



The Jurassic Gorgo a Cerbara palaeoscarpment (Monte Nerone, Umbria-Marche Apennine): modelling three-dimensional sedimentary geometries

Marco Romano ^{1,2,*}, Simone Fabbi ^{2,3}, Paolo Citton ^{2,4}, Angelo Cipriani ^{2,3}

¹ Evolutionary Studies Institute (ESI), School of Geosciences, University of the Witwatersrand, Johannesburg, South Africa
² A-Team (Apennine Team)

³ Dipartimento di Scienze della Terra, SAPIENZA Università di Roma, Rome, Italy

⁴ CONICET-Consejo Nacional de Investigaciones Científicas y Técnicas, Buenos Aires, Argentina

* Corresponding author: marco.romano.univ@gmail.com

ABSTRACT - In the last decades, methodologies for three-dimensional digitisation of geological outcrops have considerably grown. These methods provide to geologists powerful tools to collect, manipulate and communicate field evidence through the reconstruction of high-resolution digital models, starting from a considerable amount of raw data. Among the different methods and technologies, high-resolution Digital Photogrammetry has proven to be among the most economical and performing methods, with several applications in the field of geology *sensu lato*, including outcrop visualisation, geological site management, sedimentology, palaeontology, structural geology, geomorphology and applied geology. In this contribution, we applied high-resolution Digital Photogrammetry to a key-outcrop from the Umbria-Marche Apennines. The studied site is at Gorgo a Cerbara (Piobbico, PU), where the NW-facing Jurassic escarpment of the Monte Nerone Pelagic Carbonate Platform (PCP) is spectacularly exposed. Starting from a suitable number of photographic images of the outcrop taken from different perspectives, we reconstruct a high-definition 3D digital model of the exposed palaeoscarpment. The obtained models provide peculiar sedimentological, taphonomical and stratigraphical details, thus facilitating the comprehension of the complex sedimentary evolution of a PCP margin. 3D modelling allows to observe and display the geological features from ideally infinite perspectives, helping in the reconstruction, understanding and communication of complex three-dimensional geometries in a more direct and objective way.

Keywords: Pelagic Carbonate Platforms; photogrammetry; 3D modelling; sedimentary geometries; Umbria-Marche Apennines; Jurassic.

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1. INTRODUCTION

In the last years, three-dimensional digitisation of geological outcrops got an increasing consideration. Up to date, different methodologies allow geologists to collect, manipulate and communicate field evidence by means of highly resolved digital models, reconstructed from a considerable amount of raw data. In addition, 3D models enable digital preservation of key outcrops with regional and global significance, especially if the sites could be irreversibly modified by human action or by natural processes of geomorphological evolution (see Cipriani et al., 2016).

Although over time several methods and technologies have been proposed and applied for 3D modelling of geological contexts, such as laser scanning (e.g.

Rowlands et al., 2003; Rosser et al., 2005; Buckley et al., 2008, 2010; McCoy et al., 2010; Hodgetts, 2013) and LiDAR technology (e.g. Bellian et al., 2005; Cunningham et al., 2006; Schulz, 2007; Burton et al., 2011; Hartzell et al., 2014), high-resolution Digital Photogrammetry is proving to be by far the easiest and cheapest method. Despite photogrammetry has used with a pioneering approach since the 1970s, recently this technique is increasingly applied in different fields of the geological sciences *sensu lato*. This revival is essentially due to the development of new technologies, availability of more powerful cameras, processors and high-performance software. Compared to other methods such as laser scanning, digital photogrammetry has the advantage of being much more economical and accessible, essentially needing only a camera and appropriate software, some

also available as open source (see Falkingham, 2011; Cipriani et al., 2016). This has recently led to numerous uses of photogrammetry in geology, providing additional and powerful tools for interpreting outcrops and for communicating the results to the scientific community more objectively. To date, photogrammetric models have been used for outcrop visualisation, geological site management, and study of peculiar setting from different geological features, including sedimentology, structural geology, geomorphology and applied geology (e.g. Chandler and Moore, 1989; Lane et al., 1993; Oka, 1998; Hapke and Richmond, 2000; Mora et al., 2003; Walstra et al., 2007; Baldi et al., 2008; Sturzenegger and Stead, 2009; Cachao et al., 2011; Westoby et al., 2012; Lato et al., 2013; Martín et al., 2013; Bemis et al., 2014; Fan and Li, 2015; Cipriani et al., 2016; Vollgger and Cruden, 2016; Hayes et al., 2018; Zimmer et al., 2018). In the field of palaeontology, photogrammetry has been used to describe new specimen and taxa and to obtain *in-vivo* reconstruction starting from 3D model in both invertebrates and vertebrates (Wiedemann et al., 1999; Brassey et al., 2015; Brassey, 2016; Fau et al., 2016; Vidal and Díaz, 2017; Romano et al., 2018a, 2018b, 2019a, 2019b; Cipriani et al., 2019; Citton et al., 2019; Rubidge et al., 2019). A field where photogrammetry is providing very promising results is vertebrate ichnology, being a powerful tool both for the detailed analysis and description of new ichnotaxa and to make inferences about biomechanics and locomotion based on differential depth of impression obtainable from the high-resolution 3D models (e.g. Petti et al., 2008, 2018; Remondino et al., 2010; Falkingham, 2011; Romilio and Salisbury, 2014; Lallensack et al., 2015; Citton et al., 2015, 2017a, 2017b, 2018; Lockley et al., 2016; Razzolini et al., 2016; Romano and Citton, 2016; Lužar-Oberiter et al., 2017; Belvedere et al., 2018; Falkingham et al., 2018; Warnock et al., 2018).

In the present contribution, we discuss a 3D digital model of a peculiar geological setting in the Umbria-Marche-Sabina Domain (UMS-Central/Northern Apennines, Italy) produced by means of high-resolution digital photogrammetry. The well-exposed portion of a Jurassic submarine escarpment unconformably covered by pelagic and neritic deposits, bounding the Monte Nerone Pelagic Carbonate Platform (PCP *sensu* Santantonio, 1994), was analysed.

The obtained photogrammetric models return with high definition and detail the peculiar sedimentological, taphonomical, palaeontological and stratigraphical framework observed in the field. The interpretation of the models allows communicating, in a simple and direct way, the complex stratigraphic-sedimentological features of a PCP margin and the processes triggered within PCP/basin systems. The opportunity to display the obtained models from a theoretically infinite different perspectives represents a powerful tool for further helping in the reconstruction, interpretation and communication of complex three-dimensional geometries, and to digitally

preserve crucial outcrops frequently involved in irreversible natural and anthropic processes of geological and geomorphological evolution.

2. GEOLOGICAL SETTING

The study area is located in the northern sector of the Umbria Marche Apennines (Fig. 1), belonging to the Umbria-Marche-Sabina Geological Domain, characterised by a thick Upper Triassic-to-Neogene stratigraphic succession, whose stratigraphic evolution is widely described in literature (Farinacci, 1967; Colacicchi et al., 1970; Centamore et al., 1971; Galluzzo and Santantonio, 2002; Pierantoni et al., 2013; Fabbi, 2015; Cipriani, 2016). In the earliest Jurassic, the area was occupied by a vast peritidal carbonate platform ("Calcare Massiccio" platform; Calcare Massiccio Fm in Petti et al., 2007), which was dismembered by extensional tectonics since the Hettangian (Bernoulli, 1967; Bertotti et al., 1993; Centamore et al., 1971; Colacicchi et al., 1970; Farinacci et al., 1981; Santantonio and Carminati, 2011; Fabbi and Santantonio, 2012). Such extensional phase produced an articulated submarine topography, causing the diachronous drowning of the benthic carbonate factory and the consequent onset of pelagic sedimentation on both horsts and grabens (Morettini et al., 2002; Passeri and Venturi, 2005). The hangingwall basins of Jurassic faults experienced rapid tectonic subsidence, and, starting from the Sinemurian, were filled by a thick (several hundred meters) Jurassic-Early Cretaceous pelagic succession, composed of resediment-rich cherty limestones, marls and cherts. Differently, the footwall blocks remained at shallow depth, since small relics of "Calcare Massiccio" carbonate platforms ("Calcare Massiccio B" in Centamore et al., 1971; Calcare Massiccio B member in Petti et al., 2007; "drowning succession of the footwall blocks" in Marino and Santantonio, 2010) survived until the earliest Pliensbachian, when they simultaneously drowned due to perturbation of oceanic water conditions (Morettini et al., 2002; Franceschi et al., 2014; Masetti et al., 2016), in a passive post-tectonic regime (Santantonio and Carminati, 2011; Santantonio et al., 2017). After the early Pliensbachian, thus, the footwall blocks of Jurassic faults represented intrabasinal morphostructural highs known as PCPs (Santantonio, 1993, 1994; Santantonio et al., 2017), as they host a very thin (up to few tens of meters), Jurassic-Lower Cretaceous chert-free and fossil-rich pelagic succession (Bugarone Group, Cecca et al., 1990), coeval with the thicker basinal one (Fig. 2A).

Steep escarpments, representing inactive vestiges of roofed Early Jurassic faults, connected the top of PCPs with the surrounding deeper basins. Palaeoescarpments were the sites of stratigraphic contacts, as testified by the onlap unconformities of the pelagic succession passively filling the basin onto the pre-rift "Calcare Massiccio" unit exposed along the rift-related scarps. Jurassic escarpments commonly host ponded patches of condensed pelagites (epi-escarpment deposits

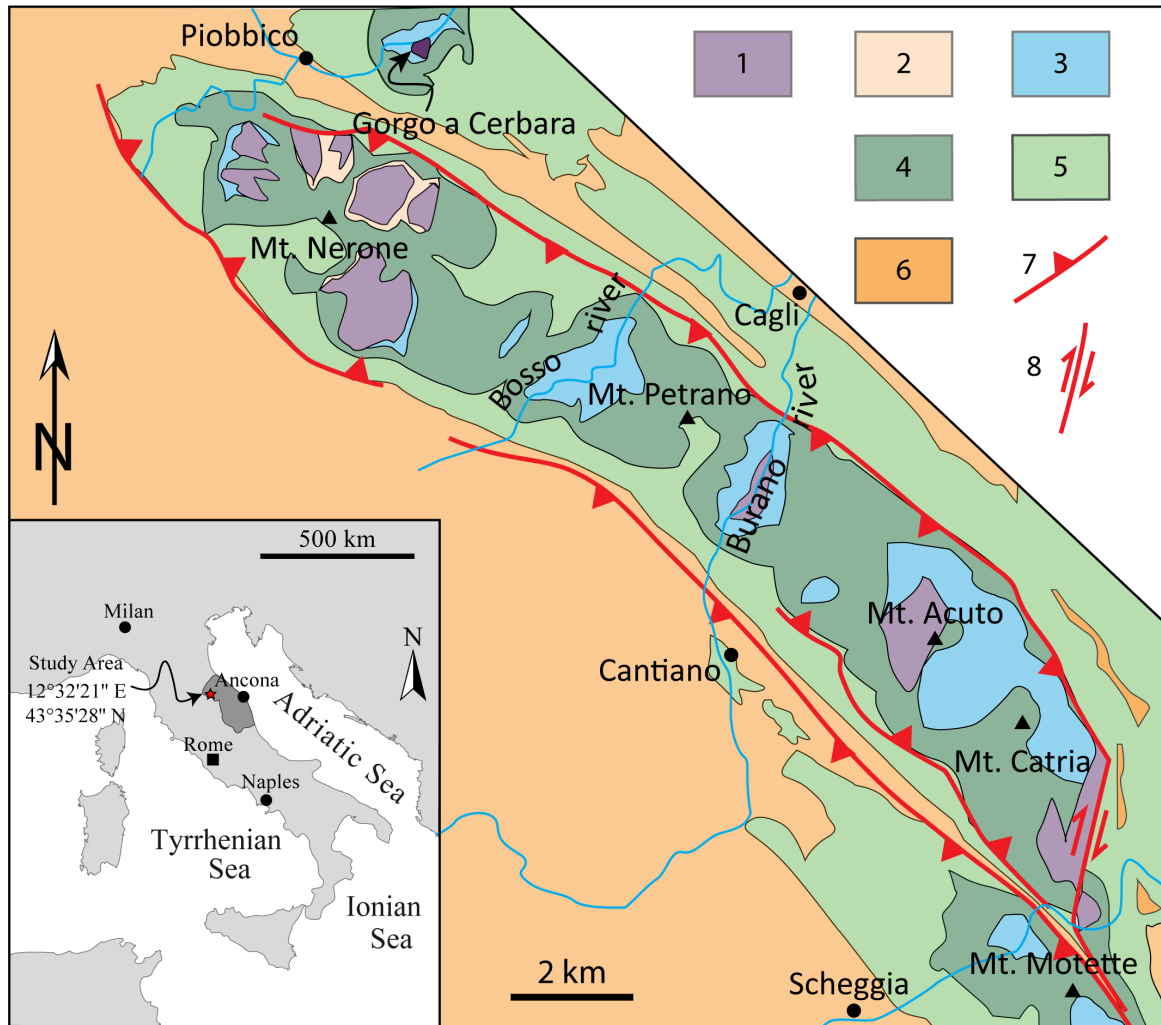


Fig. 1 - Location and simplified geological map of the Mt. Nerone-Mt. Catria ridge. 1) Calcare Massiccio Fm.; 2) Bugarone Group; 3) Jurassic basinal succession; 4) Maiolica Fm.; 5) Aptian - Oligocene deposits; 6) Miocene - Recent deposits; 7) main thrust faults; 8) strike slip fault (Modified after Romano et al., 2019c).

sensu Galluzzo and Santantonio, 2002) locally sedimented within small favourable morphologies (i.e. mesotopographical lows as collapse niches of detached blocks), in otherwise non depositional slopes (Santantonio et al., 2017). Significantly, the birth of palaeoescarpments in the earliest Sinemurian predates the drowning of the “Calcare Massiccio B”-type carbonate platforms at the top of PCPs (Fabbi and Santantonio, 2012). The latter implies that Sinemurian-earliest Pliensbachian palaeoescarpments could host both sparse patches of resedimented “Calcare Massiccio B” and patches of Sinemurian condensed pelagites (i.e. older than the typical Bugarone Group – Fig. 2B). At the stratigraphic unconformable contact with the silica-rich basinal pelagic succession, both the “Calcare Massiccio” and any interposed epi-escarpment deposit are often silicified (Santantonio et al., 1996); silicification is indeed an important feature for recognising stratigraphic (rather than tectonic) boundaries such as palaeoescarpments (Galluzzo and Santantonio, 2002; Di Francesco et al., 2010; Santantonio et al., 2017).

Regionally, the palaeotopographic irregularities were generally blanketed by the Maiolica Fm in the earliest Cretaceous, albeit with localised phases of revived tectonics (e.g. Fabbi, 2015; Fabbi et al., 2016; Cipriani, 2016, 2017; Romano et al., 2018b; Cipriani and Bottini, 2019a, 2019b).

The study outcrop (lat. 43°35'28"N, long. 12°32'21"E) is in the deeply-incised valley of the Candigliano River, close to the Gorgo a Cerbara quarry (less than 3 km E of Piobbico-Pesaro-Urbino, Marche) (Fig. 1). Gorgo a Cerbara is a classical section for the Jurassic of the UMS Domain (e.g. Elmi, 1981; Immerz, 1985; Cecca et al., 1987, 1990; Kälin and Ureta, 1987; Cresta et al., 1989; Marino and Santantonio, 2010) and is part of the Monte Nerone PCP/basin system. Monte Nerone represents one of the largest PCPs of the UMS and is a particularly representative site for Jurassic palaeontology and sedimentology (e.g. Centamore et al., 1971; Farinacci et al., 1981; Alvarez, 1989a, 1989b; Cecca et al., 1990; Mariotti, 2003; Romano et al., 2018b, 2019c; Cipriani et al., 2019; Citton et al., 2019), as it was studied since the

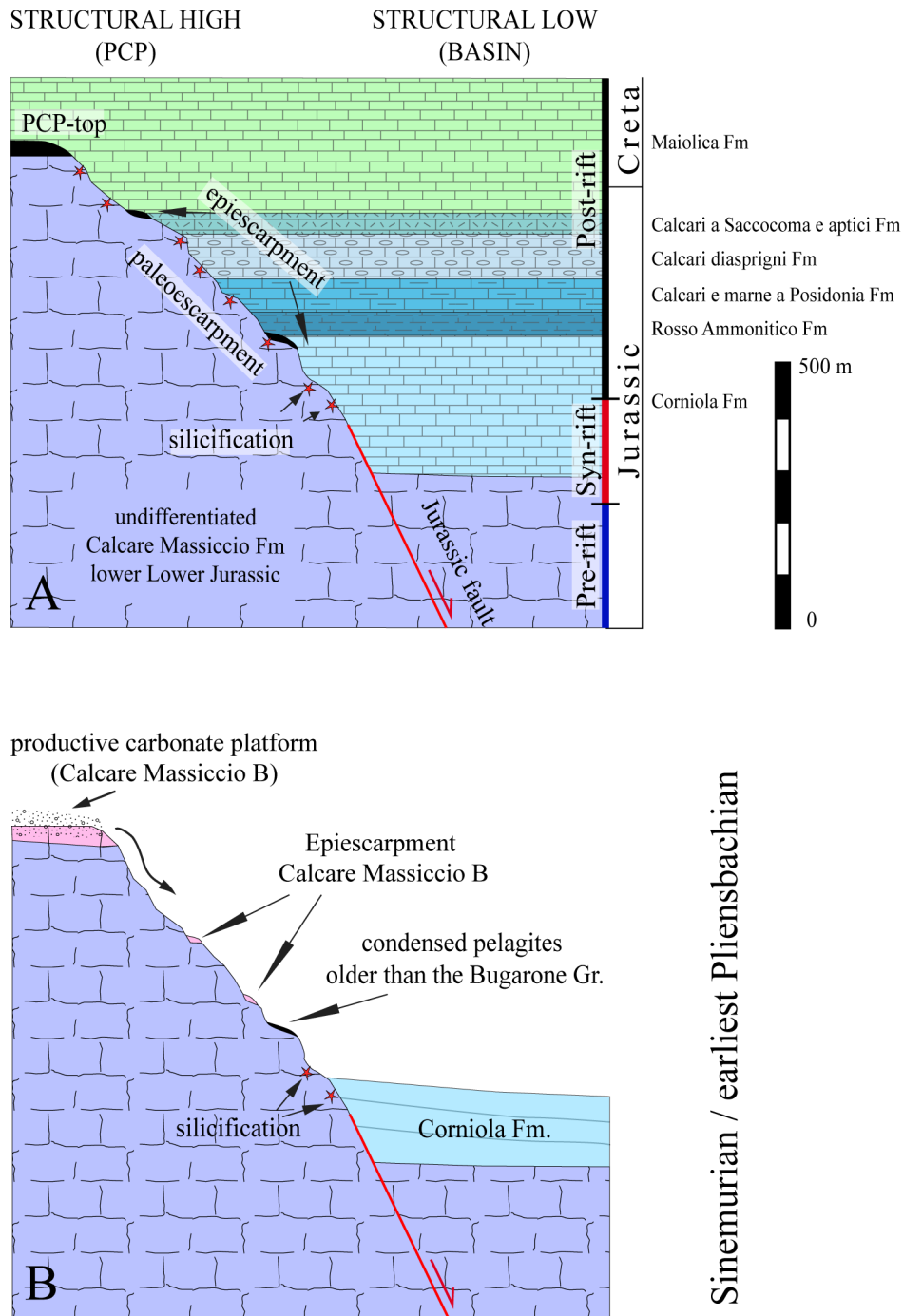


Fig. 2 - A) General stratigraphic setting and main features of a Jurassic PCP-basin system in the UMS Domain (Modified after Santantonio et al., 2017); B) Schematic reconstruction of the Monte Nerone PCP and Gorgo a Cerbara paleoescarpment in the Sinemurian-early Pliensbachian.

XIX century (Zittel, 1870). The NW-facing margin of this Jurassic morphostructural high is spectacularly exposed at Gorgo a Cerbara (Fig. 3). We focused the attention on the lower portion of this Jurassic submarine escarpment, characterised by an irregular, silicified, palaeo-surface of pre-rift “Calcare Massiccio”. Small patches of “Calcare Massiccio B”-type facies, late Sinemurian-earliest Pliensbachian in age (“unconformity-bounded drowning succession” in Marino and Santantonio,

2010), and cephalopod-rich pelagites of late Sinemurian (Lotharingian-Cecca et al., 1987) age, in the form of scattered epi-escarpment deposits, rest unconformably on this complex onlap surface. The whole structure is covered with an angular unconformity by the basin-fill pelagites of the Corniola Fm, “middle”-late Pliensbachian in age.

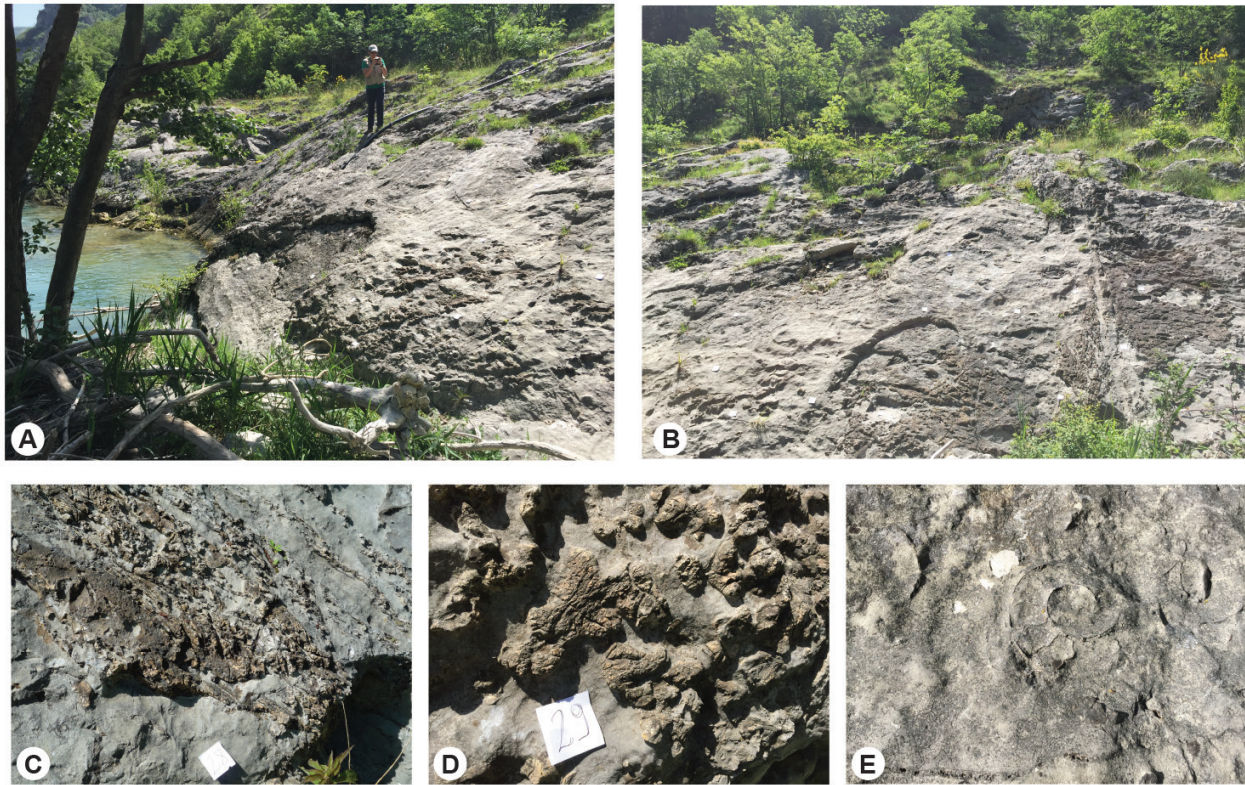


Fig. 3 - A) and B) The Gorgo a Cerbara palaeoescarpment outcrop at Piobbico (PU) bordered by the Candigliano river; C) and D) details of the irregular, silicified, palaeo-surface of pre-rift “Calccare Massiccio”; E) section of a large ammonite in the upper Sinemurian epi-escarpment deposits made of condensed Corniola-type (diameter: 22 cm).

3. MATERIAL AND METHODS

For the production of the photogrammetric model, 347 photos of the outcrop were taken from different angles, trying to always have at least 60% overlap between contiguous photos. The software used is Agisoft PhotoScan Standard Edition, version 1.4.0 (Educational License), which enables automatic generation of point clouds, polygonal models, georeferenced orthomosaics, textured and DSMs/DTMs from still images. High-resolution Digital Photogrammetry is based on Structure from Motion (SfM) (Ullman, 1979) and Multi View Stereo (MVS; Seitz et al., 2006) algorithms, with an accuracy for close-range photography in the obtained models of up to 1 mm. Geometrically the software needs only three photos from different angles for each single point for the reconstruction of its position in space; however, for extensive subjects, such as large surfaces, more than 200 shots are needed to make sure that every single point has been covered, without shaded or hidden objects or surfaces portions. The repeated overlap does not generate noise, rather the redundancy could add a lot of information for the final dense clouds.

The photos were aligned in the software using the function “Align Photos” which led to the construction of the initial “Spars Point Cloud” (Fig. 4A). Then, several steps have been conducted to calibrate the cameras and to reduce the errors due to “reprojection error”,

“reconstruction uncertain” and “projection accuracy”. The subsequent phase consisted in the reconstruction of the “Dense Cloud”, where the missing points among those acquired in the model are geometrically and mathematically reconstructed. This phase leads to the dense point cloud where it is already possible to appreciate the almost final result of the model (Fig. 4B). In the last step a mesh was generated starting from the dense point cloud, i.e. a complex polygonal surface made of vertices and faces on which the program literally smears the raster of the photo (Fig. 4C).

The models obtained with Agisoft PhotoScan can be exported in numerous formats, including “.OBJ” and “.PLY”, the latter preferable because it also retains the raster data of the original photos on the final product. The file exported as .PLY can be opened with the open source software MeshLab, which allows numerous interesting actions and modifications, including the isolation of individual volumes and the measurement of different objects. The final reconstructed model consists of approximately 8 million vertices and 17 million faces. This means that an outcrop surface of approximately 9 square meters can be represented by a polygonal mesh with about 190 faces per square centimetre, a resolution that is more than acceptable for the purposes of the present contribution.

The studied outcrop was analysed directly *in situ*, using the classic methodologies of the field geology. A

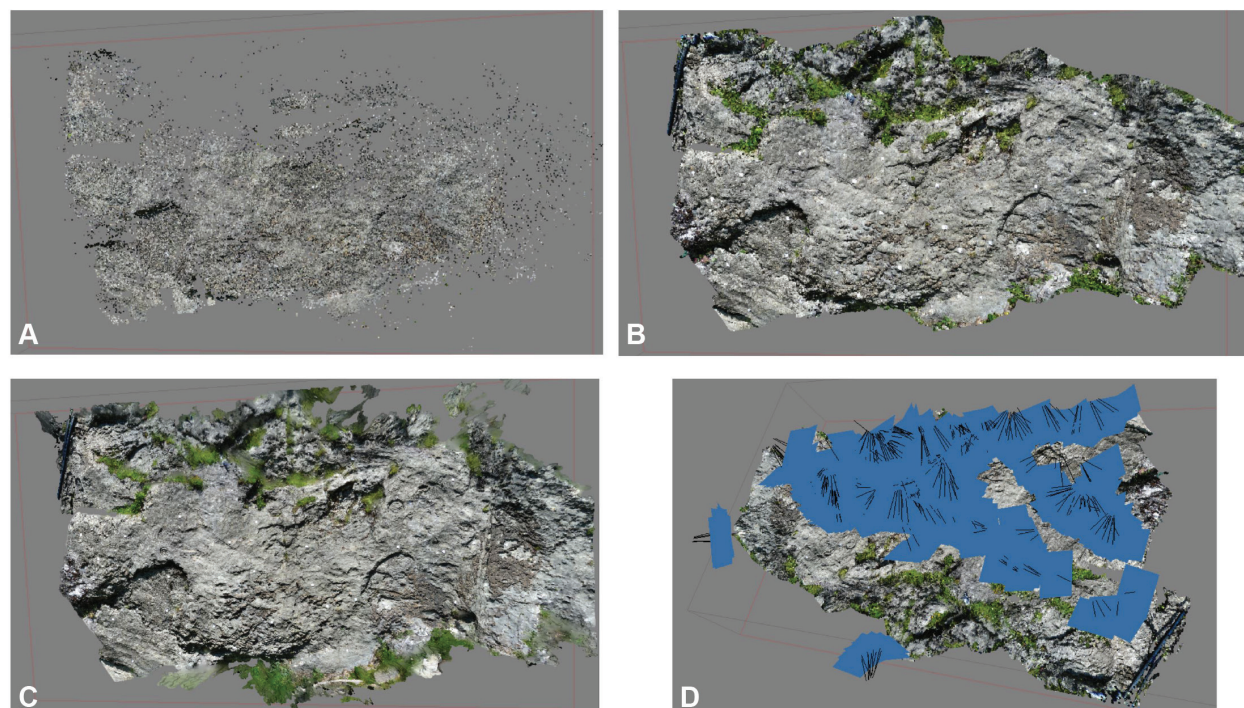


Fig. 4 - Reconstruction of the 3D model in Agisoft PhotoScan Standard Edition, version 1.4.0 (Educational License). A) Initial “Spars Point Cloud” after photos alignment; B) “Dense Cloud” after correction for “reprojection error”, “reconstruction uncertain” and “projection accuracy”; C) Final mesh of the model made of approximately 8 million vertices and 17 million faces; D) Final mesh with the indication of the angles from which the photos were taken.

Tab. 1 - Main features of the different facies recognised in the Gorgo a Cerbara palaeoescarpment.

Sample	Lithostratigraphic unit	Microfacies description	Age	Depositional setting
AC 808	Calcare Massiccio Fm	Bioclastic grainstone bearing peloids, micritic grains, cortoids, algal nodules, benthic foraminifers and microproblematica (<i>Thaumatoporella parvovesiculifera</i> , <i>Lithocodium</i> sp.) (Fig. 5D).	Hettangian	High energy, peritidal, shallow marine environment
AC 809	Calcare Massiccio B member	Bioclastic packstone with microoncooids, peloids, abundant micritic portion, sponge spicules and benthic foraminifers (Fig. 5E).	Sinemurian <i>p.p.</i>	Submarine escarpment
AC 807	“Corniola”-type condensed epi-escarpment deposit	Bioclastic floatstone with ammonites, gastropods, siliceous sponge spicules, benthic foraminifers, radiolarians and undeterminable bioclastic debris (Fig. 5F)	Sinemurian <i>p.p.</i>	Submarine escarpment
AC 810	Corniola Fm	Mudstone/floatstone with crinoids, radiolarians, siliceous sponge spicules, benthic foraminifers and ammonites (Fig. 5G).	“middle”-late Pliensbachian	Basin margin

lithostratigraphic approach combined with facies analysis allowed to recognise different facies associations and to describe the depositional setting of the palaeoescarpment, as well as its space-time evolution. Several rock samples were analysed first hand and collected to produce several thin sections. Microscopical analysis of the samples

allowed to better define every single facies and to recognise in detail the limits between the different sedimentary bodies. Microfacies description of the outcropping lithotypes followed the classification of Dunham (1962) and Embry and Klovan (1971), is summarised in table 1. Microphotographs of the thin sections are in figure 5.

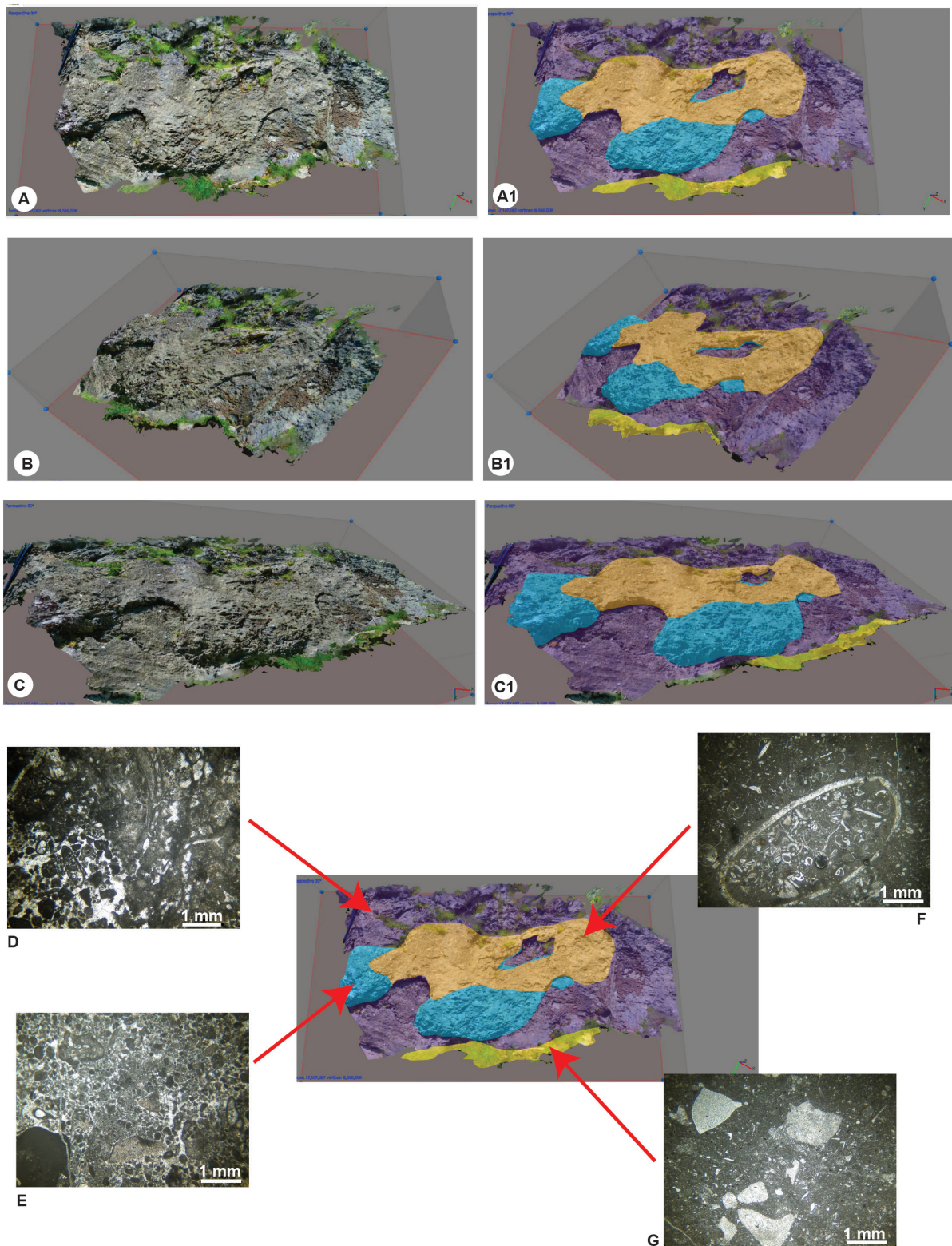


Fig. 5 - Final model of the Gorgo a Cerbara palaeoescarpment outcrop. A, B, C) Mesh model with the original texture; A1, B1, C1) final mesh with the different recognised facies indicated by different colors: pre-rift “Calcare Massiccio” in purple, epi-escarpment deposits with “Calcare Massiccio B”-type facies in light blue, epi-escarpment deposits made of condensed Corniola-type in orange, well-bedded basal pelagites of the Corniola Fm in light yellow; D) pre-rift “Calcare Massiccio” in thin section. Sample AC 808; E) “Calcare Massiccio B”-type epi-escarpment deposits in thin section. Note the coated grains dispersed in abundant micritic mud bearing sponge spicules and crinoids. Sample AC 809; F) Microphotograph of the epi-escarpment deposits made of condensed Corniola-type facies. Note the high fossil content of the pelagites. Sample AC 807; G) Thin section of the well-bedded and cherty basal pelagites of the Corniola Fm. The bioclastic pelagic facies are dominated by fragments of crinoids, radiolarians, siliceous sponge spicules and benthic foraminifers. Sample AC 810. See table 1 for the description of the microfacies.

4. PHOTOGRAMMETRIC MODEL

Figure 5 shows the model obtained from three different points of view. In the model shown in figure 5A, the 3D reconstruction does not seem to deviate much from simple photography, however once the individual units are isolated and the volumes highlighted with different colours, the complex sedimentary situation results much clearer and more evident. The pre-rift “Calcare Massiccio” representing the Jurassic horst-block is highlighted in purple (Fig. 5). The epi-escarpment deposits with “Calcare Massiccio B”-type facies are highlighted in light blue. The lack of *Agerina martana*, a characteristic taxon of the Pliensbachian facies of the “Calcare Massiccio B”, allows to speculate a Sinemurian age for these deposits. Epi-escarpment deposits made of condensed Corniola-type facies bearing very large upper Sinemurian (Lotharingian) ammonites (Cecca et al., 1987) are highlighted in orange. These lithofacies apparently cover the older “Calcare Massiccio B” epi-escarpment deposits. The well-bedded and cherty basinal pelagites of the Corniola Fm are highlighted in light yellow and characterise the lower portion of the photogrammetric model. The basin-margin Corniola Fm onlaps the pre-rift “Calcare Massiccio”, as well as the “Calcare Massiccio B” and the Lotharingian epi-escarpment deposits, burying a peculiar Sinemurian-Pliensbachian depositional architecture. These onlapping deposits caused the intense and pervasive silicification of the pre-rift “Calcare Massiccio” and of the epi-escarpment deposits. Notably, silicification affected a complex network of fractures affecting the horst-block “Calcare Massiccio”, freezing rift-related brittle deformations (Fig. 3C, 3D).

Significant details of the outcrop, such as the

silica nodules and the fossils, are rendered in the 3D reconstruction (Fig. 6). Silicification of the Calcare Massiccio, a field evidence neglected for a long-time, has proved to be a crucial evidence for recognising palaeoescarpments in the field, i.e. to identify the onlap contact of the cherty basinal formations on the footwall blocks of the horst and graben systems (Galluzzo and Santantonio, 2002; Santantonio et al., 2017). Similarly, such evidence may be a good indicator of olistoliths embedded in the basinal succession, with information on margin stability at a precise geological time, and identification of possible tectonic phases (Di Francesco et al., 2010; Fabbi, 2015; Cipriani, 2016).

5. DISCUSSION AND CONCLUSIONS

The present contribution on a peculiar depositional setting of the UMS Domain enforces the importance of photogrammetric models application in geology *sensu lato*. First, these models provide a great contribution in the outcrop visualisation, allowing to identify and highlight the geometry of rocky bodies, their structures and sedimentological features. In addition, the photogrammetric method allows a more objective communication of both starting raw data and of particular interpretation provided by authors. The geological subject can be represented both in its original conditions observable in the field, and as interpreted model, in order to keep always well-separated the original data from the interpretation by geologists. The integration of the reconstructed 3D models with the classical field-work observations may represent a crucial support for the correct interpretation of sedimentary structures, and of geometric relationships between sedimentary bodies.

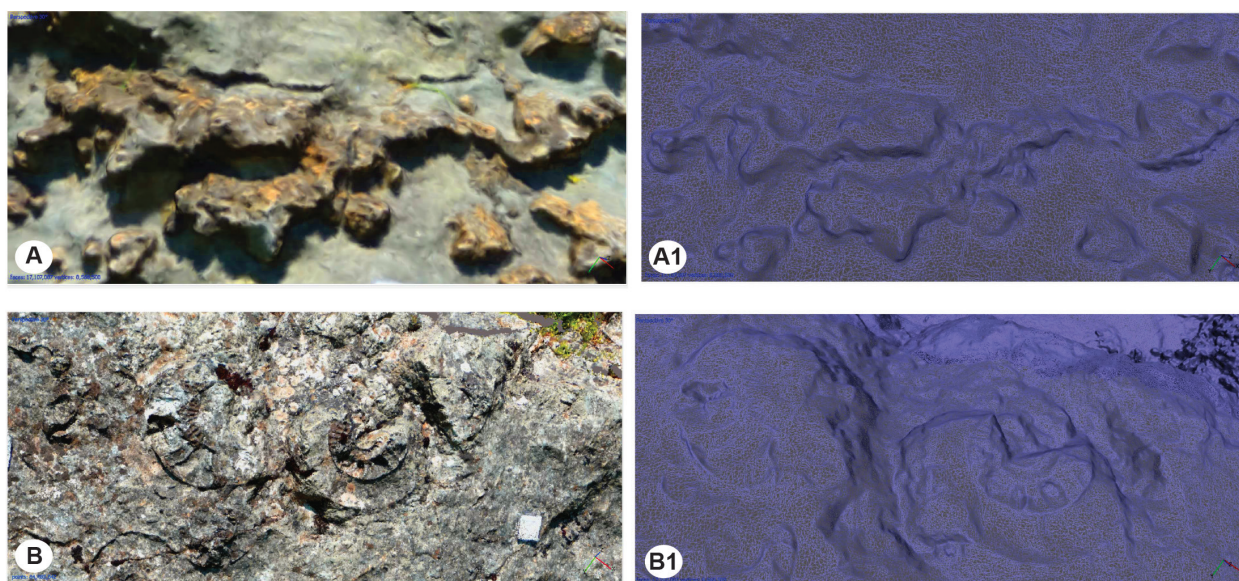


Fig. 6 - Significant details of the outcrop very well-rendered by the reconstructed 3D model; silicified palaeo-surface of pre-rift “Calcare Massiccio” and ammonites from the epi-escarpment deposits made of condensed Corniola-type facies as textured meshes (A, B) and solid models (A1, B1).

In addition, high-resolution Digital Photogrammetry allows to preserve a virtual model of crucial and paradigmatic geological sites. This is particularly important for the Gorgo a Cerbara palaeoescarpment, an important outcrop also from the historical point of view. It was indeed one of the first areas where the stratigraphic contact between the basin succession and the horst-block “Calcare Massiccio”, along unconformity surfaces (i.e. palaeoescarpments), was in fact observed and recognised in XIX century. A complex outcrop that, because of its topographic and exposition conditions, can be subject to rapid geomorphological evolution and to various kinds and grade of damage, including anthropic intervention. The lower boundary of the outcrop is in fact lapped by the Candigliano river, which leads to progressive erosion especially in the area where the basinal Corniola Fm overlies the epi-escarpment deposits (Fig. 3A). It is also worth remembering that the Gorgo a Cerbara outcrop is close to an active quarry. Recently, widening of the excavation face moved towards the study outcrop; several volumes of rocks, resulting from the enlargement of the quarry, fell along the steep slopes of the Candigliano valley. These anthropic-derived debris aprons have partially covered the analysed portion of the palaeoescarpment, hiding most of the stratigraphic and sedimentological peculiarities showed in this work (Fig. 7). Additional potential sources of damage for the site are: i) the vegetation cover, due to the destructive action over time of humic acids and roots; ii) the effect of cryoclastism; iii) karstification; iv) possible rockfall processes.

In conclusion, the use of photogrammetry has allowed the construction of a highly resolved 3D model, where individual geological units can be highlighted to improve the outcrop visualisation and to make difficult sedimentological settings easier to analyse and interpret. In addition, often a detailed photogrammetric model can highlight some aspects not noticed initially in the

field, that push the researchers to come back to the field to re-analyse the outcrops with different eyes; the new observations in turn lead to a subsequent improvement in the interpretation of the model itself, thus in a virtuous circle of “reciprocal illumination” with exchange of information in both directions.

High-resolution photogrammetric techniques further proven to be the most low-cost/high-performance tool for modelling and visualising in the field of geology *sensu lato*. Photogrammetry is used to construct wide-ranging three- and four-dimensional models rooted on fieldwork, for visualisation of geological inferences and reconstructions as well. However, we would like to stress how photogrammetry, and in general 3D modelling in geology, cannot and must never replace the work and direct analysis of the geologist in the field, but must remain simply a supporting tool for the regular and irreplaceable field operations and survey.

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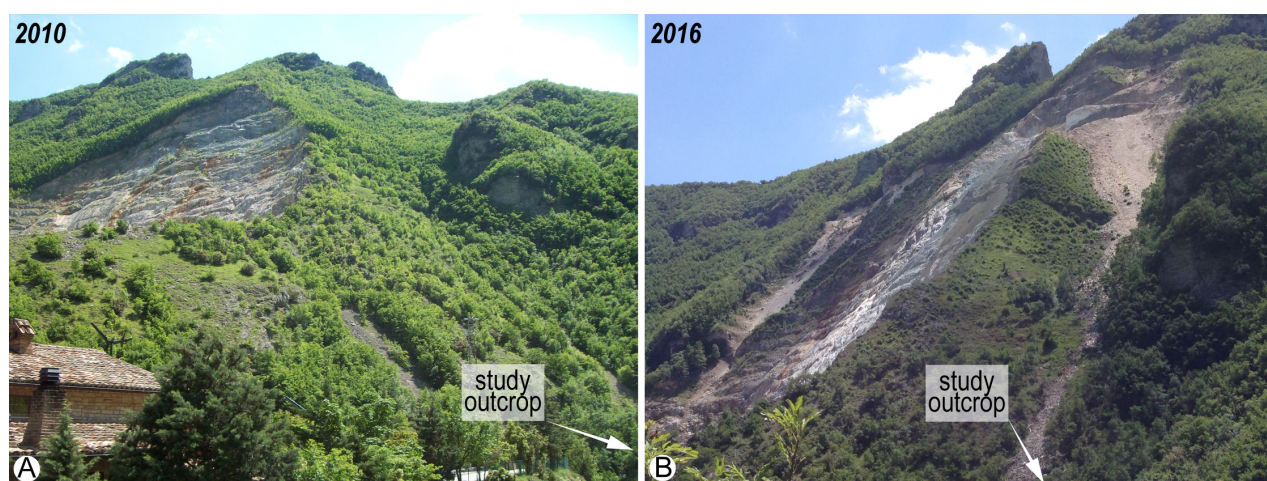


Fig. 7 - Panoramic view of the Gorgo a Cerbara palaeoescarpment site, showing anthropic-derived debris apron from the active quarry that in the last few years have partially covered the analysed tract of the palaeoescarpment, hiding most of the stratigraphic and sedimentological peculiarities showed in this work. A) Condition of the outcrop in 2010; B) condition of the outcrop in 2016, showing several volumes of rocks that fell along the steep slopes, resulting from an enlargement of the quarry.

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