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Stratigraphical and sedimentological relationships of the Bolognano Formation (Oligocene–Miocene, Majella Mountain, Central Apennines, Italy) revealed by geological mapping and 3D visualizations

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Abstract: The characterization and comprehension of buried reservoirs receive remarkable benefits from detailed studies of outcropping analogues which help to define the architecture of the buried sedimentary units and their petrophysical features. In particular, modern 3D techniques of geological data analysis can better constrain the geological mapping process and reveal the geometry of the sedimentary units with complex lateral and vertical relationships. By means of the 3D Move software, we define the sedimentological and stratigraphical relationships between lithostratigraphic units of the Bolognano Formation, outcropping in the northernmost sector of the Majella Mountain (Central Apennines, Italy). The study area belongs to the Apulian carbonate platform and the Majella Mountain represents the northward outcropping portion of its margin. The sedimentary succession of the Majella Mountain consists of Upper Jurassic to upper Miocene limestone and dolostone deposits. In the investigated area, outcropping deposits mainly belong to the Oligo–Miocene Bolognano Formation characterized by five lithofacies associations and representing a carbonate ramp developed in a warm subtropical depositional environment within the oligophotic to aphotic zone. The Bolognano Fm. represents, due to its specific hydraulic properties (e.g. porosity and permeability), an outcropping analogue of worldwide common reservoirs (i.e. porous calcarenite deposits of a carbonate ramp formed by benthic foraminifera such as lepidocyclinids, nummulitids, red algae, corals). In the study area, several geological units of the Bolognano Fm. are characterized by abundant hydrocarbon (bitumen) occurrences infilled within the high-porosity of the cross-bedded calcarenites ascribed to the Chattian and Burdigalian interval. The geological field mapping of the area and the visualization of the geological data in a 3D environment show that the unit formed by mid-ramp calcarenites (*Lepidocyclina* calcarenites 2 unit, Chattian–Burdigalian) increases in thickness towards the NE (basinward) direction as a consequence of sediment shedding from inner ramp. Our study illustrates how the geological mapping and the visualization and analysis of geological data in a 3D environment of the northernmost sector of the Majella Mountain confirms depositional models of the Bolognano Formation and represents a valid tool for the characterization of the lateral stratigraphic relationships within this formation, and hence of its potential hydrocarbon occurrences.

Keywords: Cenozoic, carbonate ramp, geological data managment, 3D environment, hydrocarbon reservoir analogue, Majella.

Introduction

Outcropping analogues are often used to constrain the general architecture of buried reservoirs, including their sedimentological and structural patterns, and petrophysical properties (Bryant & Flint 1993; Antonellini & Mollema 2000; Bryant et al. 2000; Petracchini et al. 2012; Henares et al. 2014). Geological field mapping, stratigraphy and facies mapping are useful instruments used to reconstruct geological framework, sedimentary settings and evolution of sedimentary bodies characterized by complex lateral and vertical relationships (Catalano et al. 2013; Basilone & Di Maggio 2016; Basilone & Sulli 2016). However, the mapping process and the comprehension of the three-dimensional (3D) setting of the geological structures is significantly enhanced by the use of digital data and by their visualization and analysis in a 3D environment. It is thus useful to interpret the outcropping geological formations of complex sedimentary bodies in a 3D viewing environment to better constrain their 2D (i.e. geological map) and 3D (i.e. 3D geological model) representations.

Recently, the widespread and rapid development of technologies for 3D acquisition and visualization (e.g. drones, photogrammetry, 3D modelling software) allows geological features (e.g. stratigraphic relationships between lithofacies) to be depicted and interpreted more accurately. Therefore, geological field-based investigation, which represents the starting point for any geological reconstruction, can strongly benefit from the 3D perspective, starting from the acquisition of field data to the final working out of the map (Hodgetts et al. 2004; Jones et al. 2004, 2009; Wilson et al. 2005). The integration between the classical geological field survey and the 3D digitalization and visualization of geological maps and of geological sections helps to overcome the existing limitations that are inherent in traditional methods of map production, such as the spatial precision and extent. These attributes are generally degraded when data are displayed in 2D, while they are preserved with specific spatial precision and resolution when the digitalized data are imported and presented in a 3D environment. Within this context, a detailed field-based study of a complex sedimentary bodies combined with the use of modern techniques offers the opportunity to better constrain the cartographic representation through validation of geological sections and surfaces directly in a 3D environment.

This work aims to produce a new geological map of the Bolognano Fm. carbonate ramp outcropping in the northernmost sector of the Majella Mountain (Central Apennines, Italy) and to display the sedimentological and stratigraphic relationships of its lithostratigraphic units through the visualization and presentation of geological data in a 3D environment (Suppl. mat. S1; Fig.1). The study area shows outcrops mainly belonging to the Oligo–Miocene portion of the Majella sedimentary succession. Consequently, the investigations and mapping are focused on the Bolognano Fm. (Rupelian to early Messinian). This formation represents a carbonate ramp developed in a warm subtropical depositional environment within the oligophotic to aphotic zone (Brandano et al. 2012, 2017a, b). Previously, in the field survey conducted for the Official Italian Cartography project (CARG-project), the Bolognano Formation (Fm.) was classically considered as formed by three informal members (see sheets 361 Chieti, 360 Torre de Passari, 369 Sulmona) named BOL1 (Bryozoan calcarenitic member), BOL2 (Marly member), BOL3 (Lithothamion calcarenitic member) (1:50,000 scale map, CARG project, Crescenti 2015). In contrast, recent studies (e.g. Merola 2007; Brandano et al. 2016a, b) indicate that the Bolognano Fm. may be subdivided into five formal lithofacies association: (i) *Lepidocyclina* calcarenites, (ii) Cherty marly limestone, (iii) Bryozoan calcarenites, (iv) Hemipelagic marls and marly limestones, and (v) *Lithothamnion* limestones. Each association corresponds to a single lithostratigraphic unit except for the *Lepidocyclina* calcarenites that consist of two lithostratigraphic units (i.e. *Lepidocyclina* calcarenites 1 and 2). In addition, the peculiarity of the Bolognano Fm. is that the *Lepidocyclina* calcarenite 1 and 2 units are characterized by abundant hydrocarbon occurrences that triggered the exploitation of oil accumulations between the end of the nineteenth century and

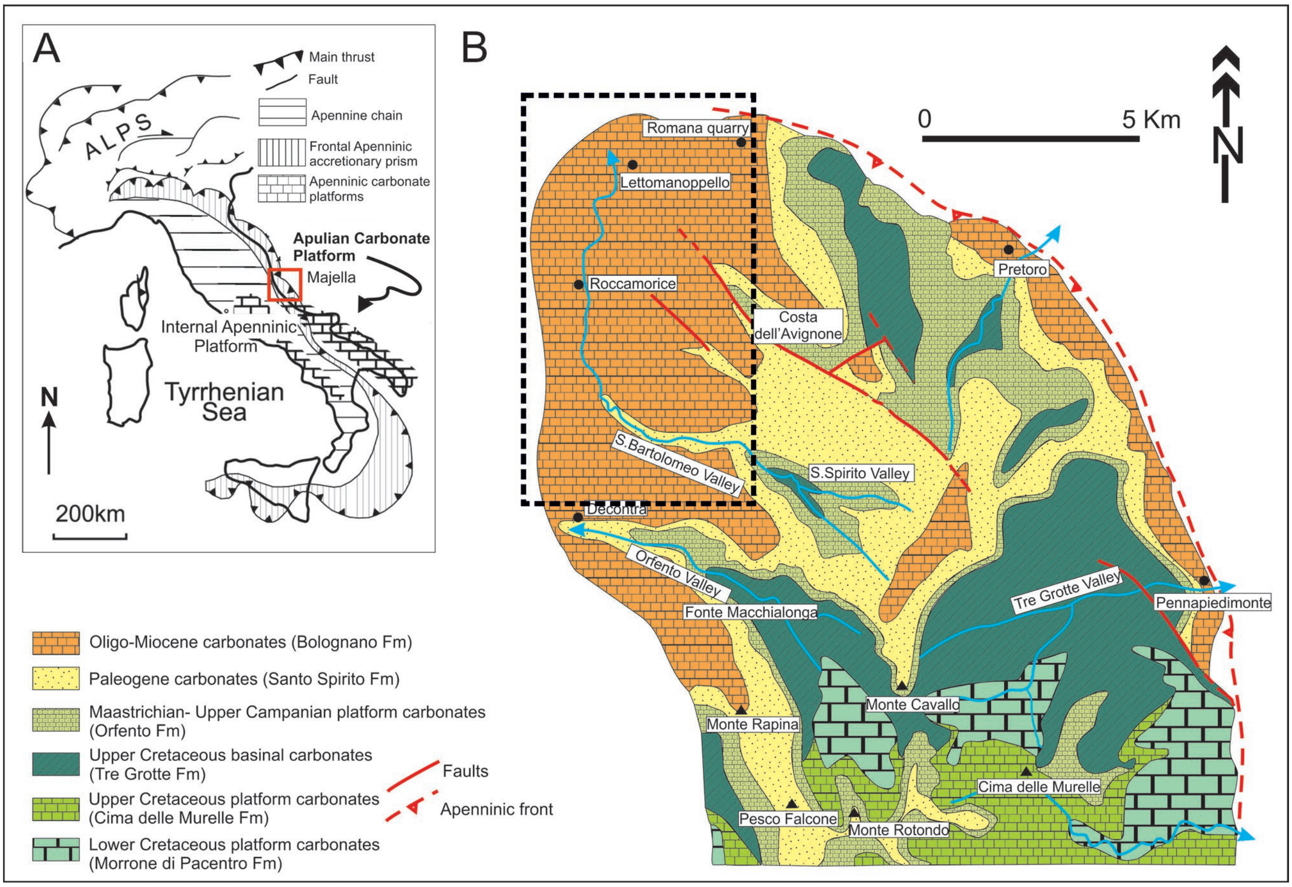

Fig. 1. A — A simplified geological map of Italy (modified from Pomar et al. 2004; **B** — Schematic geological map of Majella Mountain with the main carbonate deposits from Upper Jurassic to upper Miocene (modified from Vecsei & Sanders 1999); the dashed black rectangle indicates the investigated area where the geological map has been produced.

the 1960s. Recently, several authors have suggested that the Bolognano Fm. represents one of the main reservoir intervals of the whole Majella structure due to the sedimentological and petrophysical properties of the calcarenite units (Agosta et al. 2009; Rustichelli et al. 2012; Brandano et al. 2013; Scrocca et al. 2013; Lipparini et al. 2018; Trippetta et al. 2020). Many other carbonate reservoirs are represented by porous calcarenitic carbonate-ramp units where the main bioclastic components are represented by larger and small benthic foraminifera (e.g. lepidocyclinids, nummulitids), red algae, and corals. For example, such calcarenitic reservoirs are represented by the Perla gas field in the Gulf of Venezuela, by the Liuhua 11-1 field in the South China Sea, and by the Ombrina field in the Adriatic Sea, offshore Italy (McQuillan 1985; Zampetti et al. 2003; Sattler et al. 2004; Borromeo et al. 2011; Campagnoni et al. 2013; Pomar et al. 2015).

These units are characterized by high values of effectively connected primary macro-porosity; in the case-study of the Majella Mountain the main seal is represented by the Hemipelagic marly unit of the Bolognano Fm. (Lipparini et al. 2018; Trippetta et al. 2020). Consequently, the investigated area offers the possibility to map the key elements of a complex petroleum system (rock reservoir and seal) characterized by an intrinsic heterogeneity as a result of the lateral variability in facies associations other than the distribution of diagenetic features (Pomar & Ward 1999; Moore 2001; Tomassetti et al. 2018; Brandano et al. 2020). As a consequence, geological mapping and the understanding of the stratigraphic and sedimentological features of carbonate deposits is particularly significant in carbonate reservoirs (Gudmundsson 2011). In this work we highlight the importance of mapping of all the Bolognano Fm. lithofacies and, through the validation and analysis of the data in a 3D environment, we assess geometrical relationships between the lithofacies units and hence their control on the distribution of bitumen.

Regional setting

The study area is part of the Apennine fold and thrust belt as a consequence of the eastward migration of the chain-foredeep system toward the Adriatic foreland that affected the study area after the end of the early Pliocene and continued at least until the Late Pliocene (Fig. 1a; Ghisetti & Vezzani 2002, Scisciani et al. 2000; Patacca et al. 2008; Cosentino et al. 2010). The Majella Mountain is characterized by a large NW–SE to N–S trending thrust-related fold (Fig. 1b). This structure is 35 km long with an axial plunge both to the north (gentle) and to the south (steeper). The eastern limb of the Majella anticline is delimited by a regional W-dipping and E-verging thrust, with several kilometres of displacement (e.g. Patacca et al. 2008). The western limb is truncated by the W-dipping Caramanico Fault and displaced, with an estimated offset of about 3.8–4.2 km in correspondence of the fold axial culmination. Fault displacement gradually reduces northward following the decrease in structural elevation. The studied area is crosscut by NW–SE oriented faults with normal and oblique to strike-slip components. Although contrasting interpretations have been proposed for the tectonic evolution and structural setting of the Majella area, particularly regarding the deep structural setting and the Caramanico Fault (Scisciani et al. 2000; Ghisetti & Vezzani 2002; Patacca et al. 2008), it is generally agreed that the present-day structural elevation of the Majella Mountain (almost 3000 above sea level) was reached only in the final stages of orogeny-related contractional deformations.

The sedimentary successions outcropping in the Majella Mountain were deposited in the southern margin of the Mediterranean part of the Tethys from the Early Cretaceous. This margin was characterized by several shallow water carbonate systems among which the Latium–Abruzzi carbonate platform and the Apulia carbonate platform represent the most extensive carbonate platforms of central-southern Italy (Bernoulli 2001; Cosentino et al. 2010; Tomassetti & Benedetti 2020). The Majella structure is located in the northern portion of the Apulian carbonate platform margin (e.g. Cosentino et al. 2010; Vezzani et al. 2010; Santantonio et al. 2013). The Majella sedimentary succession consists of Lower Cretaceous to upper Miocene limestone and dolostone carbonate deposits (Figs. 1b, 2) (Crescenti et al. 1969; Accarie 1988; Eberli et al. 1993). During the Cretaceous, the Majella structure was characterized by approximately E–W oriented depositional environments constituted by inner platform, platform margin and slope-to-basin successions (Fig. 2) (Bernoulli et al. 1992; Vecsei et al. 1998; Eberli et al. 2004). Inner platform succession is represented by the Morrone di Pacentro Fm. (Late Jurassic–Early Cretaceous) and is developed towards the south (Figs. 1, 2) (Crescenti et al. 1969). An unconformity testifying to an important emersion phase of the platform (Albian–late Cenomanian; Fig. 2) separates the Morrone di Pacentro Fm. from the Cretaceous margin succession represented by the Cima delle Murelle Fm. (early Cenomanian–late Campanian) (Vecsei et al. 1998). A steep, non-depositional escarpment separated the platform from the pelagic basin that extended further to the north (Figs. 2 and 3; Vecsei et al. 1998). The slope-to-basin succession is represented by the Valle dell'Inferno (middle Cenomanian–early Turonian) and Tre Grotte (late Turonian–late Campanian) Fms. (Fig. 2) (Vecsei 1991; Vecsei et al. 1998). By the late Campanian, the basin was infilled by onlapping sediments that allowed the progradation of the platform evolving into a distally steepened carbonate ramp (Orfento Fm.) (Fig. 2; Mutti et al. 1997). However, more recently, this formation has been interpreted as a bioclastic wedge representing a carbonate delta drift (Eberli et al. 2019). The following Santo Spirito Fm. (Danian–Rupelian) was deposited on the Mesozoic platform units; this formation is thin and discontinuous when it overlies the former platform top, while it is more continuous in the northern parts, over the platform margin and slope. Discontinuous coral patch reefs (Danian to lower Rupelian) developed in the inner sectors of the middle ramp, strongly controlled by the sea level fluctuations (Vecsei & Moussavian 1997; Brandano et

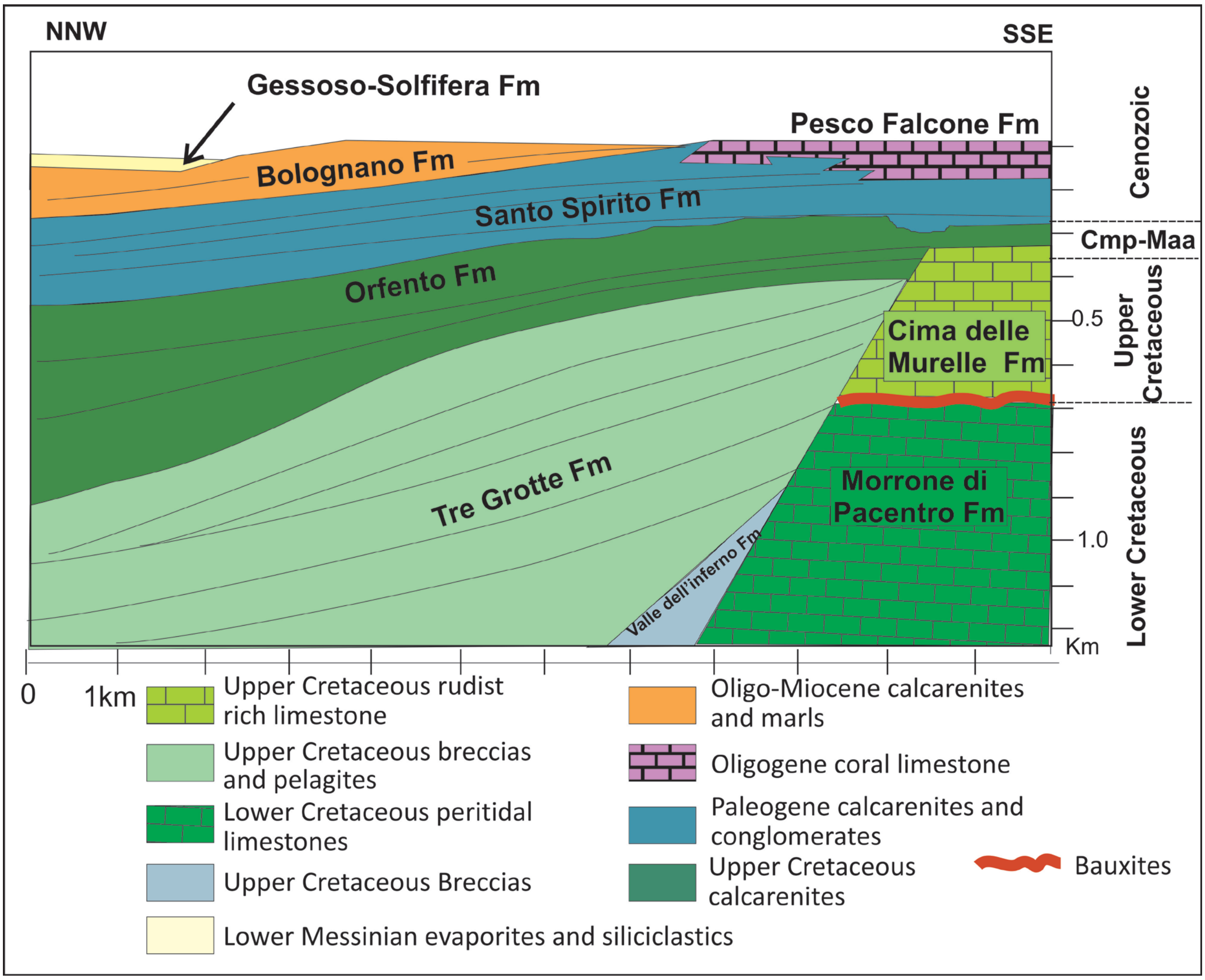

Fig. 2. Schematic stratigraphic architecture of the Majella carbonate platform (modified after Vecsei et al. 1998).

al. 2019a). An unconformity separates the Santo Spirito Fm. from the overlying Bolognano Fm. (Rupelian–early Messinian) (Mutti et al. 1997) (Fig. 2). This formation represents a carbonate ramp that persisted until the early Messinian, when it was uncomformably overlain by the deposition of the hemipelagic formation of the *Turborotalita multiloba* marls (Carnevale et al. 2011; Patacca et al. 2013) followed by the mudstone and evaporite deposits of the Gessoso–Solfifera Fm. that represent the deposits related to the Messinian salinity crisis (Fig. 2) (Crescenti et al. 1969). The carbonate sedimentation of the Majella structure ended in the early Pliocene, when the Majella Mountain was involved in the development of the foredeep system related to the Apennine orogeny (Cosentino et al. 2010).

Methods

The mapped area covers almost 22.7 km^2 of the northernmost sectors of the Majella Mountain between the San Bartolomeo and Santo Spirito valleys (Fig. 1). The good exposures in the study area have allowed a detailed mapping that focused on the analysis of lithofacies and their sedimentary and structural features (e.g. faults). Through such observations, it has been possible to draw physical correlations between the sedimentary units of the Bolognano Fm. and to characterize its facies architecture. Field mapping was firstly performed on the 1:10,000 scale, using an enlarged 1:25,000 IGM (Geographic Military Institute) topographic map (Regione Abruzzo Cartographic Service Opendata; http://opendata.regione.abruzzo.it/). The field mapping has allowed us to recognize and to map five of the six lithofacies associations forming the Bolognano Fm. These lithofacies were defined on the basis of their lithology, textural characteristics, sedimentary structures and fossil content. Field observations were complemented with the petrographic examination of 300 thin sections for textural characterization and identification of the skeletal components.

The first geological map (Suppl. mat. S1) obtained from the field survey has been georeferenced and digitized by means of the open source software QGIS (version 2.18.16) and Corel Draw 2018. The georeferenced map and the attitude

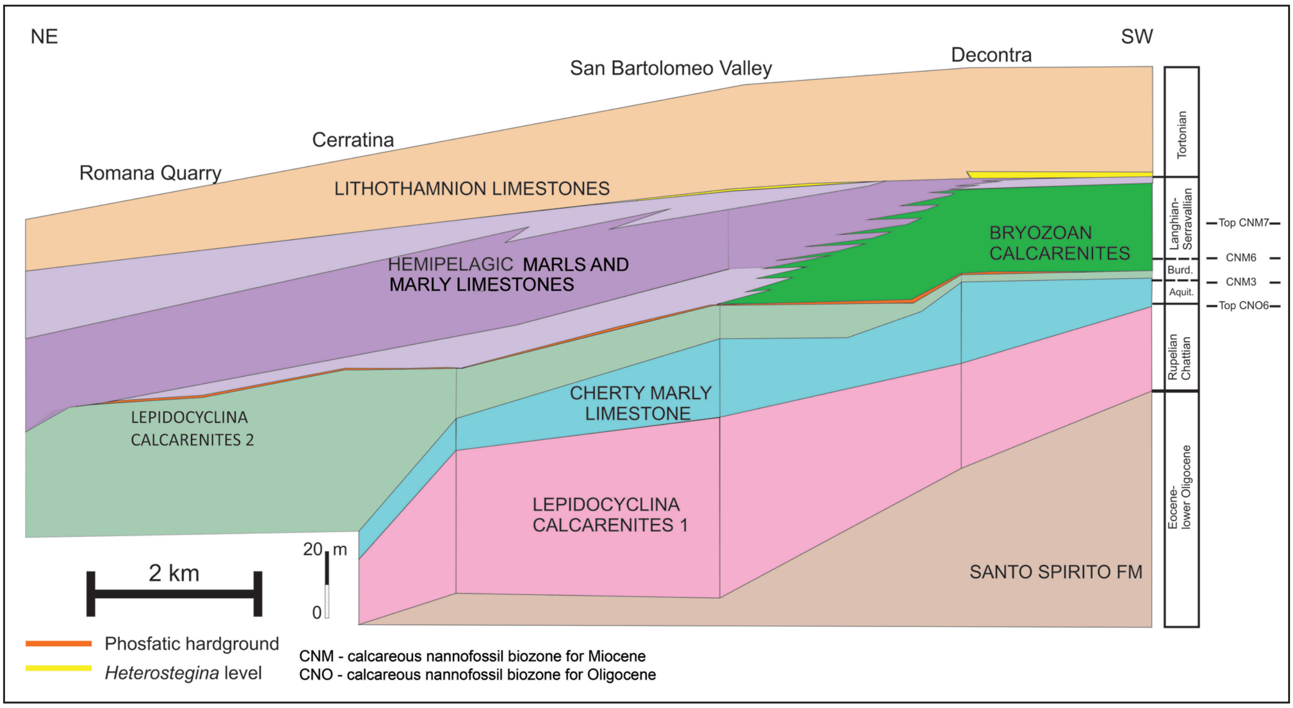

Fig. 3. Stratigraphic architecture of the Bolognano Formation showing the geometrical relationships of the five lithofacies associations and the biostratigraphic constraints based on the nannoplankton biostratigraphy of Raffi et al. 2016 (modified after Brandano et al. 2016a).

data of the geological units and faults have been imported in the Move software (©Midland Valley, version 2017.2). The vector-based geological map has then been draped upon a 10 m-cell size Digital Elevation Model (DEM; Tarquini et al. 2007) and the dip data have been distinguished according to the relevant geological units. Several geological sections have been created using the vector-based data imported in Move: the topography profile of each geological section has been extrapolated from the DEM and the intersections of geological boundaries and faults along the traces of the geological sections have been automatically collected. The attitude data of the geological units and of the faults have been then projected along the sections in accordance with their geometric relationships (i.e. along dip or along strike projection). The projected attitude data have been used to construct the geological horizons using the kink band method and considering the geological boundaries along the sections. The geological sections and the geometries of the lithostratigraphic units have been analysed in 3D in order to better define the lateral and vertical stratigraphic relationship variations of the five outcropping lithofacies associations constituting the Bolognano Fm. and, as a consequence, to refine their representation on the geological map.

Results

A sedimentological and stratigraphical overview of the lithofacies associations of the Bolognano Fm. and in part of the Orfento Fm. and Santo Spirito Fm., cropping out in the south-eastern and southern sectors of the mapped area, are presented below.

Orfento Fm. and Santo Spirito Fm.

The Orfento Fm. crops out in the south-eastern sector of the studied area (Cerratina–Piano delle Cappelle area; Suppl. mat. S1) with a thickness up to 150 m. The Orfento Fm. consists of poorly cemented, highly porous grainstones to packstones, composed of skeletal debris produced mainly by fragmentation of rudist shells, ranging in size from silt to coarse sand. Coarser intervals, characterized by pebble- to boulder-size clasts, are referred to channelized breccias (Vecsei et al. 1998; Eberli et al. 2019). Some metres (up to 30 m) of the upper part of the Orfento Fm. crop out; this portion is represented by bioclastic calcarenites (grainstones and packstones) with fragments of rudists. The Santo Spirito Fm. consists of thick beds of resedimented coral-algal and larger benthic foraminifera calcarenites alternating with fine calcarenites and calcareous marls characterized by chert in nodules and beds. In the study area, the Santo Spirito Fm. reaches almost 90 m (Suppl. mat. S1). By means of nannofossil assemblages, the Santo Spirito Fm. is dated to late Lutetian to early Rupelian (Raffi et al. 2016; Cornacchia et al. 2018) (Fig. 3).

Stratigraphy of the Oligocene–Miocene Bolognano Fm.

The Bolognano Fm. may be subdivided into five lithofacies association organized in six informal lithostratigraphic units because the *Lepidocyclina* calcarenites lithofacies is subdivided into two different lithostratigraphic units (*Lepidocyclina* calcarenites 1 and 2 units).

The *Lepidocyclina* calcarenites 1 facies association is a coarse-grained bioclastic deposit with dominant grainstone and packstone textures (Figs. 4b,c, 5a–f). It is characterized by four lithofacies: (i) planar cross-bedded grainstone (Fig. 5a), (ii) moderate-angle cross-bedded grainstone to packstone (Fig. 5b,c), (iii) sigmoidal cross-bedded grainstone (Fig. 5d,e), and (iv) bioturbated marly packstone to wackestone (Fig. 5f). The first three lithofacies show compound to cuneiform to sigmoidal-shaped cross-beds with planar (10 cm to 20 cm thick) and sigmoidal cross-bedding (20 cm to 60 cm thick), generally dipping between 10° and 20° towards the WNW, and subordinately towards N and NE. Lithofacies (i) has lamination with discordant bedding planes geometry; lithofacies (ii) has concordant to parallel bedding planes.

Compositionally, these three lithofacies are made up of well-rounded red-algal debris, nodules (both geniculated and non-geniculated coralline algae), small rhodoliths, fragmented larger benthic foraminifera (lepidocyclinids, nummulitids, amphisteginids), and small benthic foraminifera (rotaliids, planorbulinids, alveolinids, discorbids, rare miliolids) (Fig. 5a–e). Accessory components are represented by planktonic foraminifera, echinoid and mollusc fragments, bryozoans, and serpulids. The last facies consists of highly bioturbated horizontally bedded, fine-grained packstones to wackestones with calcareous beds 10-to-30 cm thick separated by thin clayey marl intervals (up to 1.5 cm thick). Sedimentary structures are often obliterated by *Thalassinoides* traces. Skeletal components are represented by abundant planktonic foraminifera dispersed in a brownish matrix and by small benthic foraminifera (*Lenticulina*, rotaliids, textularids), bryozoans, bivalves, echinoids and serpulid fragments (Fig. 5f). Glauconitic grains occur especially in bioclastic cavities, such as infills of planktonic foraminifera chambers. The *Lepidocyclina* calcarenites 1 unit is dated to the Rupelian–Chattian, SBZ22A (Shallow Benthic Zone of Cahuzac & Poignant, 1997) on the basis of larger foraminiferal assemblages (Benedetti et al. 2010; Brandano et al. 2016a).

The second unit of the Bolognano Fm. is the Cherty marly limestone (Figs. 3, 4d) that comprises three different lithofacies: (i) bioclastic packstone, (ii) cherty bioturbated packstone to wackestone and (iii) nodular bioclastic wackestone to packstone. Lithofacies (i) and (ii) of the Cherty marly limestone unit are characterized by tabular beds (20–30 cm thick) with a few centimetres of marl intervals; chert nodules and layers are characteristic of lithofacies (ii). Lithofacies (iii) shows thick nodular beds (up to 20 cm). The skeletal assemblage is represented by small benthic foraminifera (textularids, rotalids), dominant in the bioclastic wackestone to packstone facies, and planktonic foraminifera (globigerinids, globorotaliids) abundant in the cherty bioturbated packstone to wackestone and nodular bioclastic wackestone to packstone (Fig. 5g). Bryozoans, echinoid and mollusc fragments are present. Bioturbation traces (*Thalassinoides*, *Zoophycos*) and glauconite mineralization also occur in this unit. The age of the Cherty marly limestone unit is ascribed to the late Chattian–Aquitanian on the basis of nannoplankton *Sphenolithus delphix* assemblage (Brandano et al. 2016a) (Fig.3).

The third unit is represented by the *Lepidocyclina* calcarenites 2 unit. This unit shows facies characters similar to those of the basal *Lepidocyclina* calcarenites 1 unit, the only difference is represented by a decrease in abundance of larger benthic foraminifera in the upper part. This unit is topped by a well-developed phosphatic hardground. The *Lepidocyclina* calcarenites 2 are overlain by the Hemipelagic marls and marly limestone unit in the investigated area, while moving southward in the Orfento Valley they are overlain by the Bryozoan calcarenites unit. This unit can be attributed to the late Aquitanian–Burdigalian p.p. (Brandano et al. 2016a). The *Lepidocyclina* calcarenites units are characterized by the presence of hydrocarbon accumulations with the most relevant impregnations concentrated in the *Lepidocyclina* calcarenites 2 (Brandano et al. 2013; Lipparini et al. 2018).

The Bryozoan calcarenites are the fourth unit of the Bolognano Fm. (Fig. 3). It is represented by three lithofacies: (i) cross bedded foraminiferal bryozoan packstone to grainstone, (ii) foraminiferal bryozoan packstone to grainstone and (iii) coarse, larger benthic foraminiferal bryozoan packstone to grainstone. All the three lithofacies are characterized by compound cross-stratification with planar-to-straight beds up to 20 cm and dipping 10° towards WNW. The beds are separated by subhorizontal surfaces. The skeletal assemblage is dominated by bryozoans, small benthic (rotaliids, textularids) and larger benthic foraminifera (*Amphistegina*, *Heterostegina*), and by planktonic foraminifera (globigerinids, globorotalids, globigerinoids). The age of the Bryozoan calcarenites is ascribed to the late Burdigalian–Serravalian based on the stratigraphic relationships (Fig. 3). This unit lies above the top of the *Lepidocyclina* calcarenites 2 unit and it is overlain by the upper portion of the Hemipelagic marls and marly limestones unit (unit 5 of the Bolognano Fm.) (Brandano et al. 2016a).

The fifth unit of the Bolognano Fm. is represented by the Hemipelagic marls and marly limestones unit (Fig. 4e) that includes three marly lithofacies dominated by planktonic foraminifera: (i) bioturbated packstone, (ii) planktonic wackestone to packstone, and (iii) cross-bedded bioclastic packstone. These three lithofacies show subhorizontal to lenticular beds, with faint planar cross-bedding; a planar to trough cross-bedding is recognizable only in the cross-bedded bioclastic packstone facies. Generally, the beds are massive (20 to 60 cm thick) and separated by a few centimetres-thick marly layers. Intense bioturbation characterizes all deposits in the Hemipelagic marls and marly limestones unit. The skeletal assemblages are represented by planktonic foraminifera, small benthic foraminifera (textularids, buliminaceans), serpulids, echinoids, brachiopods and bivalve fragments (Fig. 5h). The Hemipelagic marls and marly limestones unit is attributed to the late Burdigalian to Serravallian based on the occurrence of nannofossil *Sphenolithus heteromorphus* assemblages (Brandano et al. 2016a).

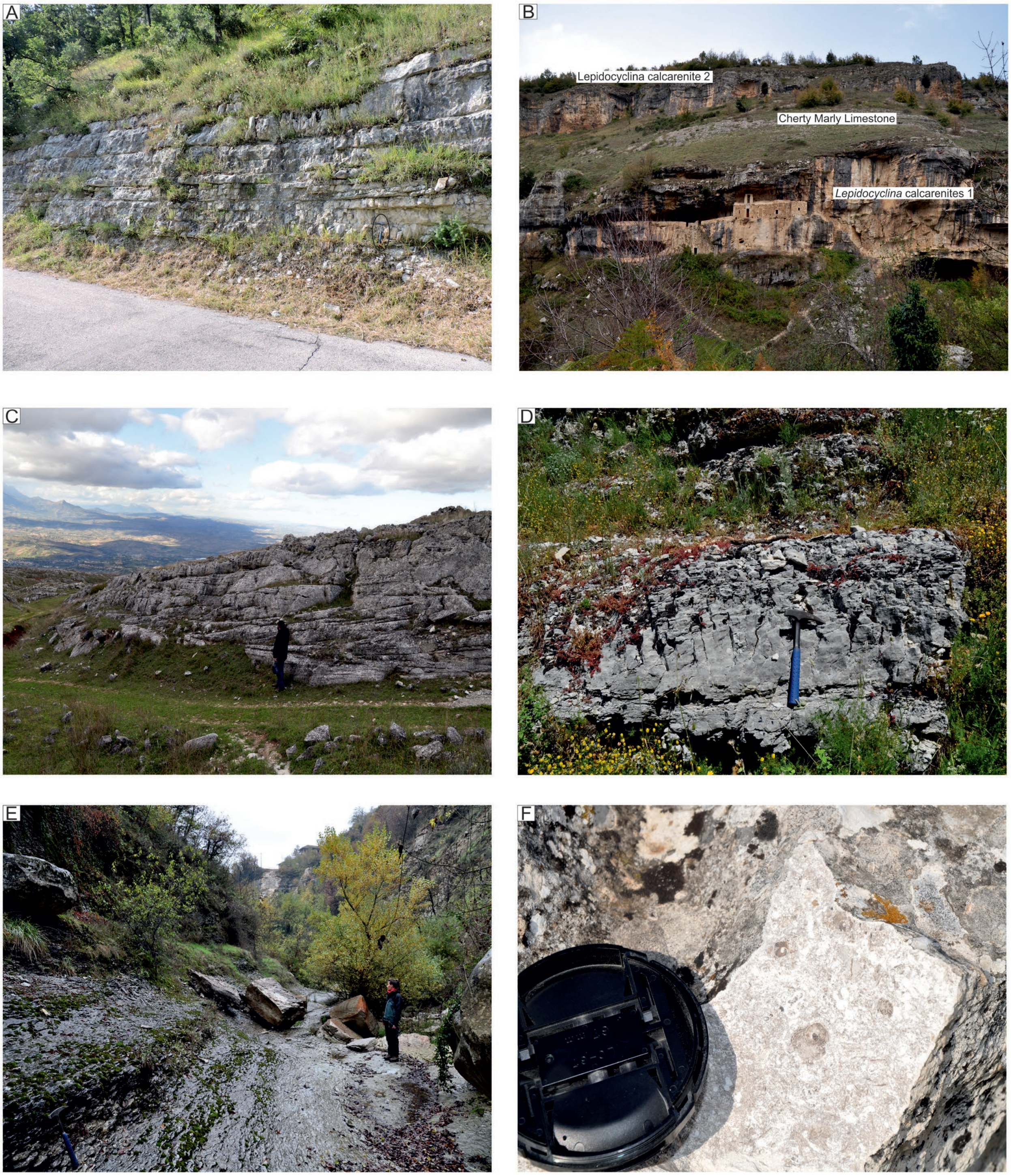

Fig. 4. Field photograph of lithofacies associations of the Bolognano Formation. **A** — Santo Spirito Fm. outcropping in the south-eastern sector of the investigated area. The fine-grained calcarenites and calcareous marls characterize this formation. Hammer for scale (35 cm). **B** — Panoramic view from San Bartolomeo Valley (south-western sector of the map) showing the stratigraphic relationship between the *Lepidocyclina* calcarenites 1 (the lowermost unit at the base of the photograph), the Cherty marly limestone unit (unit in the middle in the photo) and the *Lepidocyclina* calcarenites 2 (the uppermost unit). It is fascinating how the San Bartolomeo hermitage is built inside the *Lepidocyclina* calcarenites 1 unit. **C** — *Lepidocyclina* calcarenites 2 unit characterized by cross-beds with sigmoidal shape with sets up to 60 cm thick and laterally traced up to 70 m; person for scale is 1.80 m in height. **D** — Cherty marly limestone unit showing horizontal and bioturbated beds (0.10 to 0.30 m thick); hammer for scale (35 cm). **E** — Hemipelagic marl and marly limestone unit characterized by alternation of horizontally bioturbated calcareous marls and clayey limestones. Person for scale (around 1.7 m in height). **F** — *Lithothamnion* limestones unit showing free red algal branches and the planispiral larger benthic foraminifera *Heterostegina*, both being dominant in the *Heterostegina* floatstone to rudstone lithofacies that represent the basal part of the *Lithothamnion* Limestone unit. Photograph cap is around 10 cm in diameter.

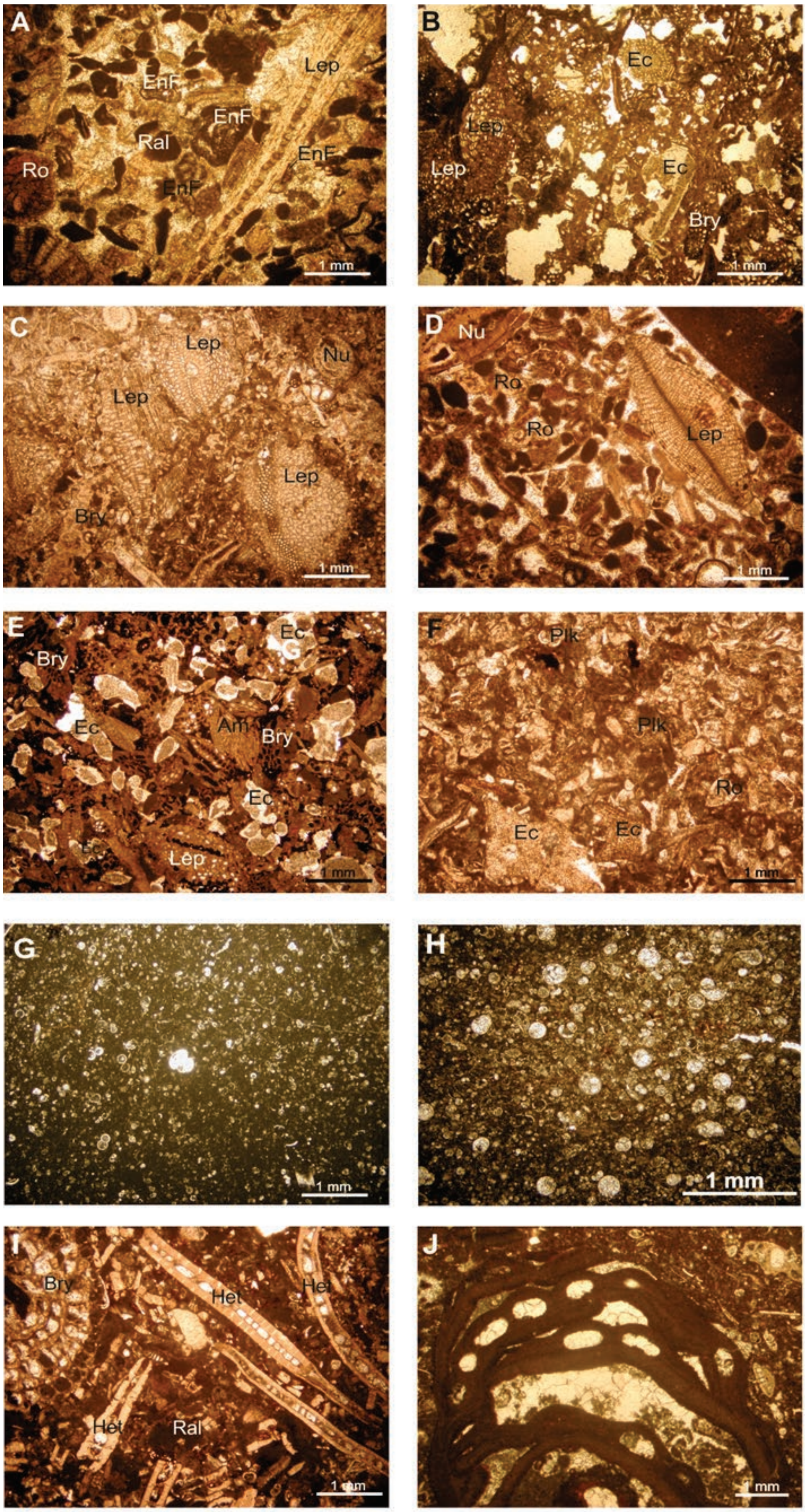
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Fig. 5. The Bolognano Fm. microfacies associations. **A–F:** Thin sections of lithofacies associations characterizing the Lepidocyclina calcarenites units. **A** — Planar cross-bedded grainstone facies with lepidocyclinids, small benthic foraminifera as rotaliids, red algal fragments and echinoid fragments; **B, C** — Moderate-angle cross-bedded grainstone to packstone with lepidocyclinid specimens and remains of bryozoans and echinoids; **D** — Sigmoidal cross-bedded grainstone with coarse and moderately sorted texture with dispersed bioclastic fragments, *Lepidocyclina* sp., nummulitids, rotaliids; **E** — Sigmoidal cross-bedded grainstone showing bitumen-bearing impregnations infilling the intraparticle and interparticle porosity; **F** — Bioturbated marly packstone to wackestone formed by planktonic foraminifera, echinoid fragments, and bryozoans; **G** — Thin section of Cherty marly limestone unit dominated by planktonic foraminifera; **H** — Thin section of Hemipelagic marls and marly limestone unit with abundant planktonic foraminifera tests of orbulinids and globigerinids; **I, J** — Thin sections of *Lithothamnion* limestone unit showing the *Heterostegina* floatstone to rudstone lithofacies (**I**) and the floatstone to rudstone lithofacies with free-living red algal branches (**J**), with a multi-layered encrusting thallus of a melobesioid (*Mesophyllum obsitum*) forming a small rhodolith. Scale bars: 1 mm; Lep=*Lepidocyclina*, Bry=bryozoan; Ec=echinoid, Ro=rotaliid, Ral=red algal fragment, Het=*Heterostegina*, EnF=encrusting foraminifera, Nu=nummulitids, Plk=planktonic foraminifera, Am=*Amphistegina*.

The sixth unit forming the Bolognano Fm. is represented by the *Lithothamnion* limestone (Figs. 4f, 5i,l). This unit consists of five lithofacies: (i) *Heterostegina* floatstone to rudstone, (ii) free-living red algal branches floatstone to rudstone, (iii) red algal bindstone, (iv) bioclastic packstone, and (v) cross-bedded bioclastic packstone with bivalves and vertebrates. The first three lithofacies show massive beds (50 cm up to 1.5 m thick) mainly tabular, subhorizonal and sometimes nodular. The fourth lithofacies shows lenticular beds (up to 40 cm thick) with low-angle, curved to undulating laminae, forming hummocky cross-stratifications. The fifth lithofacies (up to 1.5 m thick) shows lenticular beds (30 cm) with cross-stratification with planar to curved bedding surfaces.

These lithofacies contain larger benthic foraminifera as *Heterostegina* (Fig. 5i), *Operculina* (dominant in the *Heterostegina* floatstone to rudstone), *Borelis*, small benthic foraminifera (mainly buliminaceans, textularids, discorbids, nubecularids), as well as subordinate rotaliids (*Elphiudium*, *Lobatula*, *Rotalia*), miliolids (*Triloculina*), encrusting foraminifera (*Planorbulina*), coralline red algae forming small rhodoliths (Fig. 5l), free-living branches and nodules, crusts. Coralline algae, with all these different growth-forms, are the main components of the free-living red algal branches floatstone to rudstone and the red algal bindstone lithofacies associations. Other components are represented by planktonic foraminifera (*Orbulina*, globigerinids, globigerinoids), sponge spicules, bryozoans, and echinoid fragments, bivalves and brachiopods. Some vertebrate remains together with disarticulated bivalve valves and fish teeth also occur in the fifth lithofacies of the *Lithothamnion* limestone unit. The *Lithothamnion* limestone also shows local hydrocarbon accumulations. The age of the *Lithothamnion* limestone unit is ascribed to the Tortonian–early Messinian interval based on its stratigraphic position, since the *Lithothamnion* limestone unit lies above the Hemipelagic marls and marly limestone unit and below the lower Messinian *Turborotalita multiloba* Marls (Patacca et al. 2013; Brandano et al. 2016b; Cornacchia et al. 2017).

Geological map description and 3D visualization

The geological mapping of the northernmost sector of the Majella Mountain has allowed the identification and the tracing of the lithostratigraphic units of the Bolognano Fm. In this area, only the third unit of the formation, represented by the Bryozoan calcarenites, does not outcrop because this unit is located southward of the investigated area in the Orfento Valley (not included in the presented map). In the study area, the lateral and coeval deposits of the Bryozoan calcarenites are represented by the Hemipelagic marls and marly limestone unit (Fig. 3).

The lateral and stratigraphic relationships of the lithofacies associations of the Bolognano Fm. have been checked through the analysis of several geological cross-sections extracted from the 3D model (Suppl. mat. S1; Figs. 6, 7). The geological cross-sections helped, firstly, to better constrain the cartographic representation of the study area geology. The final version of the geological map is the result of this cross-sections validation (Suppl. mat. S1). Secondly, the lateral and vertical stratigraphic relationships of the units of the Bolognano Fm. have been detected and confirmed by the analysis of the data presented in 2D and in 3D. As an example, Figure 7 shows the lateral variation of the thickness of the *Lepidocyclina* calcarenites 2 unit which tends to decrease toward the SW reaching a thickness of few metres (about 10 m) whereas the *Lepidocyclina* calcarenites 1 unit is almost constant throughout the study area, slightly decreasing toward NE. In the Cerratina area (Suppl. mat. S1) the *Lepidocyclina* calcarenites 1 (up to 30 m) overlies the Santo Spirito Fm., that is in turn overlain by the uppermost portion of the Orfento Fm. The Cherty marly limestones unit occurs in this area above the *Lepidocyclina* calcarenite 1, reaching a maximum thickness of 20 m in the south-western part of the mapped area. A normal fault system (N150 striking and dipping about 60° to SW) affects these units in the Piano delle Cappelle area and it is characterized by two main faults with about 240 m of throw, which separate the Piano delle Cappelle and the Acquafredda sectors. In this sector, hydrocarbons are present (see Suppl. mat. S1), occurring in the hangingwall of the Piano delle Cappelle fault system, and in the *Lepidocyclina* calcarenites units. In the Piano delle Cappelle area, the *Lepidocyclina* calcarenites 2 unit is well-exposed and shows, as described before, variable thickness that progressively increases towards the NE sector of the map from the Cerratina–Piano delle Cappelle area to the Romana Quarry (near the Lettomanoppello village), increasing in thickness from 45 to 90 m. This change in thickness reflects a wedge-shaped geometry that is clearly recognizable in the 3D visualization of cross-sections (Figs. 6, 7). This unit displays spectacular cross-bedded dunes

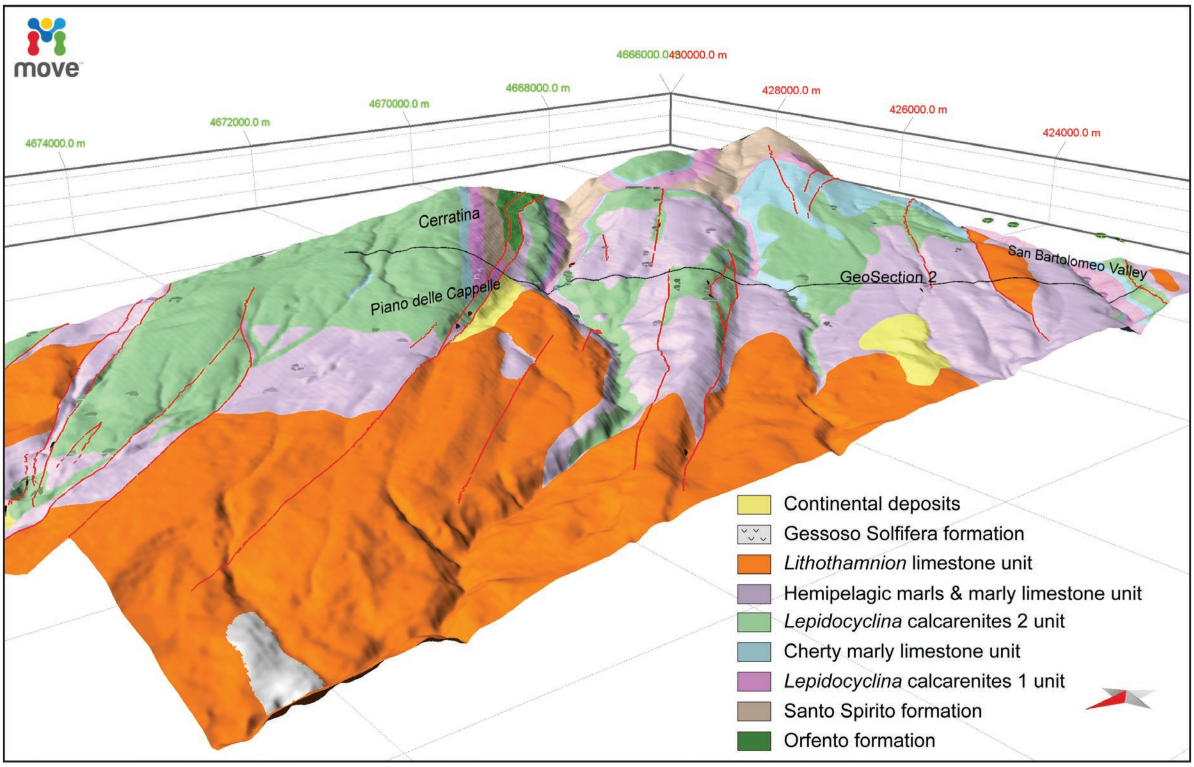

Fig. 6. 3D view of the vector-based geological map showing the stratigraphic units composing the Bolognano Fm. between Lettomanoppello and San Bartolomeo valley. The geological map created in QGis has been draped upon a 10 m-cell size grid DEM (no vertical exaggeration; Tarquini et al. 2007). Vector-based dip data representing the attitude of geological layers, distinguished according their geological units, and of faults have been imported in the 3D environment. Several geological sections have been made using the tools of the Move software (version 2017.2; © Midland valley) and the 3D visualization helped to better defined the uncertainties in the geological mapping and to analyse the geometrical relationship of the Bolognano architecture. The black line named "GeoSection 2" shows the location of the trace of the geological section shown in Figure 7.

with cuneiform to sigmoidal-shaped beds, dipping toward WNW. The top of the *Lepidocyclina* calcarenites 2 unit is characterized by a phosphatic hardground rich in shark-teeth and it marks the boundary with the overlying Hemipelagic marls and marly limestone unit. The marly unit is overlain by the shallow-water unit of the Bolognano Fm. represented by the *Lithothamnion* Limestone formation. This unit has a constant thickness of 20–30 m in the Majella Mountain area. It is well recognizable and exposed in the NW sector of the map. The *Lithothamnion* Limestone constitutes the youngest unit of the Bolognano Fm. in the studied area.

Discussion

The lithofacies associations of the six units of the Bolognano Fm. represent the deposition of a wide middle to outer carbonate ramp characterized by heterozoan skeletal carbonates in the meso-oligophotic to aphotic zone (*sensu* Pomar & Haq 2016), where mesophotic meaning middle light conditions (<20 % of surface light intensity), oligophotic implies poor light condition (<4 % of surface light intensity) and aphotic refers to independence from surface light intensity.

This carbonate ramp model is in agreement with the classical scheme proposed by Buxton & Pedley (1989). In this scheme, middle ramp environment is characterized by foraminiferal and coralline algal packstone to wackestone deposits; whereas the outer ramp environment consists of benthic (both larger and smaller) and planktonic foraminiferal wackestone to packstone deposits. The environment between the inner and middle ramps is generally occupied by seagrass meadows. The seagrass deposits are generally characterized by epiphytic dwellers biota association (i.e. miliolids, encrusting foraminifera, peneroplids) and absence of sorting and sedimentary structures as a consequence of sediment baffling, trapping and stabilization by seagrass (Pomar et al. 2004; Brandano et al. 2019b).

During the Chattian to Burdigalian age, the carbonate ramp of the Bolognano Fm. was affected by strong and continuous currents on seafloor that favoured the reworking and shedding of skeletal components from the shallowest inner ramp zone to the middle and outer ramp environment, promoting the development of a large submarine dune field (Brandano et al. 2012) represented by the cross-bedded *Lepidocyclina* calcarenite units. In particular, this submarine dune field characterizing the *Lepidocyclina* calcarenites 2 unit is well recognizable in the outcrop of the Piano delle Cappelle area (Suppl. mat. S1).

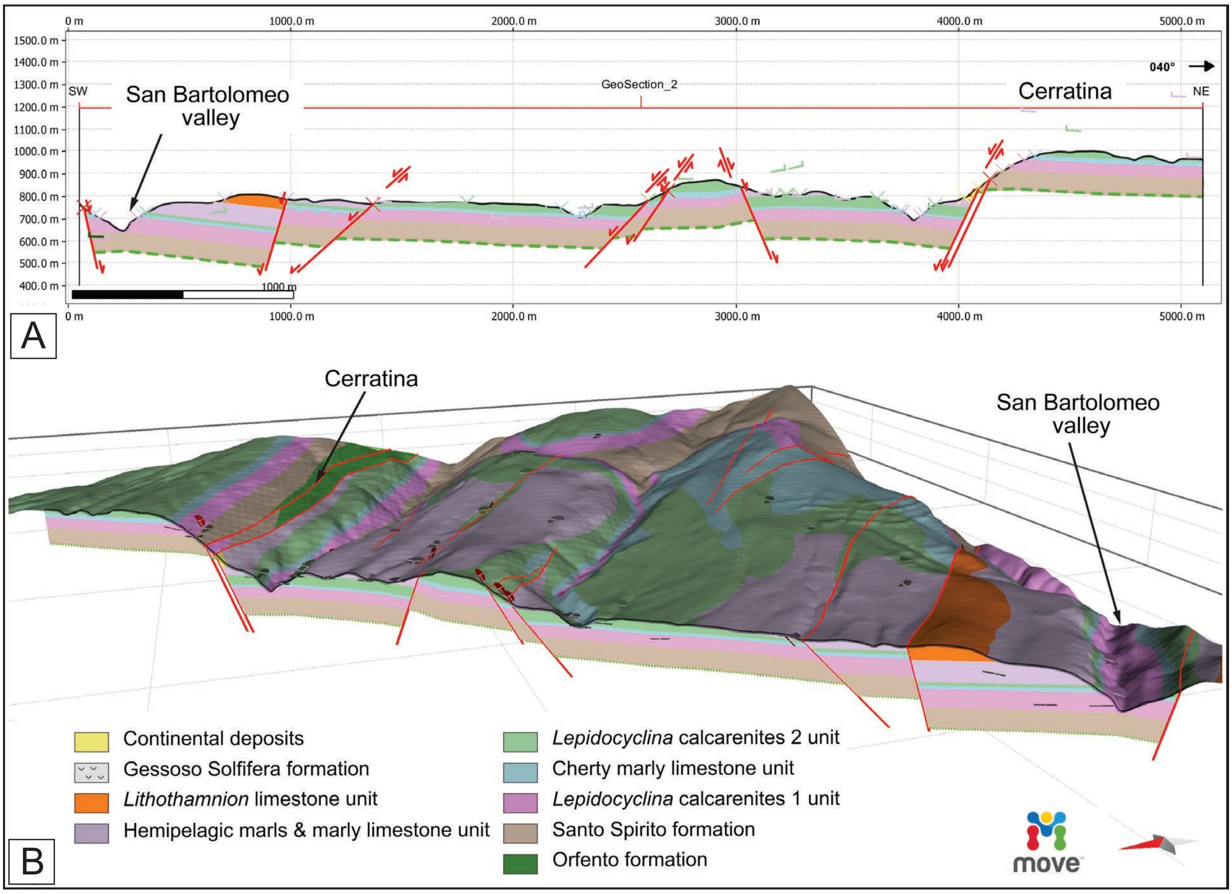

Fig. 7. A — Example of a geological section made in the Move software (© Midland valley). The topography profile has been extrapolated from the DEM and all the intersections of geological boundaries and faults lines along the trace of the geological section (see Fig. 6) have been automatically collected (see crosses along the topographic profile). The dip data of geological layers and of faults have been projected along the trace in respect of their geometric relationship (i.e. along dip or along strike projection). **B** — 3D visualization of the geological section of Fig. 7a. Several geological sections have been made and analysed in 3D environment to better constrain the geometry of the Bolognano units. Note the variation in the thickness of the *Lepidocyclina* calcarenites units. The *Lepidocyclina* calcarenites 2 unit becomes thicker toward NE and, in contrast, the thickness of the *Lepidocyclina* calcarenites 1 unit remains almost constant between Cerratina and San Bartolomeo valley (Fig. 6). Location of geological section is shown in Figure 6.

The geological mapping and the 3D visualization of the northernmost sector of Majella (Figs. 6, 7) shows several stratigraphic insights. The general stratigraphic architecture, as reconstructed previously by stratigraphic outcrop-based correlations (Brandano et al. 2016a), is confirmed by the results of the 3D analysis. However, this analysis highlights the thickness variations of different units of Bolognano Fm., in particular a northward increase in the thickness of two units, namely, the *Lepidocyclina* calcarenites 2 unit and the Hemipelagic marls and marly limestone unit. The increase in the thickness of the Hemipelagic marls and marly limestone unit cannot be appreciated in this map (Suppl. mat. S1; Figs. 6, 7) because a large portion of the thickness of this unit was eroded probably during the glacio-eustatic sea level fall coinciding with the Ser4/Tor1 (*sensu* Hardenbol et al. 1998). On the contrary, the northward increase in the thickness of the *Lepidocyclina* calcarenite 2 unit is clearly observable in the geological section of Figure 7. This increase reflects a northward increase in accommodation space as well as a northward increase in sediment accumulation rate, toward the pelagic environment of the Paleo-Adriatic domain. This observation is in agreement with the *Lepidocyclina* calcarenites 2 depositional model predicting a progressive shed of sediment produced in the middle ramp towards the distal sectors of the outer ramp, where these transported sediments mixed with the autochthonous component and enhanced sediment accumulation (Brandano et al. 2012). The middle ramp was characterized by a submarine dune field, which can be evaluated in detail in terms of width and length by means of the map that has been worked out (22.7 km^2 Suppl. mat. S1). It is important to note that this unit represents the main rock reservoir of the Bolognano petroleum system, which as a potential size that can be better evaluated also from the map produced with this work. In contrast to the *Lepidocyclina* calcarenites 2 unit, the thickness of the *Lepidocyclina* calcarenites 1 unit does not markedly change between Cerratina and the San Bartolomeo valley. The details of the modelling of the reservoir, hydrocarbon distribution, reservoir architecture and volumes of hydrocarbons in place have been presented in Lipparini et al. (2018).

Conclusions

The geological field survey and the three-dimensional visualization of the map performed with the Move software here show the geometrical and the spatial relationships between the five lithostratigraphic units of the Bolognano Fm. In particular, the 3D visualization documents the stratigraphic architecture of the Bolognano Fm. and confirms that the thickness of the *Lepidocyclina* calcarenites 2 unit, representing a submarine dune field and the major reservoir of the Bolognano petroleum system, increased in a basinward direction towards the north. The geological patterns of the investigated sector of Majella Mountain provide an extraordinary opportunity to observe an exposed combination of some of the main fundamental elements of a petroleum system as reservoir, seal, and trap geometry.

Furthermore, the present work highlights the relevance of studies on outcropping analogues to better characterize the architecture of the buried carbonate reservoirs. In particular, this work shows the advantages of using digital data, visualization and analysis in a 3D environment to reconstruct the geological framework, the three-dimensional sedimentary setting and the evolution of sedimentary bodies characterized by complex lateral and vertical relationships.

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Supplementary material S1 "Vector-based georeferenced geological map of the Bolognano Fm. between the Lettomanoppello and San Bartolomeno Valley, Majella Mountain (Central Apennines, Italy)" is available online at http://geologicacarpathica.com/data/files/supplements/Tomassetti_Suppl_Material_S1_CartaGeo.pdf.