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Geostatistical relationships between mechanical and petrophysical properties of deformed sandstone

Reza Alikarami [a,b,*], Anita Torabi [a], Dmitriy Kolyukhin [a], Elin Skurtveit [a,b,c]

[a] Uni CIPR, Uni Research, P.O. Box 7810, N-5020 Bergen, Norway
[b] Earth Science Department, University of Bergen, P.O. Box 7800, N-5020 Bergen, Norway
[c] Norwegian Geotechnical Institute, NGI, Sognsveien 72, N-0855 Oslo, Norway

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ABSTRACT

Petrophysical and mechanical properties of sandstone reservoirs are likely to change as a result of faulting. In this paper, we investigate the distribution of deformation features (structures) such as fractures and deformation bands in the Navajo and the Entrada sandstones in the fault core and damage zones of two faults in two localities in southeast (Cache Valley) and central (San Rafael Swell) Utah. These two localities had different degree of calcite cementation and hence are of interest to study the mechanical and petrophysical properties of these localities, in order to find out the impact of cementation on these properties and their possible relations. We have performed in-situ measurements by Tiny-Perm II and Schmidt hammer to examine the distribution of permeability and strength/elasticity of rock within the damage zone of these faults. We have studied the statistical relation between (i) Tiny-Perm II measurements and Schmidt hammer values, (ii) permeability and uniaxial compressive strength, and (iii) permeability and Young's modulus of deformed rocks. The statistical results demonstrate that there are correlations between the studied parameters, but the dependencies vary with the degree of calcite cementation in mineralogically similar sandstones (quartz sandstone). Statistical results demonstrate to first approximation that an exponential law is more suitable for description of the relations (i), (ii) and (iii) of non-cemented Navajo sandstone whereas for cemented Navajo sandstone these relations are better approximated by power law.

1. Introduction

Rock deformation starts by either fracturing or formation of deformation bands depending on the initial porosity of rock [1,2]. Deformation of low porosity rocks typically occur by fracturing where the energy needed for cracking/fracturing is less than the energy required for shearing and rearrangement of grains [1]. Fractures are either tensile fractures or shear fractures. Tensile fractures or joints are fractures with no visible differential displacement on two sides of them, whereas shear fractures are fractures with relative displacement parallel to fracture plane [3]. In this study, the term fracture has been equally used for both types. When the space between fractures walls is filled with secondary minerals such as calcite or quartz, they are called veins. Contrary to low porosity rocks, deformation of porous rocks occur by grain sliding and rearrangement of grains as well as by grain size reduction and crushing, which leads to nucleation of different types of deformation bands at the transition between elastic and plastic deformation [1,2,4]. Deformation bands are small-scale mm-thick tabular structures with millimeter to centimeters displacement, and the most common types of deformation bands, cataclastic bands involve grain crushing and compaction [4] and may form in the damage zone of faults. These bands were observed in our studied localities.

Fractures and deformation bands, depending on their types can affect the petrophysical properties of rock, such as porosity and permeability [5], and its mechanical properties, such as compressive strength and elasticity [6], in different ways. For instance, porosity and permeability are reduced within cataclastic bands (especially compaction bands) with respect to their host rocks, while compressive strength and Young's modulus of the material inside the band could be higher than the adjacent host rocks [1,4–9]. In dilation bands, with band perpendicular extension and favorable creation condition of low mean stress [1,4,10], while porosity increases and compressive strength and elasticity decrease, depending on pore tortuosity and change in specific surface area, permeability may decrease or increase [10–12]. Fractures on the other hand tend to increase porosity and effective permeability [8,9,13] and decrease the effective rock strength and

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[*] Corresponding author at: Uni CIPR, Uni Research, P.O. Box 7810, N-5020 Bergen, Norway. Tel.: +47 55 58 36 78; fax: +47 55 58 82 65.
E-mail address: reza.alikarami@uni.no (R. Alikarami).

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elasticity (if applied compressive stress is not normal to the fracture) [6,14]. One of the main aims of this study is to understand the possible impact of these deformation structures (fractures and deformation bands) on the petrphysical and mechanical properties of deformed sandstone reservoirs in the damage zone of faults. Therefore, our measurements are considered to show the effective properties of the damage zone although we have avoided measuring on the fractures. From now on we use petrphysical and mechanical properties, such as permeability, compressive strength and Young's modulus, as of/equal to effective permeability, effective compressive strength and effective Young's modulus.

In general, in pressure sensitive rocks such as porous sandstones subjected to volumetric deformation, depending on the stress level, petrophysical properties such as porosity and permeability as well as mechanical properties such as rock strength and elasticity may change. For instance higher overburden/confining pressure is likely to be accompanied by compaction, which results in lower permeability [15–21] and higher rock strength/elasticity [21–24]. Another important aim of the present study is to understand the possible relation between petrophysical and mechanical properties of deformed rock. Dependence of rock strength on porosity has been studied in porous rocks such as sandstones and chalks by many researchers [25–30]. Palchik [25] has studied the relationship between uniaxial compressive strength and porosity by uniaxial compression test, and Palchik [26] has studied the application of Mohr–Coulomb failure criterion to the porous sandy shales. He found that an increase in porosity leads to a decrease in the cohesion, friction angle and peak axial stress of cylindrical samples from southern part of Donetsk city (Ukraine) during triaxial compression tests. Palchik and Hatzor [27] have examined the influence of porosity on tensile and compressive strength of porous chalks (Adulam chalks) by means of uniaxial compression, point load and indirect tension Brazilian tests using dry cylindrical specimens. They reported that the tensile and compressive strengths are inversely related to porosity through exponential relations. Schöpfer et al. [29] employed the Discrete Element Method (DEM) to investigate the effect of porosity and crack density on elasticity and strength of rock which was represented by bonded, spherical particles. He found that higher porosity and crack density decrease the elasticity and strength of rock.

There are also extensive studies on how rock's permeability and porosity are related. The base for most of the porosity–permeability models is the Kozeny–Carman equation which links permeability to the pore geometry characteristics, i.e., porosity, hydraulic radius, tortuosity and specific surface area [12,31–33]. Pape et al. [32] derived the permeability from industrial porosity logs employing a fractal pore space geometry in which effective radius, tortuosity and porosity are connected through the fractal dimension D. Afterwards, they estimated the permeability using a power-law relation between permeability and porosity.

While there are extensive studies on the dependence of permeability and rock strength on porosity and overburden pressure, there is no study on the possible relationship between permeability and rock strength, the properties that can be obtained from in-situ field measurements. In the present work, we have studied this relationship, the connection between fluid flow characteristics and mechanical properties of sandstone, in order to be able to forecast these properties from each other. This is of great importance in understanding of the behavior of rock when subjected to stress and has implications for fluid flow and storage underground. We have performed two field studies in southeastern and central Utah on faulted Navajo Sandstones. The Navajo Sandstone is a producing petroleum reservoir and currently a candidate reservoir for CO_2 storage in Utah, USA. In the studied localities, the Navajo Sandstone show different degree of calcite cementation from non-cemented to fairly cemented sandstone. We conducted extensive permeability (by a Tiny-Perm II) and hardness measurements (by a Schmidt Hammer) at the damage zone of the studied faults to examine the distribution of rock permeability and compressive strength/Young's modulus in faulted sandstone reservoirs. We employed geostatistical analysis on the field measured data such as Tiny-Perm II–Schmidt Hammer values (*TP*–*HR*) as well as calculated data such as permeability–uniaxial compression strength (*K*–*U*) and permeability–Young's modulus (*K*–*E*) to find out if there is any relation between these parameters, and whether this relation is statistically significant. We employ different statistical approaches to suggest the most suitable relations. We examine linear, exponential and power law statistical relations on our data. Our statistical method is based on using maximal likelihood estimation to find the best relations, and testing the relations significance level. Our main goal in the present study is to find out the possible relations between mechanical and petrophysical properties of deformed sandstone such as *TP*–*HR*, *K*–*U* and *K*–*E*. We also compared the results from two studied localities to find out the effect of cementation on permeability and compressive strength/Young's modulus of rock as well as on the relations between these rock properties.

2. Methods

We have performed two extensive structural field studies on faulted Navajo and Entrada Sandstones in southeastern (Cache Valley) and central (San Rafael Swell) Utah, USA. We have measured in-situ permeability by a Tiny-Perm II and rock hardness by Schmidt hammer type N in the damage zone and core of the studied faults. The Tiny-Perm II and Schmidt hammer values were used in empirical relations to calculate permeability, uniaxial compressive strength and Young's modulus.

2.1. Rock permeability and compressive strength/Young's modulus

We have measured in-situ permeability and rock hardness in the damage zones and fault cores at every 2 m along the scan-lines almost perpendicular to the faults. Tiny-Perm II is a portable air permeameter used for measurement of rock matrix permeability on outcrops. A portable permeameter is basically an annulus through which air can be released into porous media. The permeameter measurements are localized with a depth of investigation of less than four times the internal radius of the tip seal [34]. This means that the investigation depth of the Tiny-Perm II, with the inner tip diameter of about 9 mm, is less than 18 mm. Within fractured zones, we put the Tiny-Perm II on the intact portion of deformed rock with distance more than the investigation depth of Tiny-Perm II to the fractures. For measuring the permeability of deformation band we put the Tiny-Perm II on the deformation band. We did not observe any visible slip surface in the deformation bands. We used the empirical relation (Eq. (1)), provided by the user's manual of the instrument, to convert the Tiny-Perm II readings to the permeability. The relation used to calculate the permeability is given by:

$$TP = -0.8206\log(K) + 12.8737 \quad (1)$$

where TP is the Tiny-Perm II reading, and K is the permeability in mD. The recommended permeability measurement range for rock is approximately from 10 mD to about 10 D by the manufacturer. For Tiny-Perm II measurements we took three readings on each test spot, to examine the repeatability and minimize the possible user based errors, and then used the average value of the readings to calculate the permeability of the spot.

In-situ values of rock hardness have been measured by Schmidt Hammer type N. Schmidt hammer is a device that has been used