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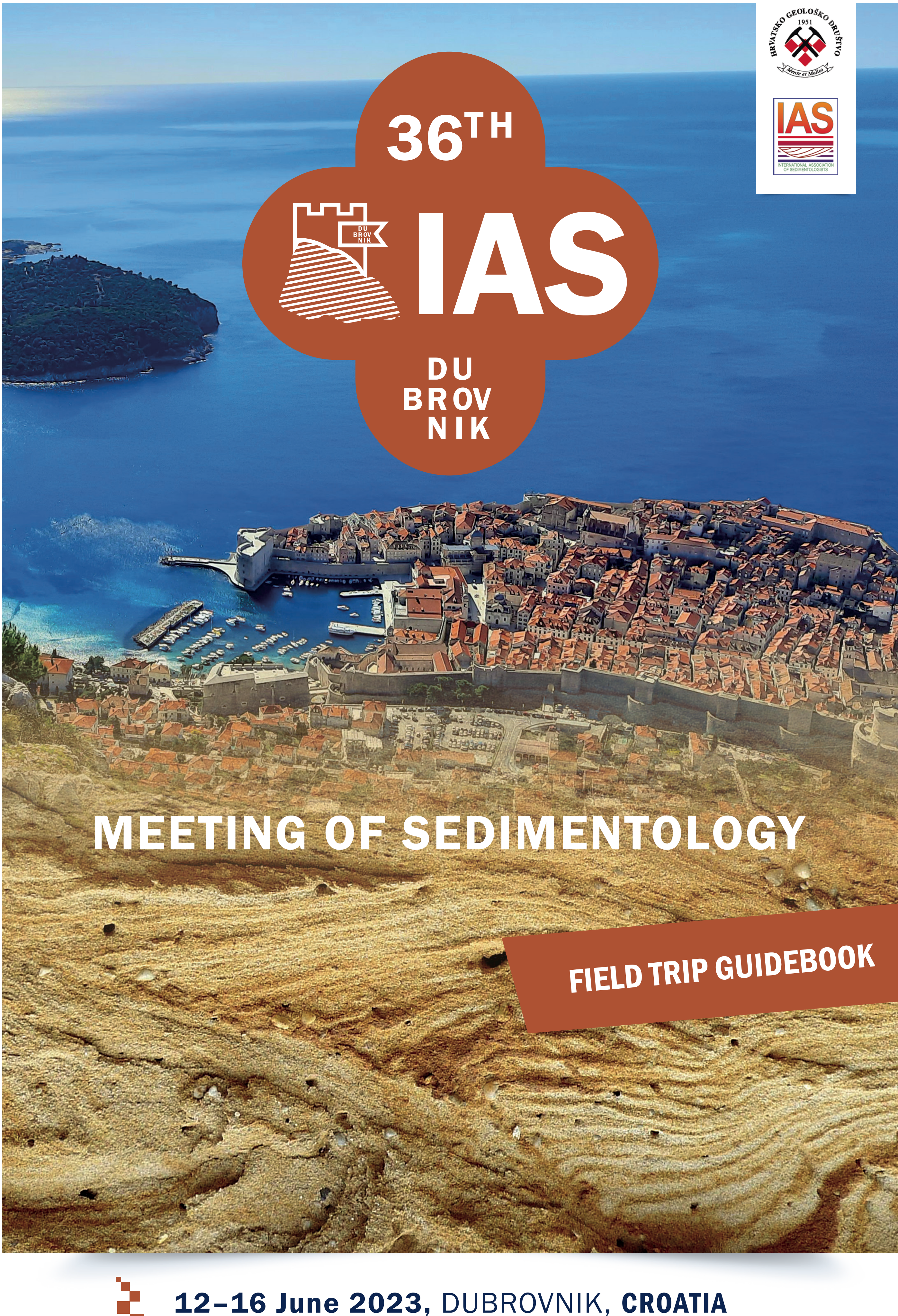

36TH IAS DUBROVNIK

MEETING OF SEDIMENTOLOGY

FIELD TRIP GUIDEBOOK

12–16 June 2023, DUBROVNIK, **CROATIA**

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36th International Meeting of Sedimentology
June 12–16, 2023, Dubrovnik, Croatia

FIELD TRIP GUIDEBOOK

Sedimentary cover of the Adria and its surroundings

from aborted rifting in the central Adriatic to the post-collisional deposition in the Dinarides, the Southern Alps, and the Pannonian basin

Edited by: Tvrtko Korbar, Marijan Kovačić and Igor Vlahović

Contents

Foreword

Dear colleagues,

Forty years after the 4th IAS Regional Meeting that was held in Split (1983), and twenty years after the 22nd IAS Meeting of Sedimentology that was held in Opatija (2003), the international sedimentological community decided to gather again in Croatia for the 36th IAS Meeting of Sedimentology in Dubrovnik.

Field trips are an integral and very important part of every IAS meeting, and we are proud to highlight the guidebooks of the meetings held in Croatia:

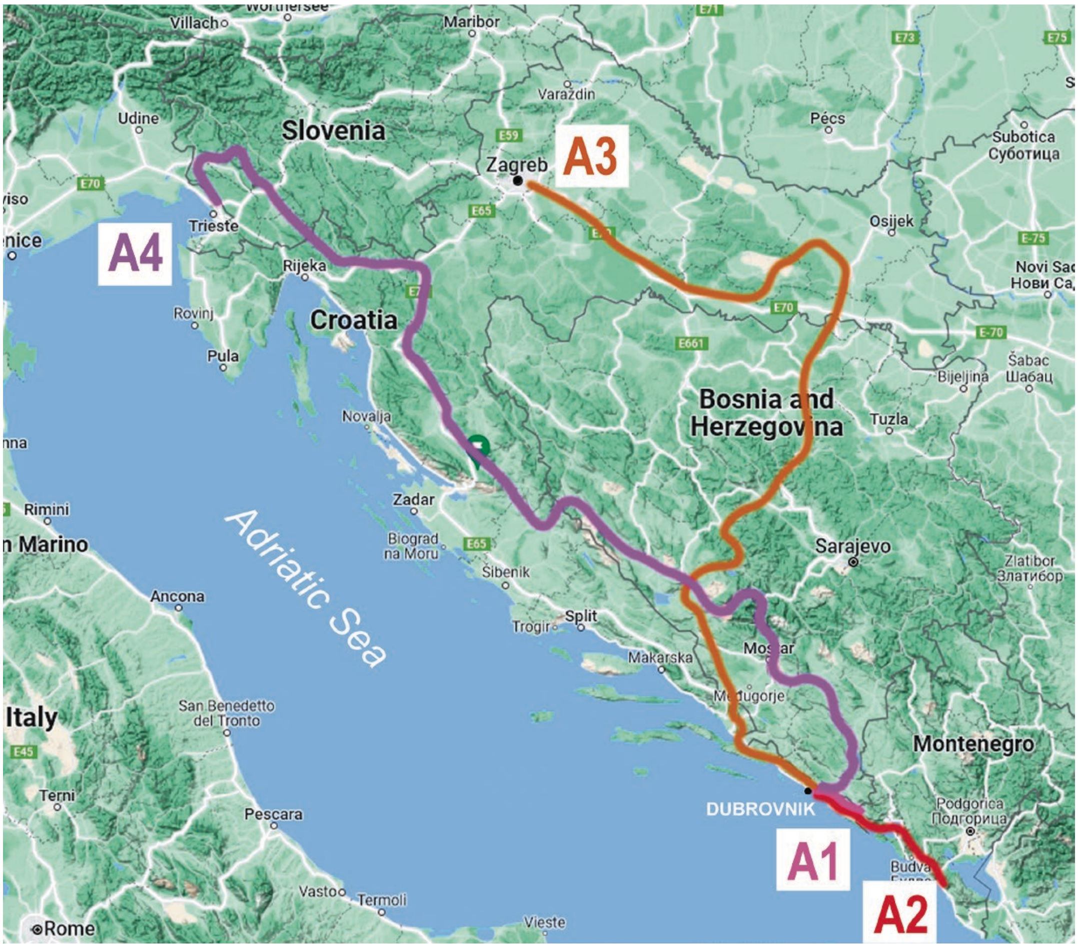
In 1983, **Ljubomir Babić** and **Vladimir Jelaska** edited a guidebook with field trips from Istria to Dalmatia and thus enabled the authors to somehow break the ice for international cooperation in these areas but also to chart the path for numerous sedimentological successors in Croatia and Slovenia that contributed and are still contributing to the completion of knowledge about the geological evolution of the region;

In 2003, **Igor Vlahović** and the late **Josip Tišljar**, edited a guidebook with field trips focused on more stratigraphical and sedimentological details and extended sedimentological interests all the way to the Alps (Slovenia) and the Pannonian Basin (northern Croatia), holding the door wide open for international cooperation.

Given the fact that in the eastern Adriatic region and its wider hinterland, Phanerozoic sedimentary rocks cover the vast majority of the territory, the region is still underexplored. That is why we also invited authors that traditionally deal with Mesozoic basinal deposits that crop out in Montenegro, as well as authors working on mass wasting deposits and Quaternary glacial, colluvial, lacustrine and aeolian sediments. Thus, even after 40 years of presenting the sedimentology in the region, we manage to offer new sedimentological delicacies that the authors have packaged into nine field trips through Croatia, Montenegro, Bosnia and Herzegovina and Slovenia, all ending or starting in Dubrovnik – the pearl of the eastern Adriatic in the south of the Republic of Croatia.

We are proud to present the Field Trip Guidebook of the third, now already traditional IAS Regional Meeting in Croatia that is organized every 20 years (1983, 2003, 2023, ...). We hope that you will enjoy the regional sedimentary geology, and that many of us will meet again somewhere in Croatia in 2043...

The Editors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DUBROVNIK

Geology of the Old Town of Dubrovnik

Tvrtko Korbar, Tonći Grgasović and Ladislav Fuček

FIELD TRIP B1

36TH IAS DUBROVNIK

Geology of the Old Town of Dubrovnik

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Abstract

The Old City of Dubrovnik is on the UNESCO World Heritage list and is recognized as the "Pearl of the Adriatic" that adorns the southern coastal part of the Dinaric Karst. Both the southern and northern elevated parts of the Old Town are built on Mesozoic carbonate rocks deposited on the Adriatic Carbonate Platform (AdCP). The carbonate bedrock is strongly deformed since major compressional deformations of the AdCP succession began in the Eocene during the early orogenic thrusting and formation of the External Dinarides fold and thrust belt. The late orogenic complex tectonic deformations are still ongoing, and the area is characterized by occasional strong seismicity. The deformed packages of stratified limestones and dolomites of the Old Town bedrock show sedimentological features typical of peritidal subtropical sedimentation on the AdCP, while rare key microfossils allow age determination. The northern part of the Old City is situated on the Lower Cretaceous limestones while the southern part is built on the Upper Cretaceous dolomites. The central low-lying part of the town is built on anthropogenic infill of a narrow late Holocene embayment characterized by superficial Quaternary sediments overlying the heavily fractured carbonate bedrock. The exposed karst cavities are mostly filled with speleothems, indicating long-term karstification and denudation. The southern rocky shore is in patches covered by thin recent supratidal aragonitic encrustations known as pelagosite. Since geodetic data and coastal geomorphological features indicate recent surface deformations, the newly discovered geological structure of the Old Town of Dubrovnik should be taken into consideration during regional seismo-tectonic investigations.

Introduction and geological setting

The Old Town of Dubrovnik is an iconic old city situated on the eastern Adriatic coast in southern Croatia (Fig. 1). Since 1979, the Old City of Dubrovnik has been included on the UNESCO World Heritage list, recognized as the "Pearl of the Adriatic" (https://whc.unesco.org/en/list/95/). The Old Town is not only built mostly of various types of stone that originated from the surrounding area (Belamarić, 2015), but also of imported dimension stone from the broader Mediterranean region, since the city has a millennial history. Such an exceptional architectural masterpiece certainly deserves a comprehensive detailed study on the origin of the building stone in the future.

Geomorphologically, the area belongs to the Dinaric Karst (Mihevc *et al.*, 2010; Pikelj & Juračić, 2013). Tectonically, the area belongs to the External Dinarides (Korbar, 2009; Fig. 1), a NW–SE striking fold-and-thrust belt built of deformed, exhumed and eroded Palaeozoic to Cenozoic predominantly carbonate rocks, most of which represent deposits of the Adriatic Carbonate Platform (AdCP, Vlahović *et al.*, 2005; see also field trip A1, this volume). The carbonate successions were detached from the Adriatic microplate (Adria) upper crust during the early orogenic thin-skinned phase of the Alpine orogeny in the region (Schmid *et al.*, 2008).

One of the regional tectonic models imply a main regional, late orogenic, right-lateral (dextral) fault zone striking NW–SE along the coastal mountain belt of the external Dinarides, while left-lateral (sinistral) WNW–ESE striking faults are conjugated to the main one (Picha, 2002). The system could be active, at least closer to the main Dinaric fault zone, as documented in the area NW of Dubrovnik (Govorčin *et al.*, 2020), although the authors did not connect the seismic event with the left-lateral faults proposed earlier (Picha, 2002). The fault system could accommodate up to 5 mm/year northward movement of Adria (Bennett *et al.*, 2008), and is either derived from a basal thrust (Schmitz *et al.*, 2020), or dissects the thin-skinned structures along the regional thick-skinned crustal transpressional zones (Picha, 2002; Korbar, 2009). However, the two active tectonic patterns are not necessarily mutually exclusive, but may rather coexist laterally along the strike of the External Dinarides.

Regardless of which active tectonic regime prevails in the area, it occasionally causes strong earthquakes (Herak *et al.*, 1996; Kuk *et al.*, 2000; Markušić *et al.*, 2017). Besides, active surface deformations are

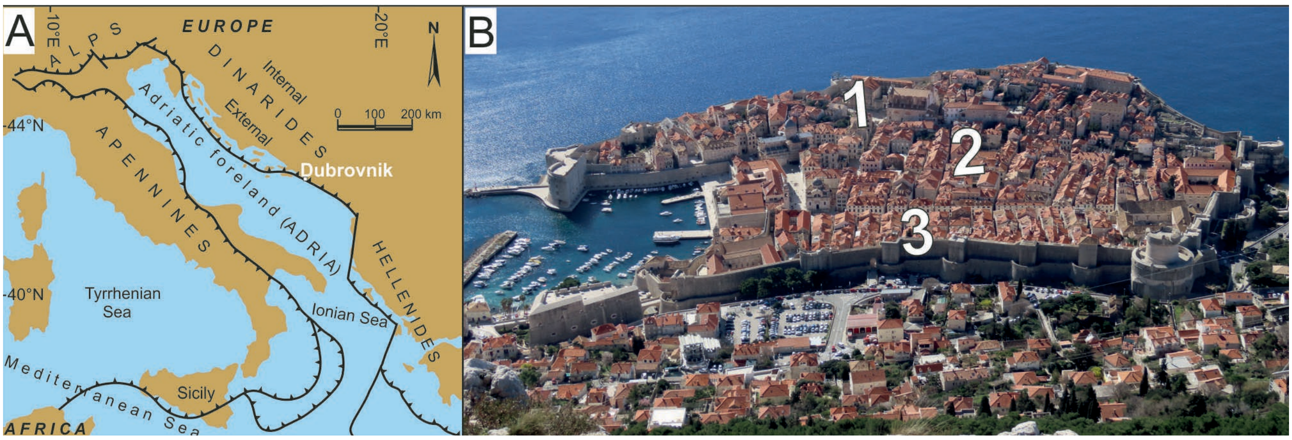

Fig. 1. A) Overview map of the central–northern Mediterranean showing the main orogenic fronts of the indicated fold-and-thrust belts, and the location of Dubrovnik. B) Panoramic view of the Old Town of Dubrovnik from the north (Srđ hill): 1 – southern bedrock ridge, 2 – central filled and flattened part, and 3 – northern bedrock ridge (cf. Stanko *et al.*, 2023; see Fig. 2).

reported from the wider area in the Old Town of Dubrovnik. While uplifted tidal notches indicate historical co-seismic uplift (Faivre *et al.*, 2021), geodetic data indicate recent (inter-seismic) subsidence of the area (Grgić *et al.*, 2020). Therefore, further terrestrial geological mapping and analyses of subsurface geological data in the wider area (e.g., Šolaja *et al.*, 2022) are crucial for a better definition of the active faults and the kinematics in the region.

The general geological structure of the Dubrovnik area is shown on the "Dubrovnik" sheet of the Basic Geological Map of the former Yugoslavia at 1:100,000 scale (Marković, 1971). This is the only sheet covering predominantly the territory of Croatia that was compiled by Serbian geologists, without collaboration with Croatian experts. Later regional investigations and local studies that included geology were based mostly on the geological data from the official map. The local geotechnical research (Građevinski institut, 1981) included numerous boreholes, drilled through the superficial deposits down to the bedrock in the central flatten part of the Old Town, thus improving the knowledge of the local geology.

The latest geological research in the Old Town (Stanko *et al.*, 2023) resulted in the recognition of known regional lithostratigraphic units and their more complex geological relationships than shown on the official geological map (Fig. 2). The results imply a more complex tectonic structure in the wider area of Dubrovnik than previously considered. Furthermore, the newly discovered faults are very important for regional structural-tectonic and seismotectonic investigations in the area. This guide includes important new Micropalaeontological evidence and a description of the general sedimentological characteristics of the lithostratigraphic units, as

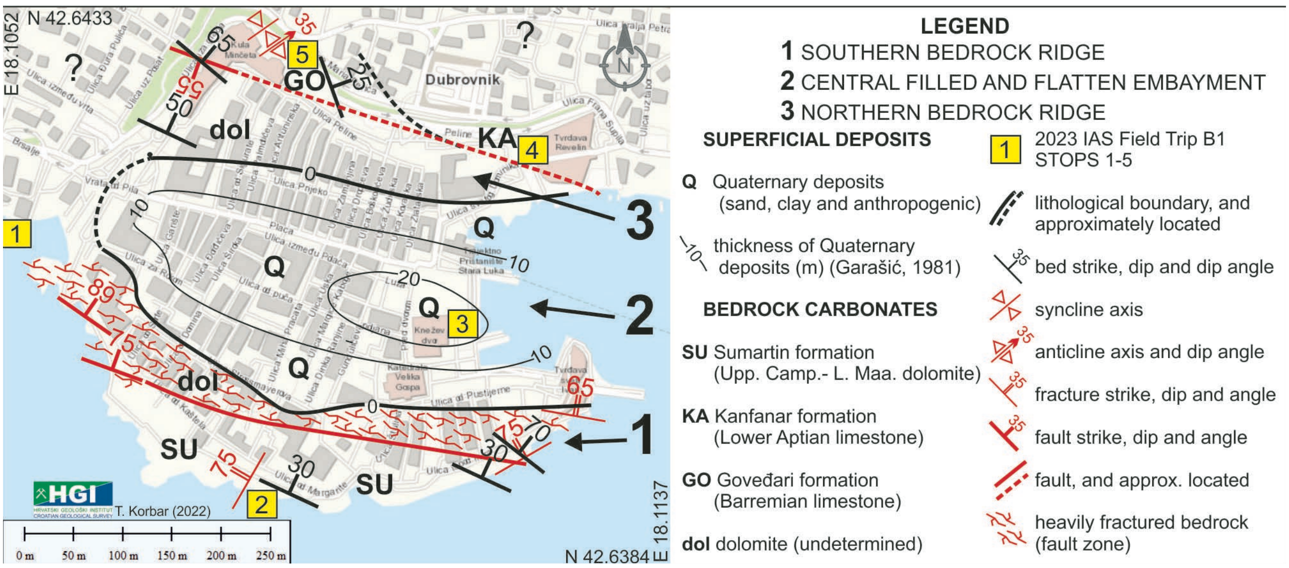

Fig. 2. A schematic geological map of the Old Town of Dubrovnik (modified after Stanko *et al.*, 2023) and field trip stops (yellow highlight): 1 – Lovrijenac, 2 – Buža, 3 – The Old Town Port, 4 – Revelin, 5 – Minčeta. Topographic background: World Topo Map.

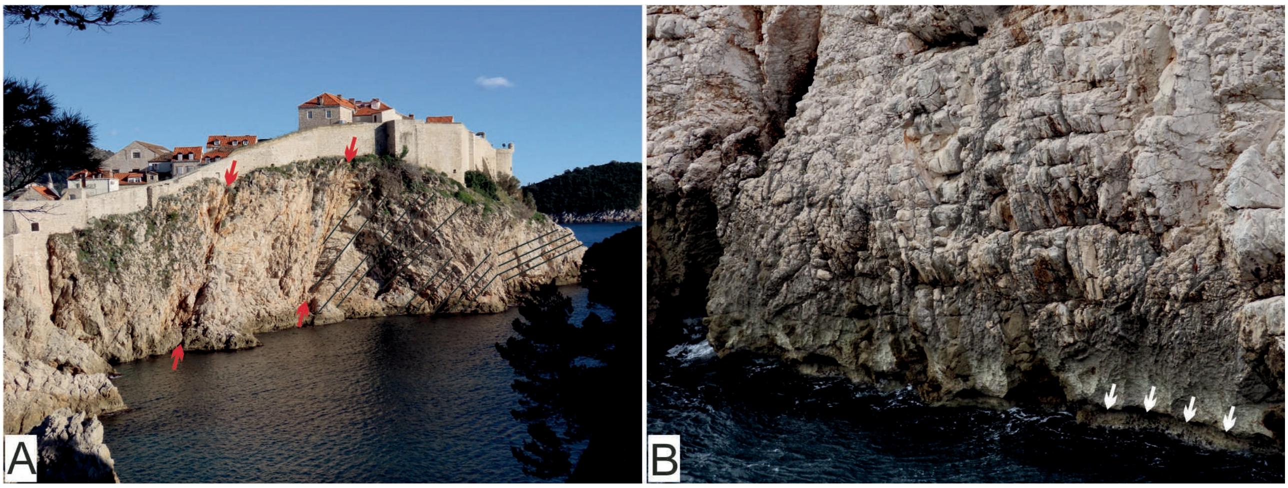

Fig. 3. A) The view from the west (from the Lovrijenac Fortress) to the southern bedrock ridge of the Old Town of Dubrovnik. Note the heavily fractured reddish-coloured bedrock dolomites along the WNW–ESE striking fault zone and the steeply inclined fault planes (indicated by red arrows). Thick-bedded Maastrichtian dolomite south of the fault zone (bedding planes are marked by black lines). B) Coastline west of Lovrijenac Fortress. Note the tidal notch that is above the mean sea level (white arrows).

well as other geological and geomorphological features of this historic urban area.

Description of the stops

the Old Town of Dubrovnik is built on three geomorphological and geological entities: the southern bedrock ridge, a central filled and flattened part (former embayment), and the northern bedrock ridge (Fig. 2; Stanko *et al*., 2023). The bedrock carbonates were deposited during the Cretaceous as part of the Adriatic Carbonate Platform (AdCP) succession (Gušić & Jelaska, 1990; Vlahović *et al*., 2005), and were strongly deformed during the Dinaric orogeny (Korbar, 2009). The superficial deposits cover the bedrock palaeorelief in the central part of the Old Town, and represent the Quaternary infill of a former small valley striking E–W. The valley was initially filled by (lacustrine?) clay that is overlain by sand. The sand was once at the bottom of the embayment that was formed during late Holocene sea level rise. The embayment was finally flattened by anthropogenic deposits for the purpose of extension of the city area (Jelić, 1994).

Stop 1. Lovrijenac: Southern bedrock ridge

The southern bedrock ridge is built of brownish-grey, thick-layered predominantly crystalline dolomites (Fig. 2). A few steeply NNE dipping fault planes strike along the northern belt of the ridge and delimit the northern heavily tectonically fractured crystalline dolomites on the north from the succession of well-bedded dolomites along the southern coast (Fig. 3A).

The coastline around the Lovrijenac Fortress is characterized by a well-preserved tidal notch that is tens of centimetres above the mean sea-level (Surić *et al*., 2014; Fig. 3B), although geodetic data show clear recent inter-seismic subsidence of the area (Grgić *et al*., 2020). The discrepancy implies a potentially significant historic co-seismic uplift of the bedrock.

Stop 2. Buža: Bedrock dolomites, speleothems and pelagosite

There are passages (*buža* in the local dialect means a hole) through the Old Town walls that allow access to the southern coast built of the well-bedded dolomite bedrock that is inclined generally to the NE (Figs. 3A and 4). A succession of thick-bedded, brownish-grey dolomite more than 50 m thick is characterized mostly by a microcrystalline structure with numerous fenestrae and bioturbated horizons. Light-grey horizons (bands) are dolomites characterized by preserved structures (Fig. 4C), e.g. dolowackestones and dolopackstones rich in shallow-water microfossils: benthic foraminifera and algae. Synsedimentary, in situ disintegration of some thin layers led to the formation of intraformational breccia that are observed in places (Fig. 4D).

The exposed formerly open fractures and karst caverns within the dolomites are filled by reddish-brown speleothems (Fig. 4B). The fractures were thus formed during the older palaeotectonic events, while former karst cavities indicate long-term karstification and surface denudation (corrosion).

The southern rocky shore is in patches covered by recent, black, microstromatolitic encrustations known as pelagosite, up to a few metres above the mean sea-level, (Figs. 4E–F). Pelagosite is a type of microbialite – specific morphological and sedimentological form of aragonite with up to 2% of organic

Fig. 4. A) Dubrovnik Old Town walls and a succession of peritidal dolomites at Buža (southern bedrock ridge). B) Reddish-brown speleothems fill the former karst cavern in dolomites. C) Thick-bedded grey dolomites. The light-grey bands are dolomites characterized by preserved structures. D) Intraformational synsedimentary breccia composed of fragmented thin layers of light-grey dolomites. E) Black patches of supratidal aragonite crusts known as pelagosite. F) Close-up of the pelagosite.

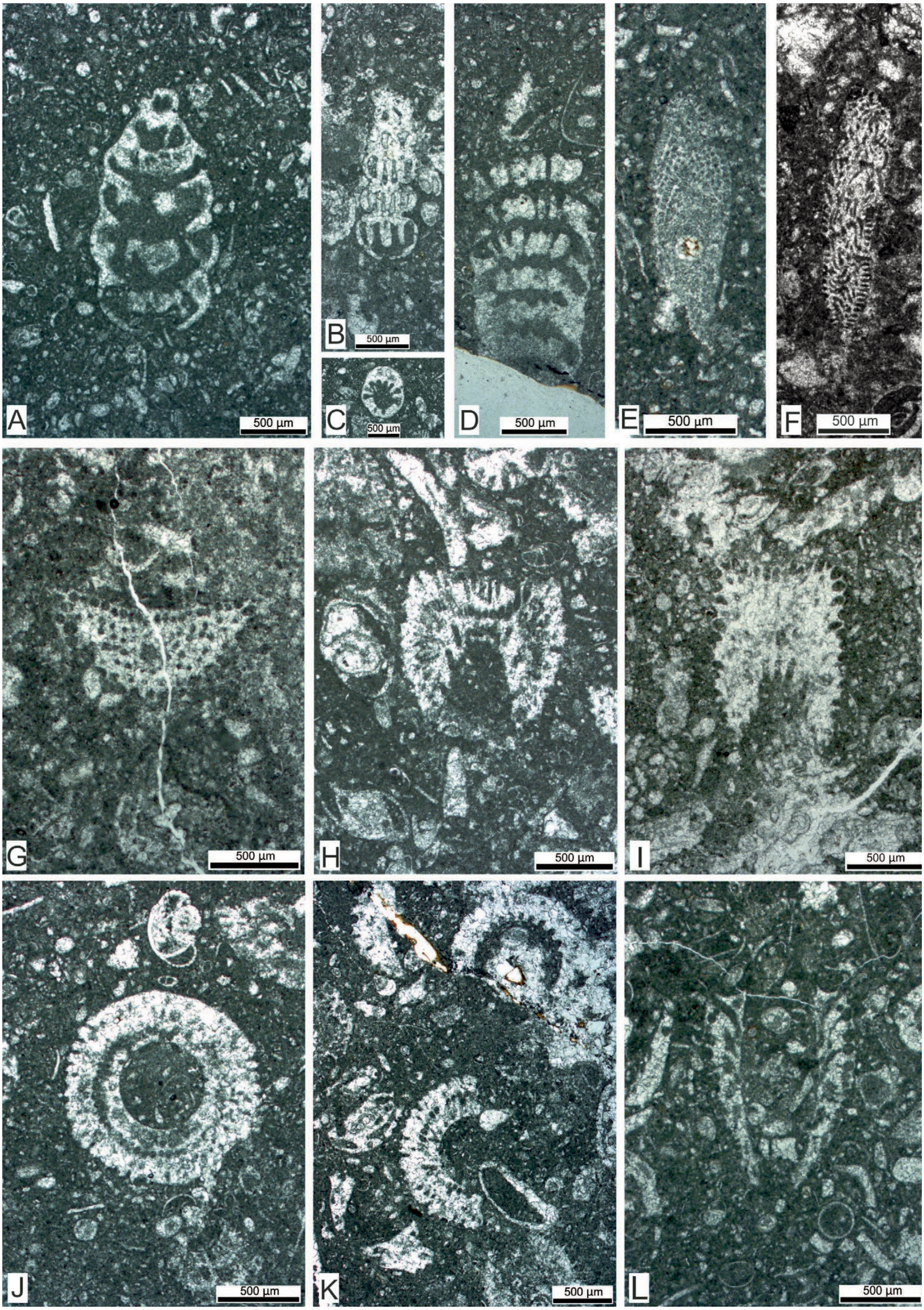

Fig. 5. Photomicrographs of the upper Campanian to lower Maastrichtian microfossils from the dolomite with preserved structures (Buža, southern coast of the Old Town Dubrovnik). A–D) *Rhapydionina sp.* E–F) *Sigalveolina renzi* (Fleury). G–I) *Pseudocymopolia anadyomenea* (Elliott). J–L) *Cymopolia* sp.

matter. Pelagosite crusts form in the supratidal zone (supralitoral) on the warmed rocky substrate exposed to the marine waves (splash zone). Specific biogeochemical processes that are supported by cyanobacteria led to the precipitation of aragonite on the places exposed to the sunlight that are frequently wetted by abundant sea spray (Montanari *et al.*, 2019).

The bedrock dolomite is sampled in the lower (coastal) part of the exposed succession at Buža (Fig. 4A). Micropalaeontological analyses of thin-sections revealed a relatively rich microfossil association of foraminifera and calcareous algae (Fig. 5). We determined the foraminifera *Rhapydionina* sp. and *Sigalveolina renzi* (Fleury). The genus *Rhapydionina* (Figs. 5A–D) is widely known from the peri-Adriatic upper Campanian to Maastrichtian inner-platform facies (Fleury, 2014), and is also proven in the biostratigraphy of the AdCP (Stache, 1889; Gušić & Jelaska, 1990; Velić, 2007). However, our material do not allow determination to species level. The genus *Sigalveolina* (Fleury, 2018), along with the species *S. renzi* (Figs. 5E–F; former *Murciella renzi*) is considered as a guide fossil for the "CsB6b" zone that has a stratigraphic range from the upper Campanian to the (?) lower Maastrichtian (Fleury, 2014). The species also appears in the lower part of the Sumartin formation on the island of Brač (Gušić & Jelaska, 1990) that is upper Campanian to lower Maastrichtian in age (Steuber *et al.*, 2005).

We also determined the Dasycladalian calcareous algae *Pseudocymopolia anadyomenea* (Elliott) and *Cymopolia* sp. (Figs. 5G–I). This is the first report of *P. anadyomenea* outside the Middle East where it is described from the Maastrichtian Tanjero Formation of Iraq (Elliott, 1959), and from the Late Maastrichtian Tarbur Formation of Iran (Rashidi & Schlagintweit, 2019). Relatively numerous sections of algae with vesiculiferous branches could be determined only at the generic level as *Cymopolia* sp. (Figs. 5J–L), since the material is mostly not well preserved and insufficiently abundant for more precise determination. It seems, however that this is a new species, since it differs from the upper Maastrichtian representatives of the genus *Cymopolia* (Parente, 1994, 1997).

According to the aforementioned microfossil association, the age of the well-bedded dolomites along the southern bedrock ridge is determined as upper Campanian to lower Maastrichtian. Thus, the succession of the peritidal dolomites at Buža is referred to the lower part of the Sumartin formation where dolomite prevails (Gušić & Jelaska, 1990).

Stop 3. The Old Town Port: Quaternary superficial deposits

According to the borehole and geophysical data (Građevinski institut, 1981; Fig. 2), the central, flattened part of the Old Town of Dubrovnik is filled by the Quaternary superficial deposits, which cover uneven and heavily fractured carbonate bedrock (Stanko *et al.*, 2023). The natural Quaternary sediments are up to 20 m thick in the central part of the city port (Fig. 6A), and are overlain by up to a few metres of anthropogenic deposit that fill the former, shallow, east–west trending embayment, which was open to the sea to the east (Jelić, 1994). The lower part of the natural sedimentary infill is predominantly clay while in the upper part sand prevails (Građevinski institut, 1981). The sand crops out along the coast north of the Old Town port (Fig. 6B).

Stop 4. Revelin: Lower Aptian limestones

In the eastern part of the northern bedrock ridge, in the basement of the Revelin Fortress, there is an outcrop of massive yellowish-grey limestone more than 20 m long (Fig. 7A). The massive limestone is composed predominantly of skeletal wackestones to packstones and oncoid floatstones that contain requieniid rudists as well as a rich microfossil assemblage.

The massive yellowish-brown micritic limestones contain a relatively rich microfossil association of benthic foraminifera, calcareous algae and fragments of rudist bivalves. Numerous sections of *Lithocodium–Bacinella* aggregates (Fig. 7B) as well as the foraminifera *Praechrysalidina infracretacea* Luperto Sinni, *Voloshinoides murgensis* Luperto Sinni and Masse, miliolids and other benthic foraminifera were found (Fig. 7C), along with rare low-conical orbitolinid foraminifera that most likely belong to the benthic foraminiferal species *Palorbitolina lenticularis* (Blumenbach) (Figs. 7D–E). The microfossil association indicates an upper Barremian to lower Aptian age (Velić, 2007).

Thus, the massive rock unit represents one of the most significant lithostratigraphic units within the Lower Cretaceous succession of the AdCP – the Kanfanar formation (Vlahović *et al.*, 2005). This unit marks the onset of the early Aptian oceanic anoxic event OAE-1a, and is used for correlation of the strata in the Tethyan realm (Huck *et al.*, 2010). The outcrop is probably conformably underlain by Barremian limestones cropping out west of Revelin, along the northern bedrock ridge, although the succession is not continuously exposed (Fig. 2; see Stop 5).

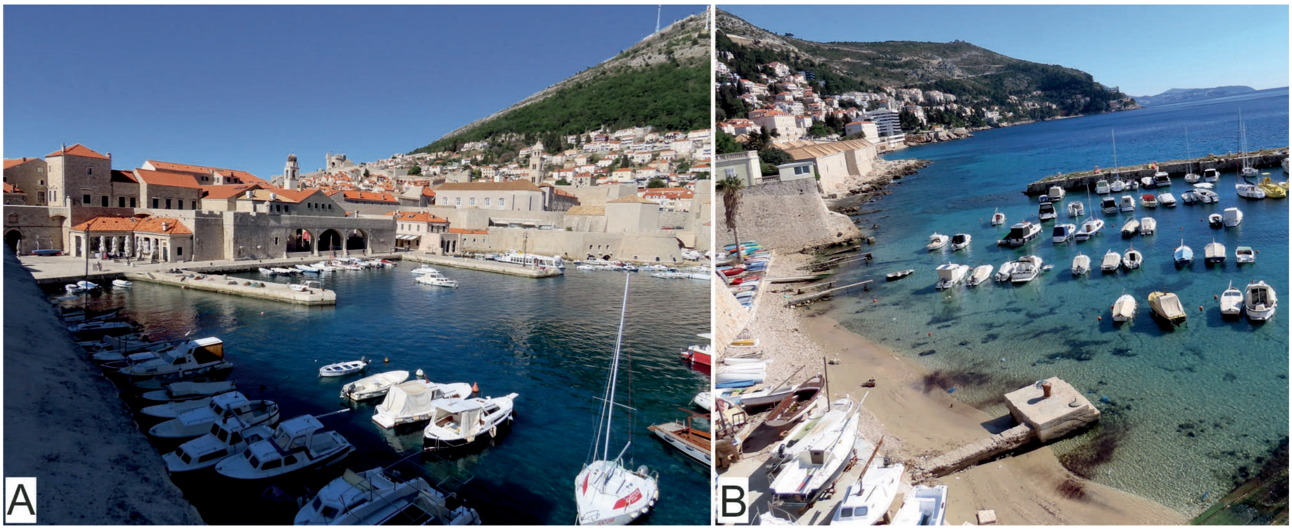

Fig. 6. A) Central part of the Old Town of Dubrovnik port. B) Outcrop of Quaternary sand along the northern coast of the port.

Fig. 7. A) Outcrop of massive yellowish-grey limestone in the basement of the Revelin Fortress (black arrow). B) Photomicrograph of a typical *Lithocodium–Bacinella* biogenic structure. C) Photomicrograph of *Praechrysalidina infracretacea* and *Voloshinoides murgensis*. D–E) Photomicrographs of low-conical orbitolinid foraminifera, the most probably *Palorbitolina lenticularis*.

Fig. 8. A) NE dipping thin to medium-thick bedded Lower Cretaceous peritidal limestones that comprise the northern bedrock ridge. Iza Grada Street is cut into the rock. Minčeta Tower is in the background. B) SW–NE striking anticline of the locally folded Lower Cretaceous peritidal limestones. Minčeta Tower is in the background.

Stop 5. Minčeta (Iza Grada Street): Northern bedrock ridge

The northern bedrock ridge is composed of bedded crystalline dolomites to the south and the well-bedded limestone to the north, and the layers of both units are generally inclined to the NE (Fig. 2). The lighter brownish-grey limestone succession is characterized by alternations of thicker layers of peloidal packstones and thinner layers of microbial laminites, and are referred to as the Lower Cretaceous (Barremian) Goveđari formation (Husinec, 2002; Husinec *et al.*, 2016). Locally, in the basement of the Minčeta Tower, the limestone succession is strongly folded perpendicular to the Dinaric strike (folds are of decametere amplitudes, Fig. 8).

The darker brownish-grey dolomite unit along the contact with the central flattened part of the Old Town is undetermined, although it could be tentatively referred to the Lower Cretaceous Babino polje formation (Husinec, 2002). However, the geological situation is complicated by a fault at the contact with the overlying limestones (Fig. 2).

Acknowledgements

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