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Research paper

Empirical strength prediction for preserved shales

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ABSTRACT

Clay-rich shales form the overburden in many sedimentary basins and the seals to hydrocarbon accumulations in the subsurface. Their strength properties are not well understood and they are not often cored or carefully preserved to allow laboratory measurement of their properties. This paper presents the results of geomechanical tests carried out on a global suite of temporally and spatially diverse shales in terms of unconfined compressive strengths, cohesive strengths and friction coefficients. These shales were also extensively characterised in terms of their composition, porosity, physicochemical properties, grain size and rock physics response in order to derive empirical correlations to shale strength. The dataset was expanded using measurements published in the open literature along with some proprietary measurements. What might have been presumed to be good relationships such as strength with velocity or friction coefficient with clay content/porosity were found not to be the case. The best correlations were between strength and porosity or bulk cation exchange capacity. A correlation between friction coefficient and rigid grains was noted although the variables involved were not strictly independent. The relationship with cation exchange capacity may provide the opportunity of strength prediction from dielectric logs as dispersion of the dielectric constant is directly related to cation exchange capacity.

1. Introduction

Shales form a high proportion of sediments deposited in basins worldwide and as such, knowledge of shale strength is important for seal integrity evaluation, well planning, wellbore stability, reservoir compaction and surface/seafloor subsidence. In recent years, data have become available detailing shale physical properties (e.g. Aplin et al., 1999) and other studies have evaluated the geomechanical properties of shales (e.g. Marsden et al., 1992; Olgaard et al., 1995; Horsrud et al., 1998; Cook, 1999; Petley, 1999; Dewhurst and Hennig, 2003; Nygård and Gutierrez, 2002; Nygård et al., 2004a,b; Dewhurst et al., 2008a,b; Delle Piane et al., 2011). These properties have been shown to be sensitive to factors such as composition, organic content, pore pressure and stress history.

Shale properties are important from a petroleum industry perspective as inputs for basin models, for interpretation of seismic response and with regard to wellbore stability and drillability of rocks. In exploration, shales are a critical component of the petroleum system, forming top, lateral and base seals to traps for which their capillary properties (seal capacity) and strength (seal integrity) are vital parameters in terms of exploration risk. In addition, they are often source rocks when rich in organic matter. However, shale cores are rarely taken due to cost of acquisition and the perception that little value can be gained from knowledge of their properties. However, a study by Stjern et al. (2003) indicated savings of ~US$2.5 M on one well through knowledge of shale properties and given that the field had a further 50 wells to drill, total savings would have been in excess of US$100 M. Even when shale cores are taken, the issue of correct preservation often raises its head and if not addressed, can result in desiccation and fracturing of the core, rendering it useless for geomechanical testing purposes. In addition, low porosity shales often strengthen significantly when they dry out due to capillary suction, significantly altering their elastic and deformational behaviour as well as petrophysical and

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rock physics properties and their frequency dependency (e.g. Hsu and Nelson, 1993; Lashkaripour and Passaris, 1993; Valès et al., 2004; Ghorbani et al., 2009; Dewhurst et al., 2012; Delle Piane et al., 2014). Partial saturation is also of importance for gas shales, the advent of which in recent times has kindled significant research efforts into shale rock properties. This particular paper will be dealing however with the properties of fully saturated clay-rich shales and as such these results should not be applied to partially saturated, clay-poor gas shales.

This paper takes measurements made on a selection of well characterised shales widely spread in both space and time – from the Norwegian Sea to the Australian margin, Proterozoic to Tertiary in age – and combines them with the few tests recorded in the literature on well preserved fully saturated shales (Horsrud et al., 1998; Horsrud, 2001; Nygard and Gutierrez, 2002; Dewhurst and Hennig, 2003; Nygard et al., 2004a,b, 2006; Stjern et al., 2003; Dewhurst and Siggins, 2006) along with internal proprietary CSIRO measurements to develop empirical correlations to shale geomechanical properties.

2. Previous work

Horsrud (2001) derived a number of empirical correlations to elastic and strength properties of rocks from extensive rock physics testing on preserved North Sea shale cores. Primary inputs to these correlations were porosity and compressional wave velocity. The latter was utilised across different frequencies, including sonic wireline, sonic logging while drilling and ultrasonics on core plugs and cuttings. Horsrud (2001) notes that such correlations can be complicated by stress history, geological history, pore pressure and compositional issues. The shale strength correlations outlined by Horsrud (2001) are as follows:

$$S_0 = 0.77V_p^{2.93} = 0.77\left(\frac{304.8}{\Delta t}\right)^{2.93} \tag{2}$$

where V_p is compressional wave velocity in km/s. In addition, Horsrud (2001) also noted a correlation to porosity, such that:

$$S_0 = 243.6n^{-0.96} \tag{3}$$

where n is porosity.

Ingram and Urai (1999) also documented relationships between P-wave and S-wave velocity and UCS such that:

$$\log S_0 = -6.36 + 2.45\log(0.86V_p - 1172) \tag{4}$$

$$\log S_0 = -6.36 + 2.45\text{Log}V_s \tag{5}$$

although the actual data from which these correlations are derived is not shown and the preservation state of the shales used is unclear.

Similar efforts to correlate shale strength to porosity were made for example by Lashkaripour and Dusseault (1993) and Chang et al. (2006), although most of the points used in these latter correlations come from mechanical testing of unpreserved shales. Such correlations will not predict the behaviour of preserved shales as the shale properties will be significantly altered by capillary suction resulting from the drying process, with the impact on strength being greater in lower porosity shales with smaller pore throats. Strength correlations derived from dry shale measurements would tend to over-predict shale strength.

Horsrud (2001) rightly questions the validity of trying to correlate dynamic elastic properties with properties relating to mechanical failure. This is due to different deformational mechanisms operating at different strain rates and strain amplitudes. Intuitively however, rock strength can be tied to compaction, i.e. rocks get stronger the deeper they are buried, be this by mechanical or chemical mechanisms. Hence, many of the techniques that are used for strength estimation are related to compaction dependent wireline measurements such as porosity, bulk density or compressional and shear wave velocity. There are a number of other papers that used a relationship between elastic wave velocity or dynamic elastic properties and shale strength, including Coates and Denoo (1981), Ingram and Urai (1999), Lal (1999), and Collins (2002).

Horsrud (2001) notes that friction coefficient does not generally correlate with the properties he outlines above. However, Ingram and Urai (1999) noted the use of specific surface area calculated from dielectric response to address the problem of estimating friction coefficient. Surface area can be related to the clay content and more specifically, individual clay mineral content. Smectite has the highest specific surface area (up to ~750 $m^2\ g^{-1}$), with illite (~80 $m^2\ g^{-1}$) and kaolinite (~25 $m^2\ g^{-1}$) having lower values (e.g. Mitchell, 1993). Geomechanically speaking, pure smectite is the weakest of the clay minerals, followed by illite and then kaolinite (e.g. Wang et al., 1980); hence a relationship between specific surface area and strength is likely to exist. Marsden et al. (1992) noted some correspondence between smectite content, cation exchange capacity, specific surface area and strength in a study of weak mudrocks under high stress levels but noted no such correlation for porosity or velocity. Steiger and Leung (1988), Nakken et al. (1989), Ewy et al. (1994), Wensaas et al. (1998) and Nygard and Gutierrez (2002) also observed a correlation between smectite content and rock strength.

Ingram and Urai (1999) developed the following correlation for shale friction angle (ϕ) from specific surface area (SSA) obtained using the dielectric constant method:

$$Log\phi = Log35 - SSA\frac{Log35}{1266} \tag{6}$$

They noted a scatter of data which could result in an error of ~15–20% from the use of this method which they attributed to mechanical anisotropy of the sample. Anisotropy is generally ignored in conventional analyses (Crook et al., 2002) even though it is well known that fabric and fracture development can result in directionally dependent variations in elastic properties, yield strength and post yield behaviour.

A significant amount of work has concentrated on soil mechanical theory and its application to shallow to moderately buried overburden mudrocks, under the assumption of little diagenetic alteration at these depths. Kågeson-Loe et al. (2004) note that even when shales are cored, strength tests can be time consuming and as such they developed/used a number of correlations between soil mechanical properties and strength. For example, the plasticity of uncemented, fine-grained sediments is governed by water content and the plasticity index (I_p) is known to correlate with strength in shallow sediments (<100 m burial).

Kågeson-Loe et al. (2004) used the soil mechanics approach to correlate properties derived from cuttings in North Sea Tertiary shales although they found that corrections were needed to account for non-linear strength envelopes of these uncemented clays and such corrections were made from core plugs where available. The S_0 derived from plasticity index showed good correlation with other methods of estimating S_0, including sonic- and gamma-derived S_0 values to depths of 2300 m and matched actual core plug measurements to a certain degree.

Estimates of friction angle in the study of Kågeson-Loe et al. (2004) gave consistently different results. Values derived from