SPE 28022

Influence of composition and texture on the failure properties of clastic rocks

Influence de la composition et de la texture des roches clastiques sur leurs propriétés à la rupture

Der Einfluß, den die Zusammensetzung und Struktur auf die Ausfalleigenschaften von klastischem Gestein hat

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This paper was prepared for presentation at the 1994 Eurock SPE/ISRM Rock Mechanics in Petroleum Engineering Conference held in Delft, The Netherlands, 29-31 August 1994.

ABSTRACT: New relationships are identified between the composition and texture of clastic rocks and their Coulomb failure parameters, unconfined compressive strength and friction angle. Rocks examined in this study have porosities that vary from 0% to 40% and the volume fraction of clay minerals varies from 0% to 72%. Results show that unconfined compressive strength depends on porosity, clay content and the degree of cementation. Young's modulus was found to be a better indicator of unconfined compressive strength than porosity. Friction angle depends on porosity, clay content and effective confining pressure. These results indicate that measurements of porosity, clay content, cementation and in-situ stress are required to evaluate strength variations among rocks typically encountered in a single well.

RESUME: Nous avons identifié de nouvelles relations entre la composition et la texture des roches clastiques d'une part, et leurs paramétres de Coulomb, leur résistance à la compression simple et leur angle de friction d'autre part. Les roches examinées au cours de cette étude ont une porosité qui varie de 0% à 40%, tandis que la fraction volumique de minéraux argileux varie de 0% à 72%. Nous montrons que la résistance à la compression simple dépend de la porosité, de la proportion de minéraux argileux et du degré de cimentation, et que le module d'Young se trouve être un meilleur indicateur de la résistance à la compression simple que la porosité. L'angle de friction dépend, lui, de la porosité, de la proportion de minéraux argileux et de la pression de confinement effective. Ces résultats indiquent que, même pour les roches rencontrées dans un même forage, il est nécessaire de mesurer la porosité, la proportion de minéraux argileux et les contraintes in-situ pour pouvoir évaluer leurs variations de résistance à la rupture.

ZUSAMMENFASSUNG: Neue Zusammenhänge werden zwischen der Zusammensetzung und Struktur von klastischem Gestein und ihren Mohr-Coulomb-Ausfallparametern, ihrer unbehinderten Druckfestigkeit und ihrem Reibungswinkel identifiziert. Das in dieser Studie untersuchte Gestein hat eine Porosität, die zwischen 0% und 40% schwankt, und der Volumenbruchteil der Tonmineralien schwankt zwischen 0% und 72%. Die Ergebnisse zeigen, daß die unbehinderte Druckfestigkeit von der Porosität, dem Tongehalt und Grad der Zementierung abhängt. Es wird gezeigt, daß das Elastizitätsmodul ein besserer Indikator der unbehinderten Druckfestigkeit ist als die Porosität. Der Reibungswinkel hängt von der Porosität, dem Tongehalt und einemwirksamen begrenzenden Druck ab. Diese Ergebnisse deuten darauf hin, daß eine Messung der Porosität, des Tongehalts, der Zementierung und der örtlichen Belastung zur Bewertung der Stärkenvariationen von Gestein, die normalerweise in einem einzigen Brunnen gefunden werden, nötig sind.

1. INTRODUCTION

Evaluating rock strength from geophysical measurements is fundamental to the analysis of rock deformation problems encountered in the petroleum industry and geophysics (Veeken et al., 1989; Santarelli et al., 1989; Ewy, 1991; Morita et al., 1994; Bradford and Cook, 1994). Numerical analysis of wellbore stability, sand production and in-situ stress must deal with a wide variety of rocks ranging from clay-free reservoir sandstones through siltstones to mudstones and shales. Identification of the dominant composition and textural elements governing rock failure is necessary for improving geophysical methods for measuring rock strength (Plumb et al., 1992; Herron et al., 1992).

Rock strength depends on the interaction between extrinsic and intrinsic factors. The most important extrinsic factors governing rock strength are confining pressure, strain rate and to a lesser extent temperature (von Karman, 1911; Griggs et al., 1960; Handin et al., 1963; Handin 1966; Donath and Fruth, 1971). Important intrinsic geologic factors include porosity, grain size, mineralogy and types of cement (Brace, 1961; Hoshino et al., 1972; Dunn, 1973; Fahy and Guccione, 1979; Hugman and Friedman, 1979; Dobereiner and Freitas, 1986;

Corbett et al., 1987; Plumb et al., 1992; Vernik et al., 1993; Sarda et al., 1993).

Quantitative relationships between intrinsic properties and the failure properties of rocks are poorly established because previous studies have not considered the effects of both clay content and porosity. For example, studies of clay-free sandstones have shown that the compressive strength and the brittle-ductile transition pressure are correlated with porosity (Hoshino et al., 1972; Dunn, 1973; Logan, 1986; Perkins and Weingarten, 1988; Scott and Nielson, 1991; Vernik et al., 1993). However, relations between strength and porosity are obscured when rocks contain significant amounts of clay minerals (Hoshino et al., 1972). In rocks with nearly constant porosity but varying clay content, strength decreases with increasing clay content, decreasing the average number of grain-to-grain contacts, decreasing grain size and decreasing Young's modulus (Plumb et al., 1992).

This paper identifies new first-order relationships between intrinsic rock properties and strength as measured by the Coulomb failure parameters. Unlike previous studies, a wide variety of clastic rocks are examined with volume fractions of clay ranging from 0% to 72% and porosities ranging from 0% to 40%. It will be shown that: 1) Porosity, clay content and cementation are important for establishing the relative strength among clastic rocks and (2) The dependence of strength on confining pressure is related to lithology as measured by the quantity porosity plus clay.

2. ROCK CHARACTERISATION

2.1 *Mechanical Classification*

Rocks in this study have been classified according to their dominant load-bearing solid phase to distinguish those with different textures. Three categories are defined on the basis of the volume fraction of clay minerals, V_{clay} : (1) grain-support rocks, $V_{clay} < 15\%$, (2) transitional-support rocks, $15\% < V_{clay} < 35\%$, and (3) clay-support rocks, $V_{clay} > 35\%$ (Dott, 1964; Picard, 1971). Grain-support rocks are characterised by a continuous connected network of detrital grains, average grain size 2 mm to 0.062 mm. External loads applied to grain-support rocks are carried by grain-to-grain contacts, typically quartz grains. In the transitional-support rocks, loads are distributed more equally among detrital grains and clay minerals. Grain size is poorly sorted and ranges between 0.062 mm and about 4 microns. In clay-support rocks, externally applied loads are born entirely by clay minerals. Grain size in clay-support rocks is better sorted and is typically less than 0.062 mm.

2.2 *Sample Description*

Three groups of rock samples are addressed in this study. Group I consists of 784 rocks obtained from oil field cores and quarries. These are characterised by lithology, unconfined compressive strength and porosity. An approximate upper bound on unconfined compressive strength is established by sandstones from Group I.

Groups II and III are subsets of group I. Group II consists of 142 rocks which are further characterised by Young's modulus. Young's modulus is shown to be a very good indicator of unconfined compressive strength for the broad range of rocks represented by Group II.

Group III consists of 46 rocks further characterised by the total volume fraction of clay minerals and compressive strength as a function of confining pressure. The dependence of friction angle on lithology and a dependence of the brittle-ductile transition pressure on porosity for sandstones are developed using samples from this group.

3. EXPERIMENTAL DATA

Failure parameters have been determined from a database of published and unpublished standard triaxial tests conducted at room temperature under drained conditions (Hall and Harrisberger, 1970; Hoshino et al., 1972; Dunn, 1973; Gowd and Rummel, 1980; Dobereiner and Freitas, 1986; Scott and Nielson, 1991; Jizba, 1991; Plumb et al., 1992, Cook personal communication, 1993). Sample diameters vary from 25 mm to 38 mm and length to diameter ratios range between 2:1 and 3:1. Rocks are typically saturated with brine or preserved pore fluids. Confining pressures range from 0 MPa to 1000 MPa and strain rates are in the range of 10^{-5} to 10^{-4} sec^{-1}. Young's modulus is measured on the loading cycle at 50% of peak strength.

Figure 1 shows stress-strain curves from a typical suite of triaxial tests and defines how rock failure parameters have been selected. Peak compressive strength is treated as a property of brittle rocks which is only defined below the brittle-ductile transition pressure, B-D T. (Figure 1).

4. FAILURE PARAMETERS

Rock strength can be characterised by the Coulomb failure parameters, unconfined compressive strength, C_0, and friction angle, θ. C_0 is determined from unconfined compression tests and friction angle is determined from the slope of the Mohr-Coulomb failure envelope, $\sigma_f(\sigma_3)$. The linear Mohr-Coulomb failure envelope can be expressed as

$$\sigma_f = C_0 + \sigma_3 \tan^2\left(\frac{\pi}{4} + \frac{\theta}{2}\right). \qquad (1)$$

Failure envelopes for rocks examined in this study are not well characterised by a straight line. Therefore two friction angles are defined:

(1) an average friction, < θ >, and (2) a pressure dependent friction angle $\theta(\sigma_3)$. The average friction angle is determined from the slope of the best fitting line through experimental data, $\sigma_f(\sigma_3)$.

Generally, the compressive strength of sedimentary rocks is better described by a non-linear failure envelope of the form

$$\sigma_f = C_0 + B\sigma_3^n. \qquad (2)$$

The pressure dependent friction angle is determined from the slope of the tangent to the best fitting failure envelope evaluated at a particular σ_3

$$\theta(\sigma_3) = 2\left[\tan^{-1}\left(\sqrt{nB\sigma_3^{n-1}}\right) - \frac{\pi}{4}\right] \qquad (3)$$

where B and n are parameters determined by fitting (2) to experimental data, $\sigma_f(\sigma_3)$. Notice that the linear failure envelope (1) is a special case of (2) where the pressure exponent n = 1 and $B = \tan^2(\pi/4+\theta/2)$.

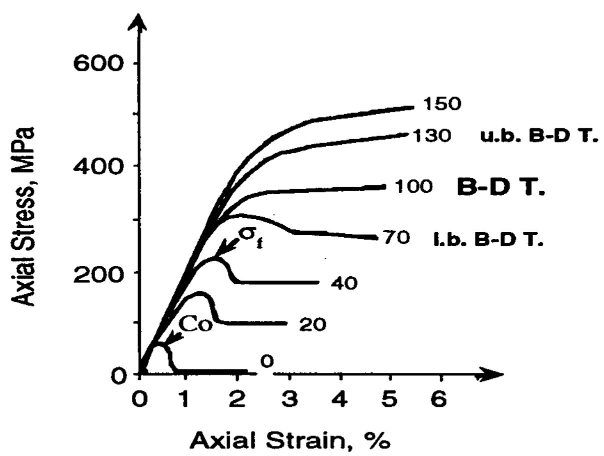

Fig. 1. Axial stress-strain curves for confining pressures from 0 MPa to 150 MPa, identifying the unconfined compressive strength, C_0, the peak compressive strength, σ_f, and the brittle-ductile transition pressure, B-D T., after Gowd and Rummel, (1980).

5. RESULTS

5. 1 *Dependence of C_0 on Porosity*

The unconfined compressive strength of 784 sedimentary rocks is plotted as a function of porosity in Figure 2. The variation of C_0 at constant porosity decreases as porosity increases. At low porosity the strongest rocks are well-cemented sandstones with V_{clay} < 5% (Clean Ss). The weakest rocks are either poorly cemented sandstones (grain support, GS) or shales (clay-support, CS). Notice the low porosity grain-support rocks with extremely low C_0. Compared to grain-support rocks, clay-support rocks generally have lower strength and less variation in strength at constant porosity.

The upper bound on C_0 is defined by well-cemented clay-free sandstones obtained from tight gas reservoirs and quarries (Dunn et al., 1973; Jizba, 1991; Scott and Nielson, 1991; Plumb et al., 1992). The upper bound on C_0 is a strong negative function of porosity in the low to intermediate porosity range but it becomes relatively independent of porosity at high porosity where sand production is a problem. The average upper bound on C_0 is approximated by

$$C_0^{u.b.} = 357(1-0.028\phi)^2. \qquad (4)$$

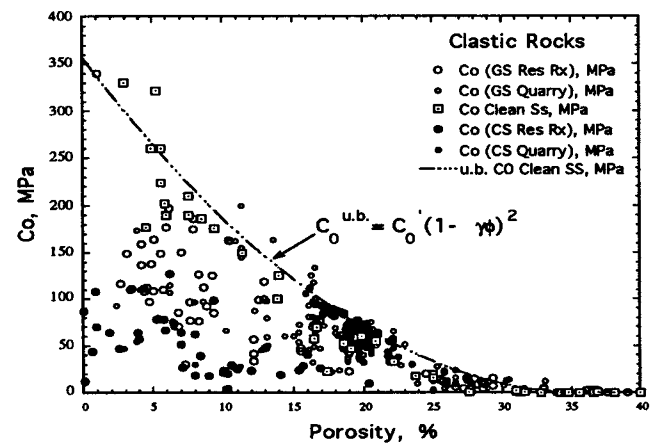

Fig. 2. Unconfined compressive strength, C_0, vs. porosity for Group I rocks.

5.2 *Dependence of C_0 on Lithology*

A clearer relationship between C_0 and lithology emerges when lithology is parameterised by the sum porosity plus clay. If we consider porous clastic rocks as a three component system comprised of grains, clays and pore space, the quantity porosity plus clay can be identified as a measure of the volume fraction of detrital grains, V_{grain}.

$$V_{grain} = 1 - \left(\phi + V_{clay}\right) \qquad (5)$$

Figure 3 shows the unconfined compressive strength of group III rocks, classified according to their dominant load bearing solid phases plotted against V_{grain}. C_0 is very sensitive to lithology at high values of V_{grain}. In contrast, C_0 becomes relatively insensitive to lithology when V_{grain} falls below about 0.6. At low values of V_{grain}, the variation of C_0 is about 100 MPa, clearly indicating that additional factors are important, possibly clay type and fluid content.

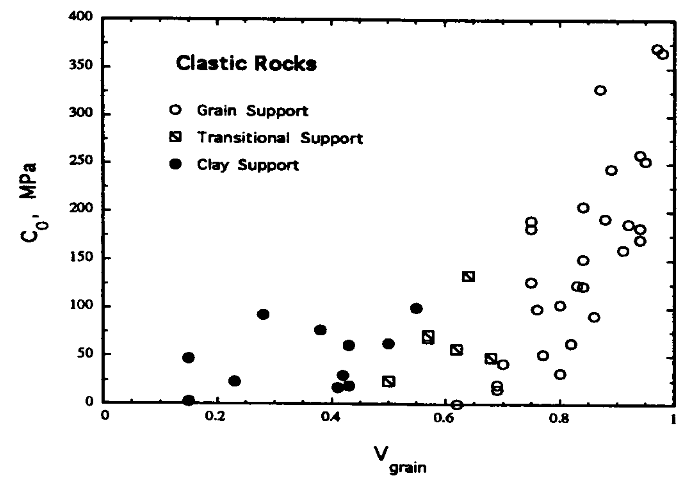

Fig. 3. Unconfined compressive strength vs. V_{grain} for Group III rocks classified by their load-bearing solid phase.

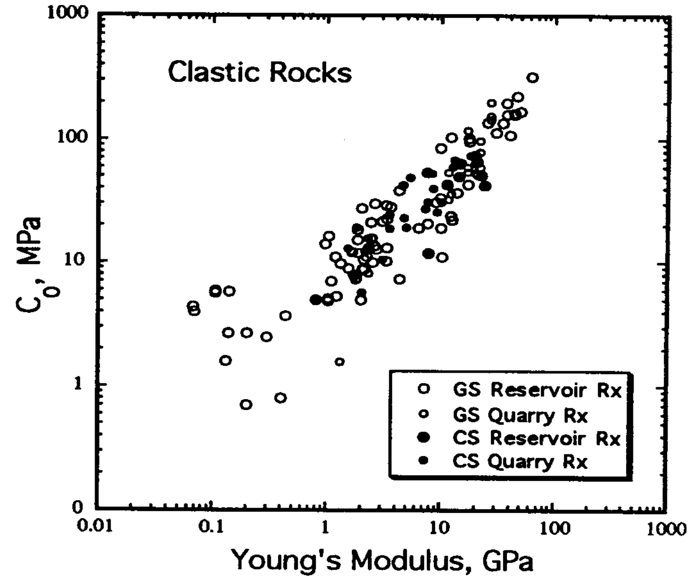

Fig. 4. Unconfined compressive strength as a function of the Young's modulus for Group II rocks classified as grain-support (GS) and clay-support (CS).

5.3 *Dependence of C_0 on Young's Modulus*

Young's modulus provides the best estimation of C_0 when comparing clastic rocks with large differences in clay content and porosity. Figure 4 shows a log-log plot of the variation of C_0 with Young's modulus for 108 grain-support rocks and 34 clay support rocks with porosity ranging from 1% to 40%. Young's modulus provides a better estimation of C_0 than either porosity or V_{grain} (cf. Figures 2 and 3). This is because Young's modulus is a direct measure of the load-bearing rock frame and because Young's modulus is correlated with the geometry and average number of grain-to-grain contacts (Digby , 1981; Dobereiner and Freitas, 1986; Plumb et al., 1992).

5.4 *Brittle-Ductile Transition Pressure*

The brittle-ductile transition pressure indicates the confining pressure above which a rock, no longer behaves as a brittle material with a well-defined peak strength. Above the brittle-ductile transition pressure rocks strain harden with increasing deviatoric stress (Figure 1). The shaded region in Figure 5 shows the approximate range of brittle-ductile transition pressures in sandstone (Logan, 1986; Scott and Nielson, 1991). The upper bound curve is defined by clay-free quartz arenites and quarzites. The lower bound is defined by the lowest strength reservoir sandstones in our database. The brittle-ductile transition pressure decreases with increasing porosity. The greatest sensitivity of the brittle-ductile transition pressure to porosity is at low porosity.

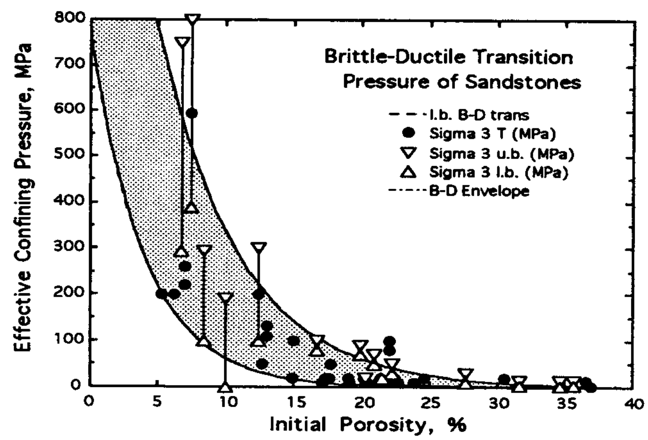

Fig. 5. Brittle-ductile transition pressures for sandstones vs. porosity (shaded region).

5.5 *Dependence of θ on Lithology*

A first order relationship is identified between average friction angle and lithology for clastic rocks representing a wide range of porosity and clay content. The relationship is observed when lithology is parameterised by V_{grain} (Figure 6). Friction angle decreases with increases of either porosity, V_{clay} or the sum of porosity plus V_{clay}. The highest friction angles are measured in low-porosity grain-support rocks whereas the lowest friction angles are found in rocks characterised by low V_{grain}. The median value of the average friction angle decreases by about 30 degrees as V_{grain} decreases from 1.0 to 0.1.

Considerable scatter is apparent in the data despite the clear trend of decreasing friction angle with decreasing V_{grain}. Nevertheless, the overall decrease of average friction angle with V_{grain} is about a factor of two greater than the variation of average friction angle at constant V_{grain}. Part of the scatter is due to the non-linear dependence of strength on confining pressure (3).

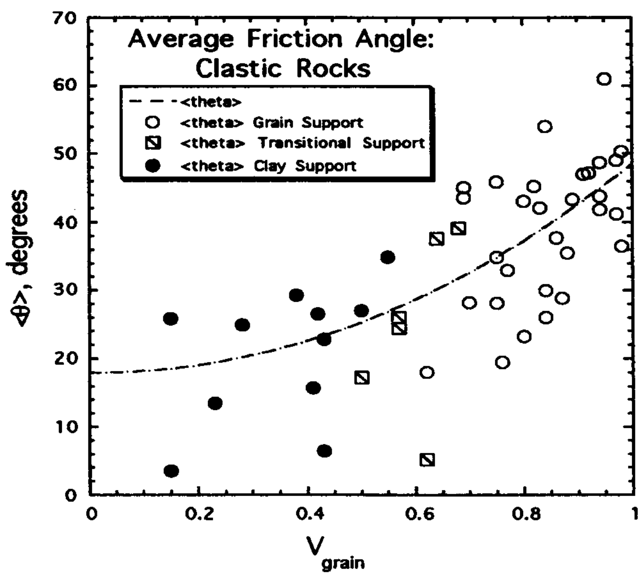

Fig. 6. Average friction angle vs. V_{grain} for group III samples.

5.6 *Dependence of θ on Confining Pressure*

A clearer relationship between friction angle and lithology is observed when we account for the non linearity in the failure envelopes. Figure 7 shows friction angle evaluated at a confining pressure of 25 MPa. The variance of the pressure dependent friction angle at constant V_{grain} is less than the variance observed for the average friction angle. Otherwise there are no additional changes in the relative relationships between rock type and friction angle. The residual variance (+/-10 degrees) in friction angle is not simply an effect of total clay content. A similar variance is observed among rocks which have less than 5% clay.

The greatest effect of confining pressure on friction angle is observed when friction angles for the same set of rocks are evaluated at different confining pressures. For example, at $V_{grain} = 0.6$, friction angles evaluated at 2.5 MPa are approximately 50 % greater than friction angles evaluated at 25 MPa. It follows from (3) that friction angle increases with decreasing effective confining pressure for all rocks with a pressure exponent less than 1. Pressure exponents

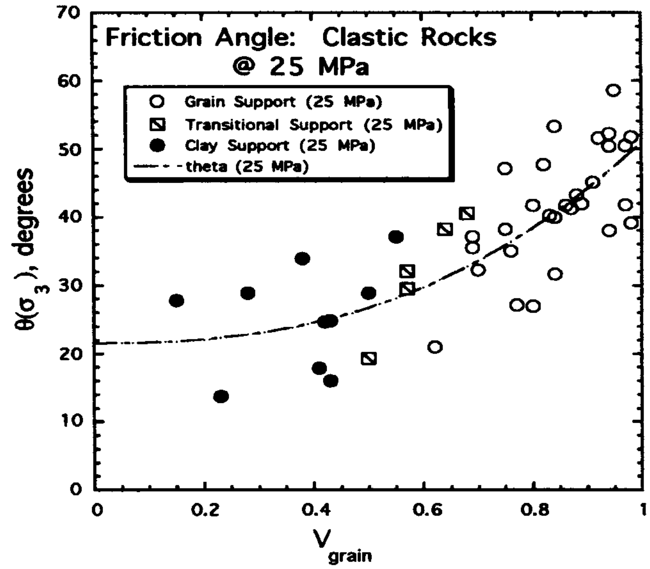

Fig. 7. Friction angle evaluated at 25 MPa confining pressure vs. V_{grain} for Group III samples.

determined for the 46 rocks examined in this study range between 0.60 and 0.80 with a median value of 0.75.

6. DISCUSSION AND OBSERVATIONS

This study has demonstrated that Coulomb failure parameters are related to measurable properties of clastic sedimentary rocks. These results are obtained for rocks representing a wide range in porosity, clay content and grain sizes.

6.1 *Unconfined Compressive Strength*

Unconfined compressive strength varies by almost three orders of magnitude among clastic rocks encountered in the petroleum industry (Figure 4). Recent studies of rock strength have focused extensively on the variations of unconfined compressive strength with porosity (Vernik et al., 1993; Sarda et al., 1993). While it is clear that C_0 can be predicted by porosity in some cases, it is clear from this study that porosity alone is insufficient when cementation and clay content varies among rocks. For example the upper bound curve on C_0 is well characterised by porosity alone whereas strength variations at constant porosity are governed more by clay content and cementation (Figure 2).

Unconfined compressive strength variations among our samples depend on at least three measurable rock properties, porosity, clay content and cementation. Porosity is a measure of consolidation and it is often correlated with the degree of cementation. However, it appears that

Young's modulus gives a better indication of the strength of the bonds between grains than porosity does. Young's modulus provided the best single parameter indicator of C_0 because it is a direct measure of the load-bearing frame and it is highly correlated with the geometry and type of grain-to-grain contacts, grain size and clay content (Dobereiner and Freitas, 1986; Plumb et al., 1992).

Deere and Miller (1969) previously identified a correlation between C_0 and Young's modulus. The principal difference between their result and the result presented here is that rocks in Figure 4 are more representative of clastic rocks encountered in the petroleum industry particularly high porosity reservoirs. Whereas the Deere and Miller (1969) study focused on higher strength rocks of interest to the nuclear weapons industry.

6.2 *Friction Angle*

A relationship between lithology and friction angle of clastic rocks has been identified when lithology is parameterised by the volume fraction of grains. Only a poor correlation was found between friction angle and porosity among group III rocks. The median value of the average friction angle varies by a factor of three among rocks with clay content varying form 0% to 70% and porosity ranging from 0 % to 40%. Friction angles are greatest for low-porosity grain-support rocks and lowest for clay-support rocks. Friction angle decreases with increasing porosity, increasing clay content or decreasing V_{grain}.

While V_{grain} explains a general trend in the friction angle data, the residual variance at constant V_{grain} remains to be explained. Part of this variance is explained by the dependence of friction angle on pressure. Part of the variance in grain-support rocks could be related to differences in grain shape (Rothenburg and Bathurst, 1992) whereas variation in clay type and fluid content may explain the residual variation in the clay support rocks. Improved rock characterisation will help resolve this issue.

Friction angle can also vary by a factor of two, for the same rock, depending on the effective confining stress. The greatest change in friction angle occurs below about 25 MPa confining stress for all group III rocks. This effect can be important when modelling rock strength at reservoir depths (Weingarten and Perkins, 1992). For example, the effective confining stress on a rock near the wellbore can be significantly different than it is in the reservoir due to elastic stress concentrations, stress relief due to plastic deformation or spatial variations in pore fluid pressures. Consequently the strength of a rock can vary significantly with distance from the well.

6.3 *Brittle-Ductile Transition*

It would appear from Figure 5 that in-situ stresses may exceed the brittle-ductile transition pressure in some of the weaker sandstone reservoirs (Plumb, 1994). Sandstones which plot below the shaded region are expected to behave as brittle materials. Sandstones which plot within the shaded region are expected to exhibit significant plastic strain, depending on their strength. Whereas sandstones which plot above the shaded region are expected to exhibit highly ductile behaviour. This information may be helpful when selecting constitutive models for simulations of wellbore stability or sanding.

6.4 *Future Work*

Initial results presented here can be improved if rocks submitted for mechanical testing are better characterised and if better methods for quantifying rock composition and texture are developed. Better laboratory methods are needed for quantifying the texture and cementation of clastic rocks. Particularly important are measures of the number of grain contacts per grain, the grain-size distribution and the geometry of grain-to-grain contacts. Improvements are also needed in the quantification of porosity and volume fractions of clays in shales.

7. CONCLUSIONS

This study has identified new relationships between rock strength and the composition and texture of clastic rocks characterised by a wide range of clay content and porosity. The major results from this data set are:

1) Porosity, clay content and the degree of cementation all have a significant influence on the unconfined compressive strength of clastic rocks .

2) Young's modulus provided the best relative indicator of unconfined compressive strength.

3) Friction angle decreases with decreasing volume fraction of grains.

4) Friction angle decreases with increasing effective confining pressure.

5) The brittle-ductile transition pressure decreases rapidly with increasing porosity in sandstones.

6) Low strength sandstone reservoirs may respond to stress in a ductile manner.

NOMENCLATURE

B	Parameter in non-linear failure criterion
n	Parameter in non-linear failure criterion
C_0	Unconfined compressive strength
σ_f	Effective stress at failure
σ_3	Effective confining stress
θ	Friction angle
$< \theta >$	Average friction angle

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