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Distribution and arrest of vertical through-going joints in a seismic-scale carbonate platform exposure (Sorrento peninsula, Italy): insights from integrating field survey and digital outcrop model

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A B S T R A C T

Through-going joints cutting across beds are often invoked to match large-scale permeability patterns in tight carbonate reservoirs. However, despite the importance of these structures for fluid flow, only few field studies focused on the understanding and estimation of through-going joint dimensional parameters, including spacing and vertical extent in relation to stratigraphy. Recent improvements in the construction of digital models of outcrops can greatly help to overcome many logistic issues, favouring the evaluation of relationships between jointing and stratigraphy at the reservoir scale.

In this study, we present the results obtained from integrating field measurements with a digital outcrop model of a carbonate platform reservoir analogue in the Sorrento peninsula (Italy). The outcrop consists of a nearly vertical cliff exposing a monocline of alternating gently-dipping shallow-water limestones and dolostones, crossed by several vertical joints of different size. This study allowed us to define how major through-going joints pass across thick beds (bed thickness > 30 cm), while they arrest against packages made of thinly stratified layers. In essence, through-going joints arrest on “weak” levels, consisting of thinly bedded layers interposed between packages made of thick beds, in the same manner as bed-confined joints arrest on less competent interlayers.

1. Introduction

1.1. Joints: a matter of scale

Joints are brittle structures showing extensional displacement across their surface (i.e. opening-mode fractures; e.g. Pollard and Aydin, 1988; Fossen, 2010). These fractures mostly occur in the upper crust, where the strength of the rock is overcome by stresses of various origins (e.g. tectonic, overburden, internal pore pressure, thermal expansion or contraction). In particular, according to linear elastic fracture mechanics, joints originate at flaws within the inhomogeneous and anisotropic rock mass. Stresses concentrate at the tips of joints, favouring and controlling the path and velocity of joint propagation (Gross et al., 1995). Joints then propagate through the medium until they abut against levels, representing a mechanical weakness or a strong competence contrast, unable to transmit the stress required for fracture propagation. These mechanical weaknesses can be either previous joints (or any other fracture) or stratigraphic discontinuities, the latter thus stratifying the rock mass in mechanical units (Gross et al., 1995; Agosta et al., 2015). Indeed, where the bedding surface represents a low-cohesion surface, joint propagation across it may be inhibited (Pollard and Aydin, 1988; Gross et al., 1995; Cooke et al., 2006), so that stratigraphy tends to strongly control the distribution of joints within the rock mass (Becker and Gross, 1996; Hanks et al., 1997; Underwood et al., 2003; Shackleton et al., 2005; Laubach et al., 2009; Zahm et al., 2010), particularly where sedimentary rocks are not intensely folded or faulted.

In low-permeability tight carbonates of buried reservoirs, joints often form a stratigraphically-controlled network, representing the main path for fluid flow. Within this network, major through-going joints, spanning from few meters to several tens of meters in

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height, can represent important conduits for fluid migration (Odling et al., 1999; Nelson, 2001). However, the vertical and lateral distribution of these major joints in the subsurface, as well as their relationships with the stratigraphy, is not easily resolvable with well or seismic data. Extrapolating the limited observations in wells is in fact a major issue in the characterization of fractured reservoirs. Because of this, reservoir models are frequently populated with information derived from the study of outcrop analogues (Becker and Gross, 1996; Antonellini, 2000; Wennberg et al., 2006; Lacombe et al., 2011; Storti et al., 2011; Barbier et al., 2012; Vitale et al., 2012; Lavenu et al., 2013; Bisdom et al., 2016; Zambrano et al., 2016), although caution should be taken when using analogues as guides to the subsurface (e.g. McGinnis et al., 2015, 2017; Li et al., 2017). Nevertheless, the use of analogues still gives valuable information otherwise not available. The need for finding general rules describing the distribution of joints at several scales has led to numerous studies on joint spatial and dimensional attributes in the last forty years (Bonnet et al., 2001 and references therein). These studies have resulted in the establishment of scale relations between several geometrical properties of joints at the bed scale (Schultz et al., 2013). These include the relationship between joint aperture and length (Olson, 2003; Odonne et al., 2007; Hooker et al., 2013; Guerriero et al., 2015) and, above all, between host-bed thickness and joint spacing (Ladeira and Price, 1981; Narr and Suppe, 1991; Gross, 1993; Gross et al., 1995; Wu and Pollard, 1995; Ji and Saruwatari, 1998; Bai and Pollard, 2000; Gillespie et al., 2001; Odonne et al., 2007; Rustichelli et al., 2013). It is worth noting that this simple bed thickness-to-spacing relation does not apply, for example, in the case of early fracturing of poorly stratified rocks with weak mechanical interfaces (e.g. Lamarche et al., 2012; McNeill and Eberli, 2012; Lavenu et al., 2014, 2015) or to some other, late formed fracture arrays as demonstrated by subsurface observations (e.g. Li et al., 2017; Marrett et al., 2017). In any case, any dependence of the joint network attributes on the occurrence of stratigraphic discontinuities requires that studies of joint dimensions in analogues of naturally fractured reservoirs are addressed at the scale of the considered stratigraphic discontinuity (e.g. Ortega et al., 2006).

Because of difficulty to access vertical exposures, analogue studies, to date, have been limited to the examination of spatial distribution and dimensional properties of joints at relatively small length scales. How large through-going joints are distributed within thick mechanical carbonate units, and where they arrest, remain poorly understood. Adding new data and techniques to contribute solving this issue is the main focus of this work.

1.2. Techniques for digital surveys

A traditional approach to resolve large width (i.e. > 100 m) outcrops is generally represented by the use of orthorectified photo-panels. This method has the big disadvantage of forcing the interpretation of the 3D nature of the fracture array into a 2D plane (Minisini et al., 2014), which implies significant errors when structures oriented oblique to the photo are studied. The most obvious bias of this approach entails that different sets of fractures, at certain angles with the outcrop wall, are all considered as a single, quasi-perpendicular set. A fully 3D approach to this issue has been addressed since the late '90s through the use of virtual/digital outcrop models (VOMs herein) (Xu et al., 2000; Pringle et al., 2001; Bellian et al., 2005; Clegg et al., 2005; McCaffrey et al., 2005, 2010; Trinks et al., 2005; Jones et al., 2011; Howell et al., 2014). VOMs are traditionally obtained by high precision terrestrial laser scanner surveys (e.g. Richet et al., 2011) and, more recently, also by Structure from Motion (SfM) photogrammetric techniques (Westoby et al., 2012), or by a combination of both. However, TLS surveys have a few intrinsic limitations (e.g. Wilkinson et al., 2016), including: (i) the weight of the field equipment, (ii) the need of scanning from multiple field-based positions and (iii) a longer acquisition time, which together makes this technique unsuitable in certain remote areas, like that of this study, where data acquisition cannot be conducted from the ground level.

On the other hand, the photogrammetric method allows the production of VOMs by means of randomly distributed photographs pointing at the same scene. In this work, outcrop images were acquired by means of an unmanned aerial vehicle (UAV, Firpo et al., 2011; Neitzel and Klonowski, 2011; Harwin and Lucieer, 2012; Torres et al., 2012), commonly referred as a drone, equipped with a mirrorless photo-camera. The outcrop is a near-vertical inaccessible cliff in the Sorrento Peninsula (southern Italy), facing southward toward the Gulf of Positano at an altitude over 1100 m (Fig. 1). This means that there were no suitable sites to shoot photographs directly from the ground, or to locate scan positions with good points of view for TLS surveying.

1.3. Scope of work

In this work, the results obtained from combined field and remote sensing observations of a 250 m wide and >200 m high carbonate platform reservoir analogue in the Sorrento peninsula (Italy) are presented. The outcrop consists of a nearly vertical cliff exposing alternating gently-dipping shallow-water limestones and dolomites characterized by the presence of several vertical fractures of different height and hence with different vertical continuity. The 3D model of the Conocchia cliff was built using the Agisoft PhotoScan software, while geostructural data from the model were acquired by means of the open source software OpenPlot (Tavani et al., 2011, 2014). The proposed workflow enables the construction of orthorectified 2D photo-panes along with the 3D spatial orientation of meter to tens of meters long fractures from an inaccessible outcrop. Field investigations conducted along the edge of the cliff, integrated with the results obtained from the remote sensing study, allowed us to unravel where major (i.e. several meters-long) bed-perpendicular through-going fractures are more likely to arrest in the shallow-water carbonate sequence.

2. Geological framework

The studied outcrop is located within the Lattari Mountains in the Sorrento peninsula (Fig. 2), in the inner sector of the southern Apennine fold and thrust belt. The Lattari Mountains mostly expose rocks of the shallow-water Triassic to Miocene carbonate succession of the Apennine Platform. This carbonate platform developed on the southern portion of the Mesozoic Adria block, at the southern margin of the Neotethys Ocean (Bernoulli, 2001). The deep Lagonegro Basin separated the Apennine Platform from the Apulian Platform to the east (Mostardini and Merlini, 1986). The passive continental margin of Adria, of African affinity, experienced later shortening related to the development of the Apennine fold and thrust belt. Since the early Miocene, post-collisional forebulge and foredeep stages affected the pre-existing passive margin successions, followed by subsequent inclusion in the tectonic wedge (Mazzoli et al., 2008; Vitale and Ciarcia, 2013). Later, during the Pliocene and Pleistocene, this portion of the belt was shaped by syn-orogenic extension (Ascione et al., 2012; Mazzoli et al., 2014), and post-orogenic strike-slip and extensional faulting (e.g. Butler et al., 2004; Ascione et al., 2013; Candela et al., 2015, and references therein). Although belonging to a different paleogeographic domain (i.e. the Apennine Platform), the shallow-water carbonates exposed in the Lattari Mountains consist of rocks very similar to those of the Apulian Platform, which constitute the reservoirs for

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