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Fracture Density as a Function of Crystal Size: Insights from a Carbonate Reservoir Analogue*

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Abstract

The relationship between fracture density and crystal size has been analyzed at the microscale in Cretaceous well-bedded carbonates at several sites across the southern Apennines. All the outcrops are characterized by decimeter to meter thick, alternating dolomitic and calcareous beds with variable textures and crystal sizes. Two types of dolomites have been distinguished in terms of petrography and petrophysics, both being related to very early diagenetic processes. The analyzed successions can be considered good analogues of the fractured carbonate reservoirs buried in Val D'Agri and hosting the major oil fields of the Basilicata region (southern Italy). The structural setting of the outcropping analogue successions is characterized by the occurrence of normal faults and two perpendicular sets of associated fractures that developed as a result of extensional tectonics during the foredeep stage, and by reverse and strike-slip faults that formed during the subsequent collisional and post-collisional Miocene to Plio-Pleistocene stages. At the outcrop scale, fracture density is heavily depending on both bed thickness and distance from main faults. The main aim of the study has been to extend the investigation at the microscale for a relatively large number of samples in order to find a relationship between crystal size, lithology and fracture density. Several samples of limestone and dolomite have been selected, showing crystal size ranging between 5 to 50 µm for limestone (wackestones to grainstones), and from 5 to 150 µm for dolomite (fine to medium and coarse dolomite). Microscan lines have been performed in thin sections and acetate peels of selected surfaces, in order to collect statistical data on fracture aperture and spacing. Regardless of the lithology, fine grained samples show very high values of fracture density (from 100 to 250 fractures per meter), whereas coarser samples are characterized by lower values (from 10 to 80 fractures per meter). A power law best fits the data, pointing out an inverse relationship between crystal size and fracture density at the microscale. The results of a detailed analysis on early diagenetic dolomitic beds (characterized by variable texture) alternating with limestones suggests that the

role of crystal size largely overcomes that of lithology, very fine grained dolomites behaving similarly to limestone beds of comparable grain size.

Introduction

In carbonate rocks, fracture networks often control migration and entrapment of hydrocarbons. Fractures form a pervasive and capillary network at the centimeter to crystal scale. The related permeability and porosity depend on the statistical distribution of apertures (Odling, 1999; Guerriero et al., 2011). The main focus of reservoir studies lies in those structures actually controlling fluid flow. However, an equally significant goal of structural analysis may be the quantification of the occurrence of fractures that do not contribute to fluid flow. Practical methods to quantify the amount of filled joints are illustrated in Laubach (2003).

Many studies demonstrated that fracture apertures show scale-independent distributions over several orders of magnitude, being well represented by power laws (Belfield, 1994; Belfield and Sovich, 1995; Marrett et al., 1999; Ortega and Marrett, 2000; Ortega et al., 2006). Therefore, a comprehensive study of features showing scale independence should be performed by integrating micro- and outcrop-scale data analysis.

Hydrocarbons of the Val D'Agri fields in southern Italy are partly hosted in fractured, low porosity, Cretaceous interstratified limestones and dolomites showing a relatively large range of textural variation. The aim of this study is to quantify the relative contribution of micro- and macro-fractures, and their associated apertures, to the longitudinal strain of beds characterized by various microtextures, particularly crystal size. Although microcracks do not contribute to fluid flow, being non-connected and usually sealed by mineralization, this may be of great help to contribute to the modeling of reservoirs attributes.

We have analyzed the relationship between fracture density and crystal size at the micro-scale in well-bedded Cretaceous carbonate successions cropping out in the Southern Apennines (Monte Chianello). These successions represent geological analogues of subsurface fractured carbonate reservoirs hosting the Val D'Agri oil fields.

The succession is characterized by decimeter to meter thick, alternating dolomitic and calcareous beds with variable textures and crystal sizes. Two types of dolomites have been distinguished in terms of petrography and petrophysics, both being related to very early diagenetic processes: a medium-grained (20 to 40 μm) and a coarse-grained dolomite (100 to 1500 μm). The limestone beds consist of ostracod wackestones or mud-rich foraminifer packstones with crystal sizes ranging between 5 to 50 μm.

Fracture analysis has been performed on couples of beds and samples with different lithological and textural characteristics, but adjacent to preserve a uniformity degree of strain field to compare and study the different response to the strain of individual petrofacies.

The analyzed successions have been deformed by early Miocene extensional tectonics related to the forebulge and foredeep stage, followed by a collisional stage encompassing thrusts and folds, and finally by post-collisional Pliocene-Pleistocene strike-slip and final extensional tectonics.

The succession is affected by pervasive sets of tensional joints orthogonal to bedding, as well as conjugate normal faults. Joints form two orthogonal sets striking NNE-SSW and WNW-ESE. At the outcrop scale, fracture density is notably depending on both bed thickness and distance from major faults.

Micro-scan lines have been performed by optical microscopy (200x) on thin sections and acetate peels, in order to collect statistical data on fracture spacing and apertures. As the early fractures occur into two sets, samples have been carefully cut in order to intercept each single fracture set.

Fracture Analysis

In the following analysis, the term ‘microcracks’ is used for fractures involving a single or few neighboring crystals, showing low aspect ratio values.

Taking into account exclusively macro-fractures in calculating maximum fracture density (MFD), limestone show higher values of fracture density with respect to dolomites (Figure 1). The data are best approximated by a power law including both limestones and dolomites, roughly indicating an inverse relationship between crystal size and MFD (Figure 1). In Figure 2, mean fracture aperture values detected in limestone and dolomite (including micro-cracks) are plotted vs. crystal size. The best-fit curve is a power law indicating an increase of mean fracture aperture in finer crystal sizes.

The results of the fracture analysis at the micro-scale point out the occurrence of very high values of fracture density (here measured in number of fractures/cm) for all dolomites (these being characterized by coarser crystal sizes with respect to limestones). On the other hand, limestones show a very small number of microfractures with apertures exceeding 5 µm.

Coarser dolomites shows lower values of mean fracture aperture because their crystals contain a greater number of micro-cracks than fine dolomites and limestones, thus lower aperture values are compensated by higher fracture density. On the contrary, at the outcrop scale, beds of coarser dolomites show lower values of fracture density than limestone and fine dolomite. This may be explained as, in coarser dolomites, most of the longitudinal strain is accommodated by crystal strain rather than jointing.

Conclusions

Micro-scale studies of fracture density and aperture, carried out on carbonate rocks showing a wide range of grain size values, point out that longitudinal strain in rock is accommodated by (i) jointing and (ii) brittle deformation of crystals (mainly produced by micro-cracks). These two processes can be viewed as two complementary deformation mechanisms. Microcracks do not contribute to fluid flow in reservoir rocks, as usually they are non-connected and sealed by mineralization.

The results of our analysis show that grain size is the main factor controlling the amount of finite strain related to each of the previously mentioned deformation mechanisms.

Coarse dolomite samples analyzed in this study, differently to limestone, contains a great number of micro-cracks and, therefore, high fracture density values which, in turn, are balanced by lower fracture aperture values.

The results also indicate that the role of crystal size largely overcomes that of lithology in controlling micro-scale rock strain, as very fine grained dolomite behaves like limestone of comparable grain size.

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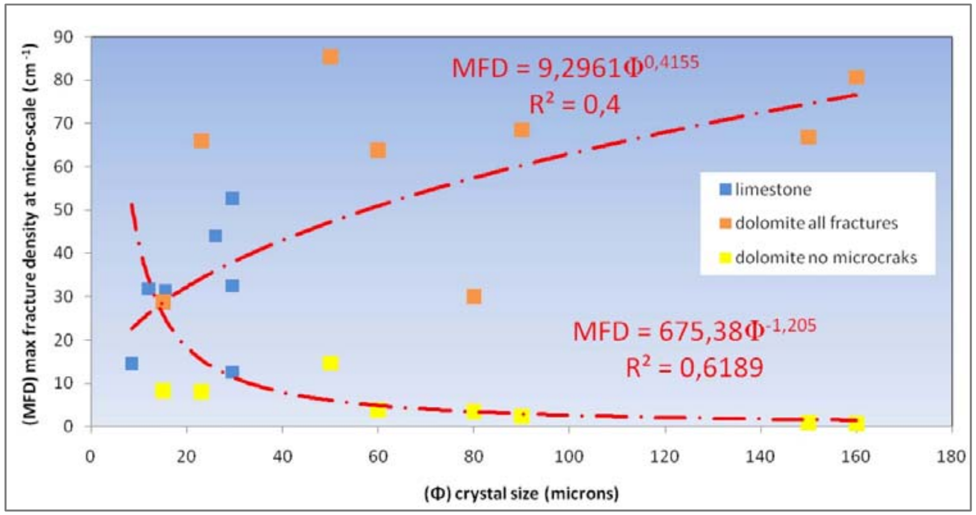

Figure 1. Relationships between crystal size and maximum fracture density (MFD; expressed in cm-1). MFD shows very high values for dolomites (characterized by coarser crystal sizes than limestones) considering all fractures (including microcracks).

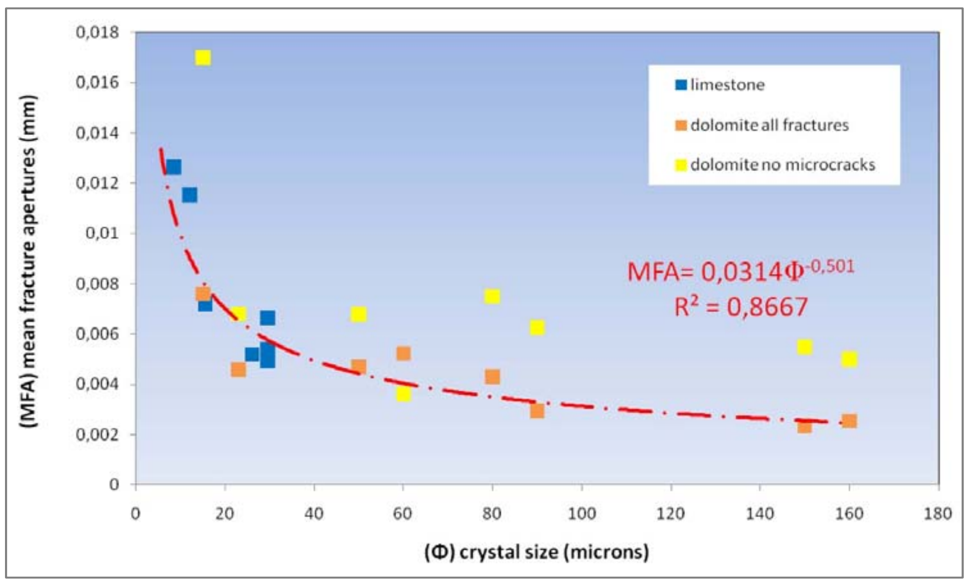

Figure 2. Relationships between crystal size and mean fracture aperture (MFA; in mm). MFA displays higher values for smaller crystal size.