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Mechanical stratigraphy and structural control of oil accumulations in fractured carbonates of the Irati Formation, Paraná Basin, Brazil

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Abstract

Fracturing analysis of low-permeability rocks as reservoir analogs have increased in recent years. The main mechanism involved in the development of secondary porosity in low-permeability, fine-grained limestones of the Irati Formation is fracturing. In these rocks, oil accumulates along fracture planes, vuggy porosity, microfractures, breccias, as well as bedding discontinuities. Joints represent the central element for oil migration and the connection between accumulation sites. Joints are unevenly distributed across the succession of rock types, where carbonate rocks have a much denser array of joints than shales and siltstones. From a mechanical stratigraphy point of view, limestones have a brittle behavior and constitute mechanical units. Ductile shale and siltstone are mechanical interfaces capable of blocking joint propagation. Joints running NW-SE are more effective in trespassing the mechanical interface and are, therefore, more persistent. Joints running NE-SW are less persistent because the ductile behavior of the first two shale beds above the limestone blocks their propagation. The spatial arrangement of regional NW-SE and NE-SW joints promoted reservoir connection, allowing oil migration and accumulation. The joints and oil migration (at least three phases) developed as a consequence of the Gondwana Breakup and are also associated with local pressure gradients.

KEYWORDS: mechanical stratigraphy; planar surfaces; fracture connection; Pitanga Structural High.

INTRODUCTION

Carbonate reservoirs are often a challenge to the oil industry. This scenario is mostly due to the complex and heterogeneous characteristics of porosity in limestones, which are frequently associated with fracturing at different scales. These characteristics, combined with the fact that structures often occur in sub-seismic scales, pose serious difficulties in predicting the quality of the reservoir (including the estimation of recovery rates) if based only in subsurface data (Burchette 2012, Shekhar *et al.* 2014, Wennberg *et al.* 2016). One way to approach the problem is by using mechanical stratigraphic controls to predict fracture density and distribution in limestones (*e.g.*, Cooke *et al.* 2006, Zahm *et al.* 2010), taking into account rock type and layer thickness. This approach is particularly important in deformed sedimentary successions, in which strain partitioning between different types of rock may create a complex network of fractures at different scales.

The study of analog outcrops provides a unique opportunity to assess three-dimensional geological features that are otherwise not detected in seismic and, sometimes, wellbore scales. Reservoir-analog outcrops are particularly useful to assess a good sampling area, how fractures are geometrically connected, how fracture porosity develops and propagate along with mechanical interfaces, and its impact on reservoir quality. Nevertheless, reservoir analogs have to be used with caution because surface processes (*e.g.*, low pressure, lower temperature, and weathering) can make the outcropping rock quite different from its subsurface counterpart. The expression of fractures in a reservoir-scale depends on differences in the tectonic evolution involving time, stress field, and burial/exhumation scenarios, which must be jointly considered within a regional perspective before more detailed approaches.

In the present work, mechanical stratigraphy analysis combined with geologic and structural field data allowed us to evaluate how the fracture network should have controlled the oil migration from outcrop to regional scale, as well as its relationship with the extensional tectonic setting of a prominent regional positive structure — the Pitanga Structural High (PSH). In this context, distinct layers are individualized within the studied rock massifs, namely:

- mechanical units: fractured rock layers with brittle characteristics, in which fracture density varies with thickness;
- mechanical interfaces, a stratigraphic horizon, typically with ductile behavior, where fractures terminate.

Thus, mechanical interfaces can be stratigraphic surfaces or stratigraphic intervals that can resist deformation (Cooke *et al.* 2006).

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The case study presented herein must be used as a one-scale starting point based on a single typology of joints. It can help the understanding, prediction, and upscaling of the fracture system as well as its influence on the oil impregnation in carbonate reservoirs within the outcrop to regional scale. Furthermore, it may contribute to understanding how fractures connect and influence fluid flow in low permeability bedded rocks affected by extensional tectonics.

GEOLOGICAL SETTING

The Irati Formation is a Late Permian unit of the Paraná Basin, an intracratonic sedimentary basin with approximately 1,500,000 km^2 distributed along central-south Brazil, Uruguay, Paraguay, and northern Argentina (Zalan *et al*. 1990, Milani *et al*. 2007) (Fig. 1A). The basin infill consists of sedimentary rocks from the Ordovician to the late Mesozoic, and volcanic rocks Cretaceous in age. The Irati Formation belongs to the first-order depositional sequence named Gondwana I [Carboniferous to early Triassic, Milani *et al*. (1998, 2007)]. The Gondwana I supersequence records the transition of Pennsylvanian glacial-influenced deposits of the Itararé Group (Schneider *et al*. 1974, França and Potter 1988, Rocha-Campos *et al*. 2008, Cagliari *et al*. 2014, 2016) to the early Triassic continental deposits of the Pirambóia Formation (Lavina *et al*. 1993, Milani *et al*. 2007).

The Kungurian age Irati Formation (Santos *et al*. 2006) is part of the Passa Dois Group (Fig. 1A) and interpreted as

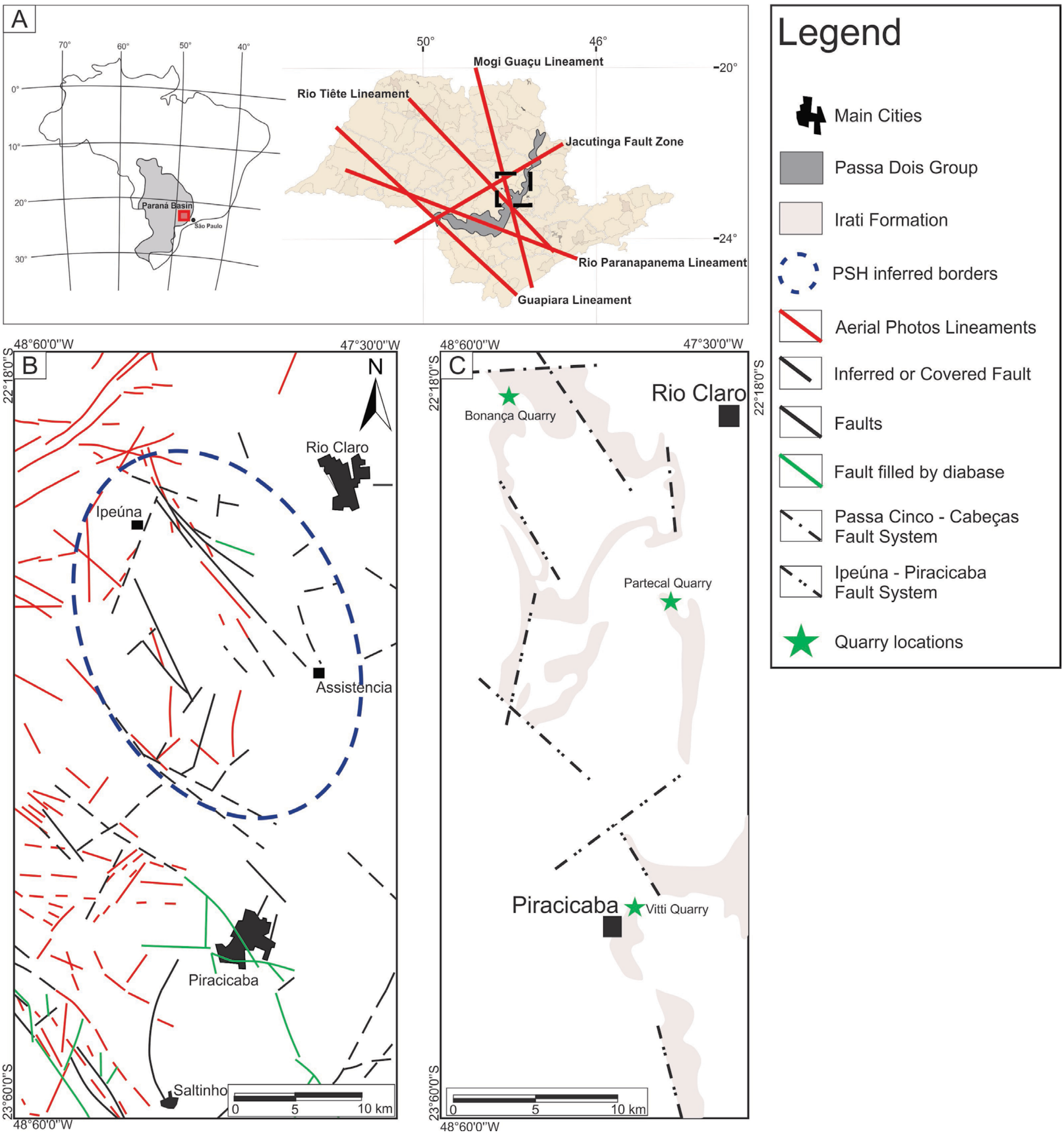

Figure 1. Study site. (A) The Paraná Basin location in Brazil and the Passa Dois Group outcrop belt highlight the main tectonic lineaments in São Paulo State. (B) Main joints and faults associated with the Pitanga Structural High in the Rio Claro-Assistência-Ipeúna region (blue circle). (C) Irati Formation in the Rio Claro-Piracicaba region and its relationship with the Passa Cinco and Ipeúna fault systems.

deposited in a mixed siliciclastic-carbonate ramp (Amaral 1971, Schneider *et al.* 1974, Hachiro and Coimbra 1991; Milani *et al.* 2007). This unit is divided into two members:

- lower Taquaral Member: a succession of about 10-meter thick organic, fossiliferous shale;
- upper Assistência Member, focus of the present study: a succession of approximately 20 meters composed of centimetric-to-decimetric intercalation of carbonate (mudstone, grainstone, and packstone), siltstone, and black bituminous shales, with a basal massive of 3 m thick carbonate bank (Schneider *et al.* 1974, Hachiro *et al.* 1993, Araújo *et al.* 2000).

The study area comprises part of the PSH, an elliptical northwestern-aligned structure (Fig. 1B). PSH is located in the intersection of three expressive alignments of the Paraná Basin basement (Fig. 1B) and sectioned by two local northwestern fault systems:

- Passa Cinco-Cabeças;
- Ipeúna-Piracicaba (Riccomini 1992, Sousa 1997, 2002, see Fig. 1C).

The NW-SE Mogi-Guaçu and Rio Tietê lineaments have the same orientation of the PSH main axis, whereas the NE-SW Jacutinga lineament is orthogonal to this structure (Riccomini 1992, Sousa 2002) (Fig. 1B). These regional lineaments have a significant influence on the evolution of local fault systems and are responsible for tectonic reactivations that have controlled sedimentation and deformation of the sedimentary succession since the Paleozoic (Zalan *et al.* 1990, Soares 1991, Riccomini 1992, Riccomini *et al.* 1992, Rostirola *et al.* 2000, Sousa 2002).

The Irati Formation is an essential hydrocarbon source unit in the Paraná Basin, mainly due to its wide distribution along the basin and the presence of shale and siltstone with extremely high total organic carbon (TOC) values, locally higher than 23% (Araújo *et al.* 2000, Milani *et al.* 2007, Souza *et al.* 2020). The study area presents many occurrences of oil and bitumen filling the vuggy porosity or joints in dolomitic limestones of the Assistência Member, Irati Formation. The reactivation of NW-SE alignments and the intrusion of several mafic diabase sills and dikes in the Cretaceous have been regarded as the local source of heat responsible for generating the hydrocarbons in the study area (Soares 1991, Araújo *et al.* 2000, Araújo *et al.*, 2005, Riccomini *et al.* 2005, Godoy 2006). However, in the last years, this hydrocarbon generation model has proven to be much more complex, involving the influence of putative hydrothermal activity and, at least, three phases of hydrocarbon migration (Sant'Anna *et al.* 2006, Mateus *et al.* 2014).

MATERIALS AND METHODS

The quarries described in this work are in areas inside the PSH (Assistência and Ipeúna municipalities) and in the vicinities of this structure (municipality of Saltinho). All data originated from vertical walls/banks and horizontal pavements from open pits in the Partecal (Assistência), Bonança (Ipeúna), and Vitti (Saltinho) quarries. The studied outcrops of the Assistência Member are about 100 m long and 30 m thick. The sedimentary facies descriptions followed the protocol of Walker (1992) complemented by petrographic analysis. The petrographic classification of carbonate and clastic terrigenous rocks followed the proposals of Dunham (1962) and Folk (1968), respectively.

All outcrops were documented with a 12 Mpx digital camera to capture close-ups and closely-spaced panoramic high-resolution photos of entire walls. Panoramic pictures organized as photomosaic were fundamental to identify and delimit the key horizons and discontinuities. The dip angle and dip direction of planar surfaces (joints), measured with a Clar-type compass, allowed us to plot stereograms in Stereonet. We also considered the density, persistence, connectivity, and opening-mode of all discontinuities measured in the field, as usually performed in structural analysis.

Mechanical stratigraphy controls in fractures and fluid distribution

Structural discontinuities, such as joints and faults, are the product of tectonic or non-tectonic processes and represent deformational features usually present in rock massifs. In the last two decades, these structures have been studied as paths to the fluid circulation in aquifers (Berkowitz 2002, Cooke *et al.* 2006, Morin *et al.* 2007) and in conventional or non-conventional petroleum systems (Di Naccio *et al.* 2005, Spence *et al.* 2014, Tavener *et al.* 2017). Thus, discontinuities are natural conduits for fluid circulation and may be associated with permeability barriers (*e.g.*, cementation) and routes (*e.g.*, dissolution), which affect fluid migration between the source rock and the reservoir.

Rheology is fundamental to assess the fracture pattern of sedimentary rock successions. When submitted to brittle deformation, competent rocks — such as limestones, cemented sandstone, and quartzite — usually develop more fractures than less competent rocks (*e.g.*, siltstone, shale, and mudstone). The latter group is mainly composed of fine-grained rocks that present a ductile behavior and block the fracture growth when submitted to the action of high tensile strength (Zahm *et al.* 2010). Consequently, coarse-grained rocks tend to be brittle and have lower tensile strength than fine-grained ones with ductile characteristics (Renshaw *et al.* 2003, Cooke *et al.* 2006). Tsang (1984) demonstrates that less persistent fractures are not capable of generating active migratory paths; however, highly persistent fractures produce effective conduits for the storage and migration of large volumes of water or different types of hydrocarbons (Cooke *et al.* 2006, Questiaux *et al.* 2010, Spence *et al.* 2014).

In sedimentary successions formed by the intercalation of brittle and ductile rocks, the brittle ones tend to show higher density and connection of joints (corridors), creating a fracture network that enhances bulk permeability (Questiaux *et al.* 2010). Some major fracture planes can section mechanical interfaces and propagate through more ductile rocks, affecting other mechanical units and connecting different tabular fracture corridors. The arrangement among discontinuities, mechanical interfaces, and mechanical units is fundamental to elucidate the controls in the fracture-network architecture (Nelson 2001, Cooke *et al.* 2006). In the Irati Formation, mechanical interfaces consist of a 5- to 10-meter thick ductile, unfractured interval of interbedded shale and siltstone of the Taquaral Member, as well as shale and siltstones beds ranging from 10 to 40 centimeters thick intercalated with dolomitic carbonates of the Assistência Member (Fig. 2). The mechanical unit comprises a brittle fine-grained carbonate, predominantly calcimudstones of the Assistência Member, with 2 to 4 meters thick and oil impregnation associated with fractures, microfractures, and vuggy porosity.

Creation of porosity in low-permeability rocks defines pathways more favorable for fluid flow (Odling *et al.* 1999, Cooke *et al.* 2006; Shackleton *et al.* 2005, Questiaux *et al.* 2010). However, Ortega and Marrett (2000) and Ortega *et al.* (2006) regarded the problem of sampling in subsurface data as limiting the understanding of the hierarchy of fractures in reservoirs. Therefore, they adopted microfractures as proxies for hierarchically scaling and predicting fractures based on the power-law relationship observed at several orders of magnitude. Using examples of bedded rocks, Guerriero *et al.* (2013, 2015) defined fractures as part of a hierarchical system in which fluids migrate from non-stratabound to stratabound joints (*sensu* Odling *et al.* 1999), *i.e.*, flowing from less to more permeable joint networks, successively until reaching the network in fault systems. These authors improved numerical simulation of fractured reservoirs, and the structural characterization became more accurate e statistically representative for reservoir simulations and management.

Fractured interval characteristics, including orientation, persistence, and density of discontinuities, result from the interaction between different aspects, such as:

- nature of contacts between stratified rocks;
- strata thickness;
- grain size;
- rocks cohesion;
- internal heterogeneities;
- tensile strength and elastic modulus;
- tectonic load;
- (paleo)stress direction and magnitude;
- diagenesis (van Gent *et al.* 2010, Spence *et al.* 2014, Saein and Riahi 2019).

These aspects allow evaluating and predicting fluid behavior through open fractures. The main controls include porosity, permeability, viscosity, wettability, and capillary pressure as parameters affected during fracture generation and propagation (Morin *et al.* 2007, Blunt *et al.* 2013, Spence *et al.* 2014).

RESULTS

Discontinuity measurements in the study area reveal a high consistency with the regional structural context, with NW-SE-,

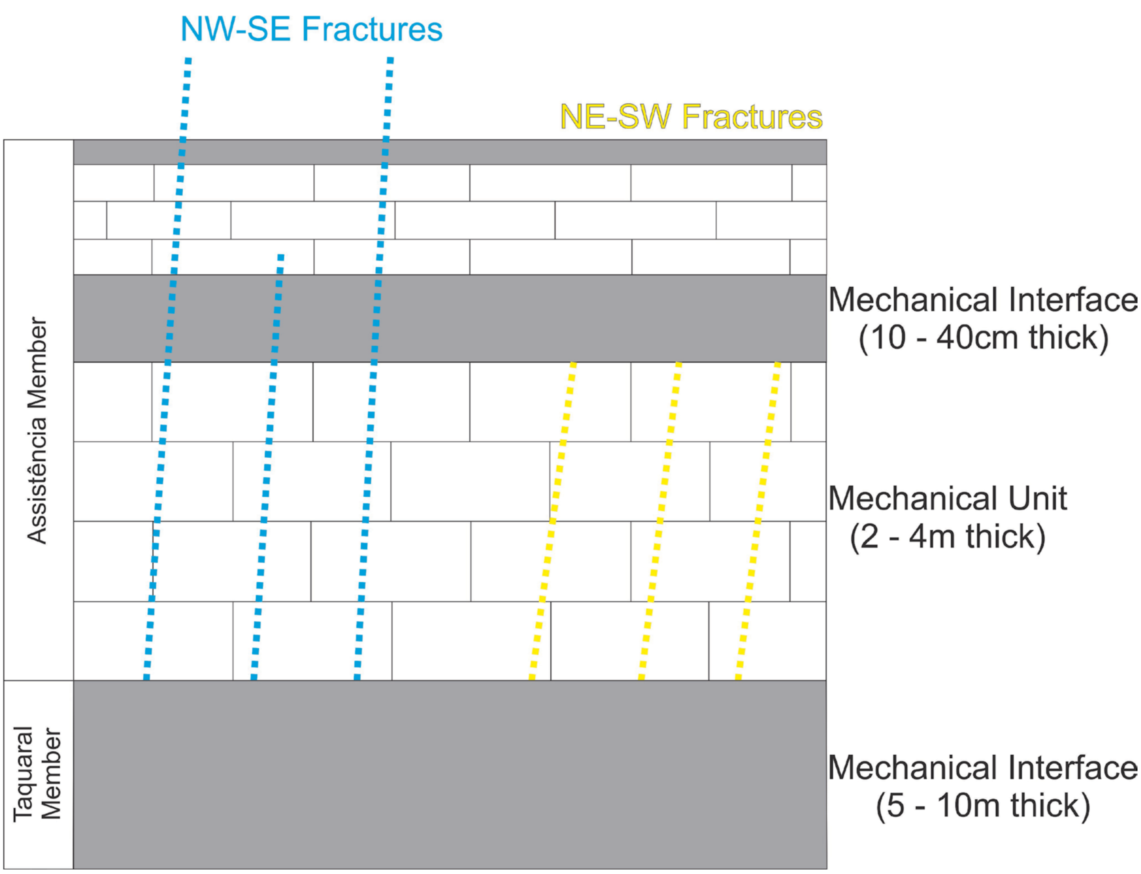

Figure 2. Characterization of mechanical units and mechanical interfaces. The first shale bed above the basal carbonate bed blocks the joint propagation, but overlying carbonate interbedded with shale/siltstone also exhibits joints. Mechanical units are brittle dolomitic carbonates, whereas mechanical interfaces are ductile beds of shale/siltstone internally deformed, but not fractured. Yellow and blue dotted lines represent, respectively, non-stratabound and stratabound fractures.

NE-SW-, and NNW-SSE-oriented joints/faults (Fig. 3). Some NE-SW joints with medium dip angle are conjugate (Fig. 3A). In the Vitti Quarry at Saltinho (Fig. 1), NE-SW and NW-SE directions predominate in relation to vertical or high dip angle faults and joints (Fig. 3B).

All joints observed in the field sectioned limestone and shale beds differently. The physical behavior of the 4-meter thick basal carbonate bed is quite different from interbedded centimetric and shale/siltstone ones and fine-grained carbonates of intermediary and upper intervals. The basal dolomitic mudstone bed (lower mechanical unit), classified as non-stratabound, is sectioned by joint sets that only occur in this bed, regardless of underlying and overlying strata. At the top, the ductile behavior of shale/siltstone beds constitutes a

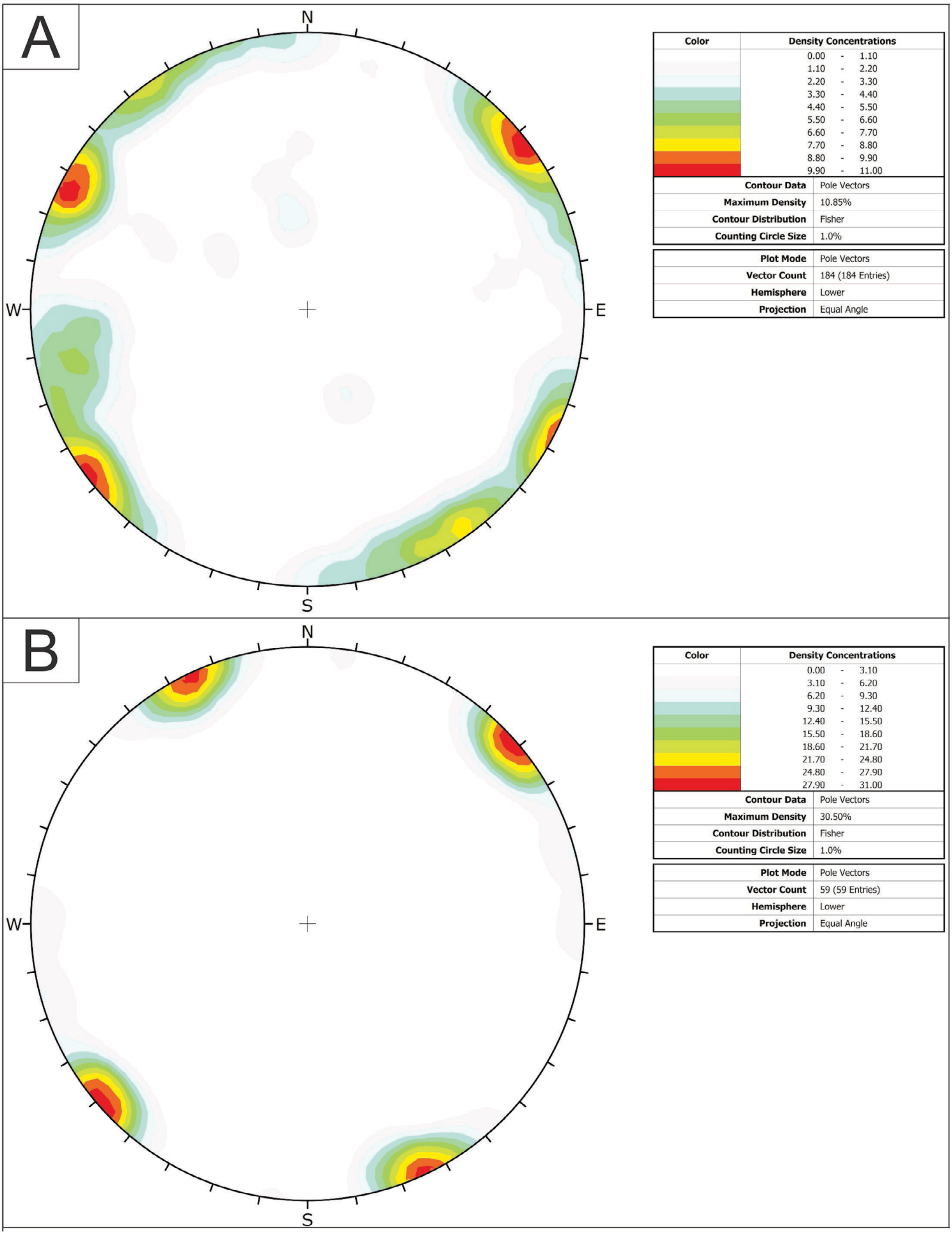

Figure 3. Joint orientations in the study area. (A) Stereogram showing the PSH structural patterns (n = 184). Maximum concentration directions of fracture families are 118/89, 73/88, 54/90, and 327/88. (B) Stereogram of sites located outside the PSH showing predominance of subvertical to vertical joints (n = 59). Maximum concentration directions of fracture families are 50/90 and 335/90.

mechanical interface that hampers the joint propagation by internal deformation (stratabound joints). Each pair of carbonate-shale beds represents distinct mechanical units bounded by mechanical interfaces.

The fractures identified and measured in the field comprise large open extension and conjugate joints, whereas the vertical walls investigated did not present fault planes. Regionally, a NE-SW fault occurs in the north part of the PSH (Bonança Quarry) associated with a breccia composed of coarse sparry calcite and calcimudstone granule-to-cobble sized clasts impregnated with oil and bitumen (Fig. 4). Oil impregnation in interconnected discontinuities of different sizes are mainly present in NE-SW- and NW-SE-oriented joints, following the regional structural pattern and representing a highly permeable conduit for oil migration and accumulation.

Based on field evidence, hydrocarbon migration and accumulation occurred in six different ways (Fig. 4):

- in highly porous concretions (Fig. 4A);
- interstitially in breccias (Fig. 4B);
- in microfractures (Fig. 4C);
- as isolated impregnation in NE-SW and NW-SE extension joints (Fig. 4D);
- vugular porosity (and microfractures) with oil impregnation (Fig. 4E);
- following the carbonate bedding (Fig. 4F);
- in the intersection of two joint planes (Fig. 4G).

Figure 5 shows two orthogonal N-S and E-W walls located in the Partecal Quarry at an Assistência-type section area. In this area, the basal mudstone bed presents two main joint arrangements according to its persistence:

- joints that only occur in the basal carbonate (mechanical unit);
- joints sectioning interbedded carbonate and shales (mechanical and interface units).

Structural control

The Vitti Quarry at Saltinho (south area) is outside the PSH (see Fig. 1) and presents both NW-SE and NE-SW joint sets, not necessarily associated with the intrusion of diabase sills and dikes. The studied areas located inside the PSH (north area) display two different structural configurations:

- Bonança Quarry at the Ipeúna area — with joints actively controlled by NE-SW fault systems;
- Partecal Quarry at the Assistência area — presenting expressive NW-SE joints.

Structural control of the south area

The area located outside the PSH limits encompasses mechanical units and mechanical interfaces of the Irati Formation. The base of the sedimentary succession has the Taquaral Member as the more prominent mechanical interface (MI-A), formed by approximately 5- to 10-meter thick shales and siltstones. This more expressive mechanical unit (MU-A) overlies the MI-A. It includes a brownish brittle fractured carbonate rock ranging from 2 to 4 meters thick at the base of the Assistência Member. Two sets of joints, NE-SW and NW-SE, are highly significant in the MU-A and follow the regional pattern of planar structures, sometimes related to diabase sills. Oil impregnations occur only in microjoints or dissolution features such as vuggies.

In the south area, many other shale beds overlying the MU-A represent mechanical interfaces (Fig. 6). However, only the first two mechanical interfaces are sufficient to block joint propagation. They are black shale beds ranging from 10 to 20 cm, named MI-B and MI-C, and are laterally continuous for hundred meters (Figs. 6A and 6B).

The NE-SW joints have their persistence limited by the first two mechanical interfaces (MI-B and MI-C) (Fig. 6A), but they are generally interrupted by the first mechanical interface (MI-B) (Fig. 6B). On the other hand, NW-SE joints show great persistence throughout the mechanical units and interfaces. Oil impregnation does not occur in joints from areas located outside the PSH influence.

Structural control of the north area (Pitanga Structural High)

NW-SE and NE-SW structures characterize the structural pattern of this region, following the arrangement of regional fault zones (Riccomini 1992, Sousa 1997, 2002). Oil impregnations in joints of different sizes are quite common in all studied sites. Figure 7 shows NW-SE joints with oil and great persistence, crossing the mechanical interface (Fig. 7A), whereas NE-SW joints have their persistence limited by MU-A boundaries (Fig. 7A).

In regions highly influenced by NW-SE structures, such as Assistência ones (Partecal Quarry), these discontinuities are more persistent along the outcrop and commonly crisscross MI-B, MI-C, and other types (Fig. 7B). The NE-SW-oriented secondary family is always limited within the mechanical unit and does not cross the mechanical interfaces. Other joints with directions not related to the primary regional NW-SE trend do not cross the mechanical interfaces and have persistence limited between the boundaries of the MU-A. In the Ipeúna area (Bonança Quarry), NE-SW joints are dominant and locally associated with breccia. This joint set presents much more oil impregnation than NW-SE-oriented ones. This area has the thickest mechanical interface observed in the study area (25–40 cm thick) and is not crossed by the joints investigated, including those present in the highly fractured MU-A with intense hydrocarbon impregnation (Fig. 7C).

DISCUSSION

Based on the dataset analyzed and considering the complexity of the relationship among mechanical units and interfaces, joint patterns, and types of porosity, we can attest the NW-SE joints present greater persistence and oil impregnation than NE-SW ones. These joints cross at least one mechanical interface (MI-B) and have a close relationship with the "Passa Cinco — Cabeças" and "Ipeúna — Piracicaba" Fault Systems, the main structural controls of PSH. Thus, deformation tends to be more intense in the NW-SE direction, allowing joints to cross mechanical interfaces and fracture several carbonates

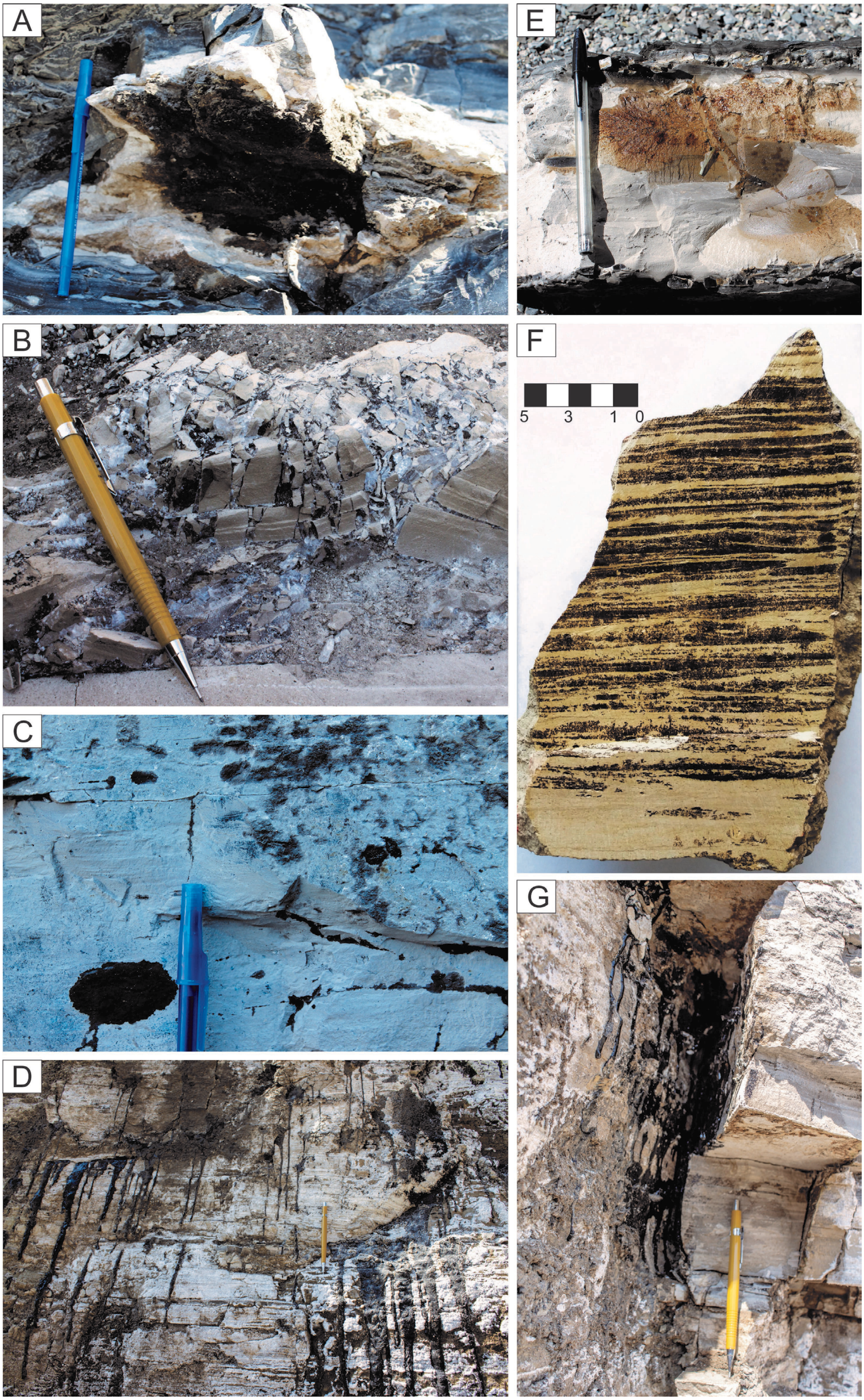

Figure 4. Occurrence of hydrocarbon impregnation in carbonate mechanical units. (A) Oil in porous carbonate concretion. (B) Breccia impregnated with coarse sparry calcite crystals. (C) Oil-filled microjoints (see above the pen). (D) Oil-filled open joints. (E) Vuggy porosity (and microfractures) with oil impregnation. (F) Oil-impregnated carbonate along the sedimentary bedding. (G) Oil impregnation in the intersection of NE-SW and NW-SE joints. The pens in A, B, C, D, and F are 13 cm long.

interbedded with shales. The NE-SW joint system tends to present low persistence, and MI-B usually blocks it. However, an exception occurred when a NE-SW fault in the Ipeúna region (Bonança Quarry) generated a breccia level without any joint crossing MI-B. The breccia is below the mechanical interface and presents oil impregnation in the matrix, the NE-SW planes, and, secondarily, in some NW-SE joint intersections.

Inside PSH, MI-B and MI-C usually have thicknesses ranging from 10 to 15 cm in the Partecal Quarry area. Thus, their thickness is considered a fundamental factor for the non-propagation

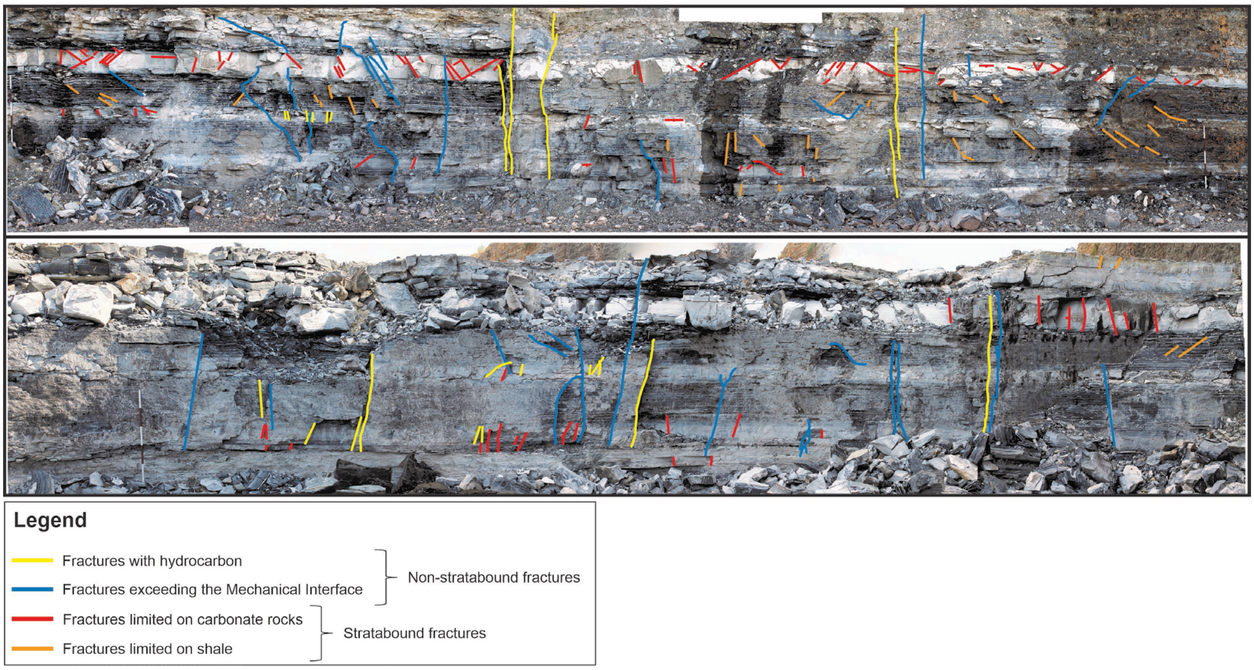

Figure 5. Photomosaic of two orthogonal vertical walls within the PSH area in the Partecal Quarry at Assistência. (A) NS wall. (B) EW wall. Note the distinct pattern of joints in terms of persistence, oil impregnation, and relationship with mechanical interfaces and units.

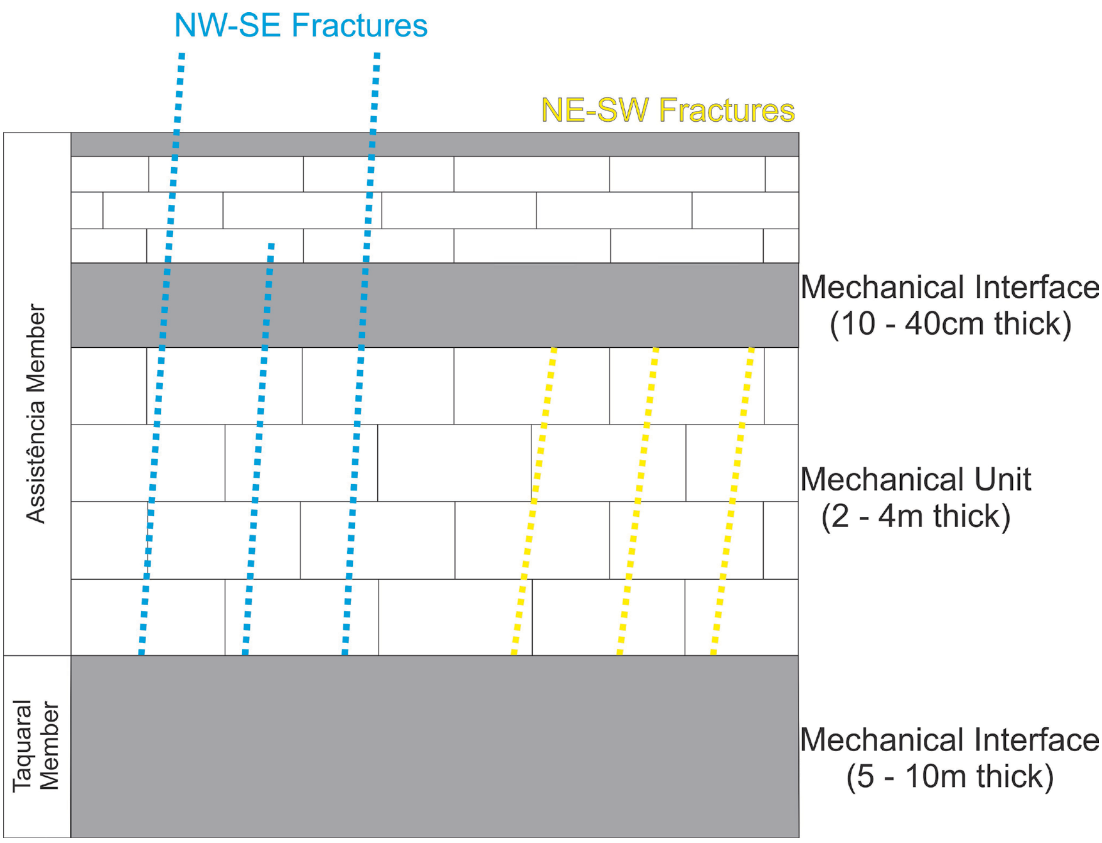

Figure 6. NE-SW joints (yellow dashed line, non-stratabound fracture) and their relationships with mechanical interfaces B and C (red dashed line) in the Vitti Quarry at Saltinho. (A) The joint does not cross the mechanical interface C. (B). Note the fracturing degree in mechanical unit A, *i.e.*, the yellowish-gray calcimudstones at the base and the interbedded shale and fine-grained carbonates above. Thicker mechanical interfaces tend to avoid joint propagation upward.

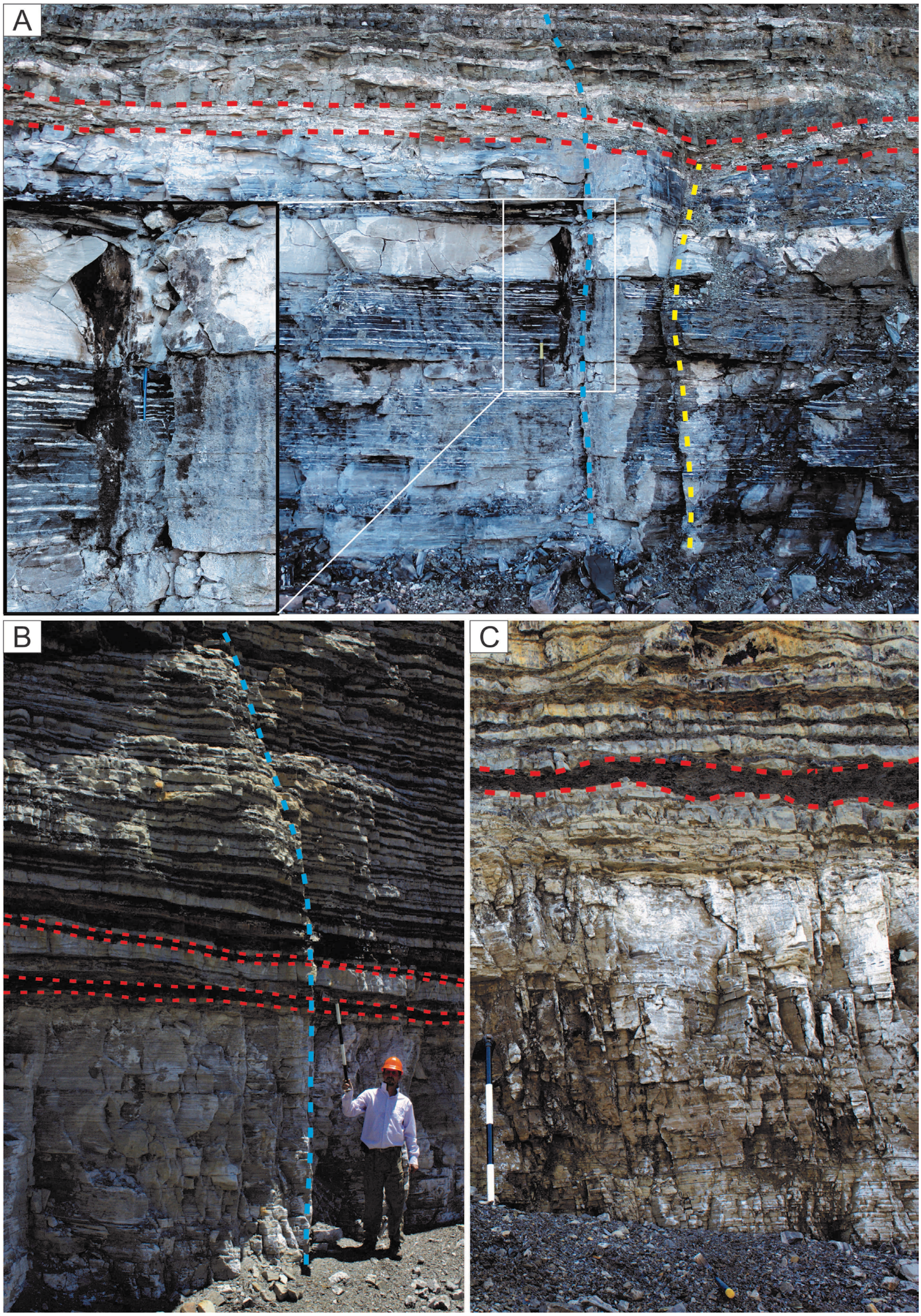

Figure 7. Carbonate outcrop from the Assistência Member, Irati Formation, in the Pitanga Structural High. (A) Oil-impregnated carbonates in the Partecal Quarry. Joints marked with blue and yellow dashed lines are NW-SE (non-stratabound) and NE-SW-oriented (stratabound), respectively. Note the oil impregnation (see inset). Red dashed lines indicate the mechanical interface boundaries. Note that the NE-SW joint on the right part of the picture has its persistence limited by the lower boundary of the mechanical interface. Hammer is 33 cm long, and the blue pencil is 13 cm long. (B) NW-SE non-stratabound joints and their relationships with mechanical interfaces B and C in the Partecal Quarry at Assistência. Note the high degree of fracturing in basal calcimudstones of the mechanical unit A at the base. A set of several thin mechanical interfaces in the interbedded shale and fine-grained carbonates allowed the upward propagation of only NW-SE joints. (C) Oil-impregnated carbonates in the Bonança Quarry. The mechanical interface (stratabound joints) is not crossed by the joints because it is thicker than other areas, blocking joint propagation. In this area, a NE-SW fault system controls the joint distribution and density.

of joints in this area. Discontinuity spacing in the basal carbonate rock (MU-A) is about 50 cm for NW-SE, 50 cm for NNW-SSE, and 80 cm for NE-SW joints. In the overlying interval composed of centimetric interbedded shales and carbonates, discontinuity spacing decreases in NW-SE joints (about 20 cm) and is higher than 2 m in NE-SW and NNW-SSE ones.

In the Ipeúna region at Bonança Quarry, the MI-B and MI-C thickness ranges from 30 to 40 cm. Discontinuity spacing in the 4-meter thick basal carbonate rock of MU-A is 50 cm for NW-SE and 40 cm for NE-SW joints. In the overlying interval with centimetric layers of interbedded shales and carbonates, spacing decreases to 10 cm or less, due to the smaller thickness of carbonate layers, and no joint crosses MI-B.

Outside the PSH context, in the Saltinho area (Vitti Quarry), joints have a similar spacing. In the basal carbonate rock of MU-A, spacing is 40–50 cm for NW-SE and 80–90 cm for NE-SW joints. In the overlying interval, spacing decreases to 10–15 cm in NW-SE joints and increases in NE-SW and NNW-SSE joints (up to 1.5–2 m).

Considering MI-B as a barrier for joint propagation, the Ipeúna region at Bonança Quarry shows an attractive small-scale reservoir model. In some regions, carbonate rocks up to 5 m thick have limits below and above in mechanical interfaces represented by MI-A (Taquaral Member, 5–10-meter thick shale), as well as MI-B and MI-C (Assistência Member, 25–40-centimeter thick carbonate/shale). This basal carbonate bed is also highly fractured, with a joint spacing of 40 to 50 cm for NE-SW and NW-SE sets. Oil impregnation is mainly present in NE-SW joints, microjoints, and interstitially in breccias. In this framework, the basal carbonate bed concentrates a large volume of oil (Figs. 4A, 4B, 4C, and 4F).

At the basin scale, the Assistência Member is isolated by two rock packages that can be interpreted as mechanical interfaces [according to Zahm *et al.* (2010)]:

- above covered by the Corumbataí Formation (mudstones and siltstones — 100 m thick);
- below the Taquaral Member (shales — 10 m thick).

Considering the results from Zahm *et al.* (2010), deformation tends to be less effective due to the high amount of mudstone and shale in these two units. Thus, the Irati Formation, more specifically the Assistência Member, is a mechanical unit of brittle behavior caused by the predominance of carbonates and the more significant thickness. The Taquaral Member (below) and the Corumbataí Formation (above) represent mechanical interfaces in regional-to-basin scale. Therefore, deformation in the Assistência Member tends to be blocked by the two mechanical interfaces mentioned above, fracturing the mechanical unit and generating pathways for oil migration and emplacement.

Taking into account the two more expressive NW-SE and NE-SW joint sets, the behavior of mechanical units and interfaces, the types of porosity, and the occurrence mode of oil in the succession, the sequence for hydrocarbon migration (Gimenez *et al.* 2016) through the permoporous system can be:

- First Stage: NW-SE joint distensions developed during Gondwana breakup and South Atlantic opening during Cretaceous. They were the first to accumulate oil in this system, but they were not efficient enough to generate significant accumulations, as they surpass the mechanical interfaces below and above MU-A;
- Second Stage: NE-SW joint distensions developed during the evolution of the Southeast Rift System (*e.g.*, Riccomini *et al.* 2004). This migration is associated with the multiphase emplacement of basic dikes and sills during the Lower Cretaceous, whose heat flow converted organic matter in oil and gas (Mateus *et al.* 2014). Oil migrated from NW-SE to NE-SW joints and secondary porosities (microjoints, porous carbonate concretion, vugs, breccia interstices, and bedding planes);
- Third Stage: Oil and gas migration due to local pressure gradients after complete cooling of dikes and sills emplaced in the host-rock (Mateus *et al.* 2014).

CONCLUSION

Joints that trespass mechanical interfaces have a close relationship in terms of orientation with NW-SE joints and fault systems responsible for forming regional structures as a response to significant events, such as the Gondwana breakup in the Lower Cretaceous and the Southeast Rift System during Mesozoic and Cenozoic. Deformation and fracturing associated with the PSH development was more intense, occurred before the formation of NE-SW joint sets, and created the first fluid paths and corridors for fluid migration.

The connection of joints into the reservoir resulted from the second deformation event. NE-SW joints superimposed the previous NW-SE ones and connected two distinct sets of joint distensions with a different extension and persistence. The rock nature and thickness of mechanical units and interfaces determined the expression of joints in distinct mechanical units and interfaces, connecting or not independent mechanical units as a function of joint propagation in different rheological media. Thick mechanical interfaces of approximately 30–40 cm are sufficient to block joint propagation and isolate it within the same mechanical unit. Moreover, porous carbonates also modify rheological characteristics and do not propagate joints, as in the case of the breccia and vugular (micro) porosity.

The migration seemed to be significant in the first phase, but the volume of oil accumulation was not large in the mechanical unit. This result is due to the high persistence of NW-SE joints that trespassed mechanical interfaces and distributed oil in other overlying beds. Joint connection occurred in the second deformation stage with generation of less persistent NE-SW joints that do not cross mechanical interfaces. NW-SE and NE-SW joint systems created a joint porosity network, in which NW-SE joints acted as a conduit for oil during migration from the source rock. NE-SW joints connected it with the former NW-SE joints, allowing the oil to spread through these two joint systems into the mechanical unit during the second and third stages of hydrocarbon migration. The most suitable reservoir in the study area is inside the PSH (Ipeúna region), where highly fractured carbonate presents oil impregnation in joints, breccias, and secondary porosity features, and no joint crosses MI-B and MI-C, which act as seals.

This study aimed to characterize the main orientation of joint sets of bedded strata of the Irati Formation in the PSH and surrounding area. The results allowed corroborating that fractures at different scales have the same trends of orientation and elucidated the relationship between fracturing and oil migration on a more regional scale. Regional approaches involving tectonics and fracturing are fundamental to understand the unconventional petroleum system of the Irati Formation as well as all cases involving fractured reservoirs. This background will allow new studies in the area to detail the connection patterns between macro- and microfractures and propose a robust model for oil migration through time.

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ERRATUM

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Where it reads:

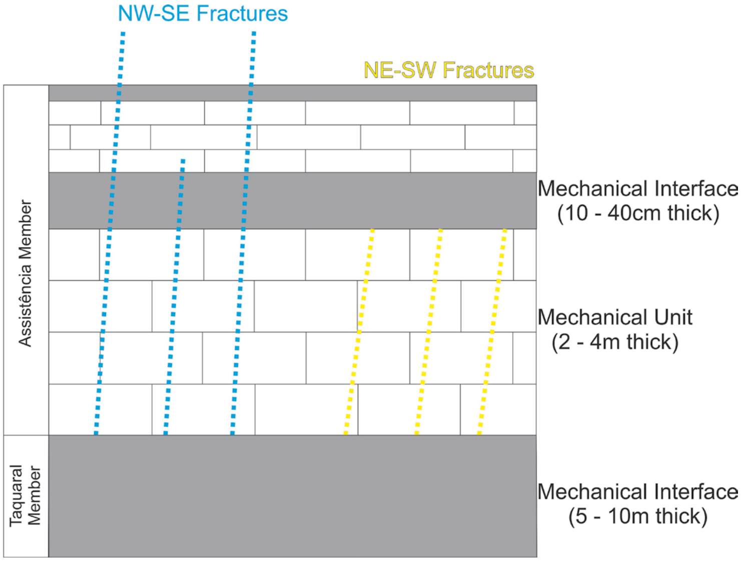

Figure 6. NE-SW joints (yellow dashed line, non-stratabound fracture) and their relationships with mechanical interfaces B and C (red dashed line) in the Vitti Quarry at Saltinho. (A) The joint does not cross the mechanical interface C. (B). Note the fracturing degree in mechanical unit A, *i.e.*, the yellowish-gray calcimudstones at the base and the interbedded shale and fine-grained carbonates above. Thicker mechanical interfaces tend to avoid joint propagation upward.

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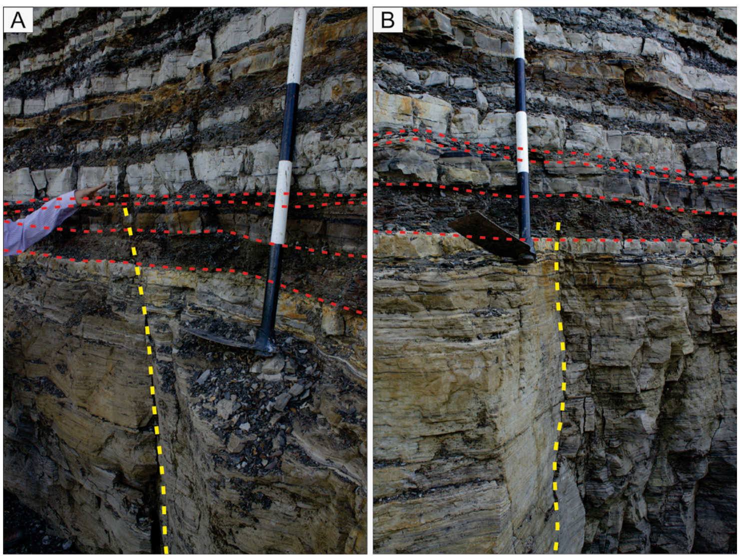

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