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Geomechanical characterization of a south Iran carbonate reservoir rock at ambient and reservoir temperatures

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Geomechanical characteristics of the reservoir and adjacent formations are important inputs to lifetime evaluation, operation and monitoring of E&P projects. Causes and cures for issues such as well instability and production decline often are found in the geomechanical behavior of the rock. Rock testing usually involves destructive tests on core samples, and it is widely acknowledged that properties should be measured at the representative conditions (T, p, σ) from which samples were taken. In this study of a well in an Iranian gas field, geomechanical units were first defined using well logs and lithological assessment. Then, based on the computed tomography images, intact samples were chosen and prepared for uniaxial and triaxial compression in both ambient (20 °C) and reservoir (90 °C) temperature conditions. The geomechanical properties at both temperatures, including uniaxial compressive strength (UCS), Young's modulus (E), Poisson's ratio (ν), friction angle (ϕ′) and cohesion (c′) were compared. Porosity is observed as the main factor influencing the geomechanical behavior, and temperature affects UCS and E values of each GMU, in two distinct ways. We noted a transition porosity of 9%; specimens above this porosity respond differently to temperature compared to specimens below this porosity. It is concluded that whenever rock solid components' thermoelastic expansion is compensated by sufficient available free space (high porosity), the rock matrix will be strengthened. Finally, we noted that this range of ΔT has no significant effect on ν, ϕ′ and c′.

1. Introduction

Geomechanics is a petroleum engineering subdiscipline developed to address mechanical behavior of the reservoir and bounding rocks during exploration and production (E&P) activities (Zoback, 2010; Aadnoy and Looyeh, 2011). Experimental tests on core samples are important tools to obtain the geomechanical characteristics of the rocks, and are normally performed at ambient (laboratory) conditions. However, there may be important incentives to address rock behavior at in-situ conditions (temperature – T, confining stress – σ'_3, pressure – p, saturation …) during the testing process (Dusseault, 2011; Araújo et al., 1997; Yavuz et al., 2010; Chen et al., 2012; Nasseri et al., 2013; Kodama et al., 2013).

Understanding temperature effects on geomechanical characteristics of the rock is of interest to oil and gas field development, viscous oil production, geothermal resource utilization, waste disposal, compressed air or natural gas storage, and crustal mechanics in general (Shafiei and Dusseault, 2013; Zhao et al., 2012; Ranjith et al., 2012; Shao et al., 2015). The influence of high temperature on mechanical behavior of rock materials has been investigated in various studies, concluding that variations in rock composition and fabric may dramatically alter the impact of elevated temperatures. Also, study of confining stress effects shows a strong impact on rock deformation and failure

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mechanisms that varies with rock type (Griggs, 1936; Mogi, 1966; Paterson, 1958). Some studies addressing coupled effects of ΔT and $\Delta\sigma'_3$ indicate that elevated temperature affects the σ'_3 at which the brittle-ductile transition occurs (Heuze, 1983; Lockner, 1995; Griggs et al., 1960; Heard, 1960; Tullis and Yund, 1977; Wong, 1982).

Generally, it is noted that an increase in temperature leads to a decrease in strength for most rocks; however, some exceptions that became stronger at higher temperatures have been noted (Paterson and Wong, 2005; Rao et al., 2007; Duclos and Paquet, 1991). The results of Lion et al. (2005) from a carbonate rock poroelasticity study at two temperatures (150 °C, 250 °C) showed that the porosity and the permeability do not change significantly, but the strength and mechanical properties are altered by temperature. Mao et al. (2009) studied the effect of elevated temperature on the mechanical properties of limestone from ambient to 800 °C; they found that increasing the temperature had a modest effect on the mechanical properties up to 600 °C, but a severe degradation in geomechanical properties occurred after 600 °C. Yavuz et al. (2010) examined the influence of elevated temperature on the physical properties of carbonates, such as porosity, bulk density, compression and shear wave velocities, showing that large alterations in physical properties occur at temperatures above 100 °C.

To expand our understanding of the effects of temperature changes on rock properties, it is necessary to do more controlled testing over relevant temperature ranges. To give an idea of what ranges might be of interest, the following processes are considered (Dusseault, 2010, 2011; Shafiei and Dusseault, 2013; Shao et al., 2015).:

- In geothermal energy extraction from hot, dry rock, $\Delta T \approx -150{-}{-}350$ °C may occur.
- In intermediate grade geothermal cases, $\Delta T \approx -50{-}{-}150$ °C may take place.
- Steam injection at $p > 10$ MPa in heavy oil projects leads to $\Delta T \approx +275{-}{+}300$ °C
- Cool waste water disposal at great depth leads to $\Delta T \approx -50{-}{-}125$ °C, similar to water flooding of a deep oil reservoir.

Besides these processes, for reliable geomechanical modeling, geomechanical properties should be defined at the expected in-situ temperature ranges.

Previously published works about temperature effects on mechanical properties of reservoir rocks are almost invariably about the impact of different temperatures on one rock unit (e.g. a single high-porosity carbonate unit), and a number of studies with no significant porosity variation have been reported (Hunsche and Albrecht, 1990; Duclos and Paquet, 1991; Lion et al., 2005; Rao et al., 2007; Mao et al., 2009; Shao et al., 2015). Based on our literature review, investigating porosity effects on the mechanical behavior of carbonate rocks at reservoir temperatures has not been studied yet, and is of interest.

This study was done on samples from one well in an Iranian carbonate reservoir. First, five distinct geomechanical units (GMUs) were identified through the cored interval, using petrophysical well logs and geological information. Second, 60 intact plugs (12 plugs from each GMU) were taken from locations determined by examining CT-scan images on the core. Third, to help establish correlations between static and dynamic geomechanical properties at true in-situ conditions, uniaxial and triaxial compression tests were performed at 20 °C and 90 °C, with the triaxial tests' σ'_3 conditions equal to the reservoir value of 30 MPa. The results were compared, and rock behavior trends identified and interpreted. The reservoir temperature and pressure were directly measured with in-situ modular dynamic tests (MDT) data. The effective reservoir confining stress was calculated from leak-off test (LOT) data and pressure information.

The intention of this study is to obtain realistic reservoir geomechanical characteristics at in-situ temperatures.

The effect of the sample moisture condition (one of the at-depth conditions) has not been considered in this study because the testing utilities and heating apparatus are not designed and modified for moisture control, so all samples were dry. We do not know if this has altered the validity of the findings, but the results seem consistent.

2. Rock specimen provenance and preparation

An interval of 400 m in a carbonate formation (Permian to early Triassic), was cored from a well in a gas field close to the Persian Gulf, south Iran, for petrographic and geomechanical studies. The interval is a carbonate sequence consisting of dolomite and limestone with occasional intercalations of thin layers of anhydrite. Based on geologic studies and petrophysical logs, five GMUs were identified and confirmed consequently by detailed thin section studies. First, sharp boundaries were noted from the four geophysical logs used: compressional wave velocity, shear wave velocity, porosity and density (DTC, DTS, NPHI and RHOB). Based on this, the five distinct GMUs were tentatively defined. Then, using up to three thin sections per meter for microscopic examination, the validity of the GMU choice was confirmed for the cored interval, and we concluded that the GMU selection also corresponded to definite and consistent lithofacies and stratigraphic subdivisions. The major lithologies, facies, depositional environments, porosity types and amounts, and diagenetic fabrics were the geological features determined from thin-section analysis. Some mismatches were noted between geological features variation and defined GMUs, generally in the transition zones between two adjacent GMUs, but each GMU had its individual and discriminatory geological characteristics.

The advantages of GMU use in engineering studies have been discussed by a number of authors including Uwiera et al. (2011) and Nygaard (2010). Careful definition of GMUs gives advantages in

- Determining efficient numbers of test specimens required for characterization;
- Achieving a representative test specimen distribution through the cored GMU; and,
- Allocating appropriate geomechanical characteristics to the GMU, based on log-lab correlations.

The combination of stratigraphic sequence and petrophysical logs accompanied with GMUs are presented in Fig. 1, with a general listing of the GMUs presented in Table 1. The compressional and shear wave velocity values are expressed relatively, given the scatter within each GMU.

GMU-A is a high-energy, grain-supported lithofacies, dominantly oolitic-bioclastic grainstone with pores mostly filled by anhydrite and calcite cement.

GMU-B is a grain-supported lithofacies, mainly oolitic packstone. Microcrystalline calcite mud fills most of the interparticle pore space and has reduced depositional porosity, but secondary porosity as a result of diagenetic aragonite dissolution is fairly common.