Marine and Petroleum Geology 73 (2016) 350–370

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

Fracture stratigraphy and fluid flow properties of shallow-water, tight carbonates: The case study of the Murge Plateau (southern Italy)

E. Panza [a, *], F. Agosta [a], A. Rustichelli [b], M. Zambrano [b], E. Tondi [b], G. Prosser [a], M. Giorgioni [c], J.M. Janiseck [d]

[a] Department of Science, University of Basilicata, Italy
[b] School of Science and Technology, University of Camerino, Italy
[c] Shell Italia E&P, Rome, Italy
[d] Total E&P Italia, Rome, Italy

ARTICLE INFO

Article history:
Received 8 September 2015
Received in revised form
4 February 2016
Accepted 16 March 2016
Available online 17 March 2016

Keywords:
Carbonate reservoirs
Fractured carbonates
Discrete Fracture Network modelling
Fracture porosity
Correspondent permeability

ABSTRACT

The work tackles the control exerted by a sub-seismic fracture network on both secondary porosity and correspondent permeability of outcropping tight carbonates. Taking advantage of excellent 3D exposures, located in the Murge Plateau of southern Italy, the fracture network is investigated at different scales of observation. The rock multi-layer is made up of 10's of cm-thick, sub-horizontal, laterally continuous limestone beds crosscut by stratabound fractures, non-stratabound fractures, and small faults named as persistent fracture zones with low amounts of offset. Stratabound fractures consist of bed-perpendicular joints and sheared joints, non-stratabound fractures of incipient, cm-offset, sub-vertical faults, whereas the 10's of cm-offset persistent fracture zones are made up of 10's of m-high, m-thick fractured damage zones. The aforementioned structural elements localize within discrete carbonate units bounded by primary features such as bed surfaces, prominent surfaces and sedimentary breccia horizons. Such interfaces therefore affected the fracture stratigraphy of the limestone rock, and thus impact the fluid flow properties of the carbonate multilayer by compartmentalizing deformation.

In the field, the fracture network is investigated by means of scanline and scan area methodologies to document the orientation, intensity, height distribution, mechanical aperture and roughness of individual fractures exposed along vertical outcrops and pavements of abandoned quarries. Then, Discrete Fracture Network (DFN) models of representative geocellular volumes are built, according to the different scales of analysis, to compute both fracture porosity and correspondent permeability (K_{xx}, K_{yy}, K_{zz}). Results of such a work show that the most prominent non-stratabound fracture set forms the major control on fluid storage and migration at the scales of single beds and bed-packages. At a larger scale, we document that fluid migration mainly occurs along the persistent fracture zones, which enhance the fault-parallel flow. As a whole, the persistent fracture zones form localized fluid conduits embedded within carbonate matrices that show isotropic fluid flow properties.

1. Introduction

In the geological record, platform carbonates form either massive and/or layered successions depending upon their original depositional environment (Tucker and Wright, 1990, and references therein). In both cases, these successions show a competing primary (matrix) and secondary (fracture) porosity in the control exerted on fluid flow (Lucia, 1999; Odling et al., 1999). Carbonates characterized by a high value of primary porosity are generally affected by compactive shear bands and/or compaction bands that dramatically reduce the porosity and the correspondent permeability of the rock mass (Tondi, 2007; Tondi et al., 2012, 2014; Antonellini et al., 2014). On the contrary, carbonates characterized by a low amount of primary (matrix) porosity, in particular those micrite-dominated (peritidal and lagoonal facies), form tight rocks often crosscut by joints (Pollard and Aydin, 1988; Peacock and Sanderson, 1995; Kelly et al., 1998; Agosta and Aydin, 2006; Tavani et al., 2008; Lavenu et al., 2013). Burial-related joints, often

* Corresponding author.
E-mail address: elisa.panza@unibas.it (E. Panza).

http://dx.doi.org/10.1016/j.marpetgeo.2016.03.022
0264-8172/

associated to bed-parallel stylolites (Arthaud and Mattauer, 1969; Groshong, 1988; Agosta and Aydin, 2006; Agosta et al., 2009; Gudmundsson et al., 2010; Korneva et al., 2014), in carbonates may show a systematic attitude displaying a spacing distribution somehow proportional to the bed thickness (Price, 1966; Huang and Angelier, 1989; Gross, 1993; Gross et al., 1995; Becker and Gross, 1996; Hanks et al., 1997; Underwood et al., 2003; Gudmundsson and Brenner, 2004; Cooke et al., 2006; Agosta et al., 2012; Gudmundsson, 2011; Rustichelli et al., 2013, 2015a; Korneva et al., 2014; Panza et al., 2015).

Over the years, two quite similar approaches, respectively fracture stratigraphy and mechanical stratigraphy, have been proposed to tackle the distribution of bed-perpendicular joints in layered sedimentary rocks. Fracture stratigraphy subdivides rocks into intervals according to the vertical extent (height), density, or some other observed attributes of fractures crosscutting a layered rock mass (Laubach et al., 2009 and references therein). Differently, mechanical stratigraphy represents a subdivision of rock into discrete fracture intervals according to the mechanical properties of these intervals (Corbett et al., 1987; Cooke, 1997; Laubach et al., 2009). Often, mechanical and fracture stratigraphy are used as synonymous terms, but fracture stratigraphy does not necessarily equal to mechanical stratigraphy due to the time-dependent character of rock mechanical properties (Laubach et al., 2009). In fact, present-day mechanical properties in a fractured rock may not be the properties under which fractures occurred. Alternatively, fractures may form in the early stages of burial diagenesis when bed interfaces did not act as mechanical interfaces (Lamarche et al., 2012). Bed-perpendicular joints, sheared joints and small faults are all structural elements below seismic resolution of great importance in the management of subsurface hydrocarbon reservoirs. For this reason, they deserve a particular attention during field appraisal and development studies. In fact, besides the inherent risk or advantages that they cause during hydrocarbon exploration in terms of migration, fault sealing, top-seal breaching, and reservoir quality enhancement (Walsh et al., 1998; Antonellini et al., 1999; Manzocchi et al., 2008; Agosta et al., 2010; Antonellini et al., 2014), all structural elements below seismic resolution may play an important role during the phase of hydrocarbon production, enhanced oil recovery and, possibly, geologic CO_2 sequestration (Damsleth et al., 1998; Ambrose et al., 2008; Esposito et al., 2010). The analysis of surface analogs is hence often key to decipher the nature, geometry, distribution and dimensional properties of structural elements below seismic resolution.

This multidisciplinary work involved sequence stratigraphy examination, structural analyses and Discrete Fracture Network (DFN) modelling of Upper Cretaceous, well-bedded limestone of the Altamura Formation. The study carbonate multi-layer is crosscut by a network of joints, sheared joints and small faults (Korneva et al., 2014; Panza et al., 2015; Zambrano et al., 2015) that crop out in the Murge Plateau of southern Italy (Spalluto, 2011). There, mesoscale bed-perpendicular fractures are either confined within single beds or crosscut several beds but confined within individual bed packages, acting as mechanical units. Small faults crosscut 10's of m-high stacks of limestone beds made up of multiple bed packages and do not solve significant amounts of offset. Since they form clusters in the carbonate multi-layer, they can be considered quite similar to the fracture corridors that traverse many subsurface reservoirs (Questiaux et al., 2010), or fracture swarms (Olson, 2004; Strijker et al., 2012), all known in literature as sub-vertical tabular fracture volumes traversing vertically rock multi-layers without significantly offsetting the individual layers (Ozkaya, 2007). All of the aforementioned structural features, which are below seismic resolution, can be therefore of a great importance in the management of subsurface hydrocarbon reservoirs. In fact, it is thought that both fractures confined within individual beds and those that crosscut several beds, as well as fracture corridors, profoundly affect the fluid flow properties of tight carbonate reservoirs (Singh et al., 2009). Even if the fracture permeability values at the reservoir condition cannot be predicted due to a lack of informations regarding the stress state, and resulting fracture apertures at reservoir conditions, the present study may therefore help to better assess subsurface conditions in terms of both fracture distribution and relative influence of the structural elements on fluid storage and migration paths. Results of this multidisciplinary study focused on the architecture of a multiscale fracture network affecting a limestone rock in which both matrix porosity and permeability are negligible (Rustichelli et al., submitted). In order to assess the role played by all structural elements below seismic resolutions on the m- to 10's of m-scale petrophysical and hydraulic properties of the aforementioned bedded limestones, an integrated field investigation and Discrete Fracture Network (DFN) modeling is carried out by taking advantage of spectacular 3D exposures.

2. Geological setting

The Murge Plateau forms the NW-trending forebulge of the flexed Apulian foreland of the Southern Apennines fold-and-thrust belt (Fig. 1 a–b), which developed in the central Mediterranean area during Cenozoic-Quaternary times due to the Africa-Eurasia convergence (Royden et al., 1987; Ricchetti et al., 1988; Dewey et al., 1989; Patacca and Scandone, 2001). A slight doubly-plunging shape characterizes the whole Apulian forebulge towards NW and SE, respectively, which is cut by numerous NW-striking normal faults along its north western and the south eastern edges (Billi, 2005). The Cretaceous carbonates of the Murge Plateau are made up of an about 3 km-thick sequence of shallow-marine carbonates (Spalluto, 2011), which covers a Permian-Triassic clastic and evaporitic succession overlying a Variscan crystalline basement (D'Argenio, 1974). In particular, two main lithostratigraphic units are recognized in the aforementioned Cretaceous carbonates, the 2 km-thick, Valanginian to Early Turonian Bari Fm., and the 1 km-thick, Coniacian to Early Campanian Altamura Fm (Laviano and Marino, 1996; Spalluto, 2011). A Cenomanian-Turonian unconformity marked by a bauxite horizon separates the two Cretaceous Fms (Borgomano, 2000). This work focuses on the Altamura Fm., which is made up of micritic and stromatolitic limestones (mainly wackestones) at the base, and of rudist-bearing limestones and bioclastic grainstones at the top (Checconi et al., 2008).

The study outcrops are located in the inactive Pontrelli and Cantore quarries (Fig. 1 c–d). At the Pontrelli Quarry site (Fig. 2), the Santonian limestone is made up of 10's of cm-thick, planar, sub-horizontal beds of whitish calcilutites (silt-grained grainstones to lime mudstones, *sensu* Dunham, 1962) either structure-less or with microbial lamination (Rustichelli et al., 2015b). There, the limestone rock is crosscut by two main sets of strike-slip faults forming an apparent conjugate geometry (Korneva et al., 2014; Zambrano et al., 2015), encompassing fractured volumes characterized by a background deformation made up of one set of bed-parallel pressure solution seams and four main sets of high-angle joints/veins and sheared joints/veins (Panza et al., 2015). The Cantore Quarry (Fig. 2) exposes an about 100 m-thick Santonian-Campanian limestone made up of alternating whitish, structure-less calcilutites (silt-grained grainstones to lime mudstones *sensu* Dunham, 1962) and fine-grained calcarenites (sand-grained grainstones *sensu* Dunham, 1962) with minor rudist floatstones and fenestral calcilutites (Rustichelli et al., 2015b). The vertical walls of the Cantore Quarry are crosscut by small faults, which consist of a few tens of m-high,