



HAL
open science

What controls diffuse fractures in platform carbonates? Insights from Provence (France) and Apulia (Italy)

Arthur P.C. Lavenu, Juliette Lamarche

► To cite this version:

Arthur P.C. Lavenu, Juliette Lamarche. What controls diffuse fractures in platform carbonates? Insights from Provence (France) and Apulia (Italy). *Journal of Structural Geology*, 2018, Spatial arrangement of faults and fractures, pp.94-107. 10.1016/j.jsg.2017.05.011 . hal-01588455

HAL Id: hal-01588455

<https://hal.science/hal-01588455v1>

Submitted on 25 Nov 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

What controls diffuse fractures in platform carbonates? Insights from Provence (France) and Apulia (Italy)

Arthur P.C. Lavenu ^{a,*}, Juliette Lamarche ^b

^aADMA-OPCO, PO Box 303, Abu Dhabi, United Arab Emirates

^bCEREGE UM 34, Aix-Marseille Universite, 3 place Victor Hugo (case 67), 13331, Marseille cedex 3, France

Fractures are widespread in rocks and regional opening-mode arrays are commonly ascribed to major tectonic events. However, fractures occur in otherwise undeformed rocks. Some of these are early-developed features independent of tectonics and forming a background network at regional scale.

To overcome this lack of understanding, two hydrocarbon reservoir analogues from platform carbonates have been targeted: the Provence (SE France), and the Apulian platform (SE Italy). In both areas, an early fracturing stage has been observed, made of high-angle-to-bedding opening-mode fractures, and bed-parallel stylolites. These features developed synchronously during the first burial stages and prior to major tectonic events. The fracture sets are not genetically related to the present-day layering. Contrarily, fractures developed in a brittle media where facies transitions were not sharp and did not act as mechanical discontinuities.

Carbonate facies distribution and early diagenetic imprint constrained the mechanical stratigraphy when fractures occurred. In addition, we observed that fractures related to late tectonic inversion were partly inhibited. Indeed, rock mechanical properties change through time. Characterizing the temporal evolution of carbonate rocks has revealed that diagenesis and sedimentary facies are the prime actors for brittleness and mechanical layering in carbonates.

1. Introduction

For more than a century, opening-mode fracture processes, mechanics, and origins have been investigated. In the first part of the 20th century, principles of fracture formation and propagation were established (Griffith, 1921; Anderson, 1942). Since the early 1960s, extensive academic research reported in theses and books, outlined attributes and refined understanding of pattern development (Price, 1966; Ramsay, 1967; Suppe, 1985; Engelder, 1985; Atkinson, 1987; Ramsay and Huber, 1987; Pollard and Aydin, 1988 and references therein; Price and Cosgrove, 1990). Since the late 1960s, natural fractures have been increasingly important to the oil and gas industry owing to the role of fractures in reservoir behavior. Researchers have worked at characterizing fractures in subsurface reservoirs (Stearns and Friedman, 1972; Nelson, 1979; Aguilera, 1980; Narr and Currie, 1982; Nelson, 1985; Narr, 1996; Aydin, 2000; Laubach, 2003; Narr et al., 2006; Gale et al., 2014), where fractures provide a pathway for fluid flow. Indeed, deciphering

fracture origin and architecture in the subsurface would help in the understanding of reservoir behavior, which is critical in the oil and gas industry.

Fractures are widespread structures in rocks, and for practical applications it is imperative to accurately predict fracture attributes that affect fluid flow, including their size and spatial arrangement. Correlating the stress-strain relationship to fracture density in folded formations (Murray, 1968; Roberts, 2001; Keating and Fischer, 2008; Hunt et al., 2009) or faulted rocks (Caine et al., 1996; Aydin, 2000; Billi et al., 2003; Kim and Peacock, 2004; Agosta et al., 2010; Matonti et al., 2012; Michie et al., 2014) are among the most widely used concepts for fracture prediction. Where folds and faults are absent, regional opening-mode arrays are commonly ascribed to major tectonic events. However, fractures occur in otherwise undeformed rocks (Laubach, 1988; Frost and Kerans, 2010). Some of these are early-developed features independent of tectonics that form a background network at regional scale. Their occurrence and architecture remains poorly known and, as a consequence, largely unquantified in reservoir modeling, especially in the case of carbonate rocks. A fundamental, but frequently overlooked aspect of fracture spatial arrangement is

* Corresponding author.

how fracture occurrence partitions within a stratigraphic sequence, in other words, the fracture stratigraphy (Laubach et al., 2009). Many outcrops have distinct segregations of fracture occurrence corresponding to depositional facies and interbeds, and in some cases these patterns correspond to current differences in mechanical properties (e.g. Corbett et al., 1987). The prevalence of late-formed, barren joints to cluster within specific beds may mask (and in many cases, probably overprint) important patterns in which early-formed fractures respond to earlier states of mechanical stratigraphy. Here we describe fracture array spatial distribution that differs from the modern mechanical stratigraphy, having unbounded fracture height patterns likely reflecting early mechanical homogeneity. Differences in height patterns are potentially important variables in governing vertical migration of fluids.

Diffuse — or regional, background — fractures (Guiton, 2001; Bazalgette, 2004; Vitale et al., 2012) are opening-mode fractures that range from barren joints to fully mineral filled veins. One set of such an array in the subsurface can comprise fully cement-filled veins in one location or bed, and apparently barren (albeit usually cement lined) joints in adjacent locations or beds; moreover, small fractures of a given set typically qualify as veins whereas larger fractures may fit a definition of joints (e.g., Laubach, 2003; Gale et al., 2004; Lander and Laubach, 2014). Arrays are low-strain features that do not require tectonic events to form (Olson et al., 2009). Diffuse arrays can arise throughout cycles of burial and uplift by processes such as regionally elevated pore fluid pressure (for example, by gas generation: Fall et al., 2015) or thermoelastic contraction during uplift (English, 2012). In carbonate rocks, an important but little appreciated type of diffuse fracture array may form in the first stages of the host rock brittle history. Owing to early and near-surface diagenesis, and consolidation and early embrittlement of some carbonate rocks (McNeill and Eberli, 2009; Frost and Kerans, 2010), diagenesis can play an essential role in fracture formation.

This paper provides insights on processes governing the occurrence, spacing, and height distribution of diffuse fractures in carbonate rocks. Synthesizing and comparing results from several recent case studies (Lamarche et al., 2012; Lavenu et al., 2013, 2014; 2015), we identify commonalities that govern the close spacing and unbounded height distributions that characterize diffuse fracture arrays in some early fractured carbonate rocks.

2. Methods

Outcrops have been selected away from fold hinges and fault zones, in order to restrict our findings to diffuse fractures only. For each outcrop, a six-step workflow was applied to fully characterize the fracture network and the host rock. The first steps consist of gathering hard data: fracture parameters (strike, dip, size, spacing, cross-cutting relationships, cement fill ...) measured using scanlines (Priest and Hudson, 1981; Priest, 1993; Zeeb et al., 2013) or scan area method — or window sampling (e.g. Wu and Pollard, 1995; Hardebol and Bertotti, 2013; Lavenu et al., 2015). The difference between the two techniques is the representativity of the sampling: the scanline method measures fracture attributes along a tape, in 1D, and the scan area method measures fractures inside a defined area (in this case, a rectangle shape), in 2D. Fractures have been analyzed in terms of geometry, chronology between the fracture sets and with stylolites, to determine cross cutting relationships. Rock samples were collected from each outcrop for further laboratory investigations. Petrophysics measurements were made to capture elasticity and porosity for each collected sample. V_p was measured in free air using a Pundit7 apparatus (©CNS Farnell Ltd.) that calculates the P-wave travel time through opposite sides of a sample. Porosity is measured on 2.54×2.54 cm (1×1 in.)

dry plugs using a helium porosimeter. Petrographic analyses were used to unravel the sequence of diagenetic phases in the host rock, using cathodoluminescence techniques (Amieux, 1981; Boggs and Kinsley, 2006) and diagenetic stratigraphy concepts (Meyers, 1974; Loreau et al., 2000; Boggs, 2009). To perform the diagenetic sequencing, we used a Technosyn Cold Cathode Luminescence 8200 Mk II coupled to an Olympus™ BH2 microscope and to a Zeiss™ MRc5 digital camera. The last step of the workflow is creating a subsidence curve for specific areas taking account of regional geology and back-stripping (Allen and Allen, 2005), to define the burial–uplift history of the host rocks. For this study, the datasets used consists of about 3500 fracture measurements, 230 samples and 280 thin-sections, collected from 14 outcrops.

We account for all available geologic attributes, both internal to the rock, such as lithology, porosity, fracture orientation, density, diagenetic phases, and external, for example structural position, regional stress, geodynamic history, to determine critical parameters that rule fracturing and mechanical property evolution.

3. Geological settings

As mentioned above, each area has been described in detail elsewhere. Here we briefly summarize the geology to provide context for our synthesis of commonalities amongst our examples.

3.1. The Provence

The Urgonian Formation is a 400 m-thick platform carbonate succession, deposited in Valanginian–early Aptian times (Masse, 1976). At that time, Provence was entirely within a tropical inner platform environment and sediments deposition evolved little throughout the region and the time interval such that the original depositional facies are essentially the same in all outcrops. We examined six outcrops of Urgonian carbonates distributed from the north to the south across the region (Fig. 2). Four outcrops are located far from folds and major faults to avoid tectonic-related fractures. Two outcrops are on the flanks of the Nerthe anticline, far from the hinges, to test the fracture/fold relative timing. One outcrop (B) is presented in Fig. 3 as an illustration.

In A, B, and C (Fig. 2), the exposure is composed of highly compacted packstones-to-grainstones containing numerous rudists, miliolids, bioclasts, and rare stromatolitic laminae but with many bed-parallel stylolites (8 per meter, Table 1) within layers and at layer interfaces. Beds thicknesses range from 0.5 to 10 m. In D, E, and F, the exposed outcrops are made of porous to microporous grainstones with rudist clasts and miliolids, and with few bed-parallel stylolites (about 2 per meter, see Table 1). Beds range in thickness between 0.5 and 6 m (see Lamarche et al., 2012 and Lavenu et al., 2013). The studied outcrops are characterized by gradual facies transitions in thick beds. Each individual bed interface is enhanced by stylolites.

Each outcrop exhibits a pattern made of two non-stratabound vertical-to-bedding fracture sets, striking about N–S and E–W, $\pm 30^\circ$. Fractures in both sets range from 0.1 to 10 m in height, and both sets are perpendicular to bed-parallel stylolites.

3.2. The Maiella Mountain

Maiella Mountain belonged formerly to the Apulian platform realm but is now a thrust-related anticline, N–S-oriented and eastward verging. The sequence exhibits an uninterrupted platform-to-basin profile of Late Jurassic to Late Cretaceous age (Accarie, 1988; Vecsei, 1991). Three outcrops were selected in the platform domain (Fig. 4). The investigated carbonate formation, so-called Lower Cretaceous *Morrone di Pacentro* Formation (Bruni

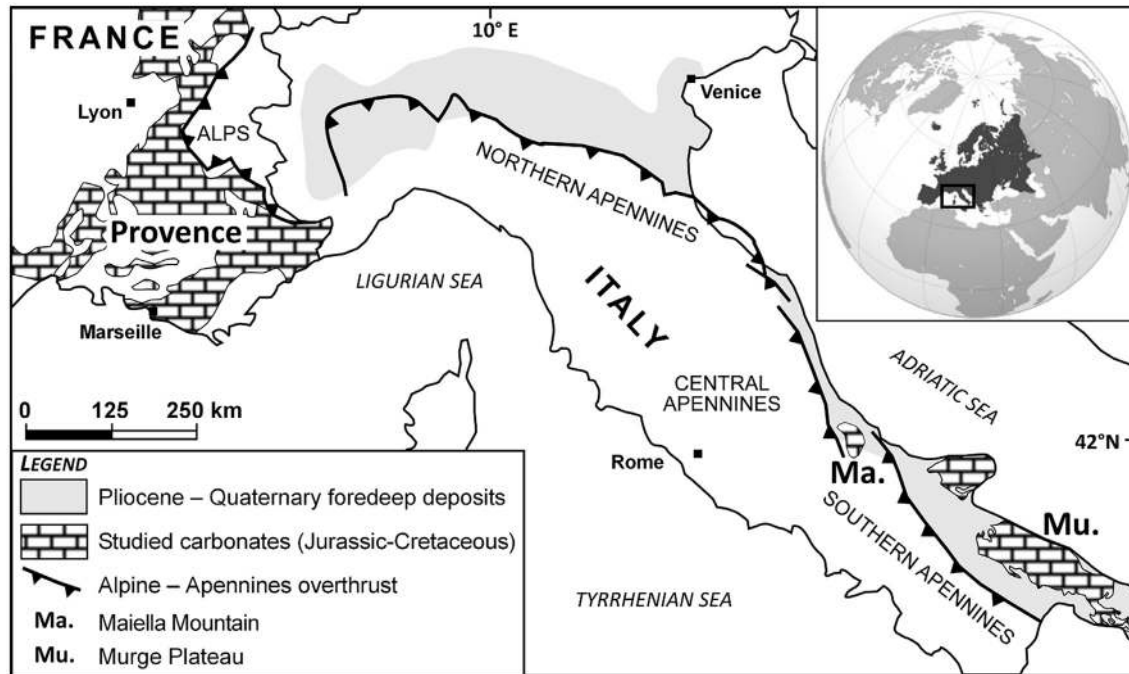


Fig. 1. Schematic map of southeastern France and Italy with the location of the studied areas.

et al., 2007), comprises 1500 m-thick inner platform deposits characterized by transitional facies variations. The observed texture gradually shifts from mudstone-wackestone with fenestrae to pelletoidal wackestone-packstone, characteristic of an inter-tosupratidal environment. Beds range in thickness between 0.5 m and 2 m. Some high-energy facies such as oolitic grainstones have been observed albeit very sparsely. The layers dip 35° eastward (Fig. 5). Fractures are vertical-to-bedding but no fracture abutment on present-day bed is evident. They are clustered into four sets: one major set N070°-oriented, 3 minor sets N030°, N120° and N160° (see Lavenu et al., 2014). Fractures range from 0.1 to 10 m apart. Bed-parallel burial stylolites are ubiquitous (average of 12 per meter, Table 1), and are located either within layers or at layer interface (Fig. 5). Fractures and bed-parallel stylolites are mutually intersecting, the latter emphasizing the present-day bedding.

3.3. The Murge Plateau

The Murge area is a NW–SE-oriented continental plateau along the southeastern shore of Italy. Like the Maiella Mountain, the Murge Plateau is part of the former Apulian platform but is in the undeformed Apennine foreland. It is made of two slightly deformed superimposed carbonate platform successions: the Lower Cretaceous-to-Cenomanian *Calcare di Bari* Formation (Borgomano, 2000; Spalluto and Caffau, 2010), and the Coniacian-to-early Campanian *Calcare di Altamura* Formation (Luperto Sinni and Borgomano, 1989; Borgomano, 2000). Five sites have been investigated (Fig. 6).

On outcrop, the *Calcare di Bari* Formation is made of thin mudstone intervals (20 cm to 1 m-thick) with levels of stromatolitic laminae, evolving to wackestone–packstone (one to 2 m-thick) with pelletoids, ostracods and foraminifers. The *Calcare di Altamura* Formation is defined at outcrop scale by an alternation of massive wackestones with benthic foraminifera and laminated mudstones, in beds ranging from 5 to 70 cm thick. Some rudist shells and bioclasts are present. These facies are characteristic of a peritidal-to-shallow subtidal depositional environment. In both formations,

the facies changes are gradual rather than sharp.

In each outcrop, the fracture pattern is made of two vertical-to-bedding sets, perpendicular to and mutually intersecting with bed-parallel burial stylolites (Fig. 7). Fractures are not — or only rarely — stratabound and range between 0.2 and 5 m in height. Fracture sets are N–S and E–W to N045° and N135° in the *Calcare di Altamura* Formation, and N070–160° in the *Calcare di Bari* Formation (Lavenu et al., 2015). Bed-parallel stylolites are common with a density ranging from 5 per meter in the *Calcare di Altamura* Formation to about 11 per meter in the *Calcare di Bari* Formation (Table 1). Bedding is clearly marked, but the present day mechanical stratigraphy does not fit with the fracture stratigraphy. Looking closely, the current bedding is enhanced by pressure solution, meaning that either the early bedding has undergone dissolution or there was no bedding at all.

4. Results

4.1. General fracture stratigraphy

The studied outcrops display high-angle to vertical-to-bedding opening-mode fractures. These fractures are arranged in at least two perpendicular sets, and as many as four in some locations. Fracture heights do not correlate to the present-day bedding. In other words, fractures that strike parallel to each other have a wide range of heights and fractures terminate vertically at different positions within the unit, not all at the same bed boundary or interface. Thus fractures are not stratabound and either cut through bed boundaries or bypass interfaces (Fig. 8). In the terminology of Hooker et al. (2013), the fracture stratigraphy is unbounded.

We interpret the unbounded height pattern to result from fracture development in a rock having little or no mechanical properties contrast. Although at present-day, bed interfaces are visible, which should constrain the fracture stratigraphy according to Shackleton et al. (2005). The lack of fracture abutment on any interface means that any mechanical stratigraphy that prevailed at the time of fracturing was insufficient to arrest fracture growth, and

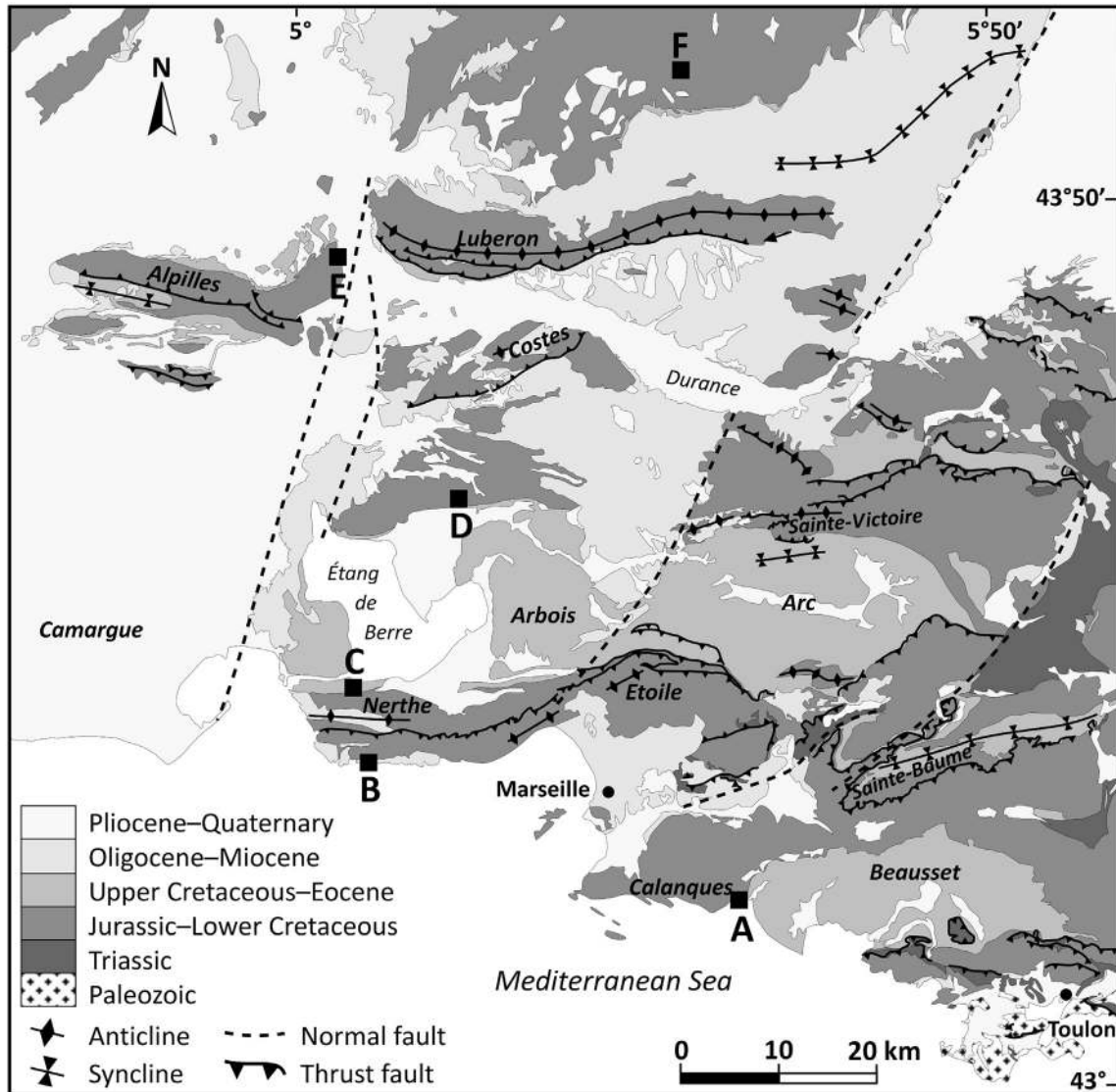


Fig. 2. Schematic structural map of the Provence with outcrop locations, modified from Lamarche et al. (2010).

that the host rock mechanical contrasts then differed from those existing today.

In addition to high-angle-to-bedding fractures, bed-parallel stylolites are present both within beds and at bed interfaces. These stylolites are mutually cross cutting with the high-angle-to-bedding fracture sets. According to Nelson (1979), fractures in rocks depict the stress state at the time of fracturing. However, the mutual cross cutting relationships between the different fracture sets does not allow clear discrimination relative to timing amongst fractures in different orientations. The Griffith theory of rupture (1921) and Anderson (1942) relate mode I failure process to a maximum vertical compressive σ_1 . In the case of tilted outcrops (B and C in Fig. 2, and A, B, and C in Fig. 4), a back tilting procedure has been applied (see stereoplots in Figs. 3 and 5). This procedure restores the layers in their original horizontal position, as well as the features contained within the layers. Back tilting the currently tilted layers to horizontal shows that the fractures stood at high-angle to vertical to bedding, and the bed-parallel stylolites were horizontal. The cross cutting relationships between both features combined with patterns in the restored state is evidence of pre-tilting/folding fracturing, when bedding laid horizontally, and

under a stress pattern with a vertical σ_1 .

Following Nelson (1981), a vertical σ_1 is consonant with the state of stress that leads to burial pressure solution. Thus, vertical-to-bedding fractures and bed-parallel stylolites developed under a similar stress state, most probably synchronously, and during the burial of the host rock. The synchronicity of fractures sets with stylolites argues for a stress pattern defined by a vertical load-induced σ_1 , and poorly differentiated horizontal components (σ_2 and σ_3) with low amplitudes (e.g. Laubach et al., 1998; Lamarche et al., 2012).

4.2. Petrophysical properties

Analyzing the petrophysical properties of host rocks reveals similarities in terms of pore types and rock susceptibility to fracturing across the investigated areas. Two main pore types have been identified: intergranular porosity and microporosity. In the case of intergranular porosity, porosity values are low: an average of 2% in the *Calcare di Bari* Formation, close to 3% in the Urganian of South Provence, and up to 7% in the *Morrone di Pacentro* Formation (Table 1). In the specific case of intergranular porosity, when values

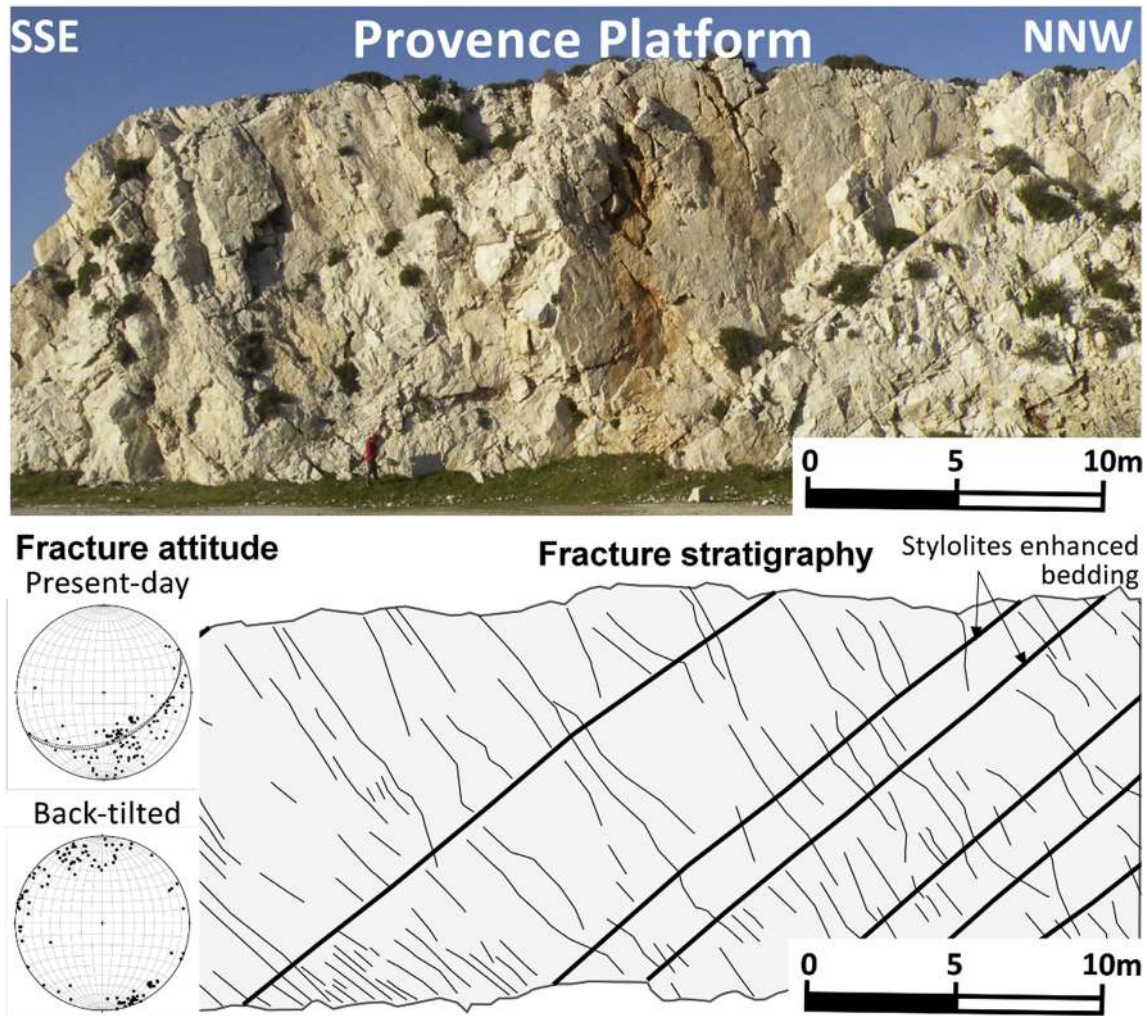


Fig. 3. Photograph of one of the studied outcrop in Provence, here on the southern flank of the Nerthe anticline (outcrop B on Fig. 2). The bottom schematic of the picture is showing the interpretation of the photograph and the stereoplots (lower hemisphere) are presenting the fractures and bedding measurements in the present-day and back-tilted position.

are low, P-wave velocity is high: about 6250 m s^{-1} in the *Calcare di Bari* Formation, 5900 m s^{-1} in the Urgonian, and 5400 m s^{-1} in the *Morrone di Pacentro* Formation, with a negative correlation trend between the 2 parameters (Fig. 9). In the case of microporosity, values range from 1 to 21%, with an average value close to 11% in the case of the Urgonian of North Provence (see Table 1 and Fig. 9). Similarly, but with a narrow scatter, porosity values of the *Calcare di Altamura* Formation range between 0.1 and 11% (Fig. 9). Such variation in porosity results in a wide scatter of P-wave velocities: between 2100 and 6300 m s^{-1} with an average value close to

4940 m s^{-1} in Northern Provence, and between 4760 and 5900 m s^{-1} in the *Calcare di Altamura* Formation (Table 1 and Fig. 9).

Intuitively, the fracture pattern appears to be intrinsically related to the host rock pore type. For instance, in the Urgonian carbonates of Provence, the northern part is dominated by microporosity and the southern part by intergranular porosity. This latitudinal dichotomy is reflected in the variation on fracture and stylolite densities: to the north, the host rock bears few to no stylolites and scarce fractures, while to the south the fracture frequency is higher with dense burial stylolites (see Table 1; see

Table 1
Summary of the main host rock parameters, for each of the investigated area, with the location, the name of the formation, the depositional environment, the age of the rock, the main pore type, the porosity range, the V_p range, the fracture/stylolite density and the maximum estimated burial depth.

Location	Formation	Age	Main pore type	Porosity (%)			P-wave velocity (m/s)			Fracture spacing (cm)	Stylolite density	Maximum burial (m)
				Min	Max	Average	Min	Max	Average			
Provence	Urgonian (North)	Barremian-Aptian	microporosity	1	20.7	10.8	2109	6295	4940.3	75	2	850
	Urgonian (South)	Barremian	Intergranular	0.2	9.8	2.7	4825	6748.3	5914.4	50	8	1100
Maiella	<i>Morrone di Pacentro</i>	Hauterivian	fracture-stylolite	0.1	3.9	0.5	4929.4	6407.7	5881	25	12	1400
Murge Plateau	<i>Calcare di Altamura</i>	Coniacian-Campanian	Micro & Intergranular	0.1	10.9	4	4757.4	6427.1	5902.3	45	5	200
		Valanginian-Cenomanian	Intergranular	0.1	4.2	2	5969.6	6513.1	6250.5	85	11	400

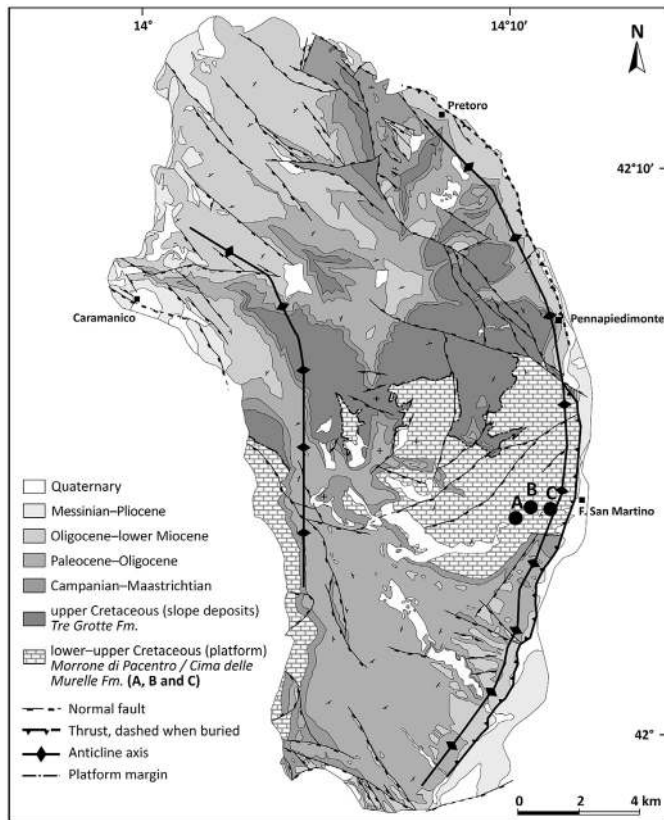


Fig. 4. Schematic structural map of the Maiella Mountain with outcrop locations, modified from Lavenu et al. (2014).

Lamarche et al., 2012). However, the rock susceptibility to fracturing not only relates to the host rock pore type but also to the volume of porosity. Indeed, the northern part of Provence is made of porous carbonates (11% in average) in contrast to the southern part, made up of tight carbonates (3%, see Table 1). Looking at the Murge Plateau, where investigated formations are low porosity (or tight) — 2 and 4% respectively (see Table 1) — the highest fracture density is observed in the most porous host rock, where microporosity is one of the main pore types (i.e. *Calcarea di Altamura* Formation).

For the case of *Morrone di Pacentro* Formation, collected samples have been categorized in two groups according to the dominant pore type. Most of the samples have fracture porosity, and in minor proportion, a matrix intergranular porosity. Since fracture porosity is difficult to measure, the values in Table 1 only depict the matrix porosity of the sample. Based on observation, samples affected by fracture porosity can be differentiated from intact samples. However, intact samples do not mean that the overall host rock is intact, but only that the collected sample does not contain visible fractures. The samples assigned to the “fracture-stylolite” group do have intergranular porosity, but this is occluded by calcite, which results in very low values of porosity (0.5%), high V_p (6400 m s⁻¹) and denser fracture pattern. Consequently, not only the pore type but also the associated cementation can drastically change the mechanical behavior of the rock.

4.3. Diagenetic history

Based on natural light microscopy and cathodoluminescence, a single diagenetic sequence has been deciphered with some variations from one investigated host carbonate to another (Fig. 10).

The major phases observed in the three areas, and the relative timing of these phases is as follows: (a) an early micritization phase affected grains and bioclasts producing either a micritic envelope or full micritization. The micritization process occurs at the water-sediment interface, meaning a development in the very first stage of eogenesis (Bathurst, 1975; Tucker et al., 1990). The micrite appears dusty grey to black in natural light (Fig. 10–7). In the Murge Plateau, a phase of dissolution has been identified and occurs after micritization (Fig. 10–7). (b) Then, an early calcite [EC] affected grains, developing as isopachously-distributed equigranular-to-fibrous cement around grains at shallow depth during eogenesis (Fig. 10–1). Consequent to the development of the early calcite, sediments lithified and turned into a brittle media. This phase of early calcite tends to preserve grains from the effects of later compaction. In Provence, this fibrous calcite is present only in the case of porous rocks, and is preceded by another phase of early calcite resulting from a neomorphism of high-Mg calcite into low-Mg calcite characterized by irregular intercrystalline boundaries, and appears non luminescent in cathodoluminescence. Tight Urgonian carbonates suffered compaction though. According to Léonide et al. (2014), in Provence both cement phases (neomorphism and fibrous calcite) occurred near the surface and in a marine environment. In the investigated platform carbonates of Maiella Mountain, the fibrous Early Calcite is overlapped by pendulum prismatic calcite (Fig. 10–5). Although the first early calcite might have occurred in marine environment, the second early calcite morphology argues for a development in vadose conditions. In any case, petrographic evidences argue for a development of both cements EC1 and EC2 at very shallow burial (Tucker et al., 1990). (c) The subsequent event observed in all the studied outcrops is a brittle event: at least one fracture phase [F/F1] developed coeval with (d) a drusy-to-mosaic blocky calcite spar [BS/BS1] which filled fractures, intergranular and intragranular pore spaces. In natural light, the BS crystals appear limpid to slightly cloudy and dull blue alternating with orange luminescent fringes in cathodoluminescence (Fig. 10–2, 4, 6 and 8). The petrographic evidence argues here for a burial-related origin of the blocky calcite (Bathurst, 1975; Tucker et al., 1990). In Provence and Maiella, a second fracturing occurred: F2 fractures developed cross cutting F1 and BS1 (Fig. 10–4 and 6). Concomitantly with F2 fractures, a second blocky spar [BS2] cement formed, with dull blue-to-violet colors under cathodoluminescence (Fig. 10–2 and 6). This cement filled F2 fractures and residual intergranular spaces. Both phases of blocky spars are responsible for porosity reduction. (e) Bed-parallel burial-related stylolites formed synchronously with fractures and blocky spars, and affected all the other diagenetic phases (Fig. 10–3 and 4). No relative chronology is clear between fractures and bed-parallel stylolites because there are an equal proportion of cross-cutting relationships. The events (c) to (e) occurred during the mesogenesis (burial diagenesis). No diagenetic phases (cementation, dissolution or fractures) related to uplift or exhumation have been evidenced. Moreover, no fractures related to the recent tectonic events have been identified in any of the studied outcrops. Only very few of the early-formed fractures have been reactivated in shear. The present study has shown in all cases that during burial, blocky cement crystallized within fractures and in surrounding pores (see Fig. 10–2, 6, 7, and 8). Locally, vertical-to-bedding stylolites related to late tectonic inversion have been observed. Although they are obvious in Maiella Mountain, they are negligible in Provence and in the Murge.

Early diagenetic processes are responsible for host rock early brittleness. As previously stated, the investigated platform carbonates are made of shallow water deposits that are characterized by gradual facies transitions without sharp mechanical limits. Early diagenetic processes converted sediments to brittle rock. Because

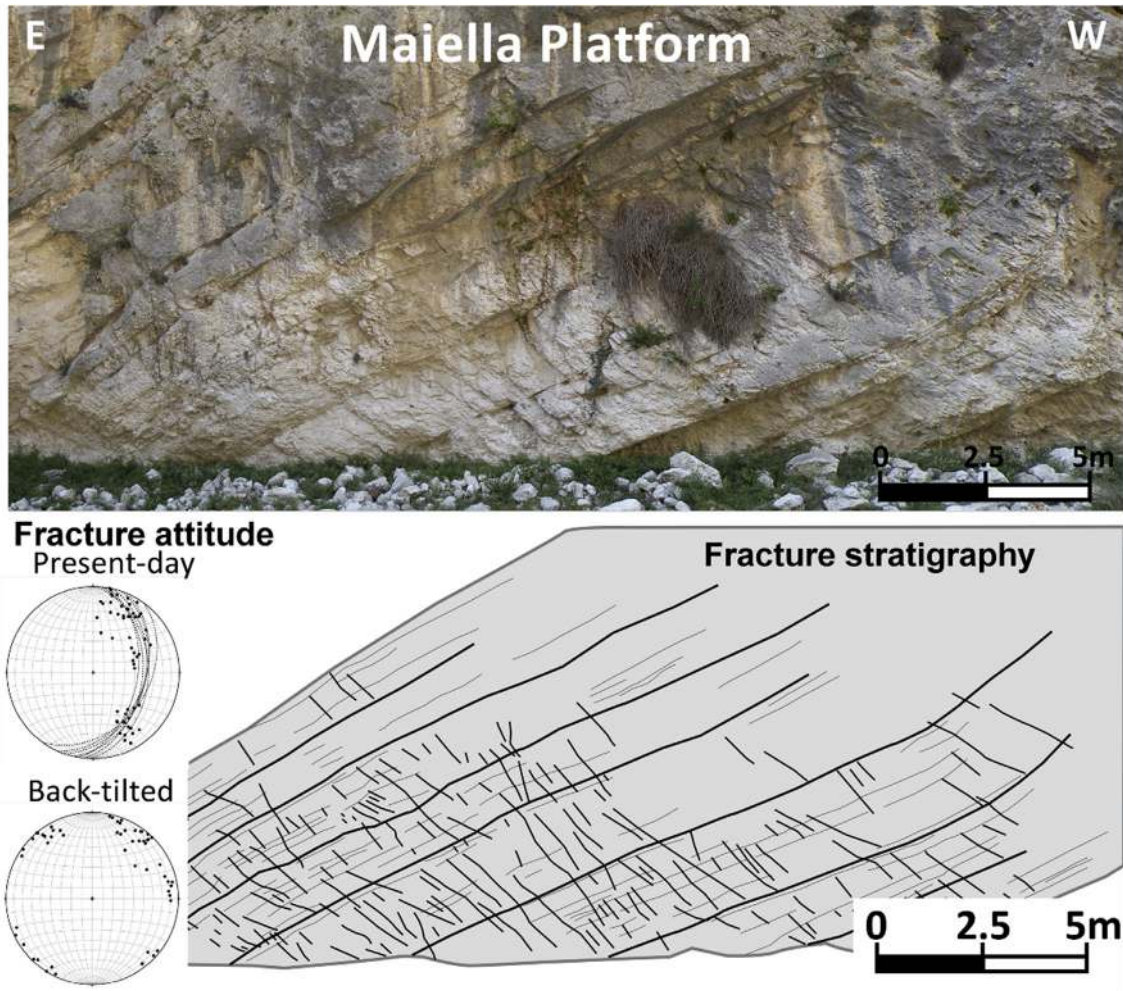


Fig. 5. Photograph of one of the studied outcrop in Maiella Mountain (outcrop B on Fig. 4). The bottom schematic of the picture is showing the structural interpretation of the photograph and the stereoplots (lower hemisphere) are presenting the fractures and bedding measurements in the present-day and back-tilted position.

early fractures have an unbounded fracture height pattern, we infer that in the early diagenetic state, the rock was extremely brittle, accounting for anomalously close fracture spacing, and interfaces were weak (or at least mechanically indistinct) accounting for the unbounded fracture height distribution. Subsequent burial cementation filled pores and strengthened previous porous parts of the rock. Because cementation and compaction acted differentially on originally mechanically similar depositional facies, late mechanical stratigraphy is more differentiated in terms of contrasts between layers and between layers and interfaces. This later diagenetic state may have been stronger and less fracture prone. Late diagenesis could also be responsible for strengthening and possibly sealing early fractures (Laubach, 2003; Olson et al., 2009; Lavenu et al., 2013).

4.4. Geodynamic evolution

Intuitively, with greater burial depth, stress is higher, and fracture-stylolite density is expected to be higher. Consideration of the geodynamic evolution of the rocks we studied shows that the relationship between structures and burial depth is not straightforward. In Maiella Mountain, the studied formation has been submitted to a simple burial-uplift history: a long-lasting burial from deposition time to Pliocene, with a maximum depth of 1.5 km, then a quick uplift during Pliocene (Fig. 11). The diagenetic

sequence compared to the geodynamic evolution allows constraining a fracturing path. The analysis of diagenetic phases has revealed that early calcites developed at shallow burial depth, what led to early host rock brittleness, and allowed fracturing when the stress conditions were favorable. In addition, fractures developed vertical and perpendicular to bedding, and synchronously with bed-parallel stylolites. Therefore, fracturing occurred in a depth window between the seafloor and a few hundred meters' depth, synchronous with burial stylolites, during the pre-folding stage of the Maiella. In Provence, the burial-uplift trend is similar for all the outcrops but with variations in the burial depth (600 m–1100 m) from one studied outcrop to another (Fig. 11). However, no correlation exists between burial depth and fracture-stylolite density in Provence (Lamarque et al., 2012). Contrarily, outcrops that have undergone the deepest burial (**A** and **D**, Fig. 2) do not have the same properties and fracture pattern. For instance, in outcrop **A**, the host rock is tight and fractured. In outcrop **D**, the host rock is porous and poorly fractured. In the same way, the outcrop that has been submitted to the shallowest burial (**B**) is made of tight fractured carbonates. Similarly to the Maiella, fractures initiated as a function of the local stress that prevailed at an early burial stage rather than relative to far-field tectonic events. The geodynamic evolution of the platform carbonates of the Murge plateau includes a very shallow burial (less than 500 m) and gentle uplift (Fig. 11 and Lavenu et al., 2015 for more details). Both fracture geometry and

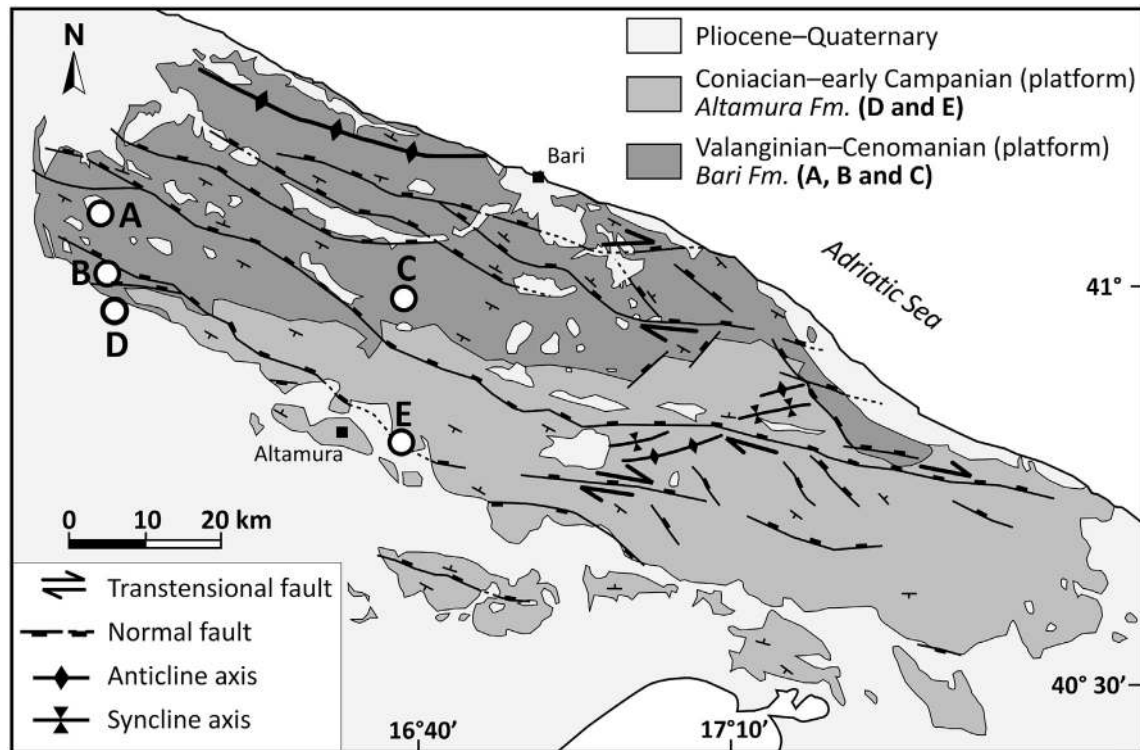


Fig. 6. Schematic structural map of the Murge Plateau with outcrop locations, modified from Lavenu et al. (2015).

diagenetic history reveal that fracture and bed-parallel stylolites developed very early in burial history. Because of the synchronous development of fractures and burial stylolites, we assume that both features occur subsequent to a vertical maximum σ_1 . The fact that fractures are clustered in two perpendicular mutually intersecting sets suggests a single brittle event, possibly involving biaxial extension (Olson, 2004). However, the formations differ in age, and the fracture pattern orientation varies from one to the other. Thus, fracturing occurred diachronously. We infer that fractures developed sequentially. Once host rock brittleness was acquired, at relatively shallow depth, vertical failure occurred following the local stress pattern that prevailed at this time. Furthermore, the diachronic fracturing in the *Calcere di Altamura* Formation did not involve the creation of new fractures in the underlying *Calcere di Bari* Formation. In fact, burial cementation (blocky spar) likely strengthened the host rock, reducing its susceptibility to fracture under mild uplift and extension.

In each case, the fracture-stylolite pattern argues for a shallow burial development of brittleness between few tens to hundreds of meter-depth, as soon as the initial sediments lithified — which can occur as fast as in a year's time (Friedman, 1998). The burial depth is not a stand-alone key for understanding fracture distribution. Although host rock fracturing likely initiated under the influence of burial-related vertical stress, drivers of mechanical behavior are the depositional facies, which control the initial mechanical properties and susceptibility to diagenesis, and the diagenetic processes that are responsible for the host rock embrittlement and inferred petrophysical properties.

5. Discussion

Modelling naturally fractured reservoirs (NFR) remains challenging. Historically, as a matter of simplification for the purposes of efficient flow simulation, fractured reservoirs have been

considered as a dual porosity media: matrix + fractures (Warren and Root, 1963). Nowadays, geological models can afford to model individual fractures in Discrete Fracture Networks (DFN), where fractures are populated in a deterministic way (Lei et al., 2017 and references therein). However, the real 3D architecture of fracture networks remains a key uncertainty. Geometry, scales, lateral and vertical variations need to be defined to fully characterize the fracture pattern in 3D. Input data to model a subsurface fracture network are limited to 1D well data and 2D/3D seismic data. Most of the time, these data are not appropriate for fracture characterization either because of a lack of spatial continuity or because of an under-size resolution of the considered object. In the case of carbonate reservoirs, fracture characteristics are strongly dependent on host rock heterogeneities that control mechanical properties and reservoir quality. Host rock lithologic heterogeneities are complex in carbonates owing to a wide range of depositional environments, facies, and diagenetic evolution. Platform carbonates in particular, are subject to early and strong diagenesis owing to rapid carbonate mineral cementation at near-surface and shallow burial conditions and the potential for subsequent differential compaction of initially highly porous, highly cemented rock (Anselmetti and Eberli, 1993; Fournier et al., 2014; Léonide et al., 2014).

To assess the 3D geometry of fracture networks and the complexity of carbonate rocks, the best alternative remains analogue outcrops (Di Naccio et al., 2005; Bertotti et al., 2009; Bisdom et al., 2014), although the tectonic, diagenetic and mechanical histories may differ from subsurface reservoirs (Laubach et al., 2009; English, 2012). In this paper, we focus on carbonate rocks of two platform realms cropping out in three different areas (see Fig. 1) to unravel the contribution of depositional facies and diagenetic processes to rock mechanical properties evolution through time—geodynamic history, and how they control fractures development and architecture. In each case study, mutual cross

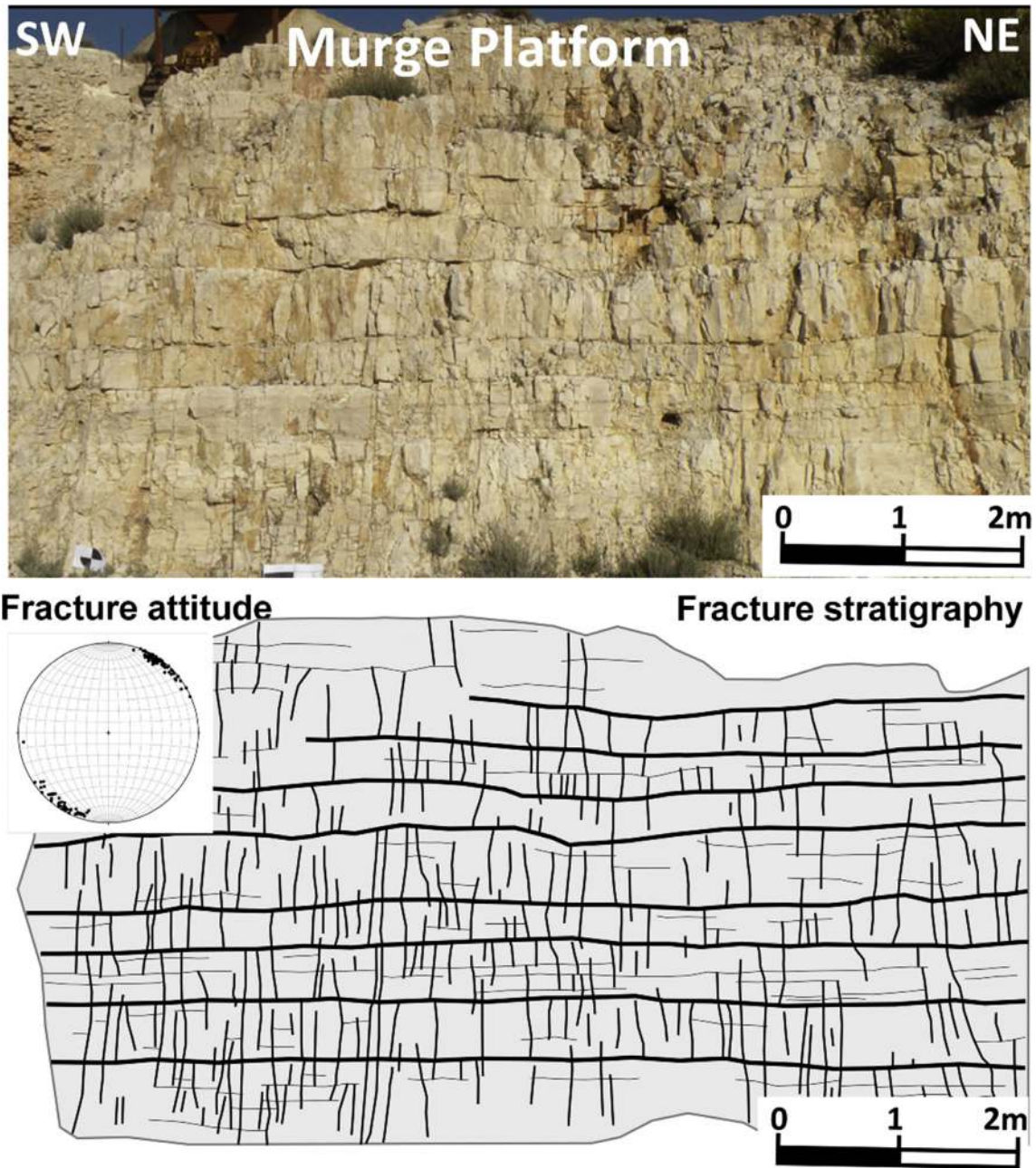


Fig. 7. Photograph of one of the studied outcrop in Murge Plateau (outcrop E on Fig. 6). The bottom schematic of the picture is showing the structural interpretation of the photograph and the stereoplots (lower hemisphere) are presenting the fractures and bedding measurements in the present-day and back-tilted position.

cutting relations amongst sets defined by orientation and associated bed-parallel stylolites show that diffuse fracturing occurred as a single brittle event, early in the burial history, and synchronous with burial. Occurrence of diffuse fractures is not related to one parameter but to a combination of several interwoven parameters, brittleness acquisition, burial loading, and subsequent cementation and compaction serving to strengthen the rock (see Fig. 12).

5.1. Brittleness acquisition of carbonates

The diagenetic history undergone by all studied host rocks includes early calcitic cements developed during the first stages of burial. These cements caused lithification and host rock early embrittlement. In addition, the fracture geometry does not mimic

the present-day mechanical stratigraphy, but rather reflects an early burial condition, different from today's mechanical stratigraphy. In these platform carbonates, diffuse fractures occurred at an early stage of the mechanical evolution of the host rock (see Fig. 12). Recently Friedman (1998), and Eberli et al. (2003) investigated modern platform carbonates in the Bahamas, revealing that lithification processes can occur in a very short time-span, from months to years — instantly on the geological time scale. In warm and protected shallow-water conditions, carbonate sediments have been rapidly subjected to early cementation: micritization processes modified the initial sediments at the seafloor level, and initiated the lithification.

The next cement phase occurring in all studied samples is an early calcite, developing as an isopachous fringe around micritized

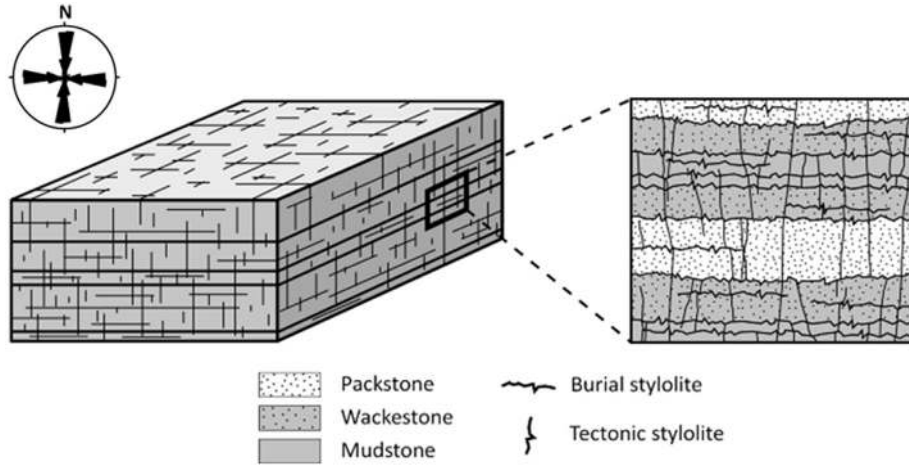


Fig. 8. Schematic of the fracture architecture at outcrop scale, with a zoom showing the relationship between fractures, bed-parallel stylolites and facies variations.

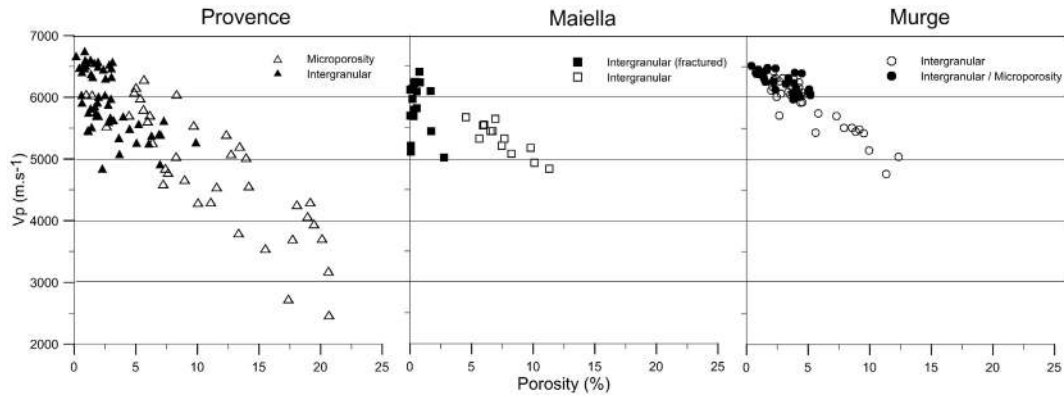


Fig. 9. Porosity versus V_p distribution for all the collected samples plotted area-wise for Provence, Maiella and Murge.

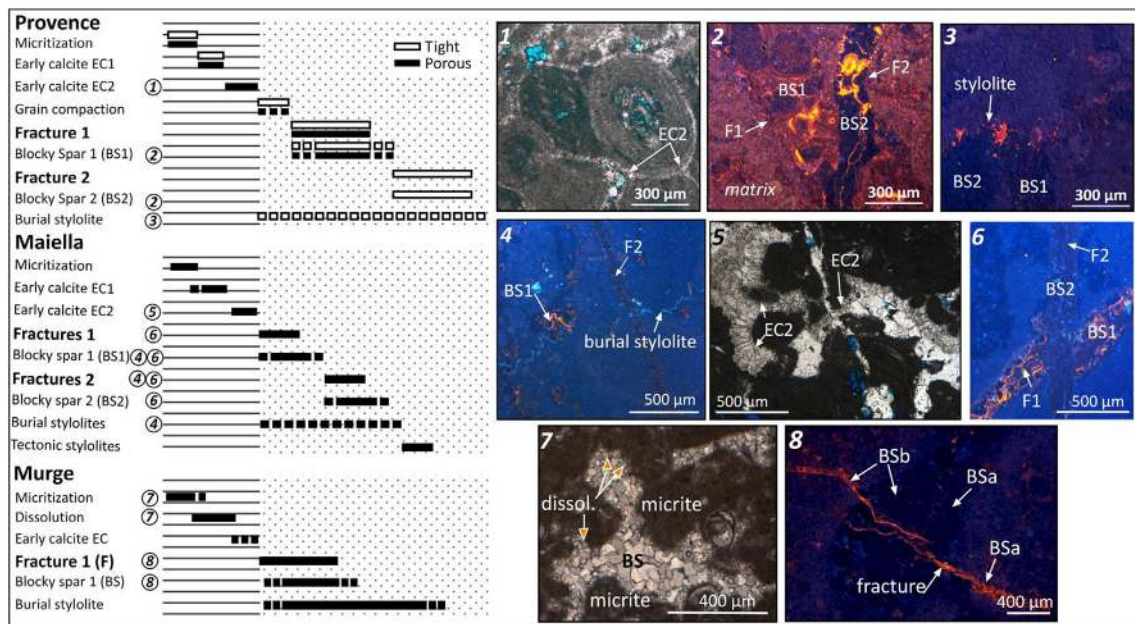


Fig. 10. Diagenetic sequences (left) for all the investigated outcrops, region-wise: Provence, Maiella Mountain and Murge. Photomicrographs (right) in natural light (1, 5, and 7) and cathodoluminescence (2, 3, 4, 6, and 8) of selected thin sections, to illustrate the main diagenetic phases.

elements (see Fig. 10). The development of these cements coated and bonded grains and clasts, forming a rigid framework (e.g. Bjorlykke and Hoeg, 1997). This reduced the primary porosity, increased the rock stiffness, and turned the sediments into a brittle rock. Evidence of compaction on cemented grains — i.e. concavo-convex and sutured contacts — argue for an early development of these calcites, before or in the first stages of the burial. In addition, the fibrous calcite morphology and distribution shows that diagenetic fluids were most probably of marine origin (Tucker et al., 1990), rather than of burial origin. A recent study on Urgonian carbonates of Provence (Léonide et al., 2014) using isotope geochemistry of ^{13}C and ^{18}O , has determined an Urgonian age — i.e. Late Barremian–Early Aptian — and a marine origin of the fluids which led to isopachous fibrous calcites. These results confirm the very early origin of the calcite, which makes the rock brittle at very shallow depth, and the marine origin of the fluids in platform carbonates.

Thus, in the very first stages of the rock development and at shallow depth the host rock is prone to accommodate brittle deformation (e.g. Frost and Kerans, 2010; McNeill and Eberli, 2009; Vandeginste et al., 2013).

5.2. Diagenesis and mechanical stratigraphy

As previously stated, fractures develop as an unbounded diffuse network. They rarely terminate on any interface (i.e. bed boundaries, bed-parallel stylolites), meaning that at the time of fracturing, the rock medium was characterized by no or weak interfaces. Yet, mechanical limits were not sharp enough to arrest fractures. However, field outcrops show obvious present day bedding, commonly pressure solution enhanced. The bed boundaries are sharp and sudden, giving rise to strong mechanical breaks. Giving that fractures developed soon after rock embrittlement, the unbounded character of fracture height remains misunderstood: either bed boundaries had no control on fracture propagation, or fracturing occurred prior to present day bedding development. This question has been addressed in Lamarche et al. (2012) and Lavenu et al. (2013), and the answer resides in the specific nature of the host rock. Indeed, while depositing, sediments are characterized by gradual facies transitions within thick beds rather than sharp facies changes. Early cements froze the initial settings, and as a consequence, the poor mechanical contrast of the original host rock (Fig. 12). Fractures initiated in this context, where facies transitions were not mechanical boundaries. Later on the apparent bedding developed as pressure-solution due to burial. Therefore, the fracture stratigraphy is strongly dependent on the host rock mechanical stratigraphy very soon after deposition (Laubach et al., 2009; Lamarche et al., 2012), and on the pre-fracturing diagenetic events (Di Naccio et al., 2005; Gale et al., 2004; Barbier et al., 2012). The fossil mechanical stratigraphy is fixed with early calcite soon after sedimentation. Actually, the fracture stratigraphy can be considered as an image of the fossil mechanical stratigraphy before burial.

Consequently, diagenetic processes are the main controlling factor for both early and late mechanical behavior of the platform carbonates. Eogenetic cementations are responsible for rock embrittlement and subsequent early fracture development at the onset of mesogenesis (Fig. 10). Later and deeper in mesogenesis, burial cementation is responsible for rock over-strengthening, which reduces the host rock susceptibility to fractures.

5.3. Inference of petrophysical properties with mechanical behavior

Although the depositional environment is common in all studied sites (platform carbonates), small differences can occur in the

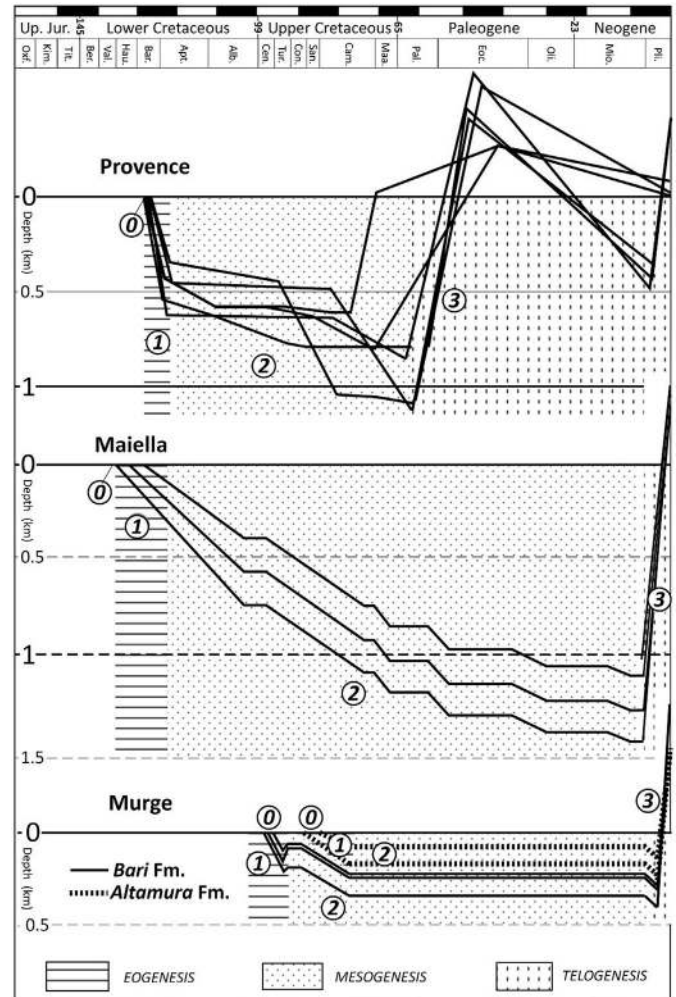


Fig. 11. Burial-uplift curves for each studied outcrops, plotted per area, with superposition of the diagenetic environments and the diagenetic events: (0) Sediment deposition, (1) early cementation, lithification and rock embrittlement, (2) fracturing, development of blocky spars and burial stylolites, and (3) tilting and development of tectonic stylolites. After Lamarche et al. (2012), Lavenu et al. (2013, 2014, 2015).

host rock. We noticed that the pore type and the facies distribution can influence petrophysics, mechanics, and thus, fractures.

At the very moment of deposition, the environment where sediments stacked rules the initial petrophysical properties: in deep water or in protected platform, where energy is low-to-moderate, micritic mud is the main component of the sediments and leads to low porosity/permeability, which slows diagenetic alteration (Anselmetti and Eberli, 1993). Where the energy moderate-to-high (in shoal or open-platform conditions for instance), sediments are mainly grain-supported. They have an initial higher porosity and permeability that allows marine and/or meteoric fluid circulation, and enhances diagenesis (Anselmetti and Eberli, 1993). Therefore, in platform conditions, carbonate sediments are prone to early cementation at shallow depth, which results in a pre- or early burial lithification (Eberli et al., 2003; McNeill and Eberli, 2009).

Although the sediments deposited in similar conditions in all the studied outcrops, the porosity and P-wave velocities vary as a function of the observed pore type, and so is the fracture density. For instance in the case of Urgonian platform carbonates, fracture density is higher in rock hosting intergranular porosity than microporosity (Table 1). According to Léonide et al. (2014),

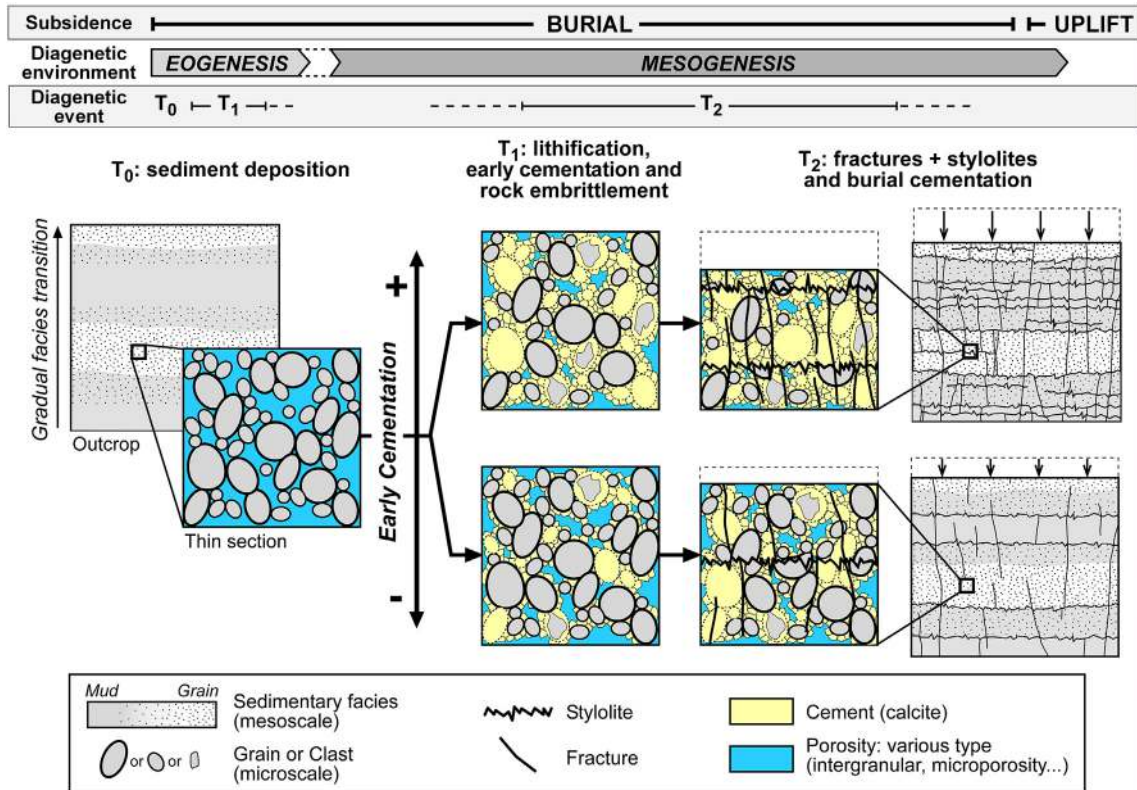


Fig. 12. Schematic of the evolution of carbonate rock through time. The middle bar compares the subsidence evolution to the diagenetic events. In platform carbonates, made of gradual facies transition, the early cementation is the key for early rock embrittlement and mechanical contrast fossilization, and the degree of cementation the main factor controlling fractures and stylolites density.

microporous Urgonian limestones did not experience porosity occlusion in the early stages of diagenesis. Contrarily in tight Urgonian limestones, porosity is occluded by early marine and/or meteoric cementation. Petrophysical measurements on the Urgonian samples confirm the conclusions of Léonide et al. (2014). Following Nelson (1981) and Wennberg et al. (2006), tight rocks are more susceptible to brittle deformation, which is in agreement with our observations in the Urgonian carbonates of Provence. Similarly, in Maiella Mountain, the most fractured samples are the ones where initial intergranular porosity has been occluded due to early cementation. Where porosity has been preserved — and more recently filled by blocky spars — early fracture density is smaller. Hence, the initial pore type and the early cementation control the diffuse fracture architecture in platform carbonates (Fig. 12). Therefore, the fracture occurrence is not only conditioned by the pre-fracturing diagenetic events, but also by the rock properties evolution through time (Voight and St. Pierre, 1974; Narr and Currie, 1982; Shackleton et al., 2005).

5.4. Stress conditions for fracturing

The studied outcrops exposed carbonates of different ages. These carbonates deposited in different paleogeographic locations, and suffered different and diachronous tectonic events. Nevertheless, in all outcrops we have observed a similar pattern made of early high-angle-to-bedding fractures. In the studied platform carbonates, the diagenetic analyzes realized on the collected samples revealed an early near-surface lithification, and subsequent embrittlement, which allows failure at the onset of mesogenesis. Fracture architecture and relationships with burial stylolites strongly argue for a compaction-related development of both

features, during host-rock burial, with a maximum vertical σ_1 and poorly differentiated horizontal σ_2 and σ_3 (e.g. Lavenu, 2013). Indeed, burial depth controls the vertical stress increase. The failure is reached when σ_1 is sufficiently higher than σ_2 and σ_3 . Once burial was initiated and stress state reached failure, fracturing occurred despite the shallow depth, with fracture density depending on host rock petrophysical properties.

Fracture timing *versus* depth aids understanding of the effect of diagenetic processes on fracturing. The present study has given evidence for a sequential fracture development once the host rock brittleness is acquired, rather than a single brittle event affecting the sedimentary pile. The platform carbonate successions of the Murge Plateau, where we observe the exact same fracture-stylolite pattern as in the Urgonian carbonates and in the Maiella are in favor for this interpretation: the fracture set orientations are strictly different in the two superposed formations (i.e. *Calcare di Bari* Formation and *Calcare di Altamura* Formation). Both fractures and bed-parallel stylolites developed step by step after lithification and early burial of each layer. Hence, diffuse fracture occurrence depends upon early host rock mechanical properties, being related to early diagenesis, and to local stress variations rather than far-field tectonics. Therefore, the very first burial stages enhance the onset of fracturing, after early diagenetic processes made the rock brittle with favorable petrophysical and mechanical properties.

6. Conclusion

Through the presented case studies, the role of early diagenesis on host rock mechanical properties, and consequently on fracture development, timing, and spatial arrangement, has been emphasized. We have shown that most of the diffuse fractures which

provide the background permeability in naturally fractured carbonate reservoirs developed in response to early burial stresses, and to diagenetic stiffening by early micritization and calcite cementation of carbonates. In the investigated platform carbonates, early diagenetic phases are enabling:

- (1) Early brittleness acquisition at the onset of mesogenesis, which leads to pervasive, closely spaced arrays of opening-mode fractures developed in flat-lying rocks far from folds and faults under small but sufficient vertical σ_1 . The diagenetic strengthening of the rock at shallow depths (0–500 m) makes failure possible for small magnitudes of σ_1 , σ_2 , σ_3 , and very young host rock (years to few million years).
- (2) Unbounded fracture height patterns and close fracture spacing unrelated to current mechanical limits. Immediately subsequent to deposition, rocks were largely undifferentiated mechanically, and interfaces and various beds (facies) that later were differentiated as a consequence of progressive burial diagenesis had little or no mechanical contrast. Later and deeper burial changes the apparent bedding by pressure-solution and compaction. Implicitly in fractured platform carbonate reservoirs, the diffuse fracture pattern cannot be predicted using usual methods based on (late) mechanical stratigraphy.
- (3) Diffuse fracture architecture, depending upon pore types and local σ_2/σ_3 orientation. Diffuse fracture occurrence in platform carbonates and distribution is neither related to large-scale deformation and tectonic inversion, nor to deep burial, nor the present-day host-rock mechanical stratigraphy.

Acknowledgments

The authors want to thank Dr. Bertrand D. M. Gauthier for supporting the study, and TOTAL for funding the R&D “Carbonate” project, in which was included the first author’s PhD project. Authors also gratefully acknowledged the laboratory technician from Aix-Marseille Université, Lionel Marié, for the amount of work he has done for making plugs and thin sections. Dr. Christophe Matonti, Dr. Arnaud Gallois, Dr. Roland Salardon, Lisa Texier and Hanane Boukbida are thanked for their help on the field and in the lab. The authors also thanks Dr. Stephen Laubach for his valuable input and corrections on the manuscript as well as Dr. David Levitt, and to the two reviewers: Ole Petter Wennberg and Veerle Vandeginste.

References

Accarie, H., 1988. Dynamique sédimentaire et structurale au passage plate-forme/bassin. Les faciès carbonatés Crétacés et Tertiaires: Massif de la Maiella (Abruzzes, Italie). Ecole des Mines, Paris, France, 287 pages, PhD thesis.

Aguilera, R., 1980. Naturally Fractured Reservoirs. PennWell Corp., Tulsa, OK, USA, 703 pages.

Agosta, F., Alessandrini, M., Antonellini, M., Tondi, E., Giorgoni, M., 2010. From fractures to flow : a field-based quantitative analysis of an outcropping carbonate reservoir. *Tectonophysics* 490, 197–213.

Allen, P.A., Allen, J.R., 2005. Basin Analysis. Principles and Applications. Blackwell Publishing, London, UK, 549 pages.

Amieux, P., 1981. La cathodoluminescence dans les roches sédimentaires. Applications sédimentologiques et diagénétiques. Université Claude Bernard-Lyon 1, Lyon, France, 214 pages.

Anderson, E.M., 1942. The Dynamics of Faulting. Oliver and Boyd, Edinburgh, UK, 206 pages.

Anselmetti, F.S., Eberli, G.P., 1993. Controls on sonic velocity in carbonates. *PAGEOPH* 141 (2–4), 287–323.

Atkinson, B.K., 1987. Fracture Mechanics of Rock. Academic Press editions, London, UK, 534 pages.

Aydin, A., 2000. Fractures, faults, and hydrocarbon entrapment, migration and flow. *Mar. Pet. Geol.* 17 (7), 797–814.

Barbier, M., Hamon, Y., Callot, J.-P., Floquet, M., Daniel, J.-M., 2012. Sedimentary and diagenetic controls on the multiscale fracturing pattern of a carbonate

reservoir: the Madison Formation (Sheep Mountain, Wyoming, USA). *Mar. Pet. Geol.* 29 (1), 50–67.

Bathurst, R.G.C., 1975. Carbonate sediments and their diagenesis. *Developments in Sedimentology*, 12. Elsevier Scientific Publishing Company, Amsterdam, Netherlands, 660 pages.

Bazalgette, L., 2004. Relations plissement/fracturation multi échelle dans les multicouches sédimentaires du domaine élastique/fragile: Accommodation discontinue de la courbure par la fracturation de petite échelle et par les articulations. Possibles implications dynamiques dans les écoulements des réservoirs. Université Montpellier 2, Montpellier, France, 251 pages, PhD thesis.

Bertotti, G., Boro, H., Hardebol, N.J., Luthi, S.M., 2009. Improving predictions on mechanical stratigraphy of buried sedimentary successions: lessons and workflow from outcrop analogs [abs.]. In: AAPG Annual Conference and Exhibition (Denver, CO, USA).

Billi, A., Salvini, F., Storti, F., 2003. The damage zone-fault core transition in carbonate rocks: implications for fault growth, structure and permeability. *J. Struct. Geol.* 25 (11), 1779–1794.

Bisdorn, K., Gauthier, B.D.M., Bertotti, G., Hardebol, N.J., 2014. Calibrating discrete fracture network models with a carbonate three-dimensional outcrop fracture network: implications for naturally fractured reservoir modelling. *AAPG Bull.* 98 (7), 1351–1376.

Bjørlykke, K., Høeg, K., 1997. Effects of burial diagenesis on stresses, compaction and fluid flow in sedimentary basins. *Mar. Pet. Geol.* 14 (3), 267–276.

Boggs, S., Krinsley, D., 2006. Application of Cathodoluminescence Imaging to the Study of Sedimentary Rocks. Cambridge University Press, New York, NY, USA, 176 pages.

Boggs, S., 2009. Petrology of Sedimentary Rocks. Cambridge University Press, New York, NY, USA, 600 pages.

Borgomano, J.R.F., 2000. The upper cretaceous carbonates of the gargano-murge region, southern Italy: a model of Platform-to-basin transition. *AAPG Bull.* 84 (10), 1561–1588.

Bruni, R., Bucur, I., Preat, A., 2007. Uppermost Jurassic-Lower Cretaceous carbonate deposits from Fara San Martino (Maiella, Italy): biostratigraphic remarks. *Stud. UBB, Geol.* 52 (2), 45–54.

Caine, J.S., Evans, J.P., Forster, C.B., 1996. Fault zone architecture and permeability structure. *Geol.* 24 (11), 1025.

Corbett, K., Friedman, M., Spang, J., 1987. Fracture development and mechanical stratigraphy of Austin Chalk, Texas. *AAPG Bull.* 71 (1), 17–28.

Di Naccio, D., Boncio, P., Cirilli, S., Casaglia, F., Moretini, E., Lavecchia, G., Brozzetti, F., 2005. Role of mechanical stratigraphy on fracture development in carbonate reservoirs: insights from outcropping shallow water carbonates in the Umbria-Marche Apennines, Italy. *J. Volcanol. Geotherm. Res.* 148 (1–2), 98–115.

Eberli, G.P., Baechle, G.T., Anselmetti, Flavio S., Incze, Michael L., 2003. Factors controlling elastic properties in carbonate sediments and rocks. *Lead. Edge* 22 (7), 654–660.

Engelder, T., 1985. Loading paths to joint propagation during a tectonic cycle: an example from the Appalachian Plateau, U.S.A. *J. Struct. Geol.* 7 (3–4), 459–476.

English, J.M., 2012. Thermomechanical origin of regional fracture systems. *Bulletin* 96 (9), 1597–1625.

Fall, A., Eichhubl, P., Bodnar, R.J., Laubach, S.E., Davis, J.S., 2015. Natural hydraulic fracturing of tight-gas sandstone reservoirs, Piceance Basin, Colorado. *Geol. Soc. Am. Bull.* 127 (1–2), 61–75. <http://dx.doi.org/10.1130/b31021.1>

Fournier, F., Léonide, P., Kleipool, L., Toulec, R., Reijmer, J.J.G., Borgomano, J., Klootwijk, T., Van der Molen, J., 2014. Pore space evolution and elastic properties of platform carbonates (Urgonian limestone, Barremian-Aptian, SE France). *Sediment. Geol.* 308, 1–17.

Friedman, G.M., 1998. Rapidity of marine carbonate cementation — implications for carbonate diagenesis and sequence stratigraphy: perspective. *Sediment. Geol.* 119, 1–4.

Frost, E.L., Kerans, C., 2010. Controls on syndepositional fracture patterns, Devonian reef complexes, Canning Basin, Western Australia. *J. Struct. Geol.* 32 (9), 1231–1249.

Gale, J.F.W., Laubach, S.E., Olson, J.E., Eichhubl, P., Fall, A., 2014. Natural Fractures in shale: a review and new observations. *Bulletin* 98 (11), 2165–2216. <http://dx.doi.org/10.1306/08121413151>.

Gale, J.F.W., Laubach, S.E., Marrett, R.A., Olson, J.E., Holder, J., Reed, R.M., 2004. Predicting and characterizing fractures in dolostone reservoirs: using the link between diagenesis and fracturing. In: Braithwaite, C.J.R., Rizzi, G., Darke, G. (Eds.), *The Geometry and Petrogenesis of Dolomite Hydrocarbon Reservoirs*. Geological Society, London, vol. 235, pp. 177–192. Special Publications.

Griffith, A.A., 1921. The phenomena of rupture and flow in solids. *Philos. Trans. R. Soc. A* 221, 163–198.

Guiron, M.L.E., 2001. Contribution de la fracturation diffuse à la déformation d’ensemble durant le plissement de roches sédimentaires. École Polytechnique, Paris, France, 257 pages, PhD thesis.

Hardebol, N.J., Bertotti, G., 2013. DigiFract: a software and data model implementation for flexible acquisition and processing of fracture data from outcrops. *Comput. Geosci.* 54, 326–336.

Hooker, J.N., Laubach, S.E., Marrett, R.H., 2013. Fracture-aperture size-frequency, spatial distribution, and growth processes in strata-bounded and non-strata-bounded fractures, Cambrian Mesón Group, NW Argentina. *J. Struct. Geol.* 54, 54–71.

Hunt, L., Chopra, S., Reynolds, S., Hadley, S., 2009. On calibrating curvature data to fracture density: causes. *CSEG Rec.* 34, 27–32.

- Kim, Y.-S., Peacock, D.C.P., Sanderson, D.J., 2004. Fault damage zones. *J. Struct. Geol.* 26, 503–517.
- Keating, D.P., Fischer, M.P., 2008. An experimental evaluation of the curvature-strain relation in fault-related folds. *Bulletin* 92 (7), 869–884.
- Lamarche, J., Jayet, O., Lavenu, A.P.C., Gauthier, B.D.M., Guglielmi, Y., Demory, F., Masse, J.-P., Marié, L., 2010. Mechanostratigraphy and Fracture Facies in Lower Cretaceous Carbonates of Provence (SE-France) [abs.]. European Geosciences Union assembly, Vienna, Austria.
- Lamarche, J., Lavenu, A.P.C., Gauthier, B.D.M., Guglielmi, Y., Jayet, O., 2012. Relationships between fracture patterns, geodynamics and mechanical stratigraphy in Carbonates (South-East Basin, France). *Tectonophysics* 581, 231–245.
- Lander, R.H., Laubach, S.E., 2014. Insights into rates of fracture growth and sealing from a model for quartz cementation in fractured sandstones. *GSA Bull.* 127 (3–4), 516–538.
- Laubach, S.E., 1988. Subsurface fractures and their relationship to stress history in East Texas basin sandstone. *Tectonophysics* 156 (1–2), 37–49.
- Laubach, S.E., Marrett, R.A., Olson, J.E., Scott, A.R., 1998. Characteristics and origins of coal cleat: a review. *Int. J. Coal Geol.* 35 (1–4), 175–207.
- Laubach, S.E., 2003. Practical approaches to identifying sealed and open fractures. *Bulletin* 87 (4), 561–579.
- Laubach, S.E., Olson, J.E., Gross, Michael R., 2009. Mechanical and fracture stratigraphy. *Bulletin* 93 (11), 1413–1426.
- Lavenu, A.P.C., 2013. Relations entre motif de fracturation et géodynamique dans les roches carbonatées. Importance du faciès de dépôt, de la diagenèse et des propriétés mécaniques de la roche. Aix-Marseille Université, Marseille, France, 176 pages, PhD thesis.
- Lavenu, A.P.C., Lamarche, J., Gallois, A., Gauthier, B.D.M., 2013. Tectonic versus diagenetic origin of fractures in naturally fractured carbonate reservoir analogue: the Nerthe anticline (southeastern France). *AAPG Bull.* 97 (12), 2207–2232.
- Lavenu, A.P.C., Lamarche, J., Salardon, R., Gallois, A., Marié, L., Gauthier, B.D.M., 2014. Relating background fractures to diagenesis and rock physical properties in a platform-slope transect. Example of the Maiella Mountain (central Italy). *Mar. Pet. Geol.* 51, 2–19.
- Lavenu, A.P.C., Lamarche, J., Texier, L., Marie, L., Gauthier, B.D.M., 2015. Background fractures in carbonates: inference on control of sedimentary facies, diagenesis and petrophysics on rock mechanical behavior. Example of the Murge Plateau (southern Italy). *IJG* 134 (3), 535–555.
- Lei, Q., Latham, J.-P., Tsang, C.-F., 2017. The use of discrete fracture networks for modelling coupled geomechanical and hydrological behaviour of fractured rocks. *Comput. Geotech.* 85, 151–176.
- Léonide, P., Fournier, F., Reijmer, J.J.G., Vonhof, H., Borgomano, J., Dijk, J., Rosenthal, M., Van Goethem, M., Cochar, J., Meulenaars, J., 2014. Diagenetic patterns and pore space distribution along a platform to outer-shelf transect (Urgonian limestone, Barremian–Aptian, SE France). *Sediment. Geol.* 306, 1–23.
- Loreau, J.-P., Durllet, C., Zimmerle, W., 2000. Diagenetic stratigraphy of discontinuity surfaces; an application to paleo-environments and sequence stratigraphy. *Zentralblatt fuer Geologie und Palaeontologie, Teil I. Allg., Angew., Reg. Hist. Geol.* 1999 (3–4), 381–407.
- Luperto Sinni, E., Borgomano, J., 1989. Le Crétacé supérieur des Murgues sud-orientales (Italie méridionale): stratigraphie et évolution des paléoenvironnements. *Riv. Ital. Paleontol. Stratigr.* 95 (2), 331–374.
- Masse, J.-P., 1976. Les calcaires urgoniens de Provence (Valanginien-Aptien Inférieur) - Stratigraphie, paléontologie, paléoenvironnements et leur évolution, 445 pages, PhD thesis, Aix-Marseille 2, Marseille, France.
- Matonti, C., Lamarche, J., Guglielmi, Y., Marié, L., 2012. Structural and petrophysical characterization of mixed conduit/seal fault zones in carbonates: example from the Castelas fault (SE France). *J. Struct. Geol.* 39, 103–121.
- McNeill, D.F., Eberli, G.P., 2009. Early load-induced fracturing in a prograding carbonate margin. In: Swart, P.K., Eberli, G.P., McKenzie, J.A. (Eds.), *Perspectives in Carbonate Geology: a Tribute to the Career of Robert Nathan Ginsburg*. Wiley-Blackwell, Malden, pp. 327–336. Special Publications of the International Association of Sedimentologists 41.
- Meyers, W.J., 1974. Carbonate cement stratigraphy of the Lake Valley formation (Mississippian) Sacramento mountains, New Mexico. *J. Sediment. Res.* 44 (3), 837–861.
- Michie, E.A.H., Haines, T.J., Healy, D., Neilson, J.E., Timms, N.E., Wibberley, C.A.J., 2014. Influence of carbonate facies on fault zone architecture. *J. Struct. Geol.* 65, 82–99.
- Murray, G.H., 1968. Quantitative fracture study; sanish pool, McKenzie county, North Dakota. *AAPG Bull.* 52 (1), 57–65.
- Narr, W., 1996. Estimating average fracture spacing in subsurface rock. *AAPG Bull.* 80 (10), 1565–1586.
- Narr, W., Currie, J.B., 1982. Origin of fracture porosity—Example from Altamont field, Utah. *AAPG Bull.* 66 (9), 1231–1247.
- Narr, W., Schechter, D.S., Thompson, L.B., 2006. Naturally Fractured Reservoir Characterization. Society of Petroleum Engineers, 116 pages.
- Nelson, R.A., 1979. Natural fracture systems: description and classification. *AAPG Bull.* 63 (12), 2214–2221.
- Nelson, R.A., 1981. Significance of fracture sets associated with stylolite zones. *AAPG Bull.* 65 (11), 2417–2425.
- Nelson, R.A., 1985. Geological Analysis of Naturally Fractured Reservoirs. Gulf Professional Publishing, Houston, TX, USA, 332 pages.
- Olson, J.E., 2004. Predicting fracture swarms — the influence of subcritical crack growth and the crack-tip process zone on jointspacing in rock. In: Cosgrove, J.W., Engelder, T. (Eds.), *The Initiation, Propagation, and Arrest of Joins and Other Fractures*, Geological Society, vol. 231, pp. 73–88. Special Publications.
- Olson, J.E., Laubach, S.E., Lander, R.H., 2009. Natural fracture characterization in tight gas sandstones: integrating mechanics and diagenesis. *Bulletin* 93 (11), 1535–1549.
- Pollard, D.D., Aydin, A., 1988. Progress in understanding jointing over the past century. *Geol. Soc. Am. Bull.* 100, 1181–1204.
- Price, N.J., 1966. Fault and Joint Development in Brittle and Semi-brittle Rock. Pergamon Press, Oxford, UK, 176 pages.
- Price, N.J., Cosgrove, J.W., 1990. Analysis of Geological Structures. Cambridge University Press, New York, NY, USA, 502 pages.
- Priest, S.D., Hudson, J.A., 1981. Estimation of discontinuity spacing and trace length using scanline surveys. *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.* 18 (3), 183–197.
- Priest, S.D., 1993. Discontinuity Analysis for Rock Engineering. Chapman & Hall, London, UK, 473 pages.
- Ramsay, J.G., 1967. Folding and Fracturing of Rocks. Mc Graw Hill, New York, NY, USA, 568 pages.
- Ramsay, J.G., Huber, M.I., 1987. The techniques of modern structural geology. In: *Folds and Fractures*, vol. 2. Academic press editions, London, UK, 392 pages.
- Roberts, A., 2001. Curvature attributes and their application to 3D interpreted horizons. *First Break* 19 (2), 85–100.
- Shackleton, R.J., Cooke, M.L., Sussman, A.J., 2005. Evidence for temporally changing mechanical stratigraphy and effects on joint-network architecture. *Geology* 33 (2), 101–104.
- Spalluto, L., Caffau, M., 2010. Stratigraphy of the mid-cretaceous shallow-water limestones of the Apulia carbonate platform (Murge, Apulia, southern Italy). *Boll. Soc. Geol. Ital.* 129 (3), 335–352.
- Stearns, D.W., Friedman, M., 1972. Reservoirs in fractured rocks. *AAPG Mem.* 16, 82–106.
- Suppe, J., 1985. Principles of Structural Geology. Prentice Hall, Englewood, NJ, USA, 560 pages.
- Tucker, M.E., Wright, V.P., Dickson, J.A.D., 1990. Carbonate Sedimentology. Blackwell Scientific Publications, Oxford, UK, 482 pages.
- Vecsei, A., 1991. Aggradation und progradation eines karbonatplattform-randes: kreides bis Mittleres Tertiär der Montagna della Maiella, Abruzen. *Mitteilungen aus dem Geologischen Institut der Eidgenössischen Technischen Hochschule un der Universität, Zürich, Switzerland*, 169 pages, PhD thesis.
- Vandeginste, V., Cédric, M.J., Manning, C., 2013. Interplay between depositional facies, diagenesis and early fractures in the early cretaceous habshan formation, Jebel Madar, Oman. *Mar. Pet. Geol.* 43, 489–503.
- Vitale, S., Dati, F., Mazzoli, S., Ciarcia, S., Guerriero, V., Iannace, A., 2012. Modes and timing of fracture network development in poly-deformed carbonate reservoir analogues, Mt. Chianello, southern Italy. *J. Struct. Geol.* 37, 223–235.
- Voight, B., St Pierre, B.H.P., 1974. Stress history and rock stress. In: 3rd International Congress of the International Society for Rock Mechanics, Denver, CO, USA, pp. 580–582.
- Warren, J.E., Root, P., 1963. The behavior of naturally fractured reservoirs (SPE 426). *SPE J.* 3, 245–255.
- Wennberg, O.P., Svana, T., Azizzadeh, M., Aqrabi, A.M.M., Brockbank, P., Lyslo, K.B., Ogilvie, S., 2006. Fracture intensity vs. mechanical stratigraphy in platform top carbonates: the Aquitanian of the Asmari Formation, Khaviz Anticline, Zagros, SW Iran. *Pet. Geosci.* 12 (3), 235–246.
- Wu, H., Pollard, D.D., 1995. An experimental study of the relationship between joint spacing and layer thickness. *J. Struct. Geol.* 17 (6), 887–905.
- Zeeb, C., Gomez-Rivas, E., Bons, P.D., Blum, P., 2013. Evaluation of sampling methods for fracture network characterization using outcrops. *Bulletin* 97 (9), 1545–1566.