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The Mesozoic palaeoenvironmental richness of the Trieste Karst

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Pre congress Field Trip N. 4

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The Mesozoic palaeoenvironmental richness of the Trieste Karst

90° Congresso della Società Geologica Italiana - Trieste, 14-16 settembre 2021. Pre congress Field Trip N. 4

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Cover page Figure: *Tethyshadros insularis* "Antonio", holotype, specimen number SP 57021.

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Abstract

The Mesozoic of the Trieste Karst is part of the 90th Congress of the Italian Geological Society, Trieste Italy, 2021. The guide aims at documenting selected outcrops located on the Karst plateau where fossil richness is related to particular carbonate platform facies associations to highlight the area as an important archive for marine and continental palaeodiversity. The Trieste Natural History Museum holds the most important collection of Late Cretaceous fossils, including exceptionally preserved dinosaurs (*Tethyshadros insularis*), reptiles, land plants, crustaceans, and fishes of the Villaggio del Pescatore geosite. At the Villaggio del Pescatore geosite fossil-rich carbonate rhythmites are spectacularly exposed on quarried surfaces. At Cava Romana it is possible to observe the Upper Cretaceous rudist-rich platform facies of the "Aurisina limestone". The Slivia quarry exposes a Cretaceous palaeokarst deposit made of large limestone blocks. The Cenomanian peritidal carbonate succession of the Moschenizza hill shows m-thick rudist limestone beds, and cm-thick dark-coloured, muddy wackestones sporadically rich in fossil land plants like *Frenelopsis*.

Key words
Upper Cretaceous, shallow-water carbonates, limestone breccia, rhythmites, foraminifera, dinosaurs, rudist, paralic environments.

Program summary

This one-day trip is the fourth (FT4) of a series of geological field trips of the 90th Congress of the Italian Geological Society in Trieste, Italy, in 2021. It focuses on some key localities of the Mesozoic succession exposed in the so-called "Trieste Karst". In this area, a thick pile of shallow-water carbonates records the late Early – Late Cretaceous evolution of the northwestern portion of the Friuli carbonate platform. Abrupt facies changes and a diverse fossil assemblage testify for palaeoenvironmental changes in an area subject to complex interactions between tectonics and base-level oscillations. The location of the described stops is shown in Fig. 1. The first stop will be at the Trieste Natural History Museum (Museo Civico di Storia Naturale) where a rich collection of Mesozoic fossils from Karst includes two exquisitely preserved individuals of the hadrosauroid *Tethyshadros insularis* (Dalla Vecchia, 2009) - nicknamed "Antonio" (SC 57021, holotype) and "Bruno" (SC 57247) are on display.

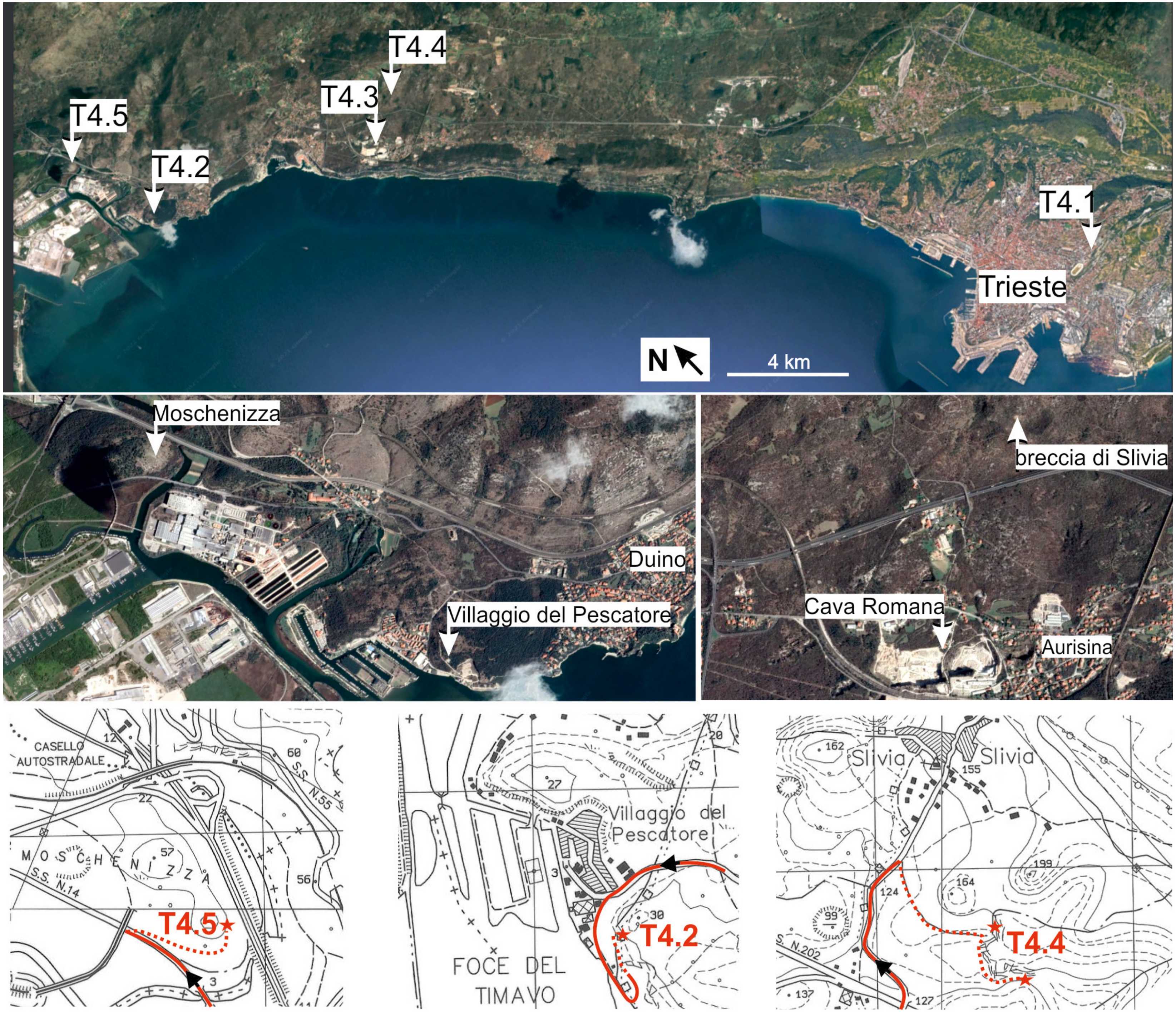

Fig.1 - Itinerary map of the excursion (satellite images taken from Google Earth).

The second stop will be at the Villaggio del Pescatore geosite (Duino-Aurisina, Trieste). At the geosite, breccias and rhythmites are superbly exposed along quarried surfaces. From these Upper Cretaceous carbonates, dinosaur, crocodilians and other vertebrate and invertebrate fossil remains were collected. The Cava Romana site (third stop) exposes the "Aurisina limestone" facies, Campanian in age, characterised by several, magnificent rudist lithosomes alternated to thick bioclastic beds represented by packstone/grainstone.
The fourth stop will be at the Slivia abandoned quarry. At the site, quarry walls expose a breccia made up of disorganised limestone blocks interpreted as related to an extensive palaeokarst system.
The fifth and last stop will be on the eastern slope of the Moschenizza hill, where a Cenomanian, peritidal carbonate succession displays an alternation of m-thick rudist floatstones, coarse-grained limestones (grainstone/packstone), and cm-thick dark-coloured, muddy, nodular, or laminated wackestones, occasionally rich in fossil land plants like *Frenelopsis*, interpreted as deposited in a paralic environment.

Safety and logistic information

Hiking shoes are required for stops at Cava Romana, Slivia quarry, and Moschenizza hill. Participants are strongly recommended to not get close to the quarry steps used for wedging. Helmets are mandatory for entering Cava Romana. Ticks may carry both Lyme disease and TBE (tick-borne encephalitis), especially during spring and summer, therefore it is highly recommended to use repellent and to wear long trousers. The mobile telephone network constantly operates; note that nearby to the national border the network may switch from the Italian to the Slovenian provider. Roaming should be "on" if a connection is required.

Hospitals

Cattinara Hospital (Trieste): Strada di Fiume 447, 34149 Trieste (TS), tel. +39 040 399 1111
Gorizia Hospital: Via Fatebenefratelli 34, 34170 Gorizia (GO), tel. +39 0481 592315
Emergency call: 112 (Ambulance, Police, Fire department, Mountain rescue)

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Accommodations

Trieste and the adjacent coast offer plenty of accommodation solutions. Information can be found on the website of the Tourist Office of the Friuli Venezia Giulia website (https://www.turismofvg.it/home).

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Geological and stratigraphic overview of the Karst carbonate succession

The Karst is a low plateau mainly made of carbonate lithologies which fall in part in Italian, and in part in Slovenian territory. The name Karst ("Kras" in Slovenian; "Carso Classico" in Italian) is commonly used to indicate a particular landscape or geomorphology resulting from surface and underground dissolution processes (karstification). The backbone of the Karst plateau, studied since the '800 (von Morlot 1848; Stache, 1889; Martinis, 1962), is composed of a thick succession of Mesozoic, Palaeocene, and lower Eocene limestone, dolostone, and breccia, followed by a middle Eocene (Lutetian) siliciclastic succession of flysch (Figs. 2, 3) with sporadic large carbonate olistoliths. This succession accumulated in the northern part of a large palaeogeographic element called Adriatic Carbonate Platform (AdCP *sensu* Vlahović et al., 2005), that extended from the present-day western Balkans to northeastern Italy and developed at the proximal passive margin of the Adria microplate since the Late Triassic. The Karst area corresponds to the so-called Friuli Platform, i.e., the northwestern limb of the AdCP that, during the Cretaceous, was bordered by the Slovenian Basin to the northeast and by the Belluno Basin to the west. All the localities that will be visited in this field trip occupied an internal portion of the Friuli Platform whose margin was to the northwest (e.g., Val Cellina area). The Cretaceous succession is dominated by shallow-water carbonates, with subordinate facies represented by fossiliferous hemipelagic limestone (e.g., Komen limestone, Palci et al., 2008) or by very proximal transitional paralic, sometimes dolomitised, carbonate deposits. There is evidence of multiple subaerial short exposures or longer exposures recorded by palaeokarst features throughout the succession. This indicates that the platform emerged repeatedly under the combined influence of tectonics and sea-level oscillations (Otoničar, 2007).
The Karst area is at the northern tip of the Adriatic plate, which underwent Permian-Mesozoic rifting and was later shortened by three orogenic belts (i.e., Apennines, Alps and Dinarides). Those belts developed three subduction zones associated with thrusts involving the Meso-Cenozoic carbonate successions (e.g. Sani et al., 2016; Cardello et al., 2019, 2021). The structural setting of the Karst is the result of the interplay of the Dinaric and Alpine tectonic phases. The Dinaric phase is testified by structural features indicating a general thrusting direction toward the southwest. Fore-bulging started in the Late Cretaceous and continued through the Palaeocene (Otoničar, 2007). The middle Eocene flysch testifies to the development of a foredeep setting associated with the growth of the Dinaric orogen (Otoničar, 2007). Subsequently, in the Neogene, the Karst was involved in the Alpine phase with NNW – SSE direction of shortening.

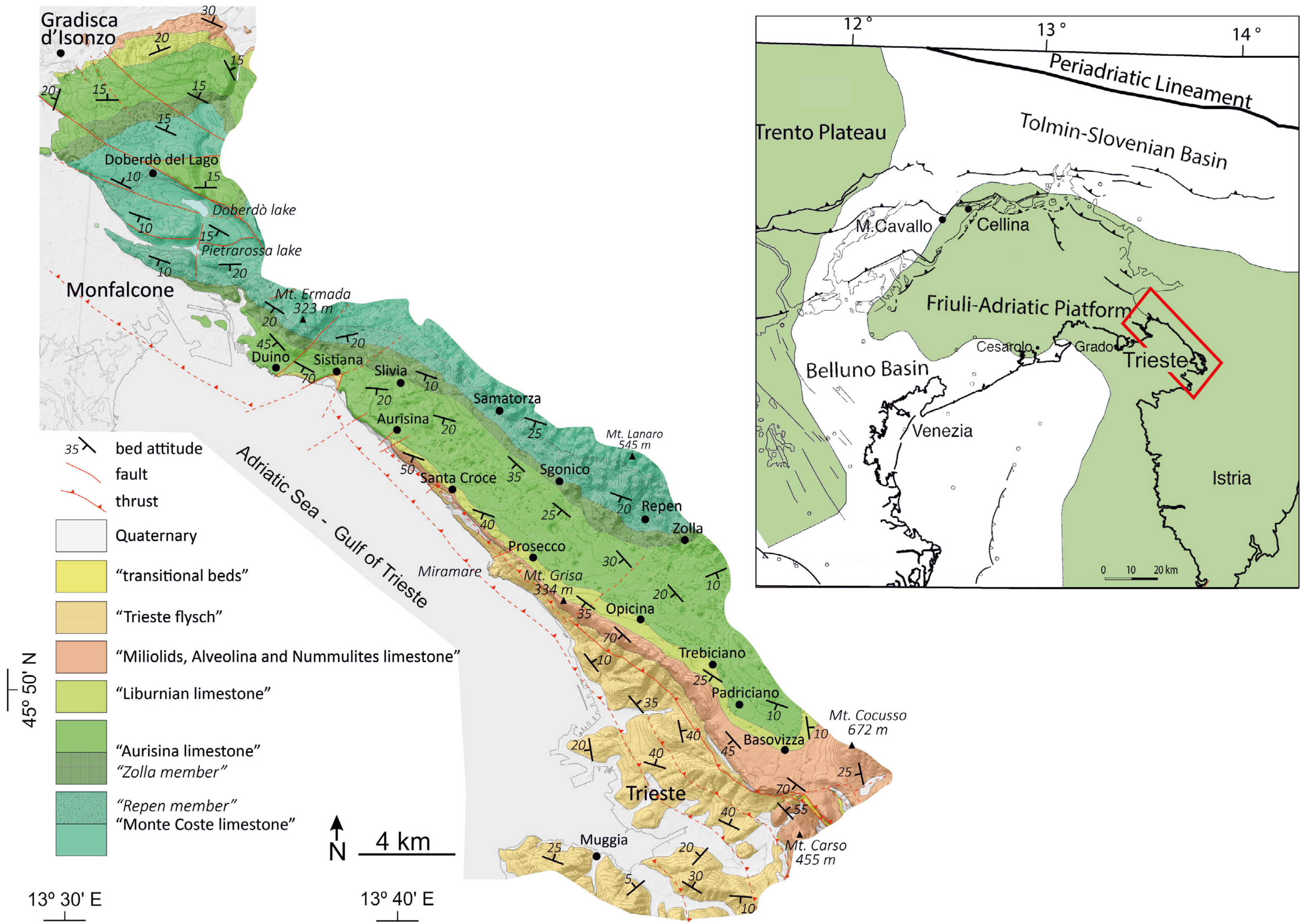
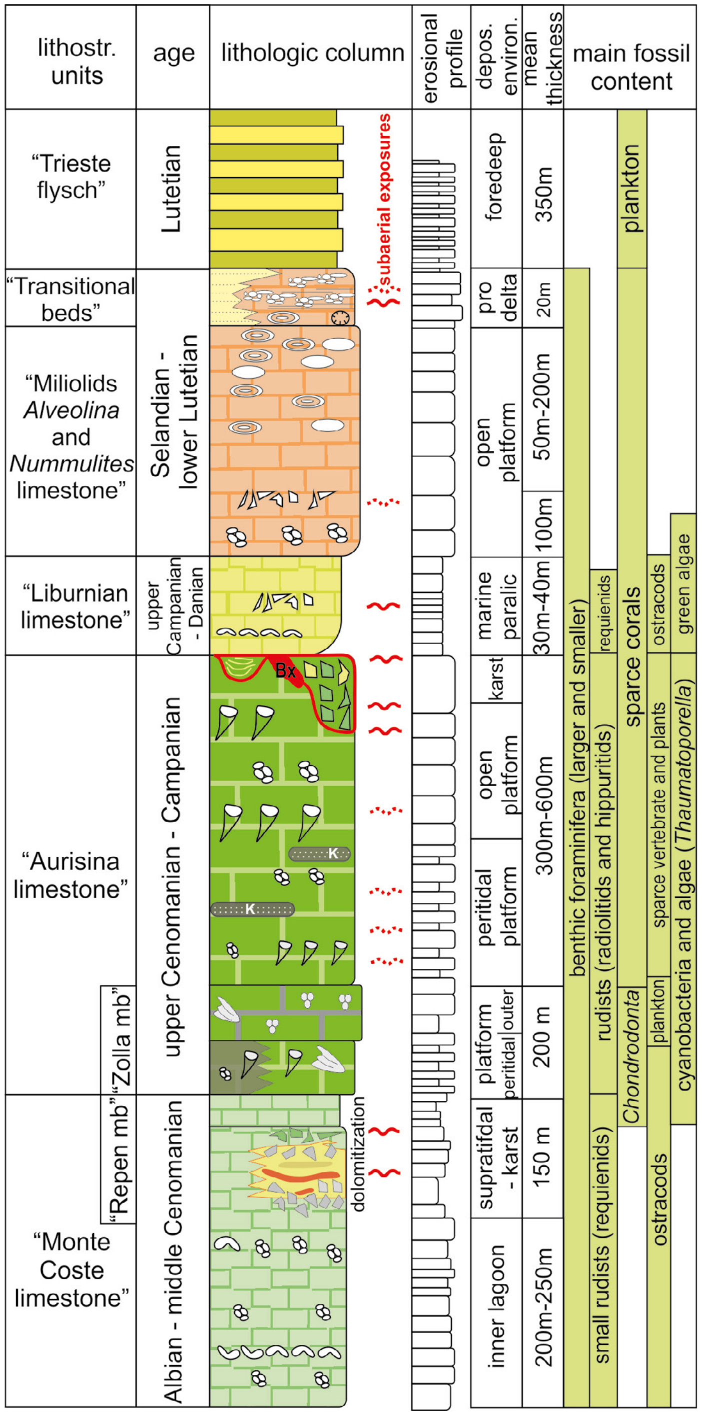


Fig. 2 - Geological map of the Italian Karst (simplified from Jurkovšek et al., 2016; the contour lines of base topographic map are 25 m spaced) and Cretaceous palaeogeographic map (modified from Picotti et al., 2019). Lithostratigraphic names under quotation marks highlights their non-standardized usage.



The lithostratigraphic succession of the Karst area is about 1500 m thick. Some authors informally subdivided it into members only (Cucchi et al., 1987), whereas others have proposed the usage of formations as well (Tentor et al., 1994; Cucchi and Piano, 2013; Jurkovšek et al., 2016). In this section, we adopt a simplified subdivision highlighting the most important lithofacies associations cropping out throughout the Karst and using the most common informal names suggested in the literature. The ranking herein adopted differs in some parts from the proposal of previous workers and includes informal non-standardised units such as formations and members. Based on their field characters, they also correspond to well representative rocky packs eligible for a possible formal definition.

"Monte Coste limestone". (*cfr*. "Povir formation" of Jurkovšek et al., 2016; "calcari di Monte Coste" of Cucchi and Piano, 2013; "Monte Coste member" and "Rupingrande member" of Cucchi et al., 1987). It represents the oldest unit in the area (Cucchi et al., 1987) and possibly corresponds to the formally defined Calcare del Cellina, a formation outcropping to the northwest nearby the borders with the Veneto region (Tentor et al., 1994; Carulli, 2006). It is mainly composed of thick-bedded or finely laminated dark-brown wackestones with miliolids, ostracods, small rudists (requienids), and stromatoporoids that alternate with thin intraclastic breccias or peloidal-miliolid grainstone layers (Figs. 4A, C, H and 8B-D). Wackestone facies are also occasionally enriched by spotted halite or other evaporite minerals (Fig. 8A). The upper part of "Monte Coste limestone" is made of thick (up to 100 m) dolomitised beds represented by breccias and peritidal carbonates intercalated, in

Fig. 3 - Simplified log of the lithostratigraphic units cropping out through the Karst (not to scale). Lithostratigraphic names under quotation marks highlights their non-standardized usage.

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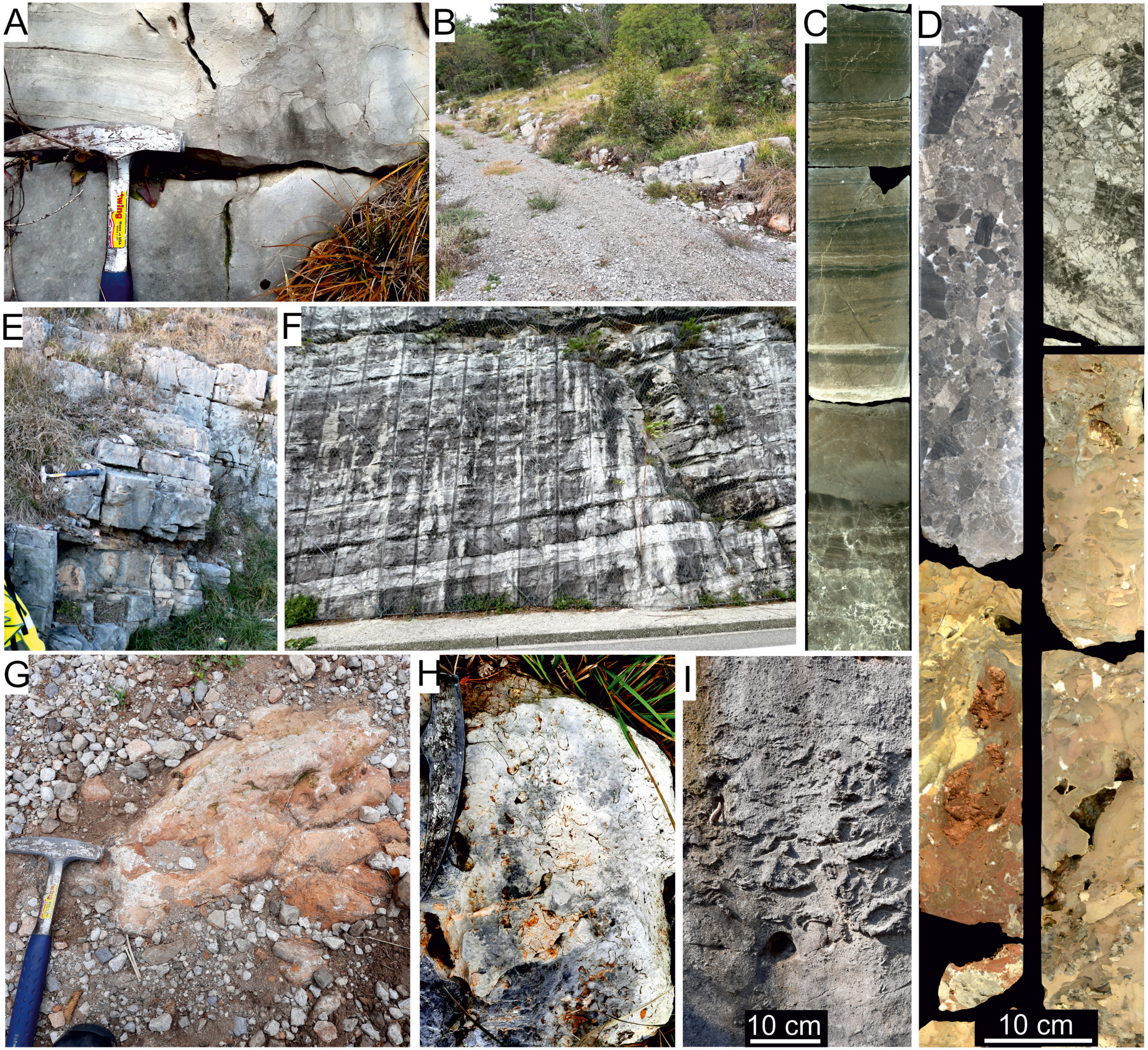
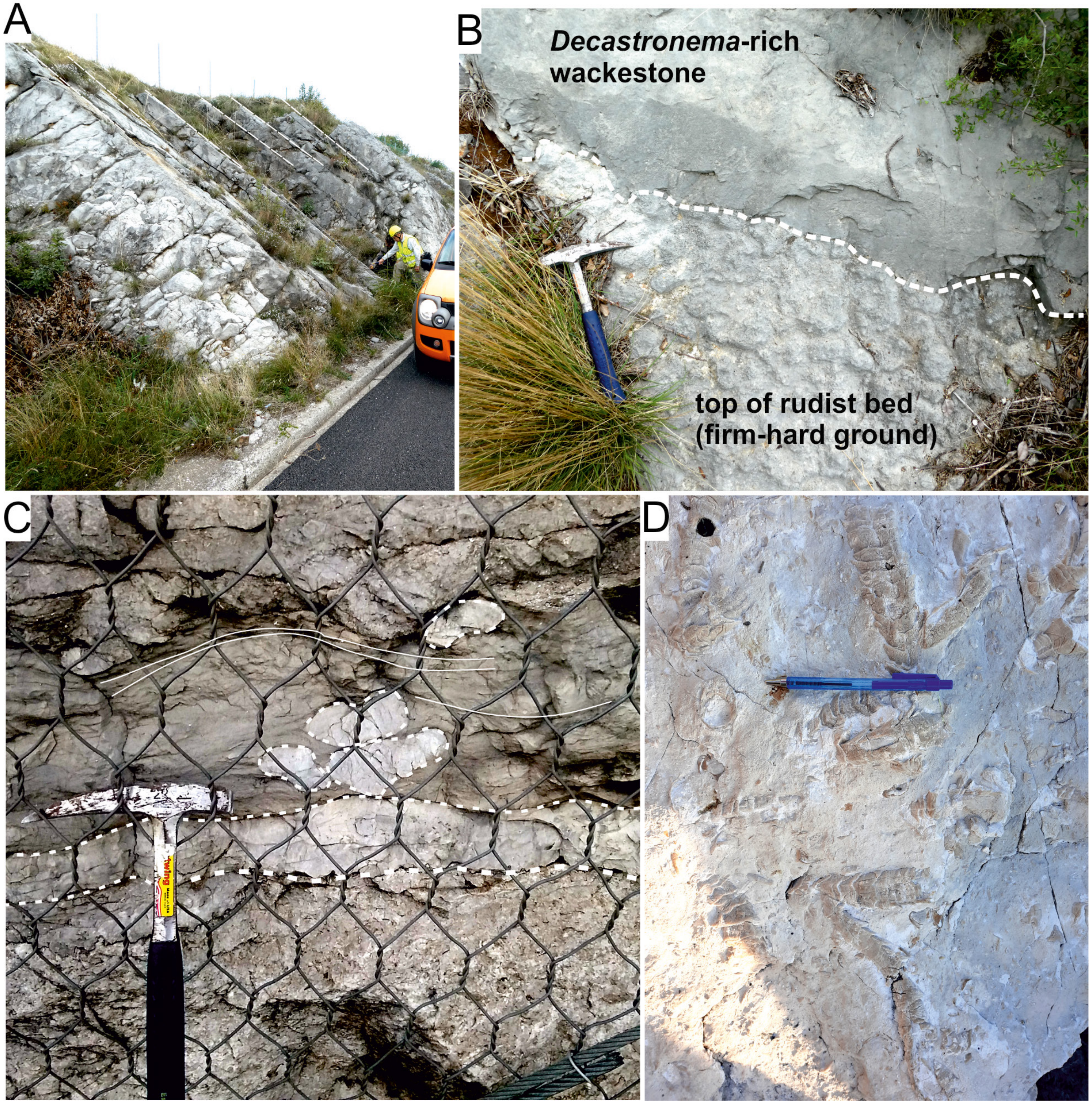


Fig. 4 - Field details and cores of the “Monte Coste limestone” (A-D, G, H) and “Aurisina limestone” (E-F, I). A) Laminated facies and intraclastic breccia. B) outcrops at Samatorza. C) Core logging showing finely laminated facies of the “Monte Coste limestone”. See D for scale. D) Core logging at Medeazza passing through dolomitised breccias, emersion levels and dolomitised beige fine-grained deposits of the “Repen member”. E, F) Peritidal stratification of “Aurisina limestone” at Devetachi (E), Lisert (F). G) Reddish dolomitised facies of the “Repen member”. H) Requienids-rich level of the “Monte Coste limestone”. I) Rudist-rich levels (Cenomanian) of the “Zolla member”.

some areas, to red-yellowish dolomitic siltstones and dolomitic breccias, possibly indicating a palaeokarst system (Fig. 4D, G). This interval is here considered as the "Repen member" or "Rupingrande member" by the Italian toponymal adopted in Cucchi et al. (1987). It extensively crops out in the southeastern sector of the Karst area (Fig. 2), whereas it tapers towards the northwestern part. The "Monte Coste limestone" represents a low energy lagoon environment characterised by local shoal bars, influenced by tides, and characterised by high rates of evaporation and supratidal deposits. The age range is Albian to Cenomanian *p.p*. Outcrops of the "Monte Coste limestone" can be observed on the roads and paths that lead to the Italy-Slovenia borders from the villages of Sales or Samatorza (Fig. 4B).

"Aurisina limestone". (*cfr*. "Repen formation", "Sežana formation" and "Lipiza formation" of Jurkovšek et al., 2016; "formazione di Monrupino" and "calcari di Aurisina" of Cucchi and Piano, 2013; "Zolla member" and "Borgo Grotta Gigante member" of Cucchi et al., 1987; "Rudisten-Breccen kalk" and "Repener strandkalk" of Stache, 1889). The unit may correspond to the "calcari di Monte Cavallo", a formation that is found in the northwestern Friuli region (Carulli, 2006). Its most notable feature in the field is the occurrence of large bivalves like *Chondrodonta*, and rudists that are present throughout the unit (lower and upper part, respectively). The lower portion is characterised by an interval here indicated as "Zolla member" (or "Col member" by adopting the most commonly used Slovenian toponymal) that is roughly equivalent to "Monrupino formation" (Tentor et al, 1994) or "formazione di Monrupino" (Cucchi and Piano, 2013). It is represented by: i) bivalve (rudists and *Chondrodonta*)-foraminiferal limestone associated with or intercalated to dolomitised/laminated dark wackestones (Figs. 4F, I and 5C) in its lower portion; ii) pelagic detrital limestone with *Pithonella* (Melis et al., 2000; see Fig. 8G) in its upper portion. Above the "Zolla member", the "Aurisina limestone" is mainly made of peritidal carbonates in which rudists, benthic foraminifera, cyanobacteria (*Decastronema* spp.), and algae (*Thaumatoporella* spp.) dominate (Figs. 4E; 5A, D and 8E, F, H). In places, these peritidal cycles are composed of an alternation of thick rudist limestone beds (mostly floatstone texture) with thin layers of *Decastronema* and *Thaumatoporella* wackestones (Fig. 5B). Locally, lenses of dark laminated facies rich in vertebrate fossils are found (e.g., Polazzo fishes; Dalla Vecchia and Tentor, 2004). The "Aurisina limestone" was deposited between the late Cenomanian and the early Campanian and represents a carbonate platform with low-energy inner lagoons, high energy shoals, tidal channels, and rudist accumulations, locally intercalated with limestone breccia by ephemeral emersions. At the top of the unit, collapse breccia (e.g., Slivia) with bauxite accumulations indicate longer emersion episodes accompanied by the development of a palaeokarst system (Fig. 6B, C). Several magnificent and well-preserved rudists from the "Aurisina limestone" are visible on breakwater blocks of the seafront of Miramare (Fig. 5D),



walking alongside Barcola harbour to the Miramare castle.

"Liburnian limestone". (*cfr*. "Liburnia formation" of Jurkovšek et al., 2016; "formazione Liburnica" *p.p.* of Cucchi and Piano, 2013; "Monte Grisa member" of Cucchi et al., 1987; "Liburnishe stufe" *p.p.* of Stache, 1889). It is mostly composed of dark-grey wackestone-mudstone with benthic foraminifera (Miliolidae, Discorbidae, and rhapydioninids such as *Rhapydionina liburnica* (Stache) and *Murciella cuvillieri* Fourcade), ostracods, sporadic charophyte oogonids and dasycladaceans green algae (Fig. 8I), organized in decimetre-

Fig. 5 - Field details of the "Aurisina limestone". A) Peritidal stratification at Sistiana, highway RA13. B) *Decastronema* facies lying on top of a rudist bed (Sistiana RA13). C) Laminated paralic muddy limestone layer bearing pebbles of whitish limestone ("Zolla member": Moschenizza hill at Lisert road cut). D) Rudists in a breakwater block at Miramare.

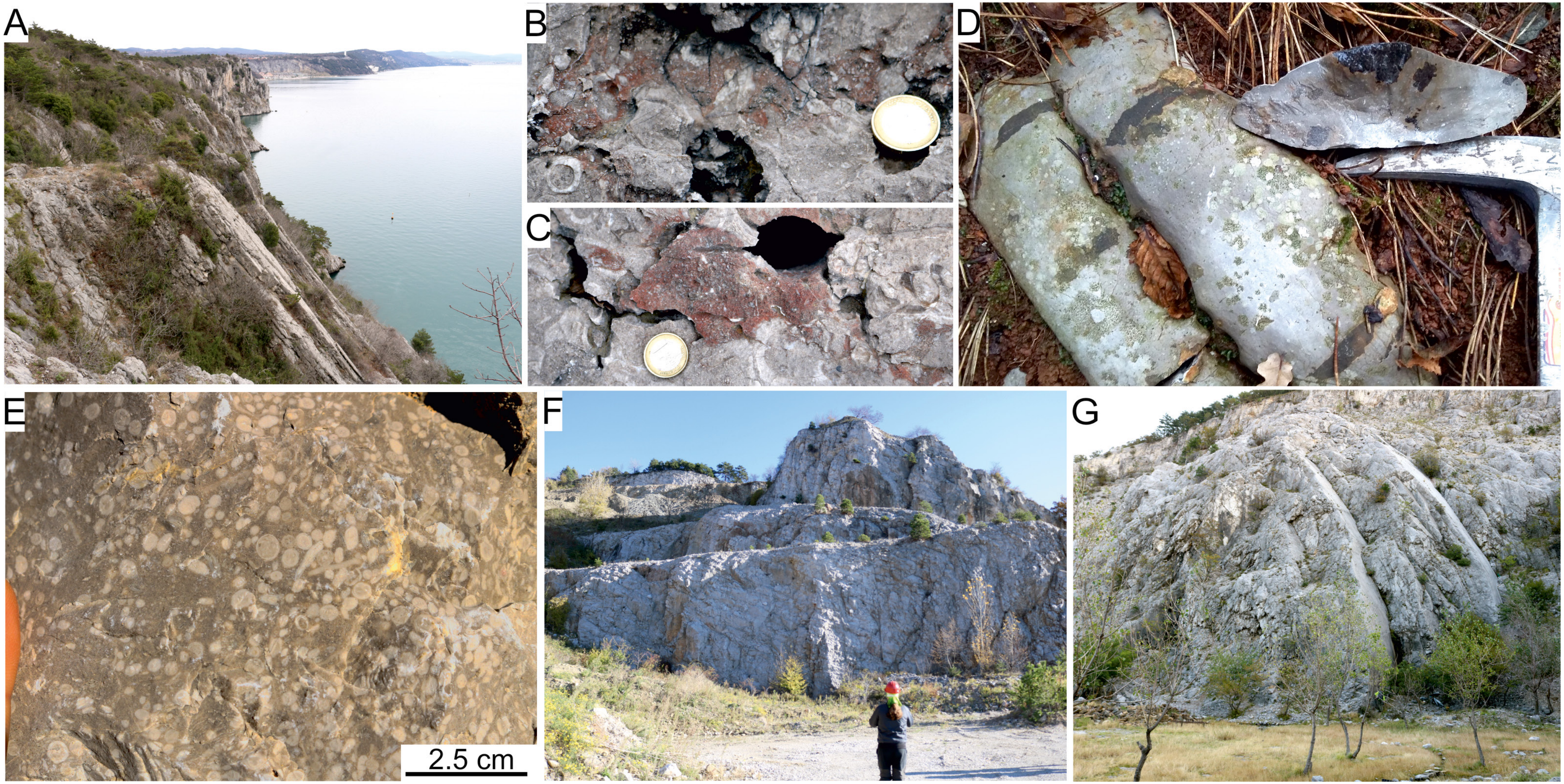


Fig. 6 - Field details of the "Liburnian limestone" and "Miliolid, *Alveolina*, and *Nummulites* limestone". A) Sub-vertical and vertical strata of the "Liburnian limestone" at Rilke trackway. B, C) Palaeokarst interesting the top of "Aurisina limestone" at Rilke trackway. D) Gray wackestone with dark intraclasts of the "Liburnian limestone" at Cotici. E, F, G) *Alveolina*-rich limestone (E) and outcrops (F, G) of the "Miliolid, *Alveolina* and *Nummulites* limestone" at Val Rosandra.

thick layers or thin laminated beds. Few beds host sparse rudists (requienids) and gastropods, whereas the entire succession displays signs of ephemeral subaerial exposures indicated by rhizolite marks, *Microcodium* (Fig. 8J) or thin reddish layers, sometimes associated with dark muddy intraclasts (Fig. 6D). The "Liburnian limestone" mostly represents a paralic environment characterised by restricted fresh-marine water circulation. The unit, whose age ranges from the mid-Campanian to the Danian, is one of the few shallow-water successions yielding the Cretaceous-Palaeocene boundary (Gregorič et al., 1998; Ogorelec et al., 2007; Tewari et al., 2007). Representative outcrops of the "Liburnian limestone" occur along the road cut nearby the AREA Science Park at Padriciano, at Rilke trackway (between Sistiana and Duino) (Fig. 6A), and in the vicinities of Cotici village (see Venturini et al., 2008).

"Miliolid, *Alveolina* and *Nummulites* limestone". (*cfr*. "Alveolinid-Nummulitid limestone" of Jurkovšek et al., 2016; "formazione Liburnica" *p.p.* and "calcari ad Alveoline e Nummuliti" of Cucchi and Piano, 2013; "Opicina member" of Cucchi et al., 1987; "Hauptalveolinen und Nummulitenkalk" of Stache, 1889). The unit is easily identifiable in the field thanks to the presence of diverse larger and smaller benthic foraminifera, along with red algae and sparse solitary corals. It is made of thick layers, sometimes massive or poorly stratified (Fig. 6F, G), packstone-grainstone and, subordinately, wackestone entirely composed by clasts of biogenic origin produced in a shallow-platform setting within the photic zone. Thin beds of dark-grey laminated wackestone may locally occur within. The most common, easily visible, larger foraminifera genera are *Coskinolina*, *Fallotella*, *Lacazina*, *Alveolina*, *Nummulites,* and *Orbitolites* (see e.g. Figs. 6E and 8K-N). The Palaeocene part of the unit, included in the underlying "Liburnian limestone" by previous authors (Bignot, 1972; Cucchi and Piano, 2013), is Selandian to Thanetian in age (Shallow Benthic Zones 2-5; Drobne et al., 2009), whereas the rest spans into the Ypresian and lower Lutetian (Shallow Benthic Zones 6-12; Drobne et al., 2009). Based on field observations the thickness of this unit may varies depending on the locality. Nice *Lacazina* and *Fallotella* are easily visible close to the parking area of Globojner Park (Padriciano). *Alveolina* and *Nummulites* accumulations can be observed walking through the Napoleonica trackway, from the Opicina obelisk to the Monte Grisa sanctuary.

"Transitional beds". (*cfr*. "Transitional beds" of Jurkovšek et al., 2016). This unit is composed of beds with a variable thickness made up of beige marls, glauconitic grainstone with planktonic foraminifera, and pockets of limestone pebbles reworked from the underlying Eocene succession, including large *Nummulites*, small clay pebbles, and corals. The vertical arrangement of these lithofacies may change depending on the location; in some places, limestone pebbles lay on the previous Eocene unit (Fig. 7A-C). The "transitional beds" testify to the onset of clastic deposition in the area following the drowning of the Eocene carbonate platform and can be referred to as an upper prodelta system (Tarlao et al., 2005). Being mostly influenced by the propagation of the Dinaric front, the age of this unit varies from the middle Ypresian (Jurkovsek et al., 2016) to the early Lutetian (Tarlao et al., 2005). The "Transitional beds" have a patchy distribution; representative outcrops are concentrated in Val

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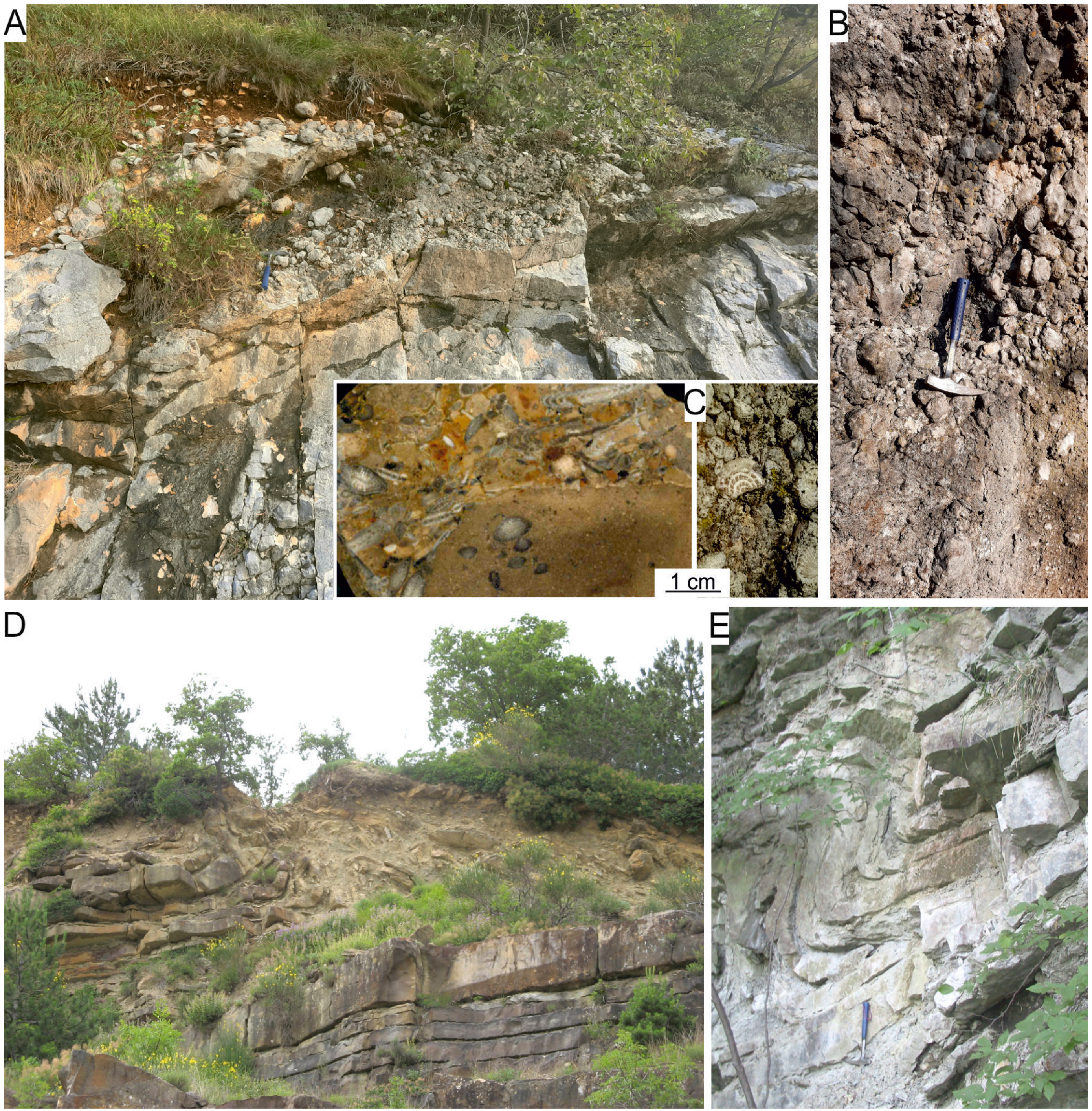

Rosandra, whereas the occurrence of limestone pebbles can be observed in front of the SISSA (International School for Advanced Studies) entrance (Fig. 7A), or along the Friuli Road (Strada del Friuli) near Prosecco (Fig. 7B).

"Trieste flysch". (*cfr*. "Flysch" of Jurkovšek et al., 2016; "Flysch di Trieste" of Cucchi and Piano, 2013). The unit includes a succession of sandstone, siltstone, and claystone, barely arranged in fining upward cycles (Fig. 7D, E). Layering is generally thinly bedded (cm), while sandstone layers can be few metres thick. The rocks are almost entirely composed of siliciclastic material with very few amounts of carbonates and could be referred to a lobate distal turbiditic system (Cucchi and Piano, 2013). The palaeontological content includes planktonic foraminifera

Fig. 7 - A, B, C) Limestone pebbles ("transitional beds") lying on top of the Eocene limestone. The pebbles also carry large flat *Nummulites*. D, E) Field aspects of the "Trieste flysch" (photos: courtesy of Sara Bensi).

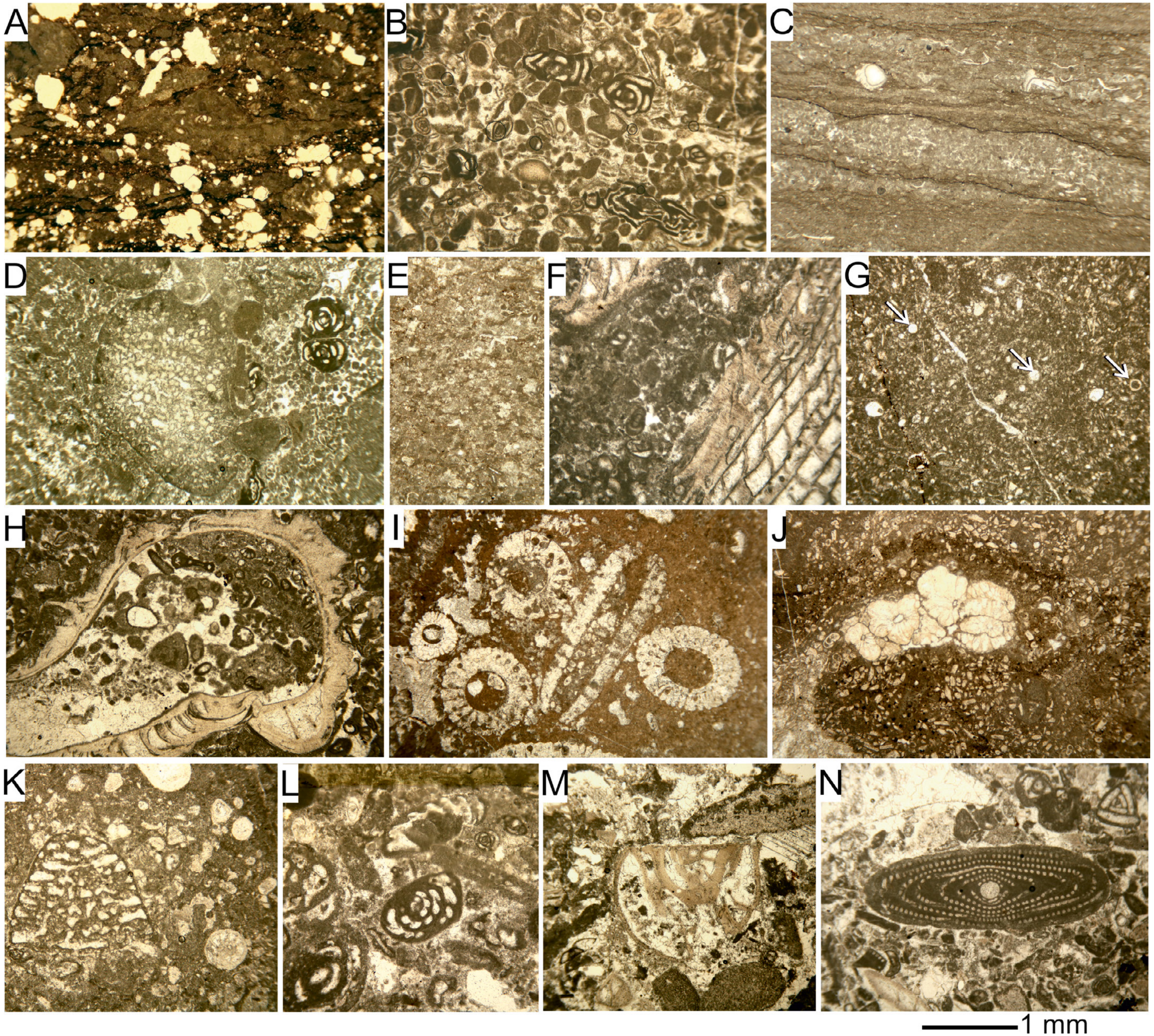

Fig. 8 - Facies examples of "Monte Coste limestone" (A-D); "Aurisina limestone" (E-H); "Liburnian limestone" (I, J); "Miliolid, *Alveolina* and *Nummulites* limestone" (K-N). A) Wackestone with halite crystals. B) Peloids and miliolids packstone-grainstone. C) Laminated wackestone with ostracods. D) Stromatoporoids? and miliolids packstone. E) *Decastronema*-rich wackestone. F, H) Rudist floatstone. G) *Pithonella*-rich (arrows) wackestone. I) Green algae (*Cymopolia*) wackestone. J) Wackestone rich in discorbids showing huge amount of *Microcodium*. K) Wackestone-packstone with *Coskinolina* and rotaliids. L) Packstone with *Hottingerina.* M) Packstone-grainstone with *Gyroidinella*. N) Grainstone with *Alveolina*.

and calcareous nannoplankton of, at least, the NP14 to NP16, suggesting that the deposition took place during the Lutetian (Bensi et al., 2007), up to the Bartonian (Cucchi and Piano, 2013). At the Miramare castle park, several metric olistoliths made up of Eocene platform carbonates occur embedded into the flysch (Tonelli, 2001). This would suggest the establishment of an articulated and instable palaeotopography at the basin edge at some point during the deposition of the Trieste flysch.

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STOP T4.1. Trieste Museum of Natural History and the fossils of the Villaggio del Pescatore geosite
Coordinates: 45°38'24.0"N - 13°48'02.4"E

Topics: Vertebrate fossil and plant remains from the Karst area, naturalistic museum.

The Natural History Museum of Trieste was established in 1846 with the original name of "Gabinetto zoologico-zootomico", upon the private initiative of some citizens. It became a civic institution in 1852 and in 1856 it was named "Civico Museo Ferdinando Massimiliano" in honour of the Archduke of Austria Ferdinand Maximillian. In 2008 the Museum moved from its historical site to its new location, the former Duca delle Puglie barracks, on the outskirts of the city. Over time, the museum collections have been enriched by botany, mineralogy, zoology, and palaeontology specimens and by an important scientific library.

The fossils collection is mainly representative of the Karst and Istria areas, and it is subdivided into historical collections and more recently acquired specimens. The most important collection is certainly represented by the Cretaceous fossils from the Villaggio del Pescatore site (VdP; at Duino-Aurisina Municipality, near Trieste) (Figs. 9, 10). The site was discovered at the end of the 1980's by Alceo Tarlao and Giorgio Rimoli and rapidly became popular primarily because of a new genus of dinosaur, *Tethyshadros insularis* (Dalla Vecchia, 2009; nicknamed "*Antonio*", specimen number SC 57021), which was first found by Tiziana Brazzati in 1994, excavated between 1998-99, and then presented to the public for the first time in December 2000 (Arbulla, 2017). The exquisitely preserved skeleton represents one of the most complete and best-preserved dinosaurs in Europe. A second individual of *Tethyshadros*, called "*Bruno*" (specimen number SC 57247), was discovered in 1999. Its skull was collected in November 2018 and its tail in July 2019. "Bruno" (SC 57247) is preserved on a fold that resulted in a plastic deformation of the axial skeleton. The tail forms a 180° angle with respect to the dorsal vertebrae and its distal part is further bended along a second fold. When compared with the holotype, this individual of *T. insularis* is 70% complete and represents a 20% larger individual based on skull length, with more massive appendicular proportions. Newly recovered individuals and partial skeletons of *T. insularis* from the VdP site provide new important elements to interpret the anatomy and systematic of this taxon. In particular, new data cast doubts on previous claims of insular dwarfism in this ornithopod dinosaur (Dalla Vecchia, 2009; Chiarenza et al., 2020). Further bony elements assigned to other individuals of *T. insularis* have been found at the VdP site. "*Primus*", partially quarried in 1992, is characterised by incomplete and articulated forelimbs (specimen number SC 57022) and represents one of the earliest findings at the VdP site. A fourth individual, named "*Secundus*" was extracted in 1997. Its remains are represented by a complete but strongly

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Fig. 9 - *Tethyshadros insularis* "*Antonio*", holotype, specimen number SP 57021.

crushed skull (specimen number SC 57026), and by a highly fractured, perhaps articulated, partly collected skeleton (specimen number SC 57256). A left pubis (specimen number SC 57023), and a cervical vertebra with rib (specimen number SC 57025) assigned to this taxon were collected as well. A survey of exposed elements at the site in 2020 indicates a minimum of seven individuals of *T. insularis* at the VdP (Chiarenza et al., 2020; Fanti et al., 2021).

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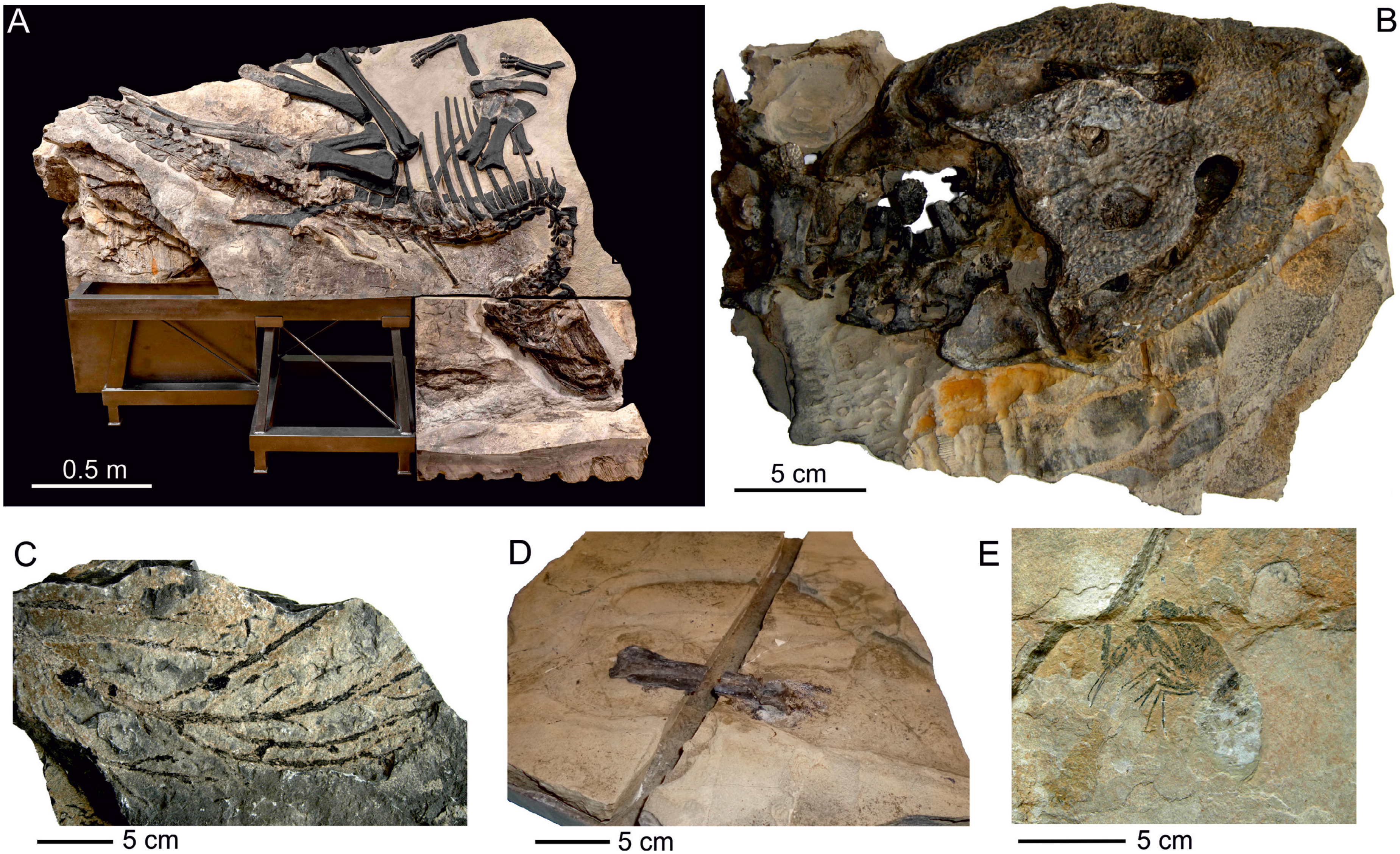

Fig. 10 - The most important fossils recovered from the Villaggio del Pescatore geosite and exposed at the Trieste Natural History Museum. Dimensions in brackets include the embedding rock. A) *Tethyshadros insularis* "*Bruno*", specimen number 57247 (250 cm x 150 cm x h 190 cm). B) *Acynodon adriaticus*, holotype, specimen number 57248 (30 cm x 23 cm x 10 cm). C) Conifer branches, specimen number 57259 (37 cm x 26 x 7 cm). D) Pterosaur bone, specimen number 57258 (31.5 cm x 26 cm x 5 cm). E) Decapod crustacea, specimen number 57057 (24 cm x 20 cm x 2.5 cm). Reproduced after approval of the Superintendence of Cultural Heritage (FVG region).

Fossil crocodiles were discovered as well. One of them belongs to a new species of Alligatoroidea, *Acynodon adriaticus* (Delfino et al., 2008; specimen number SC 57248). It is a well-preserved specimen, with a very short snout and an unusual dentition with large posterior globular teeth, and the absence of caniniform teeth, presumably an adaptation to the type of diet. *Acynodon* probably fed on slow-moving hard-shelled prey, like molluscs or crustaceans. A metacarpal bone likely belonging to a pterosaur (specimen number 13450) was also found. In addition to fossil reptiles (dinosaurs, crocodiles, or indeterminate reptiles) which constitute almost 7.3% of all discovered specimens, further vertebrate fossils (more than 63%) are represented by small teleost fishes, on average 2-3 cm long, usually found disarticulated. Fossil invertebrates were also found at VdP including decapods crustaceans, which represent the 15% of all the fossils discovered. Plant fossils are not numerous (6%). Furthermore, VdP limestone has revealed the presence of pollens in the lower part of the stratigraphic succession of the site, including a few gymnosperms and several angiospermous pollen types (Arbulla et al., 2006).
For more information: https://museostorianaturaletrieste.it

STOP T4.2. Geology of the Villaggio del Pescatore geosite
Coordinates: 45°46’42.6”N - 13°35’23.1”E

Topics: Stratigraphy and sedimentology of the dinosaur-bearing limestone.

The geosite is located in the Duino-Aurisina municipality and comprises a small portion of quarried land and a vegetated area where rock layers crop out. The geosite is adjacent to a free parking slot (Fig. 11) and was discovered about 30 years ago in Liburnian-like rhythmite limestone beds. The overall geological setting of the site and neighbouring areas has been described in several works (Tarlao et al. 1993, 1995; Dalla Vecchia, 2008, 2009) and enhanced in recent years by unpublished GIS and photogrammetric campaigns. Further comprehensive geological works carried out on the site mostly resulted in unpublished MSc Thesis made at UniTs (i.e., Attura, 1999; Palci, 2003), and guides for previous field trip excursions (Tarlao et al., 1995; Arbulla et al., 2006; Otoničar, 2016a). The most important excavation campaign at the site was conducted in 1994-1999 (Arbulla, 2017), whereas recent further punctual extractions have been carried out. Throughout the years after the discovery of the dinosaur skeletons, several geological prospections, including core drillings, have improved the knowledge of this exceptional dinosaur *lagerstätte* (Tarlao et al., 1993, 1995; Palci, 2003; Dalla Vecchia, 2008, 2020). The area where the fossil remains were found is about 70 metres long and 25 metres wide and corresponds to an

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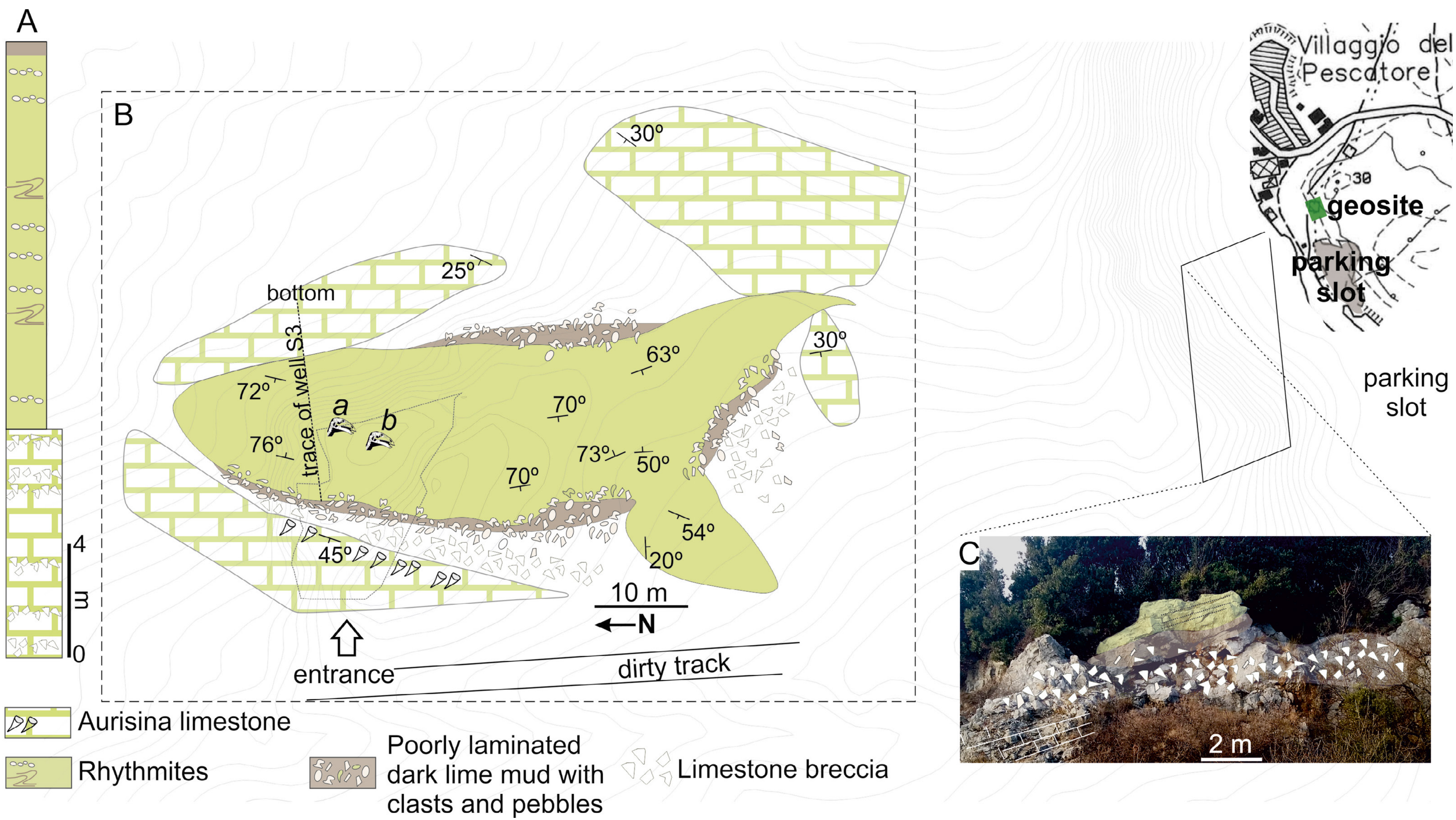

Fig. 11 – Simplified geological map of the Villaggio del Pescatore geosite (B) and simplified lithological log of the well S3 (A; from Palci, 2003 and unpublished observations). C) Field picture of the northern edge of the main quarry (parking slot) where rhythmites and breccias are visible. Dinosaur heads roughly correspond to the extraction points of "*Antonio*" (*a*) and "*Bruno*" (*b*).

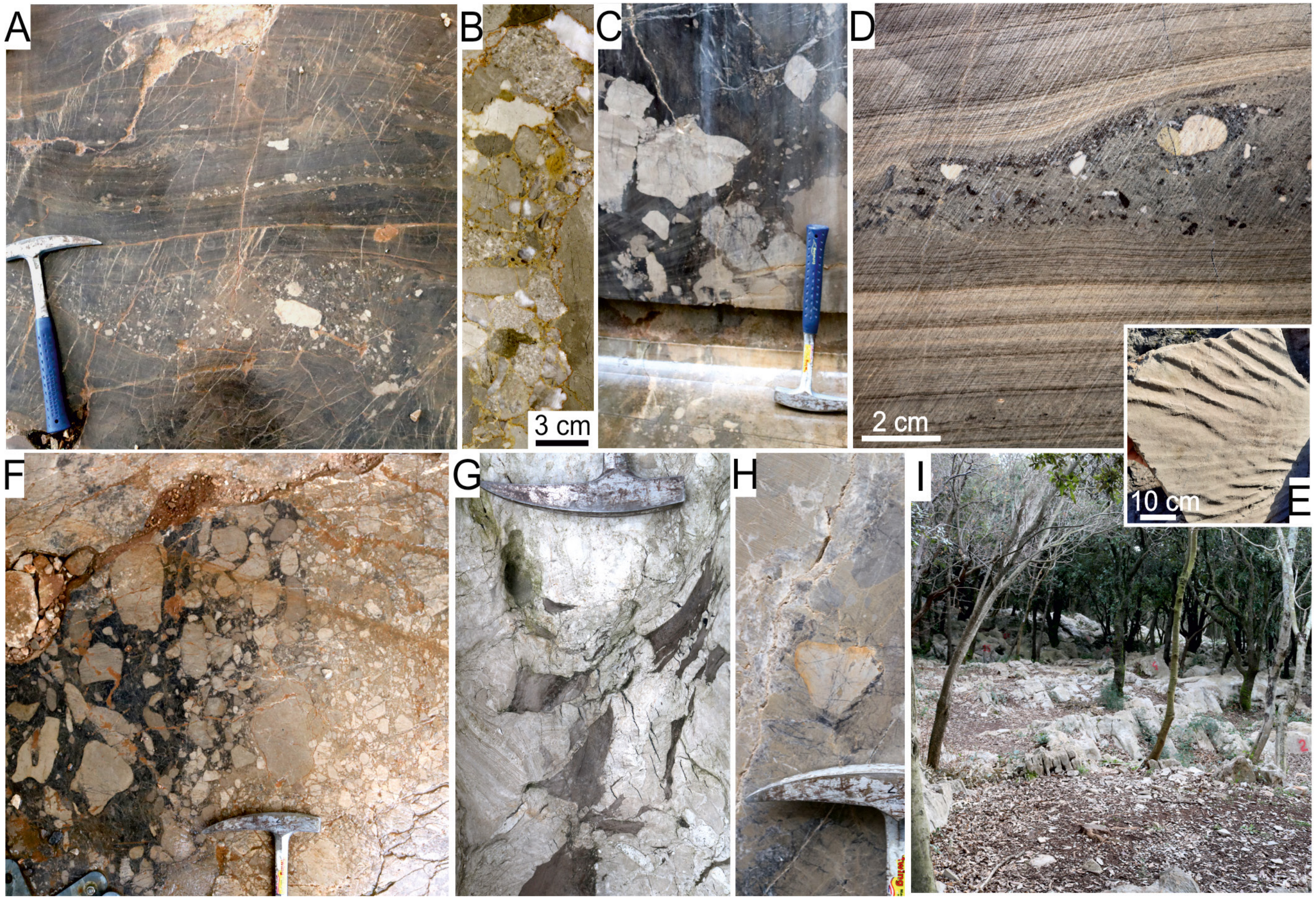

Fig. 12 - Field pictures of the Villaggio del Pescatore geosite. A) Rhythmites with clastic intercalation of carbonate breccia. B) "Aurisina limestone" polygenic breccia with large rudist fragments (from the drilled core, well S3). Note the orange pedogenetic-like material infilling the interclast space. C) Large limestone blocks immersed in a black and fine mud matrix. D) Clastic intercalation (debris flow) within the rhythmites from a quarried block. E) Ripple marks in rhythmites. F) Transition between the black matrix breccia and the matrix-free breccia at the top of the succession. G) Flame clasts made up of rhythmites included into fine-grained breccia at the top of the succession. H) Iron-stained limestone clast. I) Field view of the vegetated portion.

approximate 12 m stratigraphic thickness. It is mostly composed of dark and finely laminated carbonate rhythmites well-visible in outcrops and on the quarried surfaces (Fig. 12). Even if larger fossils were extracted, there are further visible remains throughout. The spatial relationships among the fossil-rich rhythmites and the surrounding limestone and breccia can be observed through the quarried surface, in the field (Figs. 11, 12) and through the samples recovered from the well core named S3 (Fig. 11A; Palci, 2003; Arbulla et al., 2006) that was drilled almost perpendicular to the bedding. This makes the geosite a cross-section that allows appreciating the stratigraphic organization of the deposits, which is also partly visible on a rock wall limiting the adjacent parking slot (Fig. 11C).

The lower part of the succession is represented by about seven metres of shallow-water carbonates referable to the

"Aurisina limestone", visible through the northern edge of the main quarry (parking slot; Fig. 11). Evidence of repeated, arguably not prolonged, emersion phases are testified by monogenic and polygenic limestone breccia with pinkish matrix, sometimes with a network of fractures filled by a black matrix resembling kerogen or bitumen or intercalated within orange pedogenetic-like material (Fig. 12B). Facies analysis allowed referring these "Aurisina limestone" deposits to a proximal restricted lagoon (beige-grey wackestone) alternated with high energy shoals (bioclastic packstone-grainstone). The most common bioclasts are rudists, red algae, *Decastronema*-like cyanobacterial remains, Discorbidae, few demosponges (*Sarmentofascis*), and benthic foraminifera. These latter are mainly represented by *Keramosphaerina tergestina* (Stache), *Rotalispira scarsellai* (Torre), and *Accordiella conica* Farinacci and suggest an early Campanian age (Frijia et al., 2015). In these strata, Arbulla et al. (2006) found spores and angiosperm pollen assemblage, with the occurrence of *Papillopollis aradaensis* Kedves and Pittau indicating a Santonian-Campanian age.

The fossil-rich rhythmite interval above the "Aurisina limestone" is about twelve metres thick and is made of an alternation of thin mm-thick dark organic-rich and grey-whitish thin laminae. By lithological comparison, it can be assigned to the "Liburnian limestone". It lays on the underlying "Aurisina limestone" through the interposition of a thin layer (50 cm) of brackish wackestone, sometimes brecciated (Fig. 13C), with ostracods, Discorbidae, and algae (Fig. 13D). Rhythmites are made of very fine-grained (some ten μm in size) carbonate mud with, apart from the colour, no obvious differences among the dark and light laminae (Fig. 13G, H). The rhythmites constantly contain sparse carbonate grains and a further likely event-dominated sedimentation represented by intercalations of debris flows made of mm- to cm-size limestone clasts (Figs. 12D and 13E, F) containing rare benthic foraminifera shells, few disarticulated ostracod valvae, and thin undetermined black fragments of biogenic origin (bones?; Fig. 12D). The coarser clasts (up to some centimetres in thickness) are rounded to angular platform limestone fragments, mostly represented by wackestone with oligotypic benthic fauna. Rudist bioclasts and undetermined fragments occur as well. Ripple marks occur sporadically through the rhythmite likely triggered by tractive currents (Fig. 12E).

The upper part of the succession is well-exposed at the quarried surfaces at the site entrance (Fig. 12F; Fig. 14). It shows a gradual coarsening upward of carbonate clasts and pebbles floating into a homogenous, poorly laminated, dark mudstone (Fig. 12C). This is topped by a carbonate breccia in turn overlain by a rudist-rich platform limestone. The pebbles, clasts, and breccia of this portion comprises: i) well-rounded white limestone clasts sometimes interested by traces of bioerosion (Fig. 12F); ii) angular clasts with reddish-oxidised edges (Fig. 12H); iii) clay chips-like clasts made of reworked rhythmite (Fig. 12G); iv) smaller black indeterminate

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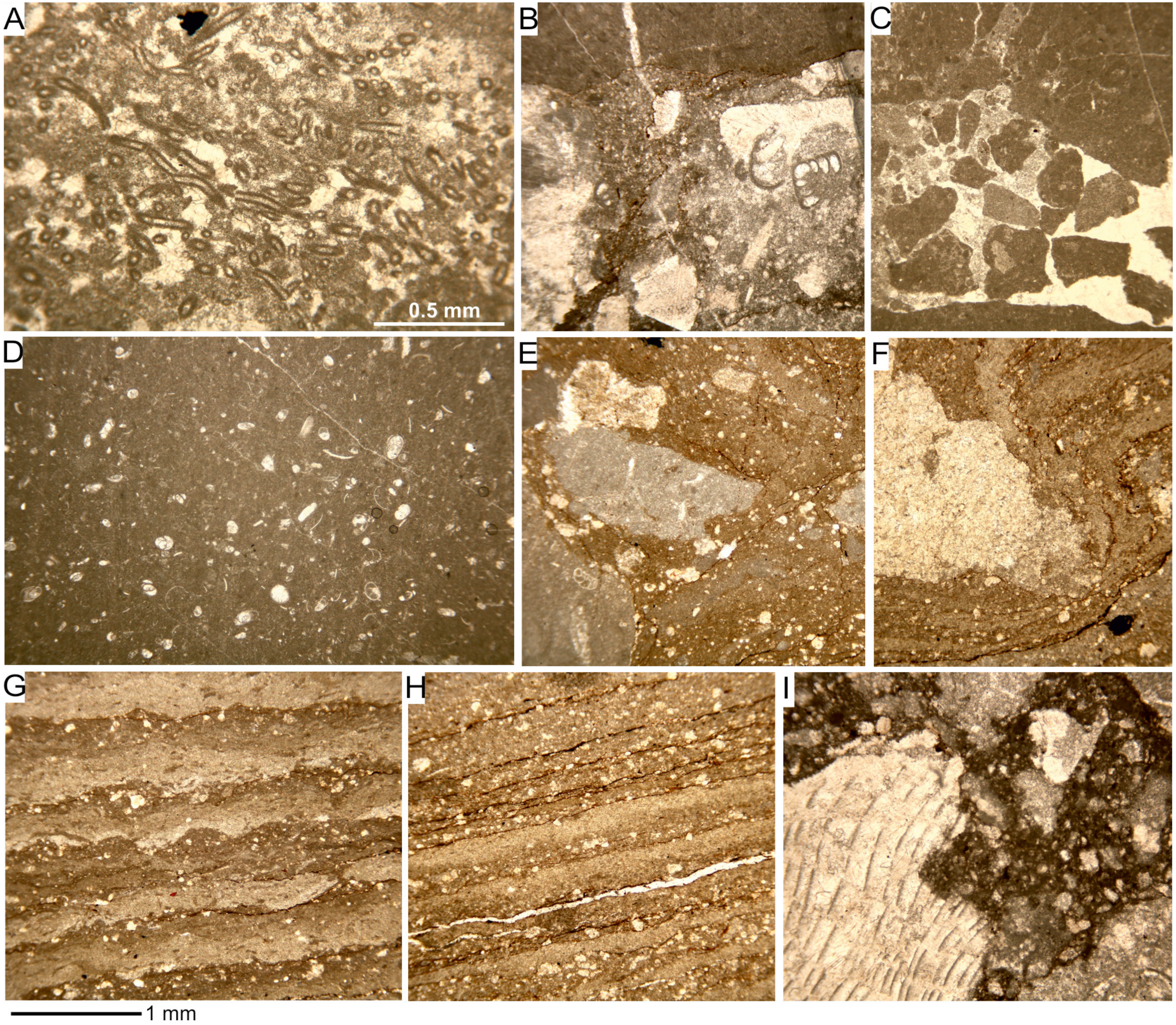

Fig. 13 - Facies of key samples recovered at Villaggio del Pescatore geosite from field and cores. A) Cyanobacterial accumulation (*Decastronema*) from the "Aurisina limestone" (in this picture the scale bar corresponds to 0.5 mm). B, C) Facies of the brecciated levels of the "Aurisina limestone". Note the presence of *Accordiella conica* in B. D) Discorbidae, ostracods and miliolids wackestone occurring few cm below the beginning of the rhythmite deposition. E, F) Small limestone clasts floating into the rhythmites. G, H) Facies of the rhythmites. I) Rudist fragment and small clasts floating into the dark matrix at the top of the succession.

grains. The overlaying carbonate platform strata hosts rudists like *Biradiolites angulosus* Orbigny and *Rajka spinosa* Milovanovic and Grubic, among others (Arbulla, 2017).

Based on a sedimentological parallel with lacustrine varvae, which deposition is driven by seasonality, Arbulla et al. (2006) have suggested that the rhythmite was accumulated in a relatively short time (thousands of years). Moreover, Attura (1999) founds highly negative $\delta^{13}C$ values, suggesting that the basin was conditioned by freshwater inputs. It has been therefore argued that the basin was characterised by a restricted fresh water-influenced environment with oxygen-depleted bottom receiving clastic flows from adjacent areas; this led Arbulla (2017), and Dalla Vecchia (2020) to interpret it as an inland cenote or a proximal marine blue hole. At the quarried surfaces, the rhythmite beds and the associated debris flow bodies generally dip at high angles and strike north-south, with a prevailing westward younging direction (Fig. 14), whereas elsewhere at the site they occur with a sensibly different attitude (Fig. 11). This calls for the occurrence of metre-scale, isoclinal slump folds that cause multiple repetitions of the stratigraphic succession in the western part of the site (Fig. 14). Such folds were interpreted as being related to syn-sedimentary tectonics by Tarlao et al. (1993). The central part of the sequence displays low-angle disconformities, trains of detachment folds, and curved and disrupted beds, which are bounded by low-angle thrust and spoon-shaped faults/shear zones. All these features are related to syn-sedimentary or early post-sedimentary mass transport processes, suggesting an increasing instability of the depositional basin (Fig. 14). Interestingly, “*Bruno*” was retrieved exactly on one of these slump folds with its tail at the 180-degree bend, and bones plastically deformed. Based on the biostratigraphic clues derived by benthic foraminifera, rudists, and palynomorphs, the age of the rhythmites is Campanian, possibly Maastrichtian (Palci, 2003; Dalla Vecchia, 2008). This time range would be assigned to all the fossil remains that include more than 200 findings of small fishes, crustaceans, plants, and coprolites as well.

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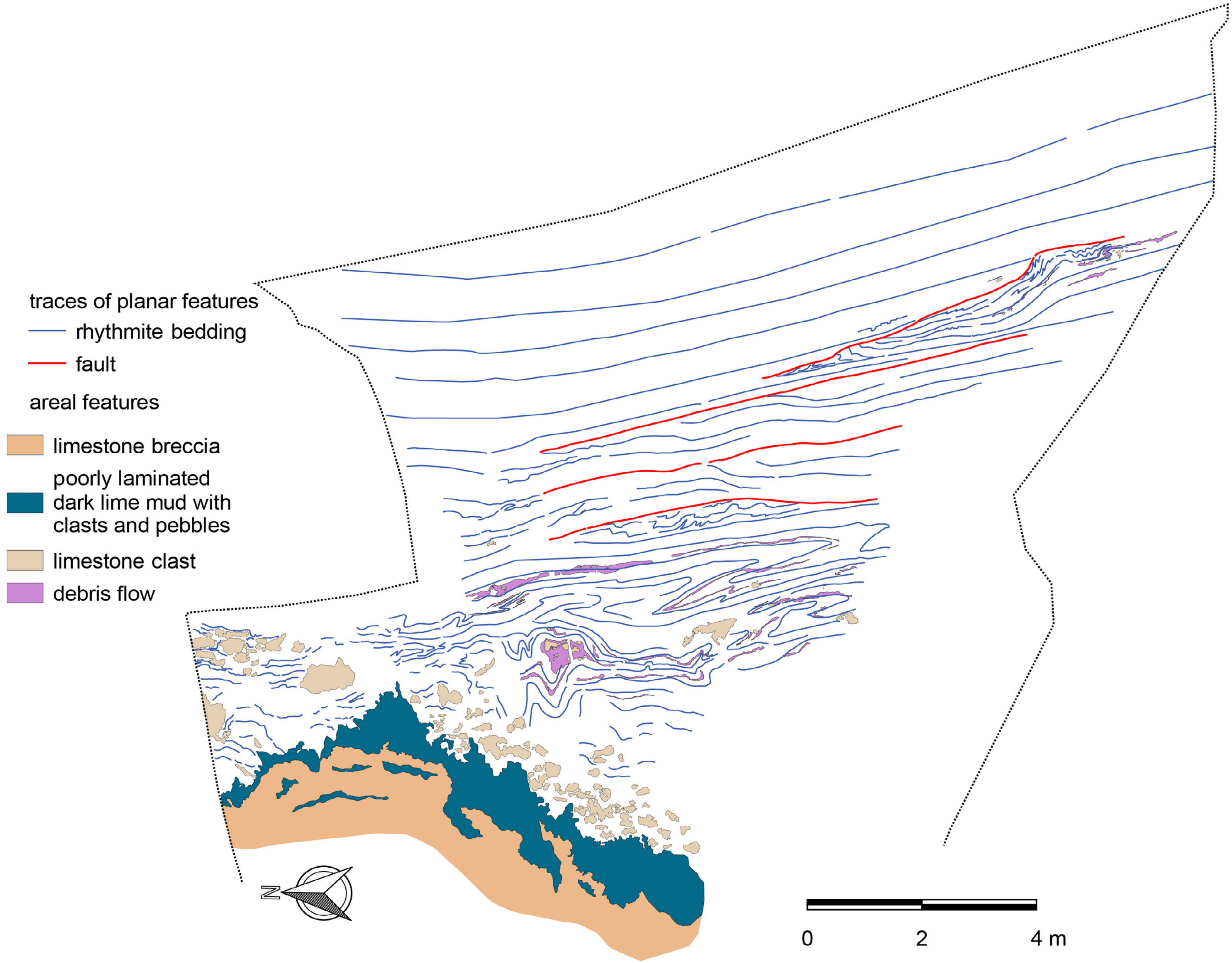

Fig. 14 - Villaggio del Pescatore geosite. Detailed geological map of the main quarried surface made from a compound of orthogonal pictures.

STOP T4.3. *Cava Romana* quarry and the rudist-rich "Aurisina limestone"

Coordinates: 45°45'26.1"N - 13°39'20.2"E

Topics: Active limestone mining, rudist-rich Upper Cretaceous carbonate platform.

The usage of the "*Aurisina marble*" extracted from the Cava Romana quarry roots back to Roman times. The first report suggests that the stone was used as a construction material for the Roman colony in Aquileia (181 B.C). The quarry was constantly cultivated since the 1st century B.C. up to the 5th century A.D. and used during the settlement of Tergeste (Trieste) and Pavia. After the fall of the Roman Empire, there is evidence of activity by Byzantines (Mausoleum of Theodoric, Ravenna, 520 B.C.) and by Venetians during the Middle Age. Once Trieste was declared a free port in 1719 by Charles VI of Habsburg, the quarry was re-activated and the stone was used in several buildings in Trieste (Piazza Unità, edificio della Borsa, Palazzo Pitteri). Once under the Austro-Hungarians, Trieste was connected with Vienna through a railway line, allowing the "*Aurisina marble*" to be used in the most important cities of the Empire; in 1890 the quarry arrived to count more than 3000 workers. After the Italian annexation, the *marble* was used in several architectural projects in Milan and United States, whereas after the Second World War was exported in numerous other countries all around the world.

Quarrying at Cava Romana interests the rudist-rich "Aurisina limestone". Informal commercial names as "*Aurisina Fiorito"*, "*Aurisina Lumachella"*, "*Aurisina Granitello"*, "*Aurisina Roman Stone"* among others are used to indicate specific facies that have particular commercial value. The first two names refer to a rudist floatstone or rudist biostromal bodies with rudists occasionally found in life position among which *Kuehnia* Milovanovic, *Katzeria* Sliskovic, *Rajka* d'Orbigny, *Pseudopolyconites* Milovanovic. The "*Aurisina Granitello"* and "*Aurisina Roman Stone"* are made of bioclastic sands (grainstone and packstone textures) with rudists, benthic foraminifera, echinoderms, and green algae. Most of these facies alternate through succession. More or less sharp firm- or hardground surfaces, linked by Sanders (2001) to brief subaerial exposures, usually mark the contact between the two main lithofacies (Fig. 15). The bioclastic grainstone/packstone is commonly arranged in m-thick beds displaying faint cross-lamination or unidirectional sigmoidal lamination (Fig. 16). Locally, *Thalassinoides* burrows (Fig. 15D) filled by bioclasts, and by muddy carbonate lithoclasts are found. The depositional environment is linked by Sanders (2001) to a high-energy shallow subtidal setting with sand dunes and tidal channels. The rudist-rich lithofacies is organised in 0.5 m up to 1.5 m-thick beds made of wackestone and mudstone with sparse elongated bioclasts. Most rudists are isolated in a non-oriented position, whereas locally they build small clusters in life position (Fig. 15C). Shell preservation is variable, ranging from well-preserved, partially

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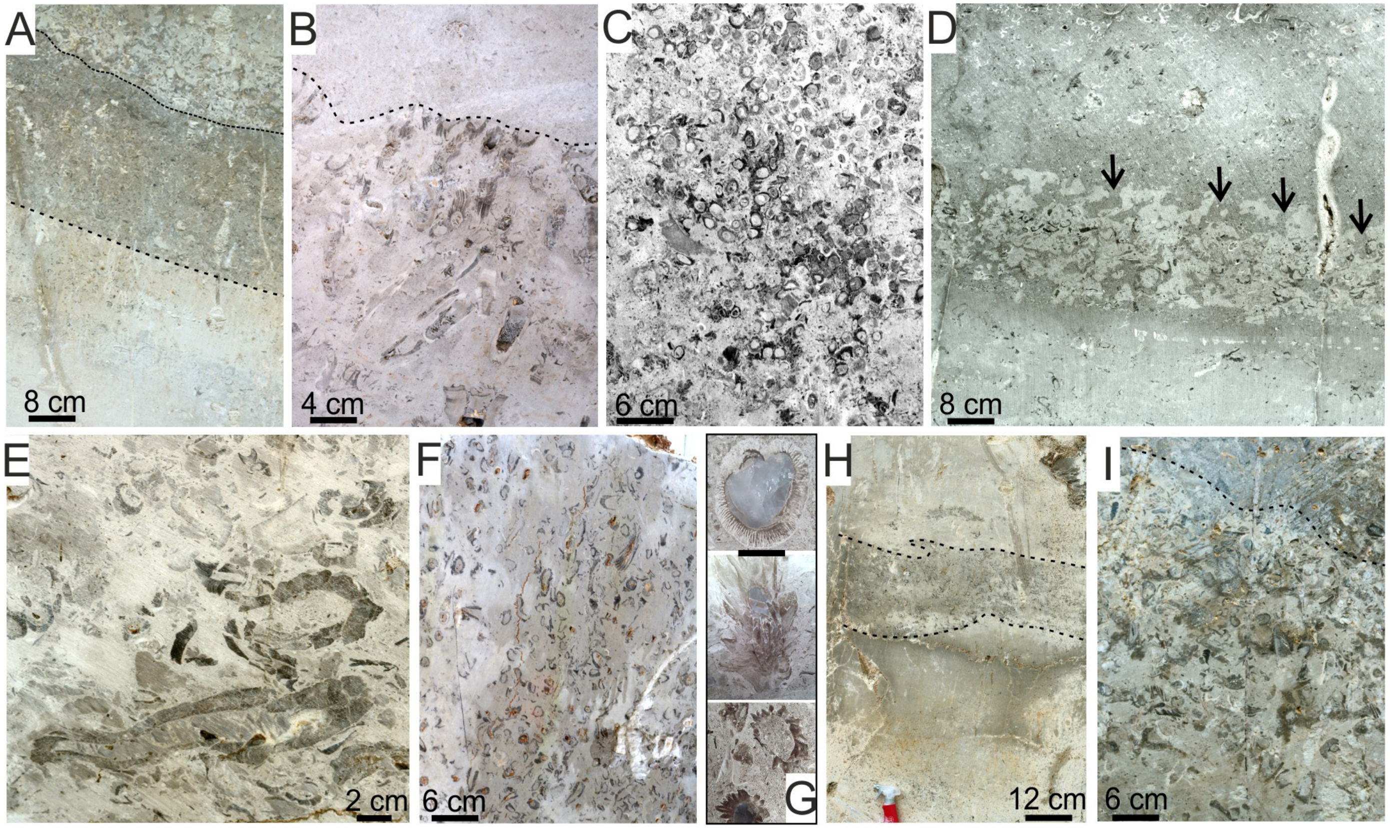

Fig. 15 - Pictures of mine cuts at Cava Romana quarry. A) from bottom to top: i) whitish limestone with sparse rudist shells; ii) dense accumulation of radiolitid shells into a gray-black matrix; iii) bioturbated level. B) sharp contact among radiolitid-rich limestone and the overlying fine-grained limestone. C) Facies of the "*Aurisina fiorito*" with a dense accumulation of rudists (radiolitids) in life position. D) Widespread bioturbations over a firm to hardground surface (arrows). E, F) Rudits (mostly radiolitid) floatstone. G) *Rajka spinosa* (bottom, middle) and a radiolitid (top). Scale bar 4 cm. H) Thin level composed of a monospecific rudist accumulation floating into a whitish-grey mud lime matrix. I) Accumulation of rudist shells surmounted by a faint firmground surface.

dissolved and filled by matrix, fragmented and crushed by vertical compaction (Fig. 15E), indicating complex taphonomy. Burrow traces of different generations are frequent and filled by a darker bioclastic packstone-grainstone. Burrows shows a reticulated network, with a preferential direction along the bedding plane. Sanders (2001) interpreted it as a biostromal structure into low to moderate energy setting, where softground to firm-/hardground may form.

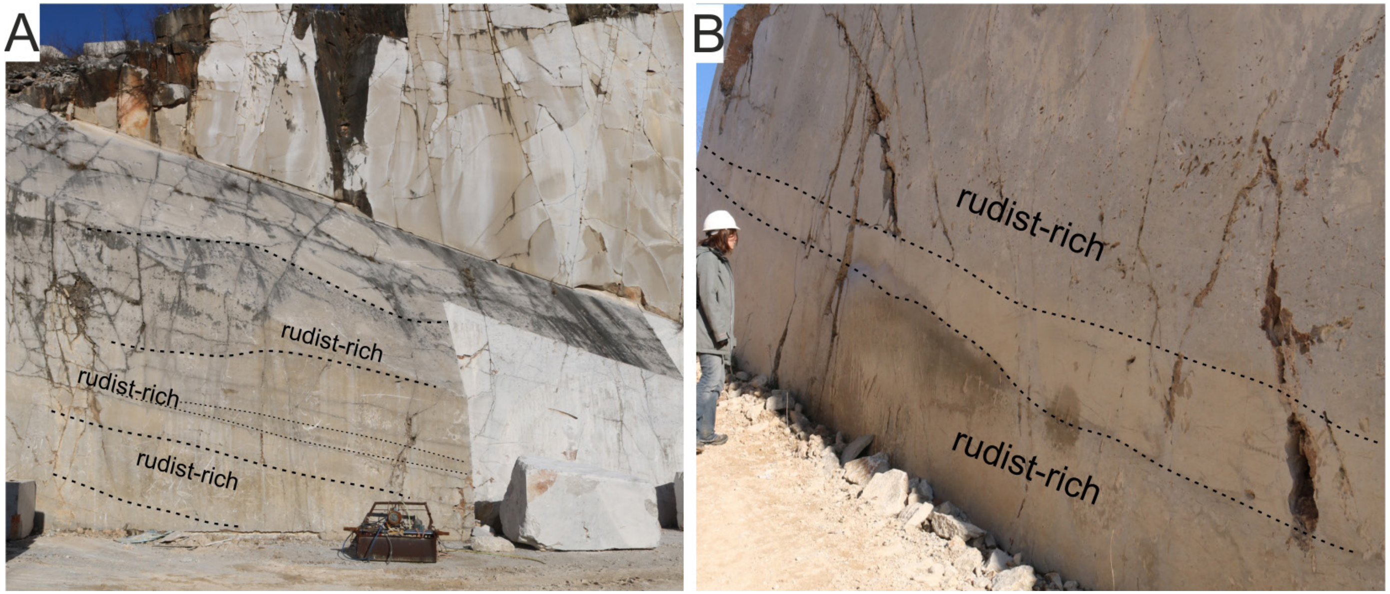

Fig. 16 - Mesoscale geometries of rudist accumulations visible from the quarried surfaces at Cava Romana.

STOP T4.4. Slivia breccia old quarries
Coordinates: 45°45’46.1”N - 13°40’09.3”E

Topics: Late Cretaceous palaeokarst, old mining site.

The Slivia breccia, also known on the market as “*Napoleon Slivia*” or “*Breccia Carsica Marble*”, among others, was widely used as ornamental building stone. In Trieste, it can be observed at the bus station ticket offices as well as on the floor of the Monte Grisa sanctuary. The best outcrops are some old quarries located about 2 km north of the Aurisina village. The Slivia breccia occupies an area of limited extension (about 45,000 square metres). The general sedimentological and palaeontological characteristics of this rock were addressed by Venturini and Tentor (2010) and Otoničar (2016b), who related the depositional event of the Slivia breccia to a Late Cretaceous palaeokarst that favoured the formation of a large volume of limestone blocks at the top of the “Aurisina limestone”. The sharp contact between the breccia and the “Aurisina limestone” is observable at the side of the main quarry (Cava 3 in Venturini and Tentor, 2010) (Fig. 17B). Larger limestone blocks are visible near this contact and are made of metric, elongated to sub-spherical boulders, mostly composed of “Aurisina limestone” rudist-rich facies and whitish muddy limestone. Adjacent quarried surfaces expose different blocks, mainly made up of rudist-rich floatstone and foraminiferal wackestone (Figs. 17, 18). Interestingly, some clasts show a

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Fig. 17 - Slivia old quarry. A) View of the main quarried surface. The highlighted clast shows a rich accumulation of the foraminifers *Keramosphaerina tergestina* (*K*) and *Murgella lata* (*M*). B) Contact among the "Aurisina limestone" and the overlying Slivia breccia. C) Different components in natural outcrop, among dark Liburnian-like clasts and rudist fragments. D-H) Quarried surfaces showing large blocks made up of rudists limestone (D, H); accumulation of sub-rounded clasts with pressure solution contacts, and whitish clasts wrapped into a reddish bauxite-related material (E); angular and sub-angular blocks with iron-stained edges (F, G).

few Campanian larger foraminifera (Fig. 17A) like *Keramosphaerina tergestina* (Stache) and *Murgella lata* Luperto Sinni, along with *Accordiella conica* Farinacci and *Reticulinella fleuryi* Cvetko, Gušić and Schroeder that, however, occur as visible components especially under thin section (Fig. 19). Blocks show stylolite contacts due to pressure-solution processes whereas, when preserved, the blocks edge is sometimes covered by iron-oxide veneer, either incrusted by bauxite-related material or palaeokarstified (Figs. 17E-G and 18B), indicating subaerial diagenesis prior to deposition. In the same places,

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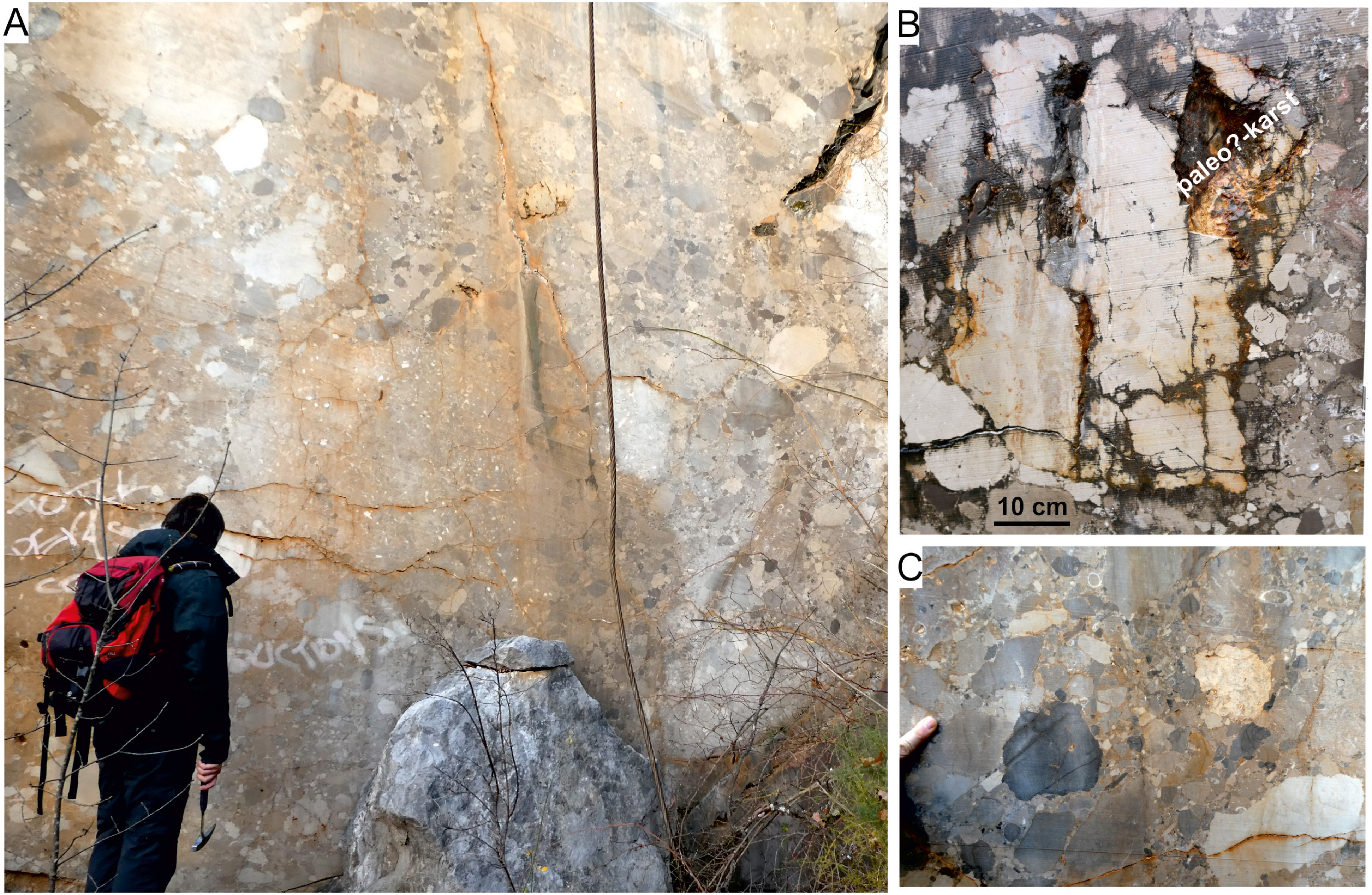

Fig. 18 - Slivia old quarry. A) Mine surface cutting the Slivia breccia. B) Large (palaeo?)-karstified block accumulated along with smaller clasts. C) Heterogeneous clasts.

a local accumulation of smaller poorly-sorted clasts generally composed of "Aurisina limestone" facies along with dark "Liburnian limestone"-*like* facies bearing *Murciella* occurs. These clasts are sometimes immersed in a bioclastic grainstone matrix with isolated, variably preserved, rudist shells (Figs. 17C and 19A, B). The components of the carbonate grainy matrix seem to indicate deposition in a submarine setting. This is even more evident in a second outcrop (Cava 2 of Venturini and Tentor, 2010) where Slivia breccia becomes rich in cm-thick layers of grainstone-wackestone with small limestone clasts. Here, a diverse benthic foraminiferal assemblage including *Accordiella conica*, *Dicyclina schlumbergeri* Munier-Chalmas, *Rotalispira maxima* Consorti, Caus and Frijia, and *Calveziconus* cf. *lecalvezae* Caus and Cornella (Venturini and Tentor, 2010) could be observed under thin section analysis (Fig. 19). These data, along with the previous foraminiferal findings within the reworked clasts, suggest that, when blocks accumulated during the early-mid Campanian (Frijia et al., 2015; Consorti et al., 2017), primary carbonate was also depositing. However, there are still some open questions. From field evidence it is not clear if the production of breccia occurred constantly in a subaerial setting and if it was driven by one or more exposures. Throughout the spectrum of observable carbonate facies, one may suspect this breccia coming from the dismantling of a considerable platform volume. However, the chaotic aspect lacking any clear sedimentary structure makes the interpretation of the depositional process quite challenging, which is possibly related to gravitative or collapse processes. Furthermore, the

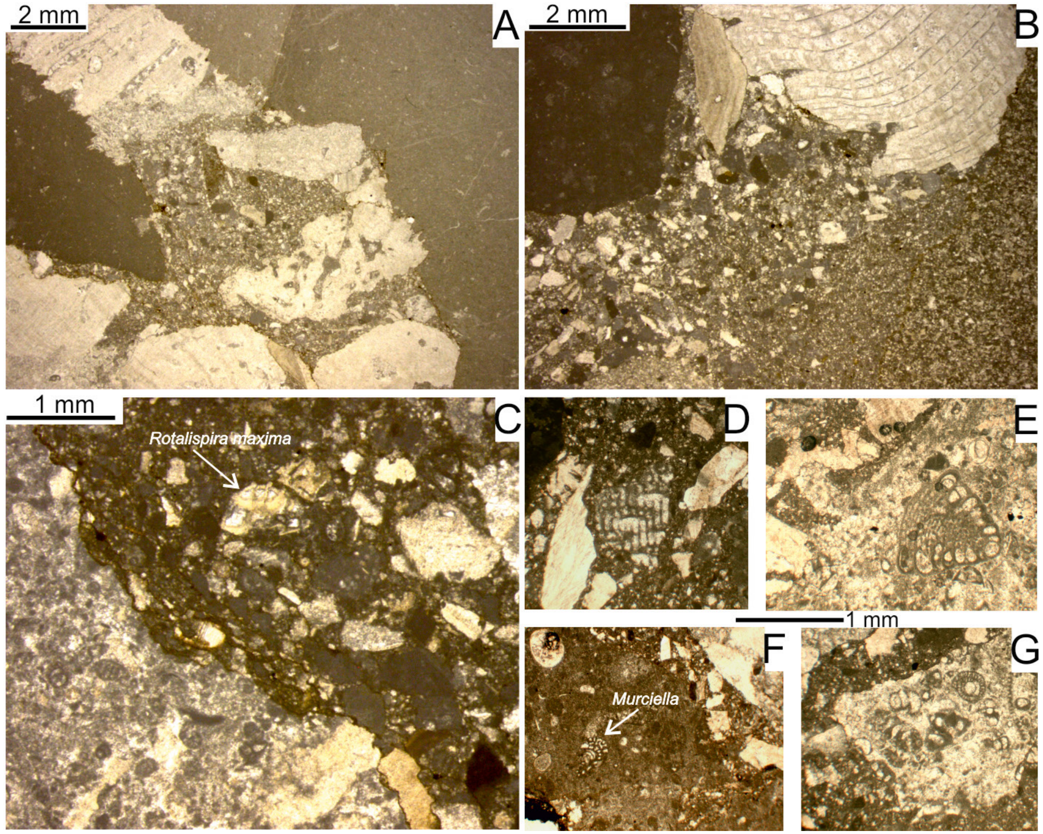

Fig. 19 - Facies (A-C) and benthic foraminifers (D-G) of the Slivia breccia. A, B) Rudstone made up of limestone clasts and rudist fragments; note the stylolitic contacts and the fine-grained matrix composed of thin limestone grains. C) Clasts floating into a dark brown matrix containing the foraminifer *Rotalispira maxima*. D) Fragment of *Dicyclina schlumbergeri* into the matrix. E, F, G) *Accordiella conica* (E), *Murciella* (F), and *Reticulinella fleuryi* (G) occurring within the clasts.

occurrence of darker clasts indicates that karstification likely occurred during -or after- the deposition of the "Liburnian limestone", possibly triggered by syn-sedimentary tectonics as suggested by Venturini and Tentor (2010).

STOP T4.5. The Cenomanian succession of the Moschenizza hill
Coordinates: 45°47'53.4"N - 13°34'55.8"E

Topics: Cenomanian peritidal succession, paralic carbonate environments.

The succession exposed at Moschenizza hill is roughly 30 m-thick and includes the lowermost portion of the "Zolla member". The micropalaeontological content, including the benthic foraminifers *Pastrikella balcanica* Cherchi, Radoičić and Schroeder, *Pseudorhapydionina dubia* (De Castro), and *Biconcava bentori* Hamaoui, suggests a late Cenomanian age for the whole succession (Fig. 20K-M). The limestone succession is mostly composed of m-thick beds of packstone and grainstone facies with abundant rudists or debris made up of rudist and *Chondrodonta* fragments, indicative of a relatively open platform environment. These deposits are also represented by well-sorted foraminiferal grainstone, possibly related to a shoal high-energy environment (Fig. 20 I, J). The carbonate matrix of these beds can be occasionally rich in organic matter and may appear brown or dark grey in colour. Beds show a general coarsening upward trend and are topped by sharp, sometimes undulated surfaces. In places, these beds alternate to cm-thick dark-grey laminated or nodular layers of wackestone-mudstone, occasionally highly dolomitised, which sometimes drape the sharp contact with the underlying limestone (Fig. 20A, C, D). The palaeontological content of these layers, studied in detail by Tentor and Tentor (2007), includes flora and fauna linked to a very proximal restricted platform setting, near to emerged areas, and referable to a paralic depositional environment. Fossil remains are mostly represented by the Cretaceous conifer *Frenelopsis* and molluscs *Anomia*-like ostreids. In thin section, it is possible to observe the presence of an oligotypic benthic fauna composed of a few small miliolid and discorbid foraminifera, ostracods, *Thaumatoporella*, and small thin-shelled gastropods (Fig. 20E-H). This evidence suggests that at Moschenizza hill deposition was driven by peritidal cyclicity in which well-oxygenated bottom waters and proximal restricted marsh environments alternated, under mixed fresh-marine water inputs. *Anomia*-like ostreids remains have been observed also in the "Liburnian limestone", possibly indicating a similar depositional environment (Tentor and Tentor, 2007).

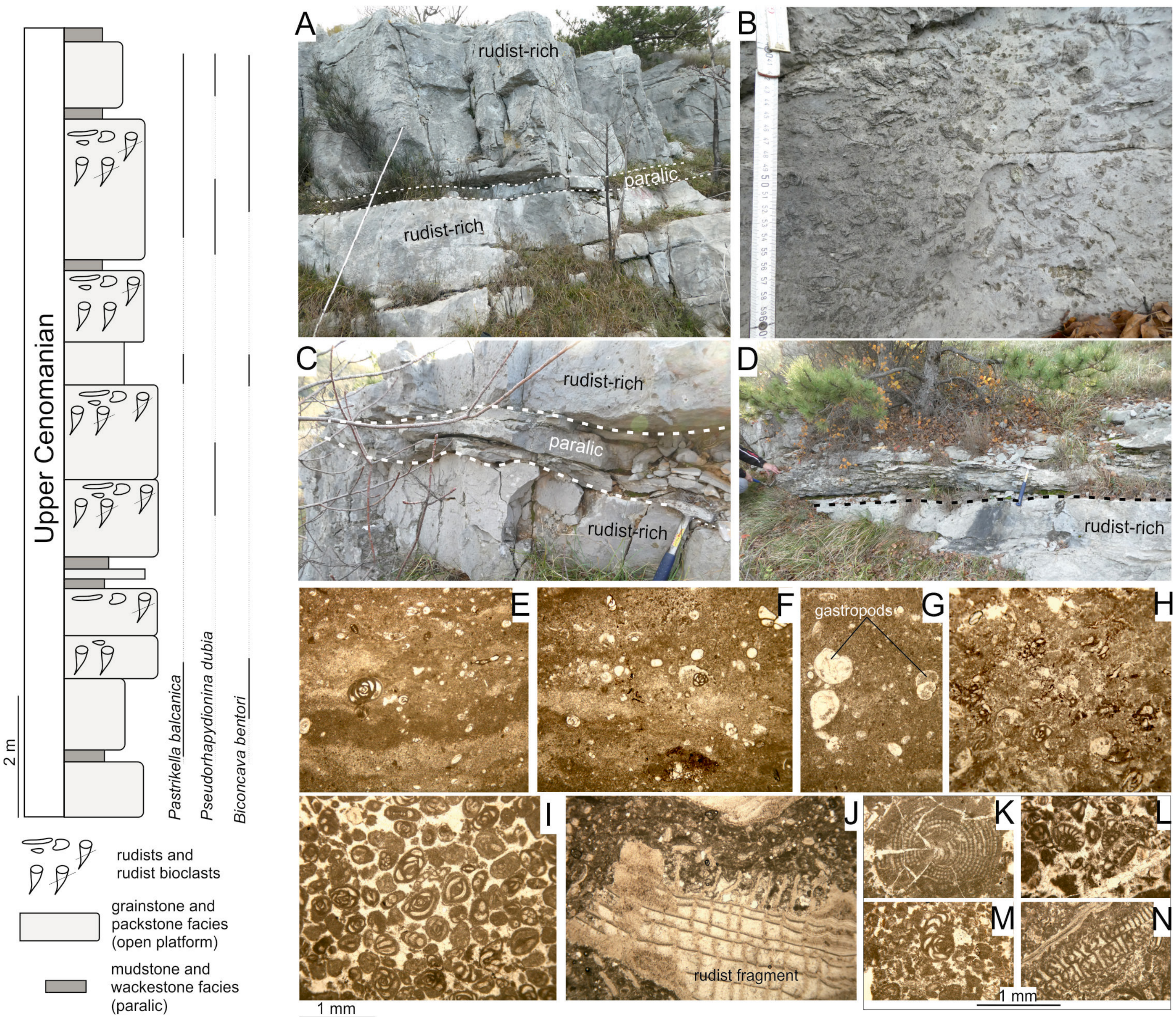

Fig. 20 - Stratigraphic section, outcrops, facies, and foraminifera of the Cenomanian succession ("Zolla member") at the Moschenizza hill. A, C, D) Laminated or nodular layers of dark-grey paralic limestone sandwiched between massive rudist-rich bodies. B) Rudist-rich limestone. E-H) Facies of the paralic limestone mostly represented by a wackestone texture with miliolids, *Thaumatoporella*, gastropods, and ostracods remains. I) Miliolids and *Pseudorhapydionina* grainstone. J) Rudist floatstone. K) *Pastrikella balcanica*. L) *Biconcava bentori*. M) *Pseudorhapydionina dubia*. N) *Dicyclina schlumbergeri*.

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