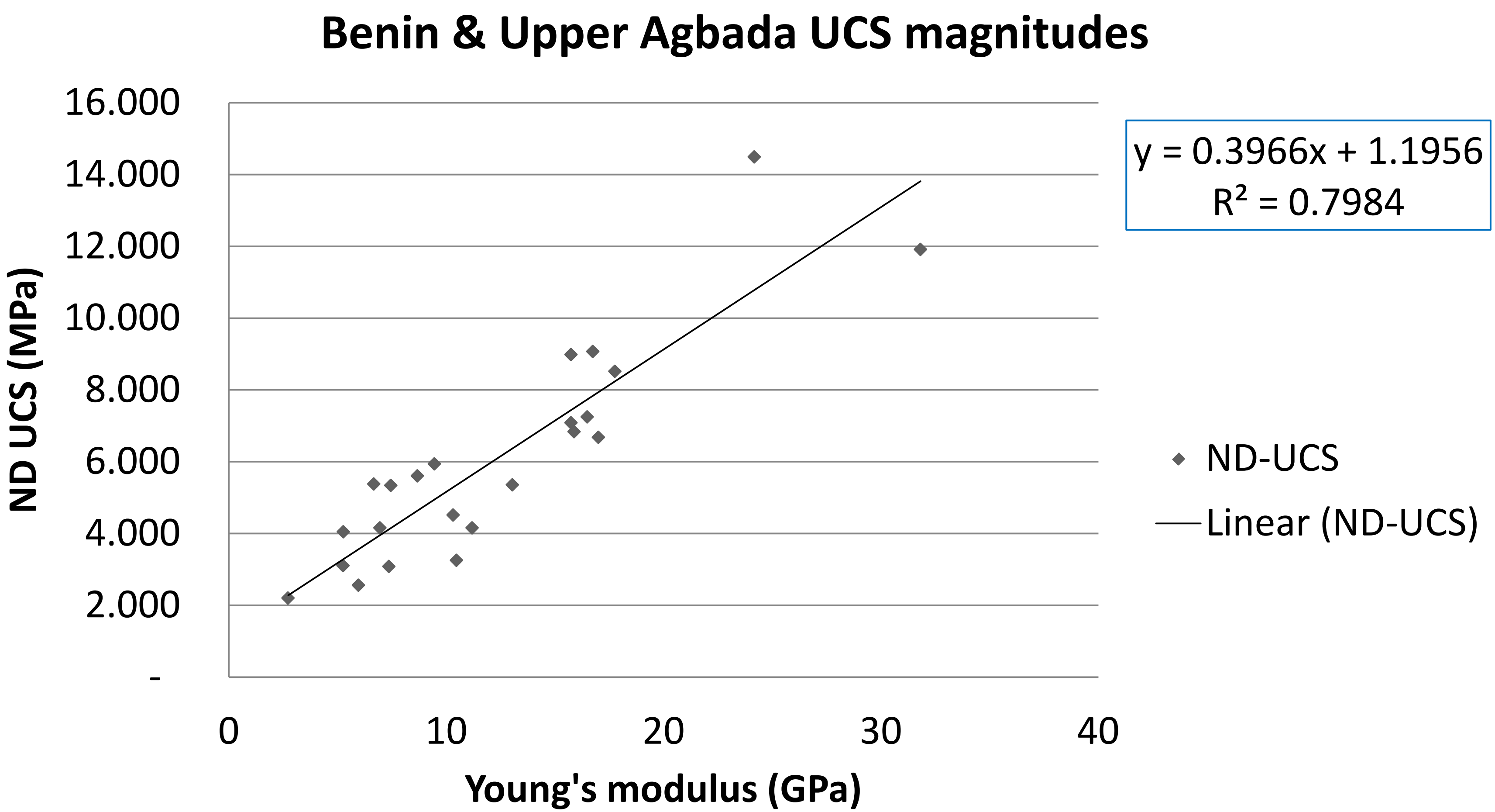


Chart 6: Benin & Upper Agbada UCS vs. Young's Modulus

Niger-Delta UCS vs. Poisson's ratio

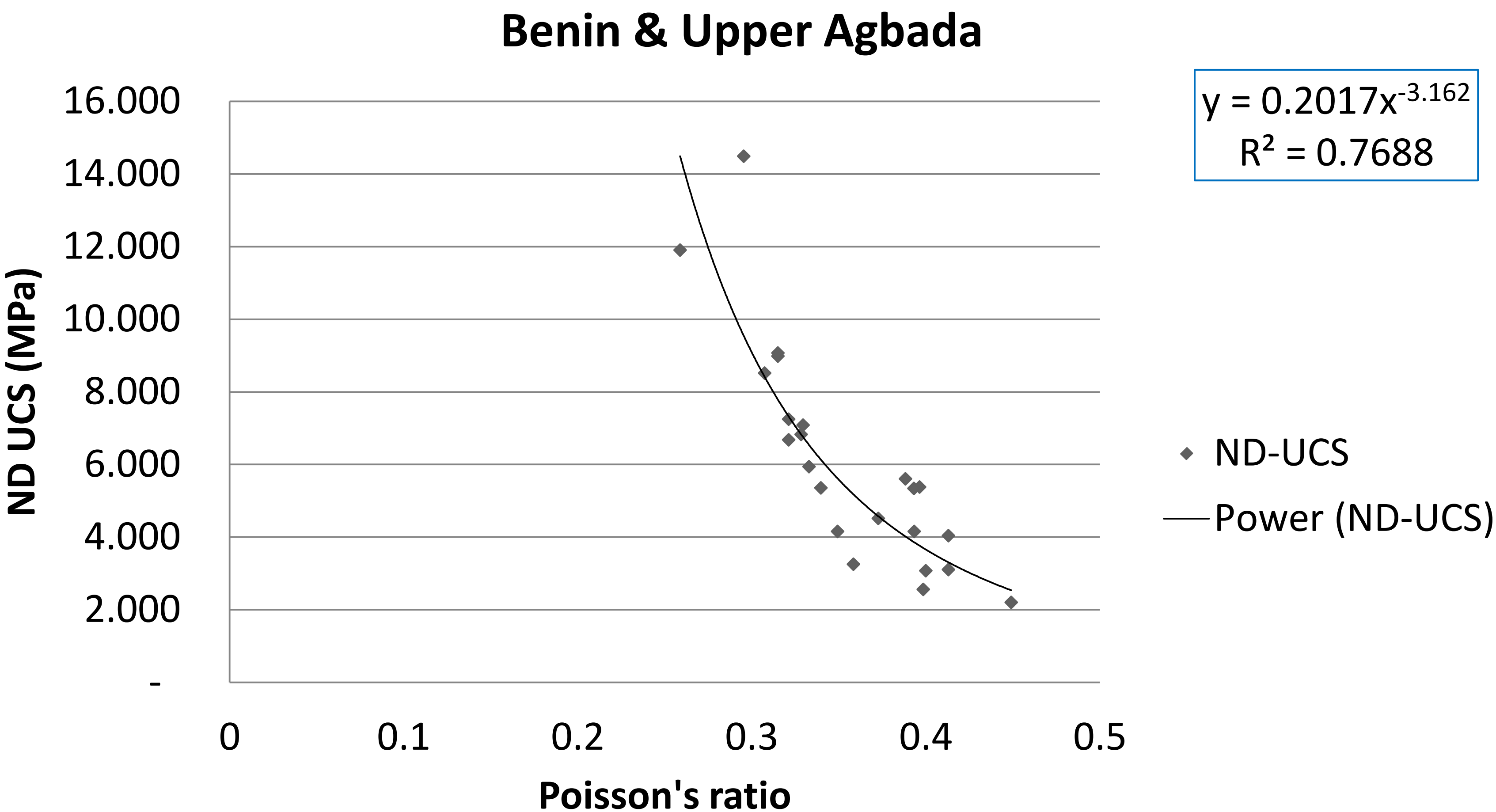


Chart 9: Benin & Upper Agbada UCS vs. Poisson's ratio

Rock strength correlation

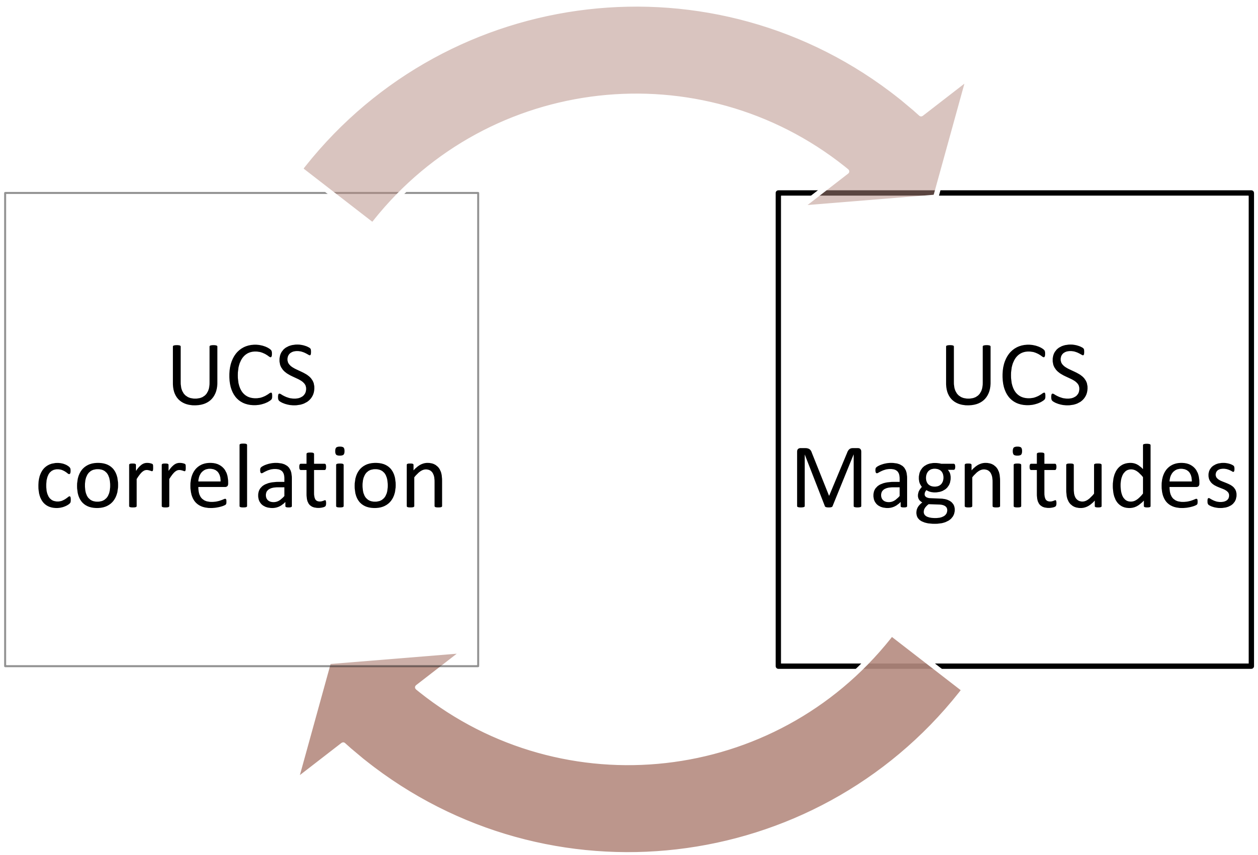


Figure 7: Relationship between measured and derived UCS values

Derived UCS correlations vs. Compressional velocity

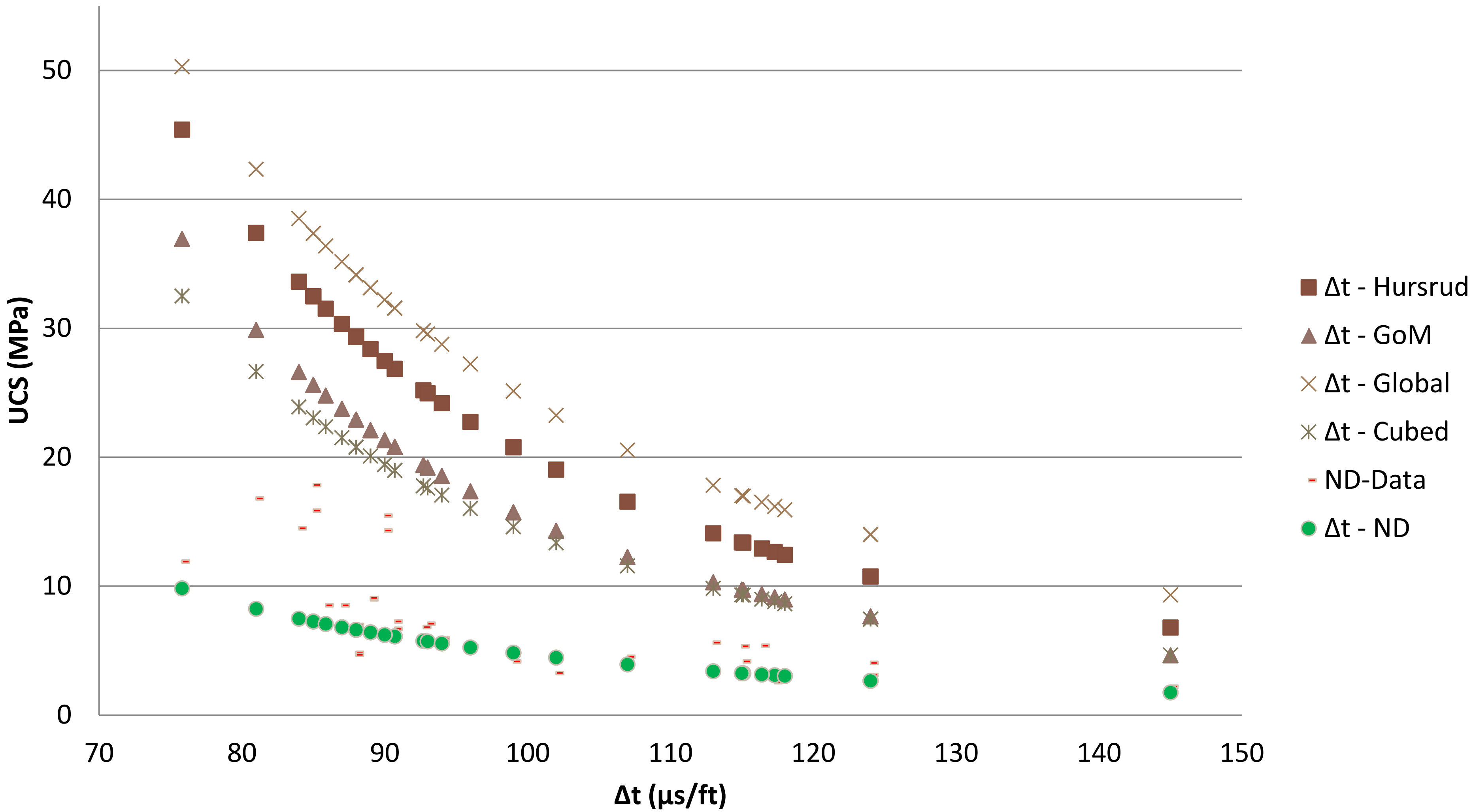


Chart 10: Derived UCS correlations vs. Compressional Velocity

Derived UCS correlations vs. Young's Modulus

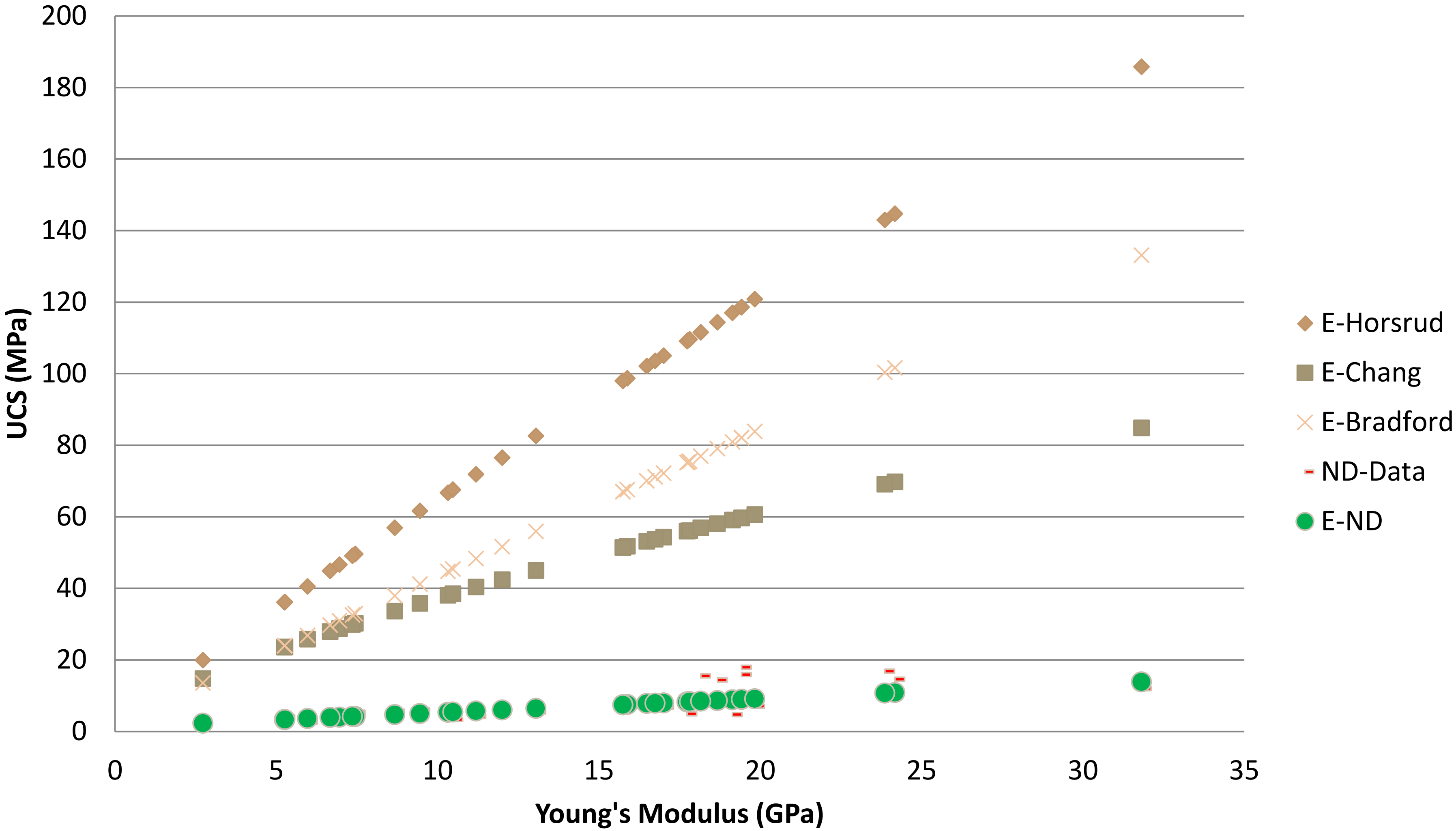


Chart 11: Derived UCS correlations vs. Young's Modulus

Conclusion: Niger Delta UCS correlations for Benin & Upper Agbada formations (Shales)

A correlation developed between formation slowness & UCS which is valid for 76% of samples tested.

$$\text{UCS} = 0.24\left[\frac{304.8}{\Delta t}\right]^{2.664} \quad (1)$$

A correlation developed between Poisson's ratio & UCS which is valid for 77% of samples tested.

$$\text{UCS} = 0.2017 * \text{v}^{-3.162} \quad (2)$$

A correlation developed between Young's modulus & UCS which is valid for 80% of samples tested.

$$\text{UCS} = 0.3966\text{E} + 1.1956 \quad (3)$$

No distinct correlation in the Lower Agbada formation.

Conclusion cont'd.

- Previously there was no published correlation for rock strength in the Niger Delta
- Derived Niger Delta correlations showed similar trends to other worldwide models with distinguishable differences in magnitude
- With proper calibration Niger Delta models can be applied to:
    - bit selection determination
    - wellbore stability modelling
    - Compaction modelling
    - and so on

Recommendations

- Data quality
  - Impact of storage conditions on sandstone samples
  - Impact of age and dryness on data quality
  - Impact of older sonic logs on data selection

Questions & Answers

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Acknowledgement

- We would like to thank the following for their immense contribution to this project:
- Dr Reza Sanaee
- Matthias Akhideno
- Richard Ebisike
- Oloruntobi Olalere
- Stephen Okonji
- Evans Isowamwen
- Fugro Nigeria Limited, Warri
- Onyum Salawu
- Shayaan & Hamdan Salawu
- Olumayowa Onabanjo

Supporting slides

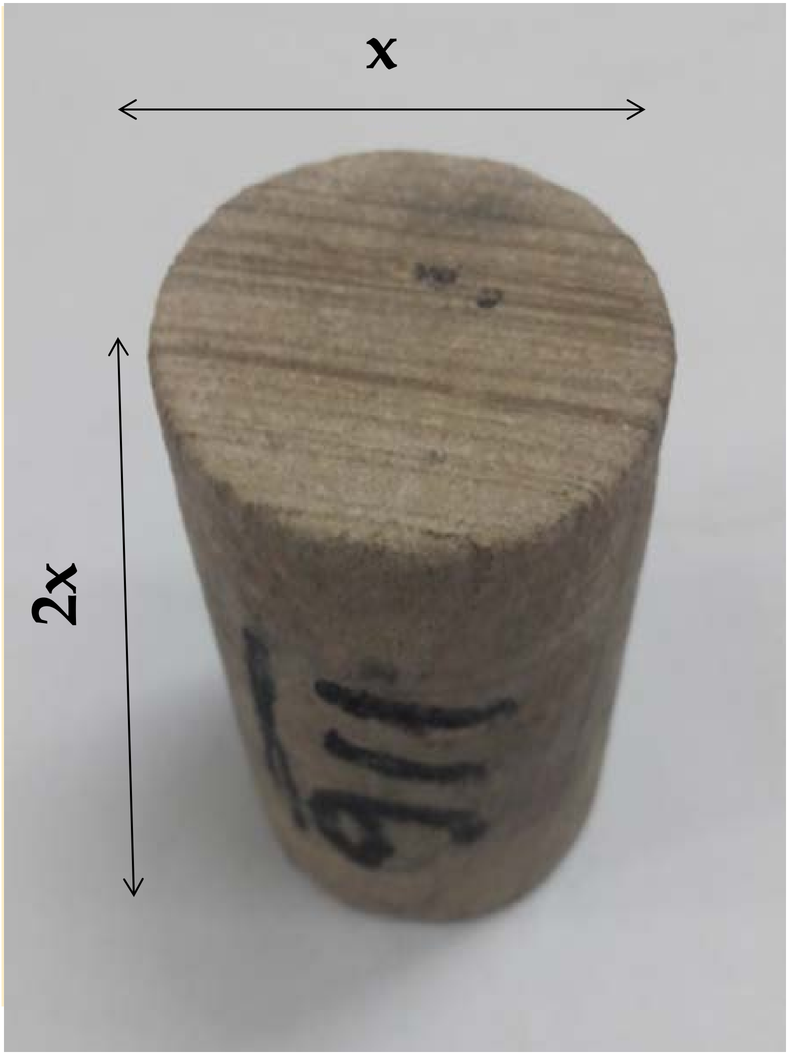
Formation evaluation data

Of particular interest to this study are some of the formation evaluation data that are related to rock strength:

- Formation Slowness (Δt)
- Young's Modulus (v)
- Poisson's ratio (E)

UCS testing – Selection criteria

- shale formations
- Diameter (D) to height ratio
- prefect cylinders
- well documented history
- Corresponding values for Formation sonic wave slowness, Poisson's ratio and Young's modulus.



Core Sample

A tested sample showing the failure path

Correlation of UCS magnitudes vs. formation evaluation data

Formation data set	Slowness (R^2)	Young's (R^2)	Poisson's (R^2)
All (Benin, Upper & Lower Agbada)	0.65	0.65	0.66
Upper Agbada	0.68	0.73	0.72
Benin & Upper Agbada	**0.76**	**0.80**	**0.77**

Calculations for unconfined compressive strength

Calculations

- The cross sectional area:

$$A = \frac{\pi D^2}{4} \quad (1)$$

- The Unconfined Compressive Strength of the sample:

$$\sigma = \frac{F}{A} \quad (2)$$

Where,

σ = Unconfined Compressive strength, KPa

A = cross sectional area, m^2

D = average sample diameter, m

F = maximum load, kN

Derived UCS correlations vs. Poisson's Ratio

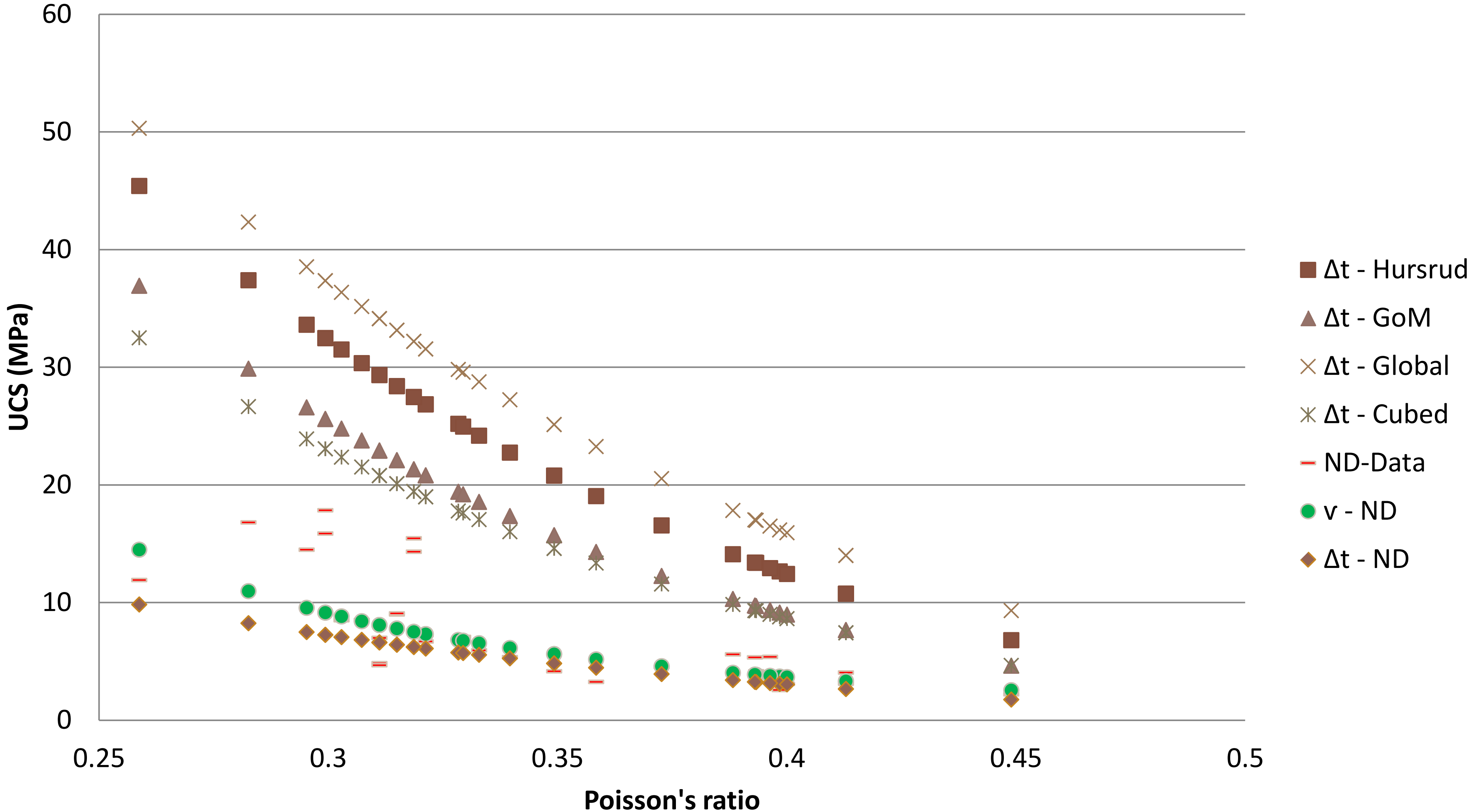


Chart 12: Derived UCS correlations vs. Poisson's ratio

Key formation evaluation equations

- Relationship between compressional slowness & shear velocity
  - Castagna (Castagna et al 1984) suggest that for clastic formations, the relationship that can be used to deduce the shear velocity is described in the equation below
  - $V_P = (1.16 * V_S) + 1.36$
- Haug's equation can be used to derive parameters of E and v from well logs
  - According to Haug (Haug et al 2007), the dynamic Poisson's ratio (ν_d) is calculated from the relationship between the P wave velocity (V_P) and S wave velocity (V_s) as:
    - $\mathrm{v} = \frac{V_P{}^2 - 2V_S{}^2}{2(V_P{}^2 - V_S{}^2)}$
  - Young's modulus can be calculated from the velocity (V_s) and rock density (ρ) as shown below (Haug et al. 2007)
    - $E = 2\rho V_S{}^2(1 + \mathrm{v})$
- The reason we selected the linear regression analysis is because of its simplicity.