Geological Field Trips and Maps

2022
Vol. 14 (1.3)

Società Geologica Italiana

ISPRA
Dipartimento per il
SERVIZIO GEOLOGICO D'ITALIA
Organo Cartografico dello Stato (legge n°68 del 2-2-1960)

Sistema Nazionale per la Protezione dell'Ambiente

ISSN: 2038-4947

Along the hidden Timavo

90° Congresso della Società Geologica Italiana - Trieste, 14-16 settembre 2021.
Pre congress Field Trip T2

https://doi.org/10.3301/GFT.2022.03

GFT&M - *Geological Field Trips and Maps*
Periodico semestrale del Servizio Geologico d'Italia - ISPRA e della Società Geologica Italiana
Geol. F. Trips Maps, Vol.**14** No.1.3 (2022), 69 pp., 42 Figs., 1 tab. (https://doi.org/10.3301/GFT.2022.03)

Along the hidden Timavo

90° Congresso della Società Geologica Italiana - Trieste, 14-16 settembre 2021. Pre congress Field Trip T2

Luca Zini[1], Chiara Calligaris[1], Franco Cucchi[1]

[1] Department of Mathematics and Geosciences, University of Trieste, 34128 Trieste, Italy.

Corresponding author e-mail: calligar@units.it

Cover page Figure: The Timavo springs: scuba-diving exploration in the Colombi cave (photo courtesy: A. Maizan).

ISSN: 2038-4947 [online]

http://gftm.socgeol.it/

Index

Information

Abstract 4
Program Summary 4
Safety and emergency numbers 5
Accommodation 5

Excursion notes

The Classical Karst.. 7
Geological and structural setting.. 10
Geomorphological settings.. 15
Hydrogeological characteristics.. 30

Itinerary

Stop 1 - Škocjan sinkhole and the epiphreatic conduits of the Timavo underground system (45° 39′ 47,96″N – 13° 59′ 21,58″E) 33
Stop 2 - Grotta Gigante cave and the other Timavo caves (45° 42′ 34,76″N – 13° 45′ 53,00″E) 43
Stop 3 – Doberdò Lake and its surroundings (45° 50′ 30,32″N – 13° 32′ 52,62″E) 52
Stop 4 – The outflows: Timavo Springs and other minor springs (45° 47′ 19,00″ – 13° 35′ 22,02″E) 57
Back to Trieste 63
References 65

https://doi.org/10.3301/GFT.2022.03

Abstract

Almost 200 years after the first studies on the Timavo River, researchers are still carrying out their investigations, thanks in part to European projects, aiming to improve the knowledge on the Reka/Timavo cross-border aquifer in order to protect the groundwater resource through quantitative and qualitative monitoring of the underground waters. The Classical Karst Region is, in fact, home to what is generically called the underground Timavo network, a set of underground drainage paths developed well below sea level. The waters flow both in large conduits and in small fractures characterizing the rock mass. Water is the engine that created all these hypogean features and the surface karst morphotypes thanks to the chemical (dissolution) and physical (erosion) processes. The topographical surface is studded with thousands of dolines. Throughout the territory, more than 5.000 caves have been explored, of which more than 150 have a development exceeding a hundred meters. Out of all of them, only less than a dozen reach the water base level (Timavo caves) and others are crossed by water during floods. In this framework is the field trip proposed in the guide book designed as an accompaniment for visitors and participants in the 90° SGI Congress. The excursion goes along the underground path of the Reka/Timavo River, starting from Slovenia, visiting the Škocjan caves in which the river disappears underground (UNESCO world heritage site since 1986). The excursion moves on to the Grotta Gigante cave with another stop at the surface dissolution laboratory and the museum, after which visitors will take part in the excellent sightseeing to be found at Doberdò Lake and at the Timavo Springs where freshwaters meet the salty Adriatic Sea.

Keywords
karst, hydrogeology, carbonate rocks, Classical Karst, caves.

Program Summary

"Along the hidden Timavo" is part of the 90th Congress of the Italian Geological Society, Trieste Italy, 2021. The guide aims at leading the reader, in the karst word, surficial (epigean) and sub-surficial (hypogean), following the water course of the Reka/Timavo River; seeing it disappear, moving over the barren landscape under which the mysterious river flows, and seeing it outflowing to the sea. While entering the karst, it will be possible to know more about the complex hydrogeology of the 750 km^2 of the Classical Karst Region; hard facts are still evasive and drive ongoing research. Scientific investigations have a dual purpose: to learn about hydrodynamics and to protect this precious water resource. Within the proposed tour, four are the expected stops (Fig. 1). From east to west: ***STOP 1*** - Škocjan sinkhole and the epiphreatic conduits of the Timavo underground system; (45° 39′ 47,96′′N – 13° 59′ 21,58′′E); ***STOP 2*** - Grotta Gigante cave and the other Timavo caves; (45° 42′ 34,76′′N – 13° 45′ 53,00′′E); ***STOP 3 -*** Doberdò Lake and its surroundings; (45° 50′ 30,32′′N – 13° 32′ 52,62′′E) and ***STOP 4 -*** The outflows: Timavo Springs and the other minor springs (45° 47′ 19,00′′N – 13° 35′ 22,02′′E).

Safety and emergency numbers

Emergency contact numbers, hospitals and first-aid
112 - Carabinieri
113 - Police
115 - Fire Department
118 - First Aid
Guardia Medica - Servizio di Continuità Assistenziale, Via Galvani, 1, 34074 Monfalcone (GO), open after 8 p.m., phone 0481 487603
Numero Unico per i Servizi Sanitari Non Urgenti di Trieste, **800 614 302, open 24 h, 365 days per year**
Hospitals
San Polo Hospital, Via Galvani, 1, 34074 Monfalcone (GO), open h24, phone 0481 4871
Cattinara Hospital, Piazza Ospedale, 1, 34100 Trieste (TS), open h24, phone 040 399 1111

COVID-19 information: asugi.sanita.fvg.it

Accommodation

There are several tourist accommodations including hotels, guesthouses, bed and breakfast, private rooms and camp sites (https://www.turismofvg.it/home).

https://doi.org/10.3301/GFT.2022.03

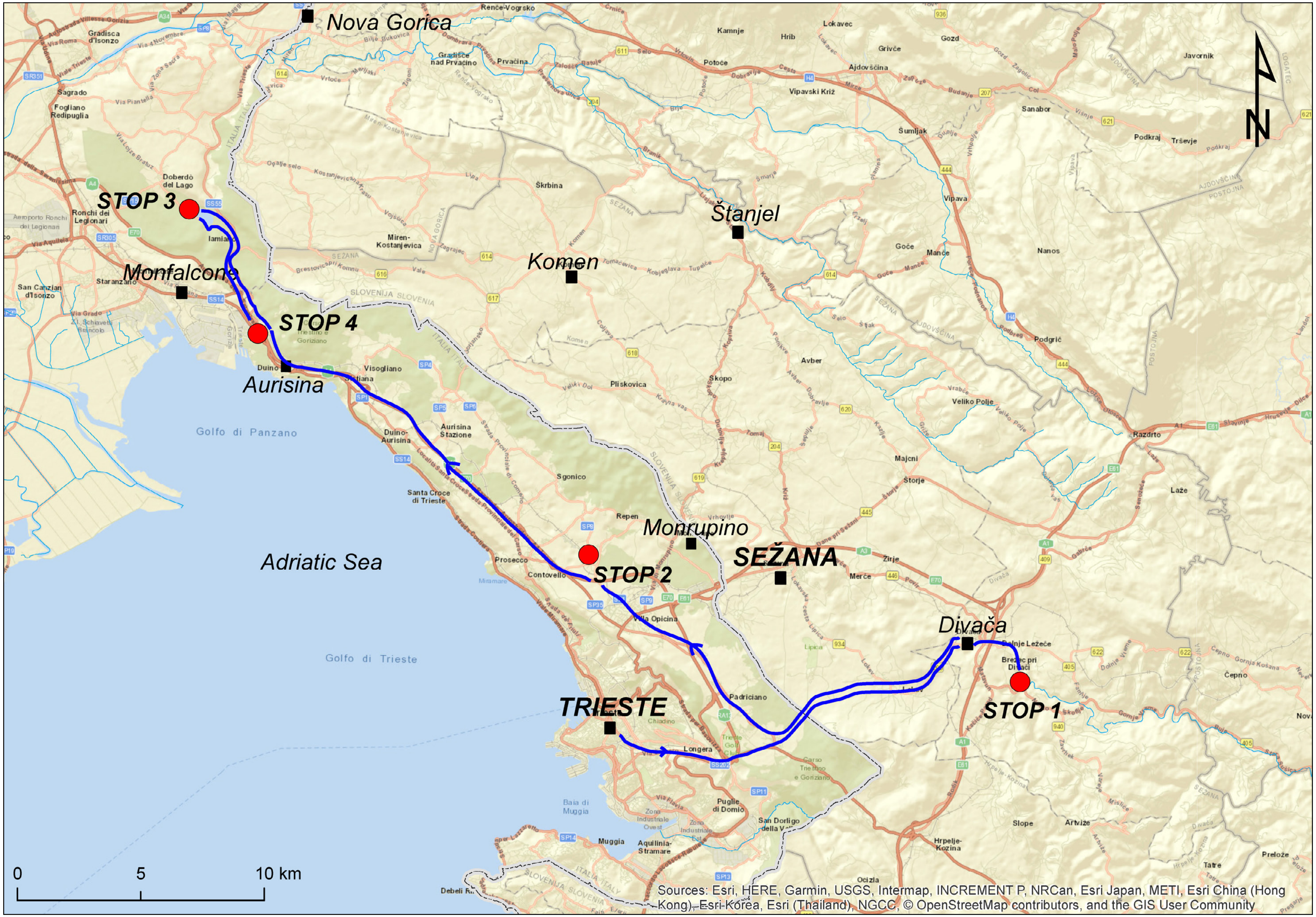


Fig. 1 - Excursion itinerary with four stops.

https://doi.org/10.3301/GFT.2022.03

The Classical Karst

"Karstology" is the name of the scientific discipline which studies karst environments; "karst phenomena" are the morphogenetic processes typical of these environments, "karst morphologies" are the features which result from these morphogenetic processes. The word "karst" includes all the connected phenomenologies, also distinguished in "underground karst" and "epigean karst" features (Cvijic, 1893).

In the Encyclopedia of "Caves and karst sciences" (Gunn, 2004), the entry "karst" reads: *"karst" is the germanicisation of a regional place name, "Kras" (Slovenian) or "Il Carso" (Italian) given to the hinterland of Trieste Bay in the northwest Dinaric area. It is believed to derive from a pre-Indo-European word "karra" meaning stone... Already in Roman times (Latin = Carsus) it defined "stony ground".... The name was promulgated by travellers in the 17th and 18th centuries and in the 19th century became widely adopted to describe the similar limestone landscapes extending from north Italy to Greece. The "father" of karst studies, Jovan Cvijić, confirmed it when he entitled the first major western monograph on solutional landscapes "Das Karstphaenomen" in 1893. Sawicki in 1909 expanded it as the global term for such topographies when describing tropical sites he had visited. It is the accepted term in China, the other great historic centre of dissolutional landscape studies*. In turn, other toponyms are derived such as Carnia, Carinthia, Carniola (Kranic, 1997).

That the Karst has its own physiographic unit, as well as geomorphological ones, has over time favored the symbiosis between the topographical unit and the phenomenological scientific meaning. After all, the Classical Karst, intended as the hinterland of Trieste, is the "Gateway to the East", an important hub between the Mediterranean and Europe, between the Po plain (of which the Friulian plain is an extension) and the Balkan Peninsula. The Dinaric Range separates Ljubljana basin from the Adriatic: the Postojna saddle is the lowest passage (610 m a.s.l.) between these two worlds, or rather, between the Alps and the Dinarides, between the Mediterranean and the Adriatic and Central Europe and the Danube.

Baron Janez Vajkard Valvasor, a very acute geographic observer of his times, wrote in 1689: ... *there is a vast desert with lakes of pure water ... the Earth is diffusely stony ... in several places the look extends miles away, but everything is grey, nothing is green, wherever there is rock ... in other places people live with abundant lake waters ... sometimes the inhabitants do not have a wood and survive with minute cultivated fields. The inhabitants, who look far for wood and water, replace them with wine, which is of good quality, red or white, of various types ... (Valvasor, 1689) (Fig. 2).*

https://doi.org/10.3301/GFT.2022.03

Fig. 2 - In this extract from the *Nova Descriptione del Friuli*, the work of an anonymous geographer from 1561, the CHARSO extends N to the Vipava River valley and S is bordered by the Gulf of Trieste and Istria. In ancient cartography, it is the term Carso that describes this area. Later, the German word Karst was coined, which entered into international use. Slovenians call it Kras. In English versions, the term Classical Karst Region is now used (modified after Cucchi et al., 2015).

The Classical Karst Region

The Classical Karst Region lies in the NW part of the External Dinarides. It represents the northernmost sector of the karst territory in the Eastern Adriatic. The Classical Karst Region is the part of the plateau where limestones and dolomites are present. It is bordered to the W and NW by alluvial deposits from the Soča/Isonzo River and the flysch outcrops of the Trieste Gulf. To the NE the flysch of the Vipava valley create a natural boundary. To the E, the plateau extends to the Notranjska Reka valley and the flysch zone of the Brkini area. The karst plateau, also known as the ‘Trieste-Komen plateau’ has a length of about 60 km and a width of about 15 km, covering an area of approximately 750 km^2 (Cucchi et al., 2015; Jurkovšek et al., 2016) of carbonate rocks Cretaceous to Palaeogene in age.

Structurally the Classical Karst Region is an asymmetrical NW–SE oriented anticline whose structure is complicated by a set of secondary folds and faults. In the coastal areas, the layers become subvertical and sometimes overturned. At the border N and S of the anticline the Eocene flysch acts as the lateral aquiclude of the carbonate aquifer.

Geomorphologically it can be defined as a mature karst, as evidenced by the density of karst features such as caves and dolines (Gams, 1993; Knez and Slabe, 2002; Blatnik et al., 2020). This intense karstification, along with the scarce presence of surface deposits (Fig. 3), favours the effective infiltration to the aquifer (Savi et

https://doi.org/10.3301/GFT.2022.03

Fig. 3 - Typical karst landscape with residual blocks and *griza* of the Classical Karst Region on the southern slope of Mt. Cosici, Povir fm. (Jurkovšek et al., 2016, *cfr.* "Monte Coste limestone", Consorti et al., 2021).

al., 2018; Nardini et al., 2021), which in turn is also reached by the leakages of two rivers present in the area (Notranjska Reka/Timavo Superiore and Soča/Isonzo). At the extreme SE of the karst plateau, the Notranjska Reka flows for approximately 50 km over a flysch basin. Once this river reaches the carbonates, it is completely swallowed, disappearing into the Vreme and Škocjan swallow holes with an average discharge of about 8 m^3/s. On the western side of the study area, the Soča/Isonzo River (with its spring in the Slovenian Julian Alps), has an influent character toward the alluvial plain, which in turn recharges the Classical Karst hydrostructure with about 10 m^3/s (Zini et al., 2013; Calligaris et al., 2019a). The third contribution is due to the effective infiltration estimated at 21 m^3/s (Civita et al., 1995). This autogenic recharge has a specific geochemical signature and was defined as *karst waters* (Gemiti, 1984; Doctor et al. 2000; Calligaris et al., 2018; Calligaris et al., 2019b).
The three inputs exit the system from a wide spring area in the line along the Adriatic Coast, which extends for about 9 km, from Monfalcone (to the NW of the Adriatic Coast) to the Aurisina spring (to the SE of the Adriatic Coast), consisting of more than 50 spring points having a total discharge of about 35 m^3/s (Gemiti, 1984; Zini et al., 2013).

Geological and structural setting

At present, the most updated geological map was created in the framework of the HYDROKARST and RoofOfRock European projects and later published by Jurkovšek et al. (2016). It is the first, and actually also the only one, at a scale of 1:50,000 related to the whole area of the Classical Karst Region and it will be the geological reference for this excursion (Fig. 4). It is the synthesis of previous Italian (Martinis, 1951; D’Ambrosi, 1953; Cucchi et al., 1989; Carulli, 2011; Cucchi and Piano, 2013) and Slovenian works (Buser et al., 1967; 1968; Pleničar et al., 1973; Jurkovšek, 2010) where, thanks to collaboration with Slovenian geologists during the most recent international projects, limestones and, subordinately, dolostones were recently grouped into informal and provisional lithostratigraphic units. Figure 5 reports the available lithostratigraphic column published by Jurkovšek et al. (2016) and the comparison with what is the ongoing researches by Consorti et al (2021).
As defined by Vlahović et al. (2005) and by Velić (2007), the outcropping rocks of the Classical Karst Region are composed of sediments of the former Adriatic-Dinaric Carbonate Platform (AdCP) having the latter, a total thickness of about 6,000 m. Only the Cretaceous - Palaeogene sequence outcrops in the Classical Karst Region, characterised by a total thickness of about 2,000 m. The sequence is the evidence of a complex palaeoenvironmental evolution, which involved the platform by causing it to pass through several marine - lagoon phases alternating

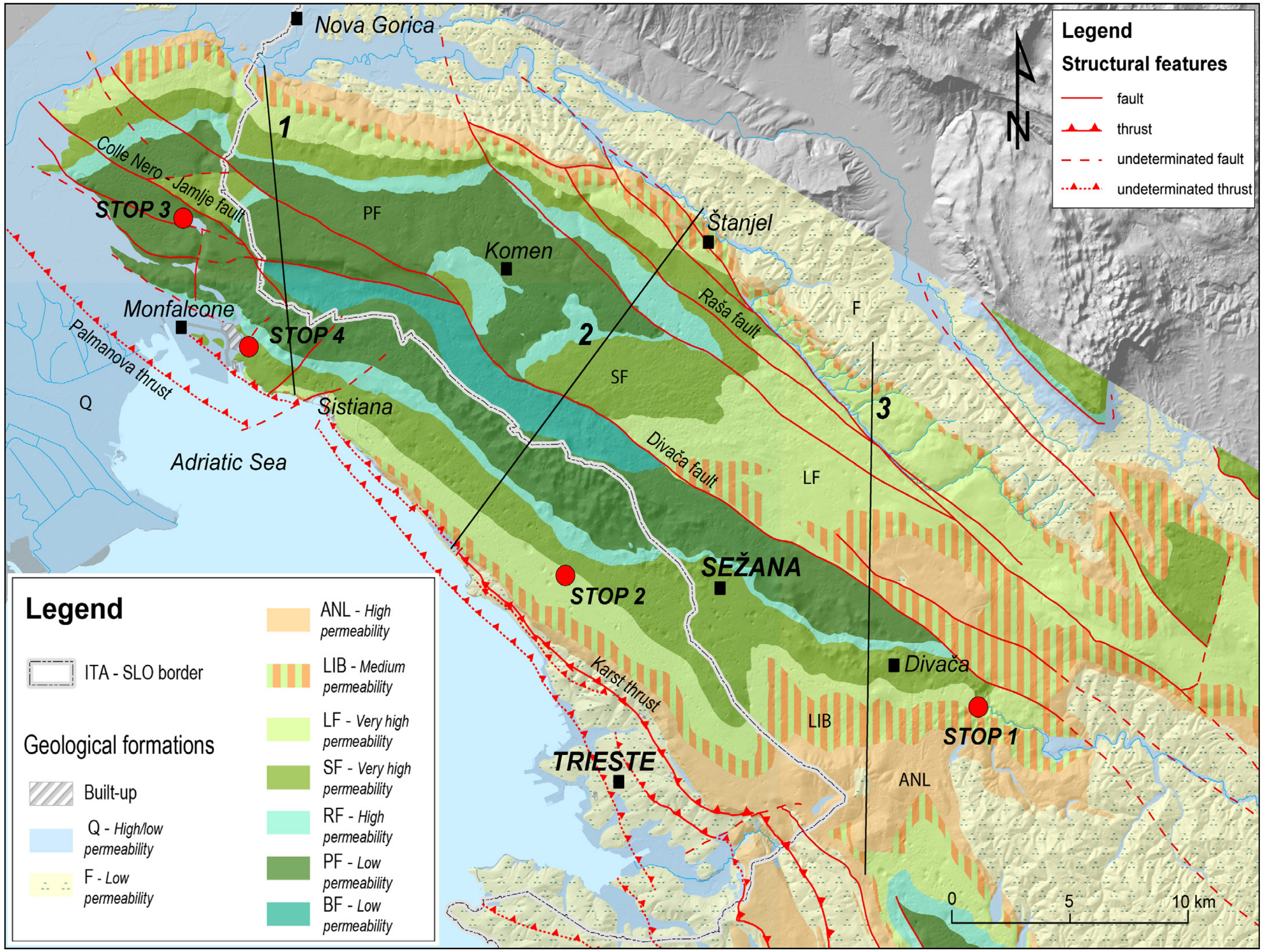
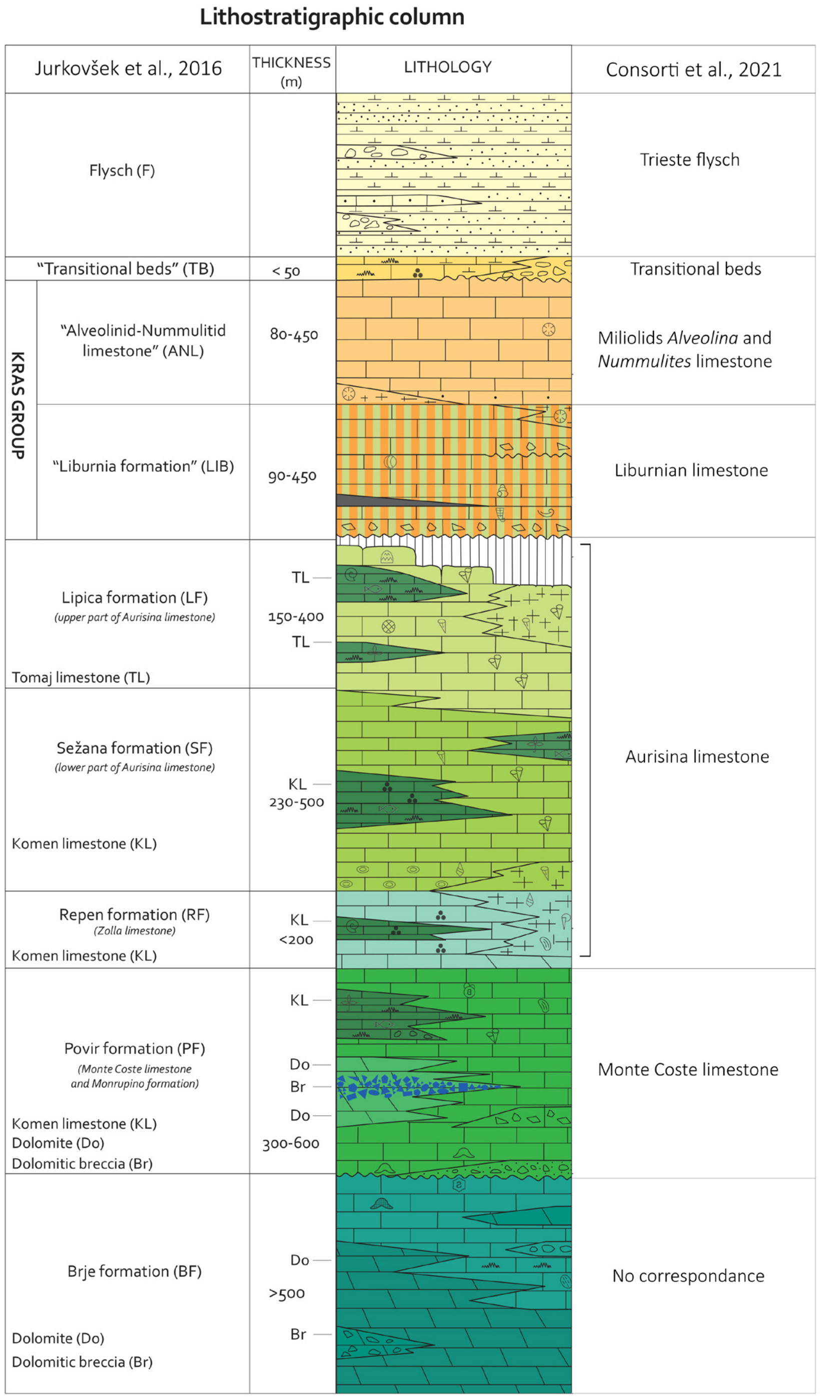


Fig. 4 - Simplified geological map of the Classical Karst Region (modified after Jurkovšek et al., 2016). In black named 1, 2 and 3, the traces of the cross-sections. Q (Quaternary deposits); F (Flysch, "Trieste flysch"); ANL (Alveolinid-Nummulitid limestone, "Miliolid, *Alveolina* and *Nummulites* limestone"); LIB (Liburnia formation, "Liburnian limestone"); LF (Lipica formation, "Aurisina limestone"); SF (Sežana formation, "Aurisina limestone"); RF (Repen formation, "Aurisina limestone"); PF (Povir formation, "Monte Coste limestone"); BF (Brje formation, no correspondence). The terms in parenthesis refer, the first to Jurkovšek et al., 2016 and the second to Consorti et al., 2021, respectively.

with emerging phases, up to the final drowning. The oldest exposed unit is the Brje formation (Lower Cretaceous) (Jurkovšek et al., 2016), deposited in a protected internal platform environment, shallow calm shelf having lagoon characteristics. The environment was often characterised by anoxic conditions and intense evaporation, by rapid sea level oscillations with alternation of evaporitic lagoon phases, marine episodes and the presence of local emersions (limestone lenses and red-yellow breccias linked to karst processes). The signs of the succeeding sea-level drop and the reestablishment of shallow-marine conditions are contained in the Povir fm. (Lower Cretaceous) (*cfr.* "Monte Coste limestone" – Consorti et al., 2021), bedded, locally platy with thicker dolomite intercalations (Fig. 6). During the Cretaceous, the drowning of the carbonate platform was almost entirely caused by the eustatic sea-level rise, which occurred in the Cenomanian and Turonian

https://doi.org/10.3301/GFT.2022.03



(Vlahović et al., 2002). The result was the deposition of the Repen fm.(*cfr.* "Aurisina limestone" – Consorti et al., 2021), characterized by the appearance of many pelagic fossils. Within the Turonian eustatic sea-level drop, the sedimentation of the Repen ended and there was the reestablishment of shallow-water environments where limestone of the Sežana fm. (*cfr.* "Aurisina limestone" – Consorti et al., 2021) sedimented. Scrolling up the lithostratigraphic sequence, it is possible to find the Lipica fm. (Upper Cretaceous) (*cfr.* "Aurisina limestone" – Consorti et al., 2021) which was deposited mostly in the open part of the shelf, locally in its restricted part, as well as in an environment with littoral conditions. Due to its structural characteristics (thick-bedded massive structure and homogeneous texture) these limestones are economically very important for the Classical Karst Region. After a subaerial exposure of this part of the platform, and palaeokarstification of the Lipica fm. (Fig. 7), a new carbonatic deposition was formed ("Liburnia formation" and "Alveolinid-Nummulitid limestone"). The Liburnia fm. (*cfr.* "Liburnian limestone" – Consorti et al., 2021) (Maastrichtian - Palaeogene = K/Pg boundary) and the "Alveolinid-Nummulitid limestone" (Fig. 8) (*cfr.* "Miliolid, *Alveolina* and *Nummulites* limestone" – Consorti et al., 2021) (Palaeocene-Eocene) formation, which in their upper boundary are clearly limited by the basinal clastites, are typical to these paralic and shallow-marine carbonates. In the Eocene, the carbonate platform was finally buried by the deep-water siliciclastic sediments of the advancing foreland basin of the Flysch (*cfr.* "Trieste flysch" – Consorti et al., 2021) (Fig. 9).

Fig. 5 - Schematic lithostratigraphic column: comparison between Jurkovšek et al. (2016) and Consorti et al., 2021.

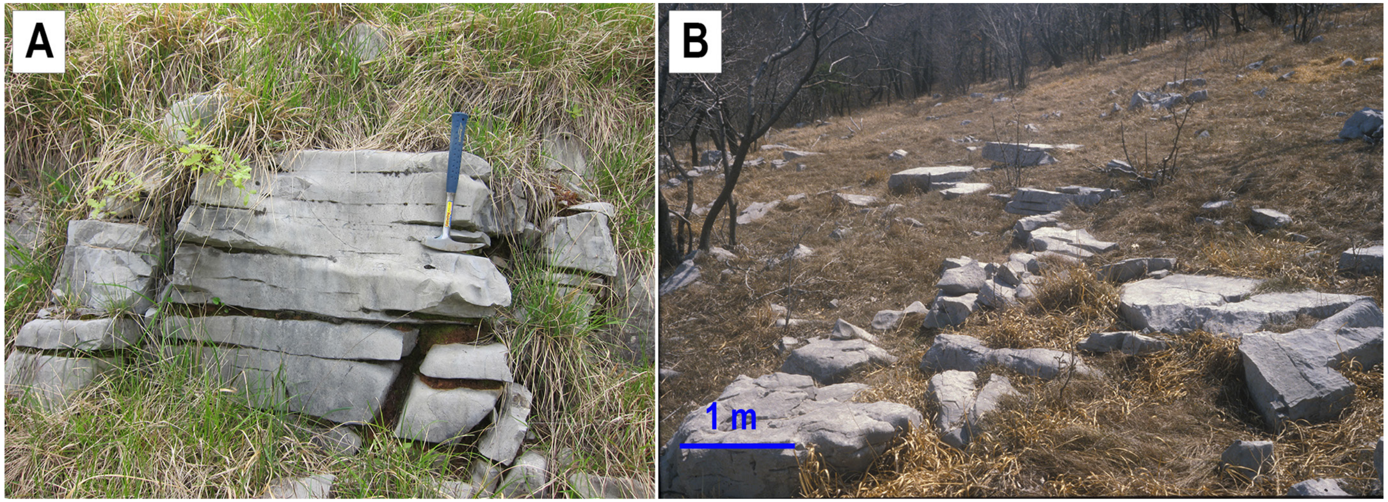


Fig. 6 - A) Platy limestones in the Povir fm. (Jurkovšek et al., 2016, *cfr.* "Monte Coste limestone", Consorti et al., 2021); B) typical landscape morphology of the platy limestones near Ceroglje (N of Sistiana bay).

Fig. 7 - Lipica fm. (Jurkovšek et al., 2016, *cfr.* "Aurisina limestone", Consorti et al., 2021): the epikarst in the rudist limestone.

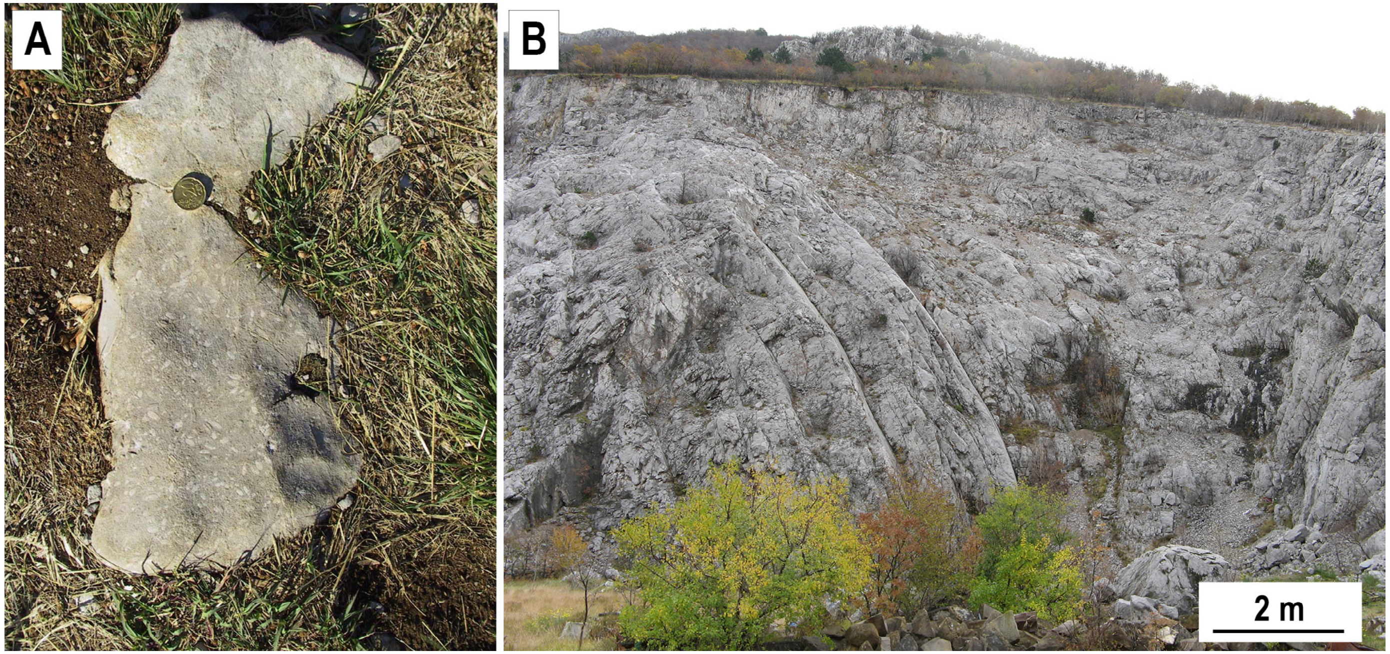


Fig. 8 - "Alveolinid-Nummulitid limestone" (Jurkovšek et al., 2016, *cfr.* "Miliolid, *Alveolina* and *Nummulites* limestone", Consorti et al., 2021) outcrop at Mt. Carso in a quarry close to the Karst thrust: (A) *Alveolina*-rich limestone; (B) panoramic view of the quarry.

Fig. 9 - Flysch (Jurkovšek et al., 2016, *cfr.* "Trieste flysch", Consorti et al., 2021) outcrop in the Rosandra Valley: detail of a small fold.

The Adria lithospheric microplate was initially connected to the African plate; starting from the Mesozoic it became independent (Jurkovšek et al. 2016). On its northern edge lies the Classical Karst Region anticlinorium. The anticlinorium itself, called the Trieste-Komen anticlinorium, is also known as the Komen thrust sheet if we define it only in a tectonic sense (Placer, 1998). Around it, looking toward the N and NE, it grades into the Gorizia and Vipava synclinorium and into the Rijeka synclinorium structure to the SW.
The anticlinorium is dissected into smaller tectonic blocks by several steep strike-slip faults NW–SE oriented (Dinaric direction) as the Colle Nero – Jamlje fault (Fig. 10), Divača and Raša faults. Important E-W oriented lower order faults can also be identified in the area. The Classical Karst Region, on its western Italian border, faces the Gulf of Trieste where a frontal Dinaric ramp system characterises the area. The system is made up by segments of the Palmanova thrust which in turn is connected towards the south to the Karst thrust (Slovenia). Along the flysch slopes and offshore, a system of minor thrusts is hypothesised (Fig. 11).
The major effect of the orogenic compression is the overthrusting of the carbonate platform succession on the turbiditic one.

Geomorphological settings

The Classical Karst Region plateau rises from the Soča/Isonzo River plain and from the sea of the Gulf of Trieste, up to altitudes ranging from hundred meters in correspondence of Doberdò del Lago in the NW, up to 400 - 450 m a.s.l. at Divača and Škocjan to the SE. With the same direction of the inclined main axis of the plateau we can identify a hilly alignment about 4 km wide which is adjacent towards the NE to an elongated depression a couple of kilometres wide. The hilly alignment is conditioned by the prevalence of dolostones outcrops over limestones, the depression follows the Divača and Doberdò faults. The northeastern part of the area is marked by a set of river networks with drainage patterns ranging from dendritic to parallel, typical of areas where low permeable and moderately erodible rocks such as marlstone and sandstone in Flysch fm. facies outcrop (Cucchi and Zini, 2009). The particular geological characteristics, the geographic location and the prolonged exposure to atmospheric agents have led the Classical Karst Region to represent the essence of karst. On the surface, during fifteen million years of evolution, the waters have eroded the flysch cover and dissolved millions of cubic meters of limestone, giving the territory a unique morphology in which the starting surface is now almost unrecognisable. In the approximately 750 km^2 that make up the territory of the Classical Karst Region, dissolutive karst morphologies that dominate the erosive ones in number and size have developed and continue

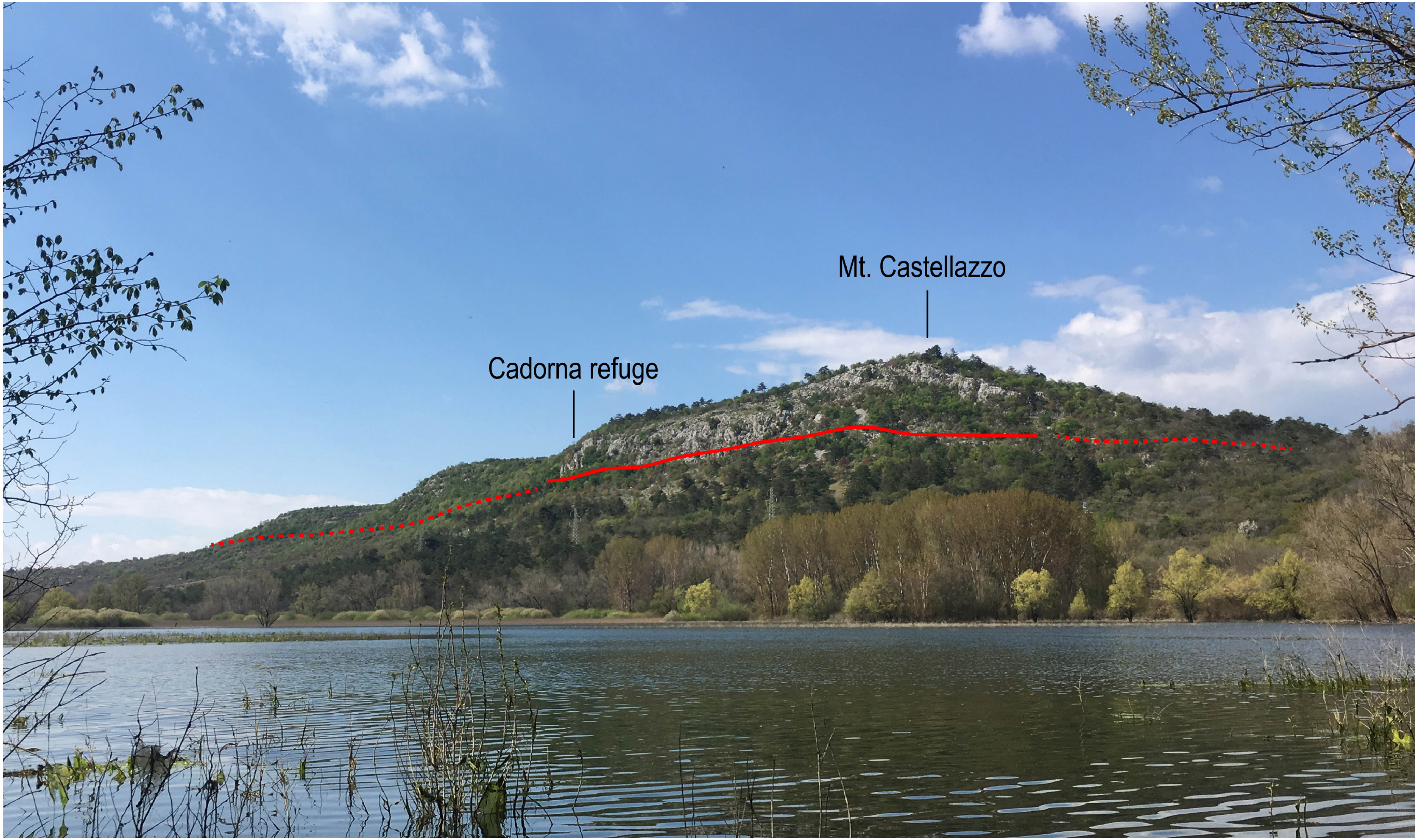


Fig. 10 - Castellazzo, Sežana fm. (Jurkovšek et al., 2016, *cfr*. "Aurisina limestone", Consorti et al., 2021) seen from Doberdò Lake. The red line represents the Colle Nero - Jamlje fault. General Cadorna visited the troops fighting at the front during World War I. He stopped in this pleasant place and the mountain hut was dedicated to him.

https://doi.org/10.3301/GFT.2022.03

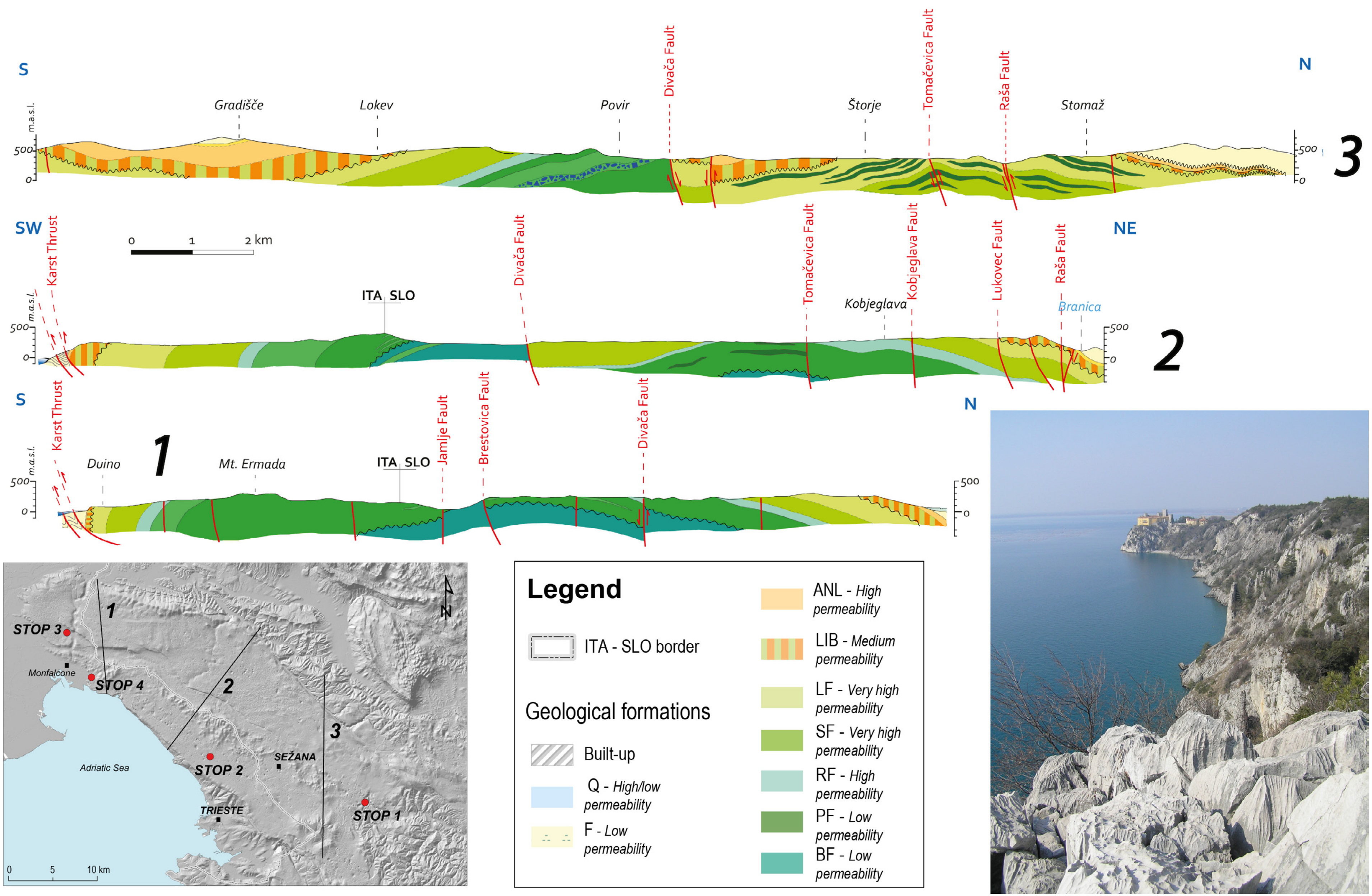


Fig. 11 - Geological cross sections (modified after Jurkovšek et al., 2016). At the bottom, a hillshade view (on the left) with the traces of the three cross sections and a panoramic view (on the right) of the carbonate karstified cliffs from Rilke track.

to develop. These morphotypes are strongly dependent on geological and structural conditions.
Karst dissolution is an extremely slow process: with current climates 0.01- 0.03 mm/year of rock are dissolved (Cucchi et al., 1996; Furlani et al., 2009a) taking thousands of years to have significant karst shapes and "relevant" morphological evolution. The result is that the landscape understood as today's morphology is very similar to the prehistoric one. This means, for example, that in the past, as now, the depressions in which to keep animals, the caves in which to shelter, the hills from which to keep watch on the territory were numerous and easily accessible.
In this environment the most representative morphological element is certainly the doline (Fig. 12) which gives the topographical surface an irregular and tormented appearance. Where the limestones outcrop, there are dolines of all sizes, but those with a diameter less than 50 m prevail. There are zones in which large depressions of considerable depth prevail (from Sežana to Sistiana passing through Monrupino, Gabrovizza and San Pelagio or from Dobravlje to Komen, or between Matavun and Divača). There are areas in which dolines are uniformly distributed and have a high density, greater than 75 dolines/km^2, as occurring in the westernmost part of the karst and in the karst of Doberdò del Lago (Fig. 13). Dolines lined up along well-defined directions are very frequent (N-S and NW-SE). The rest of the territory has a patchy distribution with a density between 40 and 75 dolines/km^2 (Zini et al., 2015).
In the study area, more than 22,400 dolines have been identified, of which about 5,900 are in Italy and 16,500 in Slovenia, covering a total surface of about 20 km^2. On the entire sample, the average diameter is less than 50 m (about 62% of the entire population). 31.5% of the considered depressions have a diameter between 50 and 100 m, while only a dozen have a diameter greater than 500 m. A recent elaboration using GIS covering the 200 km^2 of the Italian part of the Classical Karst Region (Zini et al., 2015; Cucchi et al., 2015) has identified 400 dolines with a diameter greater than 100 m and 1,600 with a diameter between 100 and 50 m. The depths of the major depressions are between 30 and 70 m. As a percentage, it is believed that almost 40% of the dolines are the result of the collapse of the ceilings of underlying caves (Cucchi et al., 2015). On the Slovenian side, two of the most notable collapse dolines must be mentioned: Radvanj with 31 ha and 820 m in diameter, and Risnik with 5 ha and 250 m in diameter, both located slightly less than 500 m south of the Divača Railway Station (Gospodarič, 1985; Šušteršič, 2006; Kovačič and Ravbar, 2013; Žvab Rožič et al., 2015).
In general, in the entire area the structural imprinting is evident on the depressions especially on the ones hosting Doberdò and Pietrarossa Lakes, two base-level poljes connected to the *Colle Nero fault*, a western extension of the *Brestovica* and the *Jamlje fault*. On the other hand, the origin of the two N-S oriented valleys has been debated.

https://doi.org/10.3301/GFT.2022.03

Fig. 12 - Solution doline very close to the road to Doberdò Lake. The bottom of the doline is usually cultivated.

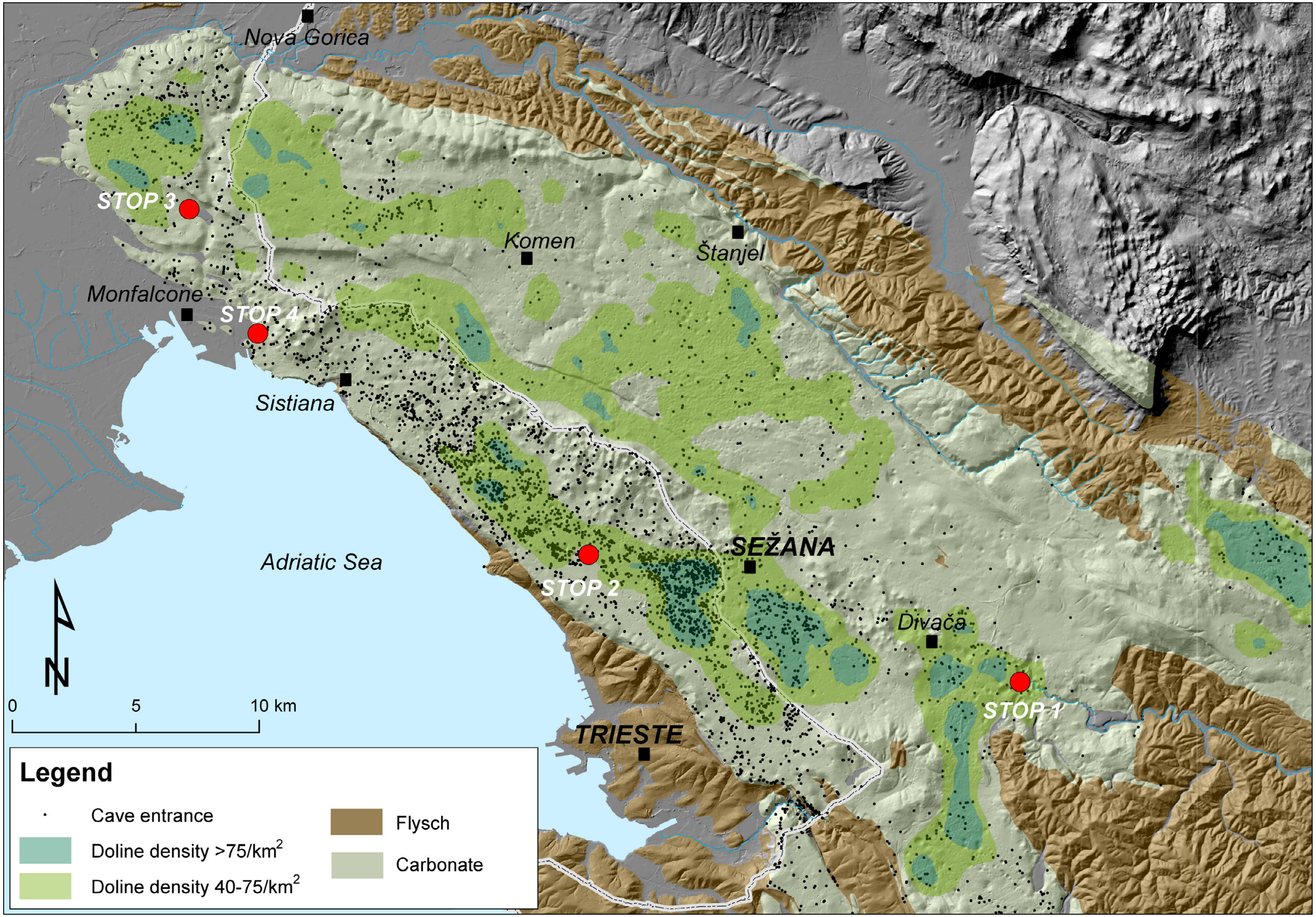


Fig. 13 - Geomorphological map of the Classical Karst Region.

Among the morphologies present in the area, the spectacular sub-vertical walls that characterize the cliff along the coast certainly stand out (Fig. 13). They are the result of the significant energy conferred on the front of the overthrust of the *Trieste-Komen anticlinorium* by the complex system of Dinaric overthrows such as the *Karst thrust* and the *Palmanova thrust* (Fig. 14).
The Val Rosandra valley, on the southern border of the Classical Karst Region, can be seen as a separate area, deeply entrenched into limestones where the morphology is mainly conditioned by lithology and tectonics.
These “large” morphologies are complemented by smaller ones which constitute the karst heritage that justifies the Classical appellation given to the Classical Karst Region: *karrenfields*, *kamenitze*, *dissolution holes*, *flutes*, *furrows*, *karst crevasses*, rounded shapes due to subcutaneous karst and sharp shapes due to accelerated dissolution by marine aerosol, *residual blocks*, *hums* and *towers*.

The epigean karst

It is in observing the so-called “small shapes” that the particularities of the epigean karst can be understood. The slow progress of dissolution, only partially accelerated by erosion, finds in geological features the conditions that lead it to give life to changing landscapes. First of all, petrography: calcite is more soluble than dolomite; micrite more than sparite; isolated crystals more than those present in the organic remains. The difference is a few hundredths of a millimetre/year, but the hundredths in a thousand years become centimetres and then meters and the differences become notable. Then the degree of subdivision: a massive layer is less affected by the processes than a decimetric one which resists even less when laminated; the intense fissuring leads to a widespread karst (*grize*), while few defined fissures leads to a karst developed in few and defined waterways (*karst crevasses*). On closer inspection, the geological observations merge with the geographic ones allowing for a different perspective. In the Classical Karst Region it is possible to observe the *solution flutes* (Fig. 15) (ITA-*scannellature*, DEU-*Rillenkarren*) and the *solution grooves* (ITA-*solchi carsici*, DEU-*Wandkarren*) due to the planar or linear flow of water which are slow and therefore active for longer if the slopes are slight, fast if the slopes are steep, meandering (DEU-*Meanderkarren*) if the area is flat. The individual karren then have sharp crests if the rock is exposed, rounded if it is or was covered by soils. If rain water is collected in a well-restricted area, a *kamenitza* can form (a Slavic term that has become international, ITA-*vaschetta di corrosione*, DEU-*Napfkarren*, ENG-*solution pan*) whose shape depends on lithology and fracturing, as well as on the speed with which it is emptied from the lateral channels. If an open fracture then captures the waters, *grikes* (ITA-*crepacci carsici*, DEU-*Kluftkarren*) are formed on the walls in which *solution flutes* form. Where sub-horizontal or slightly

Fig. 14 - Duino cliffs. In the background, the Sistiana bay with the rudist limestones of the Lipica fm. Dipping towards SE of 35°; in the foreground the “Alveolinid-Nummulitid limestone” (Jurkovšek et al., 2016, *cfr.* “Miliolid, *Alveolina* and *Nummulites* limestone”, Consorti et al., 2021) verticalised by the Karst thrust.

Fig. 15 - *Solution flutes, solution grooves, grikes* enhanced by the marine aereosol along the Duino cliffs (“Alveolinid-Nummulitid limestone”, Jurkovšek et al., 2016, *cfr*. Miliolid, *Alveolina* and *Nummulites* limestone, Consorti et al., 2021).

inclined layers outcrop, the so-called *limestone pavements* (ITA-*campi solcati*, DEU- *karrenfeld*) can be found (Fig. 16 and Fig. 17). Their appearance depends on the steepness of the exposed surfaces and the intensity and geometry of the fracturing.
Over time "*covered karst*" can develop, even where the soil is not very thick and the slopes are gentle. If the bedrock emerges from loose deposits, we can see what is called the "*block karst*" or the "*limestone pavement*" or *grize* (ITA-*pietraie carsiche*) where vegetation cannot take root due to a lack of humus and water. Residual blocks as *hum* (ITA – *torrioni*), are portrayed in Figure 18.

Rosandra Valley

"The Valley", as the inhabitants call it, is at the extreme eastern side of the Classical Karst Region plateau. It is a canyon-like valley excavated in the Cenozoic limestone by the Rosandra River and represents a rare example of karst river valley with surface hydrology. Its origin is mainly due to the presence of faults and overthrusts and the different predisposition to erosion between limestone and marls makes it a beautiful example of lithological and structural control on morphogenesis. The whole area, and in particular Mt. Stena, is characterised by surface and underground karst. 100 caves have been surveyed, some of which are more than 100 m long. Among them one of the most beautiful is the Savi cave, rich in speleothems, the growth axis of which are characterised by geochemical and physical changes (controlled by climate as well as by the dynamics of the host karst system) (Belli et al., 2013; Stoykova et al., 2003). The Valley was known also in the past seen that it was used to carry the salt from the coast to the inland villages. Therefore, the existing tracks of the railway line connecting Trieste with Erpelle built up starting from 1885, have now been converted into a bicycle path, which means that the old path is still in use. Caves with prehistoric remains, ruins of castles and hill forts, mills, country churches, the ruins of the Roman aqueduct and abandoned quarries prove the intense and ancient settlements in the area.
The Valley's peculiar climatic and geomorphologic conditions and its geographic location make it a special and important habitat (Cucchi et al., 2012).

The hypogean karst

In the area covered by the study 4,077 caves can be found, of which 3,060 are in Italy and 1,017 are in Slovenia. The numerical difference is due to the intense speleological activity in Italy since the mid-1800s, furthermore, there is a difference in the classification and cataloguing of a cave according to the long/deep characteristics: in Slovenia, a feature can be defined as a cave if it is at least 10 m long/deep, while in Italy it needs only 5

https://doi.org/10.3301/GFT.2022.03

Fig. 16 - *Campi solcati* of Borgo Grotta Gigante. A sub-horizontal layer in the Sežana fm. (Jurkovšek et al., 2016, *cfr.* "Aurisina limestone", Consorti et al., 2021) with important thickness which favours the formation of *kamenitzas, grikes* and *solution flutes*.

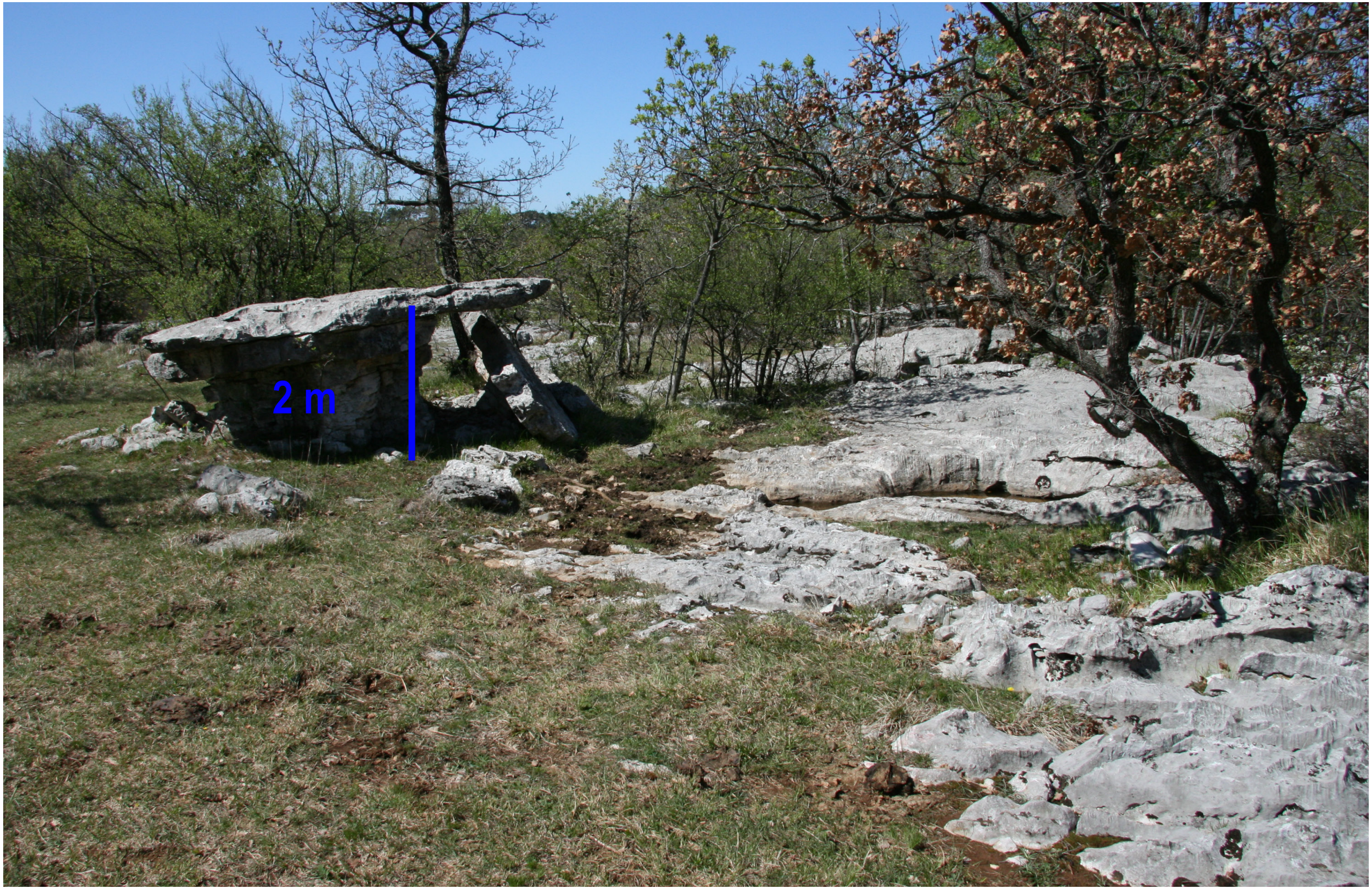


Fig. 17 - *Campi solcati* of Borgo Grotta Gigante. A thick hard-wearing layer in the Sežana fm. (Jurkovšek et al., 2016, *cfr*. “Aurisina limestone”, Consorti et al., 2021) protects the layer below from dissolution being a witness of the ancient surface.

https://doi.org/10.3301/GFT.2022.03

Fig. 18 - *Hum* near Monrupino: a residual block in the Sežana fm. (Jurkovšek et al., 2016, *cfr.* "Aurisina limestone", Consorti et al., 2021) witness to the surface of about 200,000 years ago.

https://doi.org/10.3301/GFT.2022.03

m. Drawing on the joint database specifically created for the HYDROKARST Project, it emerges that not all the caves have the same depth and importance. In Italy there are 128 caves with a plan development of over 100 m, while in Slovenia there are 116. Only about ten have a development greater than 1,000 m. Based on the ratio (S/P) between horizontal development (S) and depth (P), defined in Zini et al., (2011), three types of cave were recognised:

a) HC (Horizontal Cave): caves with mainly sub-horizontal or slightly inclined development in which the $S/P \geq 1.3$;
b) VC (Vertical Cave): caves with a prevailing vertical development in which the $S/P \leq 0.7$;
c) CC (Complex Cave): complex caves where $0.7 < S/P < 1.3$.

The analysis carried out has highlighted that about 45% of the caves have a prevailing horizontal development, while 30% have a prevailing vertical one. About 25% have a complex shape in which pits alternate with horizontal sections. Over the entire investigated population of known caves, the sub-horizontal prevail over the vertical. Among all the caves, the ones intercepting the underground waters of the Reka/Timavo River are considered the Timavo caves.

Icon caves
It is difficult to choose among the numerous caves: the Škocjanske jame, a UNESCO World Heritage site since 1986; the Kačna cave, the longest cave with its 15 km of hypogean conduits and shafts; the Grotta Gigante has been open to the public since 1908; the Trebiciano abyss, the best-known vertical cave in the area around Trieste, at its bottom flows a branch of the Timavo River; the Claudio Skilan cave with its vast halls and magnificent concretions; the underground system of Mt. Stena of great speleological and hydrogeological interest; the Grotta Impossibile which was discovered by chance during recent road construction near Trieste. Most caves can be visited, some of them being show caves, whereas other may be seen only if accompanied by expert speleologists.

Laboratory caves
In the Italian sector, thanks to the initiative of some caving groups, some caves become “laboratory caves” in the sense that instruments have been installed and/or experiments have been performed with the active collaboration of Universities and the Istituto Nazionale di Oceanografia e Geofisica Sperimentale (OGS).

https://doi.org/10.3301/GFT.2022.03

The most important laboratory-cave is the Grotta Gigante where several studies have been realised or are still ongoing such as: dating of speleothems, neotectonic studies, studies on the presence of radon gas, studies on the dissolution of carbonate rocks (Cucchi et al., 1985); on percolation (Covelli et al. 1998), on variations in temperature, pressure and humidity (Braitenberg et al., 2018), on the growth of concretions; studies on *lampenflora* (Sciuto et al., 2017). There is also equipment for studying the movements of the Earth (for more details see ***STOP 2***).
Instruments are also installed in the Trebiciano abyss where experiments have been performed on percolation, on variations in temperature, pressure and humidity, on height, conductivity and temperature of the groundwaters (Cucchi et al., 2001; Semeraro et al., 2007). A detailed sampling was carried out along the cave which led to the precise definition of the mineropetrography and stratigraphy of about 300 m of the Cretaceous succession (Ulcigrai, 1976; Forti et al., 1978).
Regarding Škocjan caves, since their discovery important research has taken place involving different fields such as geological, climatic or better speleoclimatic or microclimatic, geomorphological, hydrogeological, biological and last but not least, archeological (Kranjc, 2013). Most of the activities are still ongoing.

Show caves

The show caves are always open to the public and are easy to visit. They include Grotta Gigante (https://www.grottagigante.it/), Grotta delle Torri di Slivia (http://www.grottatorridislivia.it/) in Italy, Škocjanske jame, also known as Škocjan caves (https://www.park-skocjanske-jame.si/it/) and the Vilenica cave (https://www.visitkras.info/en/the-vilenica-cave) in Slovenia.
Easy to visit but by appointment are the Grotta Nera cave in Italy (http://www.gssg.it/grotta-nera) and the Divača cave - Divaška jama in Slovenia (http://www.divaska-jama.info/); less easily you can move down the Trebiciano abyss in order to reach one of the Timavo branches (https://sastrieste.it/index.php/trebiciano/#virtuale).
All the other caves can only be visited by well-equipped speleologists. Some, however, are protected by manhole covers or railings, so visits are subject to specific agreements with the caving groups which manage them. All the information regarding the caves can be found by consulting the Cave Registry (Italian Catasto Regionale delle Grotte del Friuli Venezia Giulia; http://www.catastogrotte.fvg.it/) and the Slovenian Cave Registry (https://www.jamarska-zveza.si/index.php/foreigners/cave-registry).

https://doi.org/10.3301/GFT.2022.03

Hydrogeological characteristics

The Classical Karst Region aquifer is characterised by the presence of two hydrogeological units: carbonate rocks, extremely karstified and with high permeability due to fissures and karst, and flysch, characterised by a low permeability. The strong contrast of permeability between these two lithological units jointly with the hydraulic gradients generated within the Classical Karst Region play an important role in recharge, flow and outflow of the groundwaters from the system. The outcrop of marly arenaceous units in the northern and southern sectors of the anticlinorium, in fact, gives rise to two lateral barriers that guide the karst development and the groundwater flows. The spring area is in fact located in the north-western sector of the hydrostructure, in the area between Aurisina and Monfalcone where the contact between the siliciclastic deposits of the Flysch and the Meso-Cenozoic limestones was identified during diving excursions below sea level (Furlani et al., 2009b).
The entire spring system is fed mainly by three different contributions: the effective infiltrations, the sinking recharge of the Notranjska and Raša rivers and the Soča/Isonzo aquifer (Fig. 19). The greatest contribution to the recharge of the aquifer is due to rainfall. In fact, the Karst is located in the transition area between Mediterranean and continental climate. The average rainfall ranges from 1,000 mm/year along the coast to about 1,800 mm/year inland, whereas average evapotranspiration varies from 450 to 750 mm. Rainwater infiltrates quickly through the articulated underground paths thanks to the scarce vegetation cover, the absence of well-developed soils and the intense and widespread karstification of the rock mass. All this means that effective infiltration represents the main contribution to the hydrostructure recharge, with an average value of about 21 m^3/s (Civita et al., 1995).
The contribution of the Notranjska Reka (Timavo Superiore) is estimated to be about 8 m^3/s (Gabrovšek and Peric, 2006), and is extremely variable with almost negligible flow rates in low water conditions but particularly intense during floods. In the north-western sector between the towns of Merna and Sagrado, the aquifer of the Soča/Isonzo plain joins with the karst waters (Timeus, 1928; Mosetti and D'Ambrosi, 1963; Gemiti and Licciardello, 1977; Cancian, 1987; Doctor et al., 2000; Samez et al., 2005; Treu et al., 2017; Calligaris et al., 2018; 2019a). In this area, especially during periods of low waters when the hydraulic gradient of the Classical Karst Region area is low, there is a significant transfer of water that recharges the hydrostructure with an estimated value of about 10 m^3/s (Zini et al., 2013; Vizintin et al., 2018; Calligaris et al., 2019a).
The genesis and development of the conduit network that drains the waters from the infiltration areas towards the springs has been and is significantly influenced by the different nature of these contributions. From Škocjan's

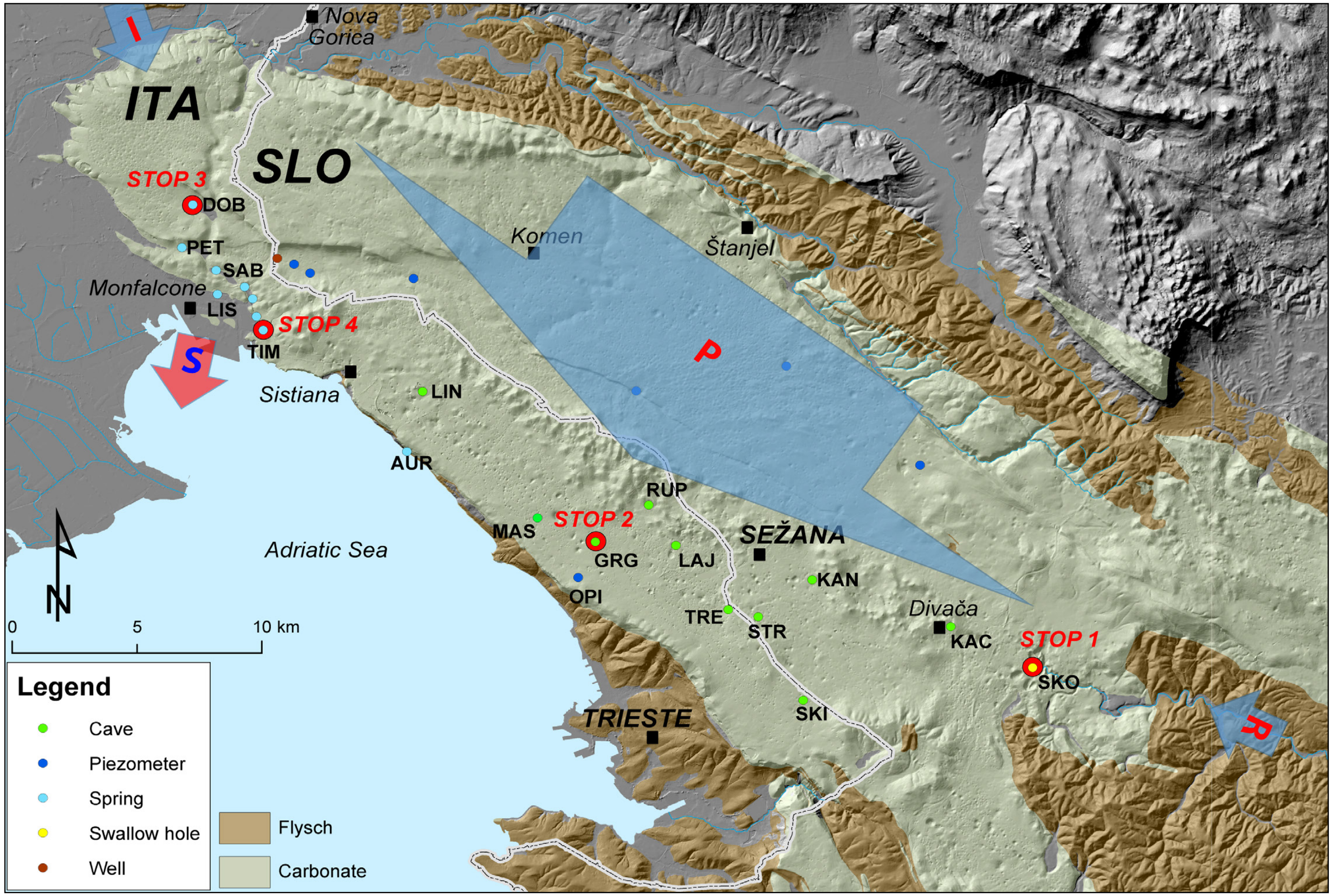


Fig. 19 - The hydrostructure of the Classical Karst Region with notable "water points": Škocjanske jame (SKO), Kačna jama (KAC), Jama 1 v Kanjaducah (KAN), grotta Claudio Skilan (SKI), Brezno v Stršinkni dolini - Jama Sežanske Reke (STR), abisso di Trebiciano (TRE), grotta Lazzaro Jerko (LAJ), grotta Gigante (GRG), abisso di Rupingrande (RUP), Opicina piezometer (OPI), abisso Massimo (MAS), grotta Lindner (LIN), Aurisina spring (AUR), Timavo Springs (TIM), Lisert springs (LIS), Sablici (SAB), Pietrarossa (PET) and Doberdò lakes (DOB). The arrows summarise the contributions of the Soča/Isonzo River from the N (I, about 10 m^3/s on average per year), those of the Reka River from the SE (R, from 0.18 to 300 with about a yearly average of 8 m^3/s), those of precipitation (P, with a yearly average of about 21 m^3/s). The red arrow indicates the outflows (35 m^3/s).

sinkhole some large conduits drain the waters into different branches with free-surface waters, underwater drowned segments and conduits below sea level which efficiently connect the cave with the Aurisina, Timavo and Sardos spring systems. In the western sector, on the other hand, the waters from the Soča/Isonzo aquifer are drained towards the springs by numerous interdependent conduits mainly developed in the saturated zone below sea level. Conduits with different hydraulic conductivity are in turn connected with the system of caves and fractures which drive the precipitations in the whole karst system.

The challenge to control the impact on this karst region are of extreme importance seeing as there are two water supply systems present in the area: the Randaccio in Italy (providing good quality freshwaters to the inhabitants of Trieste and surroundings) and the Kraški Vodovod Sežana in Slovenia just across the Italian state border, providing not only waters to the inhabitants of the Slovenian side of the Classical Karst Region (Urbanc et al., 2012; Turpaud et al., 2018), but also supplying the municipalities of the Slovenian coast in summertimes when Rižana becomes dry (for an additional cca. 120,000 people).

STOP 1 - Škocjan sinkhole and the epiphreatic conduits of the Timavo underground system

(45° 39′ 47,96′′N – 13° 59′ 21,58′′E)

*From Trieste to **STOP 1** (about 22 km, 30 minutes)*

While climbing the hill by bus it will be possible to see the passage from the verticalised Eocene Flysch to the Palaeocene limestones, which gradually become horizontal to form an anticline whose axis passes through the town of Basovizza, home of the European Synchrotron. Crossing the Italian – Slovenian border, the bus will pass close to Lipica, where famous Lipizzaner horses are bred. The Karst appears mostly covered by a thin layer of soil that supports grassy shrub vegetation. Following the outcropping Liburnian limestones affected by small solution dolines on the bottom of which red soil planted with potatoes are present, the bus will reach the town of Lokev (SLO), the seat of the Tabor Military Museum (http://www.vojaskimuzejtabor.eu/EN/index.html). Moving down in the stratigraphic succession, the path will go through the Lipica formation.

Karst outcrops are frequent; among the depressions there are numerous bedrock collapse dolines such as the impressive Risnik doline in Divača. Later, the bus will reach Matavun-Škocjan, the Visitor Center and Management Center of the UNESCO Park, where capable and competent young guides will accompany the tourists for an hour and a half during the cave-tour. The temperature in the cave is 11° C, the humidity is almost 100%, so it is advisable to dress appropriately. The underground path is easy and safe on non-slip concrete with numerous steps (flip-flops are not appropriate footwear but alpine hiking boots are also not necessary!). A government-issued identity card is required.

The Notranjska Reka (Timavo Superiore) which originates on the slopes of Mt. Dletvo on the Croatian/Slovene border, drains a basin of about 400 km^2 with an average rainfall ranging between 1,500 and 3,000 mm/year. It flows for more than 50 km over rocks in flysch facies until it passes over limestone, 7 km upstream from the Škocjan caves. From this point on, the watercourse suffers losses until it is completely swallowed within the Škocjanske jame complex (Škocjan caves) (Fig. 20). This phenomenon is particularly evident during dry periods when near Gornje Vreme all the waters disappear among the stony riverbed leaving the stream dry for several weeks. Sometimes sinkholes several meters deep open in the riverbed capturing all or part of the waters. These sinkholes, which in the past were immediately artificially filled in so as not to interrupt the activities of the mills, are now naturally filled by the river itself with its sediments during subsequent floods (Cucchi and Forti, 1981). The Notranjska Reka enters the Škocjan cave at an altitude of 317 m a.s.l., which has a development of more than 6 km. The river crosses some very deep bedrock collapse dolines (Fig. 21) (Mala dolina, 120 m deep and

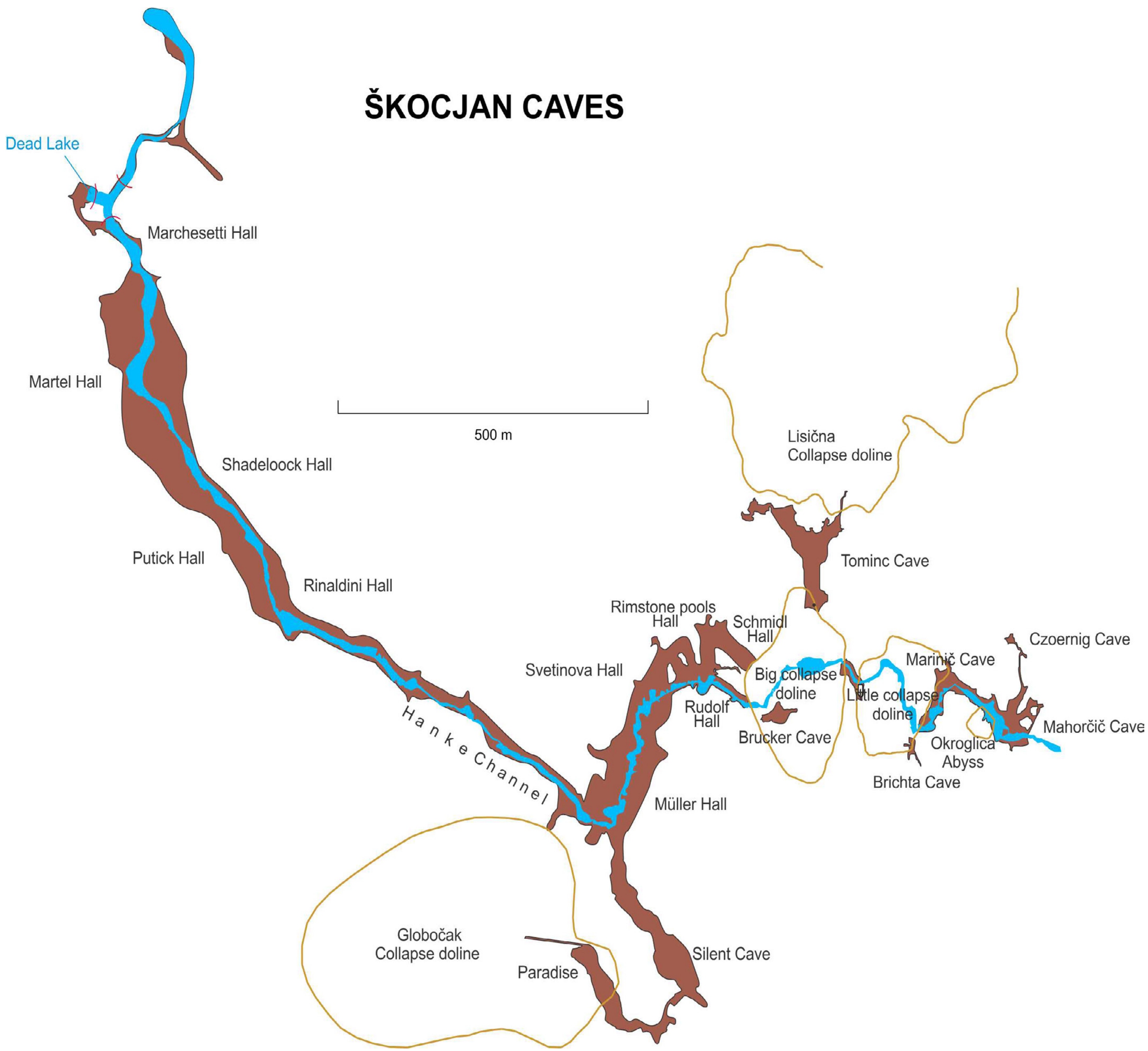


Fig. 20 - Plan of the Škocjanske jame (drawing courtesy: Park Škocjanske jame, Borut Peric).

Velika dolina with a depth of 163 m) and after having travelled about 3.5 km through a giant gorge 10 to 60 m wide and over 100 m high with about thirty waterfalls/rapids, it disappears into a sump of Dead Lake at 212 m a.s.l. (Fig. 22). Of interest, before reaching Dead Lake, you cross Martel's hall, which is the largest underground chamber in Europe and one of the largest in the world with a volume of 2.2 million m^3.

The Notranjska Reka has an extremely variable flow rate, ranging from over 380 m^3/s during floods to 0.18 m^3/s in low flow conditions with average values of about 8 m^3/s (Gabrovšek and Peric, 2006). The flow rates can be so high and the solid transport (sediments and tree trunks) so large that the terminal sump within the cave becomes blocked and the gorge and part of the sinkhole are filled with water. The cave has been used since the Copper and Bronze Ages, and its grandeur has fascinated authors since Roman times with the writings of Posidonius of Apamea

Fig. 21 - The notable sinkhole of Škocjan in the Liburnia fm. (Jurkovšek et al., 2016, *cfr.* "Liburnian limestone", Consorti et al., 2021): Mala Dolina just below the church of Škocjan and Velika Dolina in the foreground (photo courtesy: Park Škocjanske jame, Borut Lozej).

https://doi.org/10.3301/GFT.2022.03

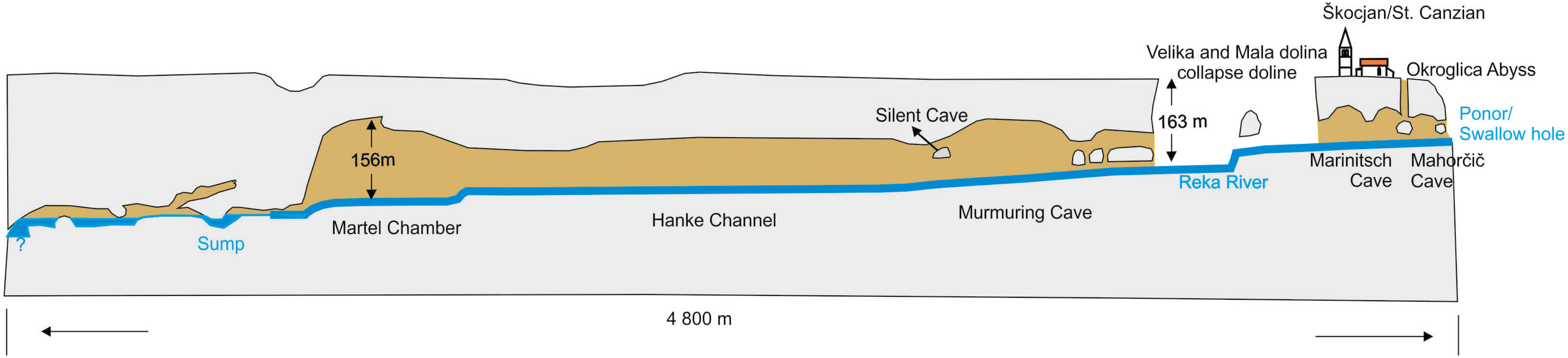


Fig. 22 - A simplified cross-section of the Škocjanske jame (drawing courtesy: Park Škocjanske jame, Borut Peric).

(135-50 B.C.). Despite this long use, cave exploration dates back to the mid-19th century when the first systematic cave explorations in the Classical Karst Region began searching for new water sources to supply the city of Trieste.

Leaving the Škocjan caves (SKO), the underground path of the Timavo continues with free-surface and submerged sections until it reaches the sector of Monrupino. From here, it continues its path in water-filled conduits below sea level. For almost 200 years, speleologists have been looking for caves that could reach one of the conduits of the hypogean path of the Timavo and today among the 4,077 caves inventoried only 5 (Timavo caves) allow access to some sections of the Reka/Timavo system: the system B3G Brezno treh generacij (3BG) - Kačna

Cave	Developement	Water-table depth from the surface	Water-table elevation m a.s.l.
Škocjanske jame (SKO)	6200	223	212
Kačna cave (KAC)	15151	280	156
Jama 1 v Kanjaducah (KAN)	1332	330	23
Jama Sežanske Reke - Brezno v Stršinkni dolini (STR)	941	340	15
Abisso di Trebiciano (TRE)	2400	329	12
Grotta di Lazzaro Jerko(LAJ)	450	300	2

cave (KAC), Jama 1 v Kanjaducah (KAN), Jama Sežanske Reke - Brezno v Stršinkni dolini cave (STR), abisso di Trebiciano (TRE) and the Lazzaro Jerko cave (LAJ).

Located about 1 km W of the town of Divača, Kačna cave is a great hypogean complex that develops in Cretaceous limestones. It is one of the first points, after Škocjan, where the waters of the underground Reka-Timavo are intercepted. The cave was first explored in 1895. The abyss opens at an altitude of 436 m a.s.l. and has a 186 m deep shaft that leads to a larger system of tunnels distributed over two levels. The upper level is hydrogeologically inactive but richly decorated; in this section the surveyed tunnels extend for about 1,5 km at altitudes of about 250 m a.s.l. The lower level, which is accessed from the upper one through a series of shafts and tunnels, develops sub-horizontally and consists of an articulated system of conduits where, during low flow conditions, the Reka/Timavo flows freely up to a sump placed at an altitude of 156 m a.s.l. During the most significant floods of the Timavo, the water level can rise up to 100 m, flooding the upper level of the tunnels. In 2010, the B3G Brezno treh generacij abyss was discovered, connecting with Lake Phare located in the south-eastern end of the new tunnels of Kačna cave, thus forming an underground system of over 15 km.

Downstream from the B3G Brezno treh generacij abyss and Kačna cave, 4 other caves have been discovered that reach the conduits of the Reka-Timavo underground system at altitudes between 23 and 4 m a.s.l. The entry points of these caves were identified in the 19th century by observing that during heavy rainfalls, an intense airflow was generated on the bottom of some dolines. These points were called “blowing holes” and were activated only by the main floods from the Timavo which, flooding the large deep underground conduits, channelled the air towards the narrow shafts linking the halls to the surface (Fig. 23).

Speleologists immediately tried to reach the underground waters of the Timavo starting from these “blowing holes”, but their explorations were often blocked by the presence of large collapse deposits. This is the example of the caves Jama 1 v Kanjaducah (KAN) and Jama Sežanske Reke - Brezno v Stršinkni dolini cave (STR) in which the Timavo water course was reached only 20 years ago. Jama 1 v Kanjaducah is located about 5 km WNW from the Kačna cave. It is 330 m deep and has an overall length of 1.5 km and is a tunnel that at a depth of about 20 m a.s.l. reaches a large epiphreatic conduit 600 m long, 50 m wide and 60 m in height. After a further 2.6 km to the E, you will reach the Jama Sežanske Reke - Brezno v Stršinkni dolini (STR) cave. The cave has two different entrances: one is called Jama Sežanske Reke (354 m a.s.l.) which reaches the Timavo conduit close to the entering sump, the second is called Brezno v Stršinkni dolini (344 m a.s.l.) and reaches the Timavo conduit close to the exit sump. In the conduit, the Timavo flows at about 15 m a.s.l. From this cave the waters can reach Trebiciano abyss through a series of still unknown sumps. The latter is the best-known vertical cave

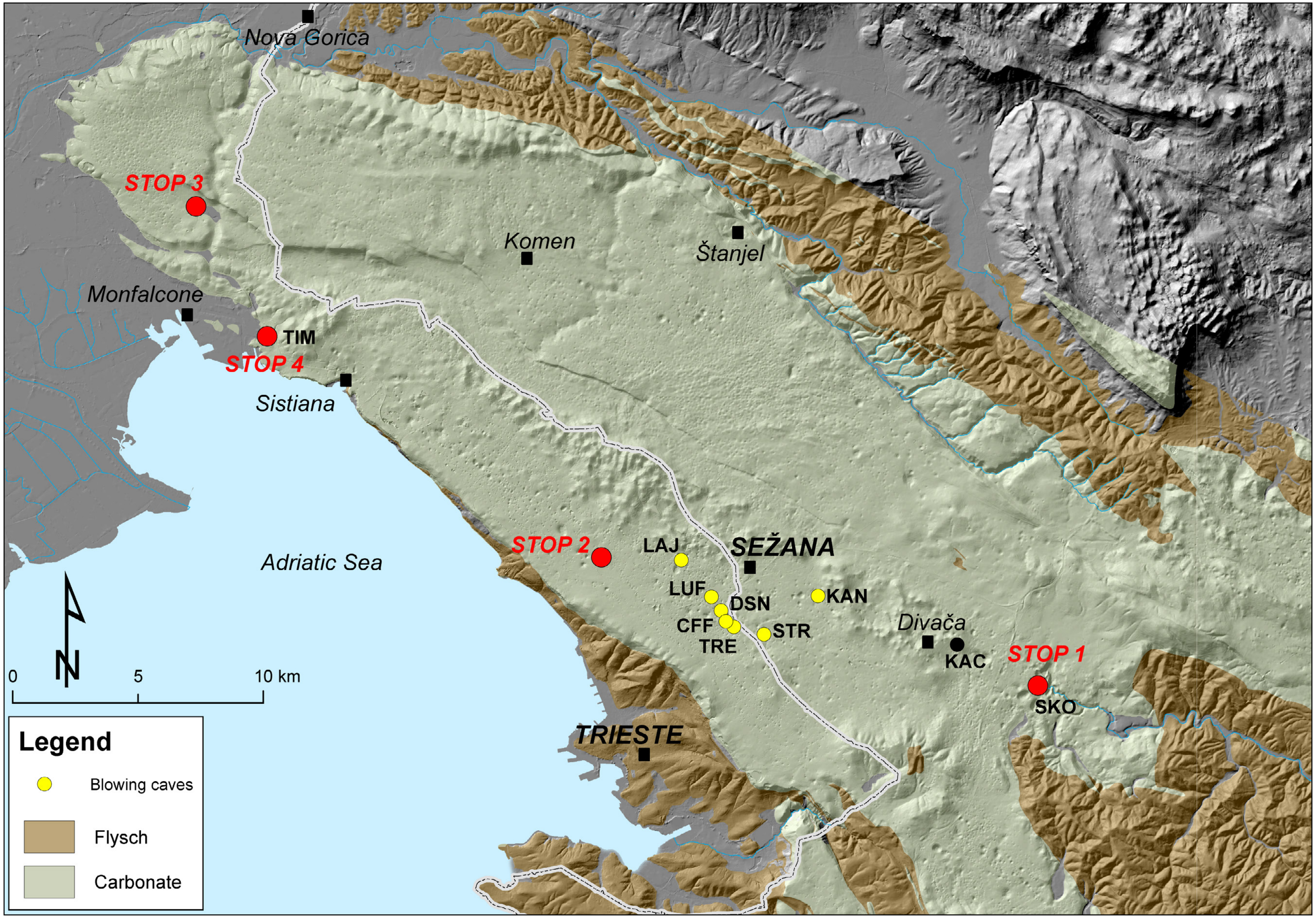


Fig. 23 - Blowing caves (blowing holes) from the Classical Karst Region (LAJ, grotta Lazzaro Jerko; LUF, grotta Luftloch; CFF, pozzo presso il casello ferroviario; TRE, abisso di Trebiciano, DSN, dolina dei sette nani; STR, Brezno v Stršinkni dolini - jama Sežanske Reke; KAN, jama 1 v Kanjaducah). Also indicated are the Škocjan (SKO) swallow hole, Kačna jama (KAC) and Timavo Springs (TIM).

https://doi.org/10.3301/GFT.2022.03

reaching the underground Timavo below. It was discovered by Antonio Federico Lindner in 1841 while looking for new sources of freshwater. Its accessibility was guaranteed after months of hard excavation work. Owned by the Municipality of Trieste, today the cave is managed by the Adriatic Speleological Society and is equipped with fixed vertical ladders. For 80 years it has held the record as the deepest cave in the world and continues to have a very important role in the karst hydrogeology investigation having become an important underground scientific laboratory. It opens on the side of a small sinkhole N of Trebiciano near the state border. As a whole, the cave has an overall plan development of over 2,400 m, a depth of 370 m consisting of about twenty shafts, from 2 to 50 m deep, through which the Lindner hall (Fig. 24) and several secondary branches are accessed (Fig. 25). The large final section, along which flows a branch of the Timavo, is mostly filled with alluvial and collapse deposits. Recent cave-diving explorations have ascertained the presence of large flooded passages that reach 40 m in depth and several hundred m in length (Fig. 26): in these waters there are a large number of other small invertebrates (Brancelj et al., 2020) and the *Proteus anguinus*, a remarkable cave amphibian and the largest cave animal, the first stygobiont mentioned in scientific writing, first described by Laurenti (1768).
The last cave intercepting the underground water course of the Timavo in this first section is the Lazzaro Jerko cave which opens near the village of Monrupino at an altitude of 302 m a.s.l. and 3.5 km N of the Trebiciano abyss. Exploration began in 1987 and required considerable effort and difficult excavation work conducted by the speleologists of the “E. Boegan” (CGEB) Cave Commission. The excavations were abandoned and resumed several times until they ended in 1999 with the discovery of a branch of underground Timavo waters. The cave is mainly vertical, with several shafts leading to two large halls, on the bottom of which water flows at an altitude of about 4 m a.s.l.
The hydrograph proposed as Figure 27 shows the connections among all the just described cave systems.

https://doi.org/10.3301/GFT.2022.03

Fig. 24 - Lindner hall in the Trebiciano abyss which opens in the dolomitic layer of the Povir fm. (Jurkovšek et al., 2016, *cfr.* "Monte Coste limestone", Consorti et al., 2021) (photo courtesy: A. Maizan).

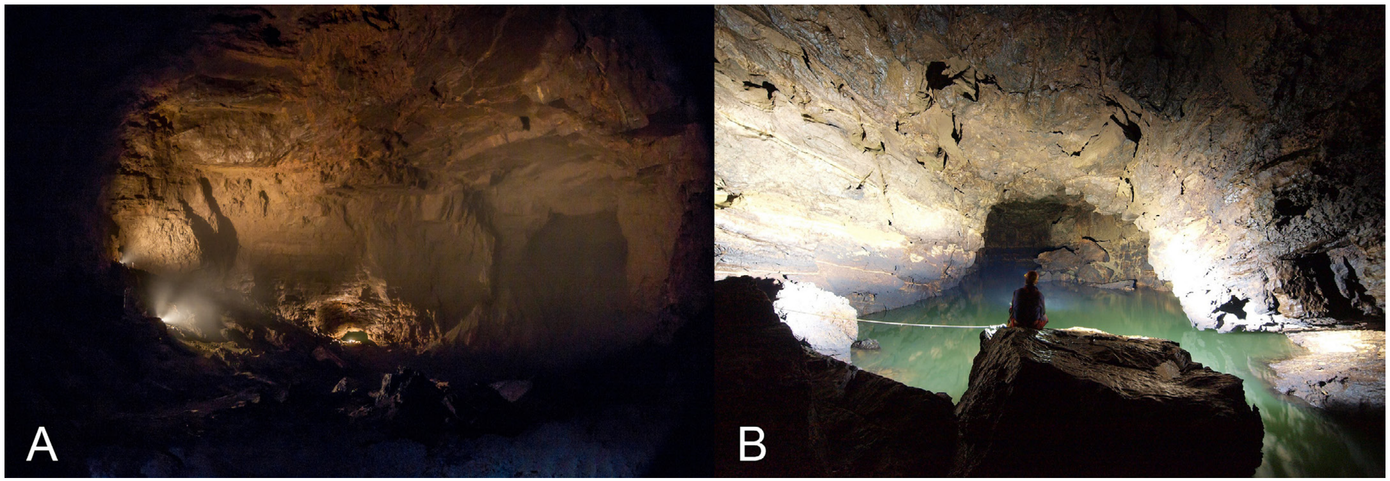


Fig. 25 - A) The Lindner hall (photo courtesy: S. Savini); B) the exit sump (photo courtesy: A. Maizan).

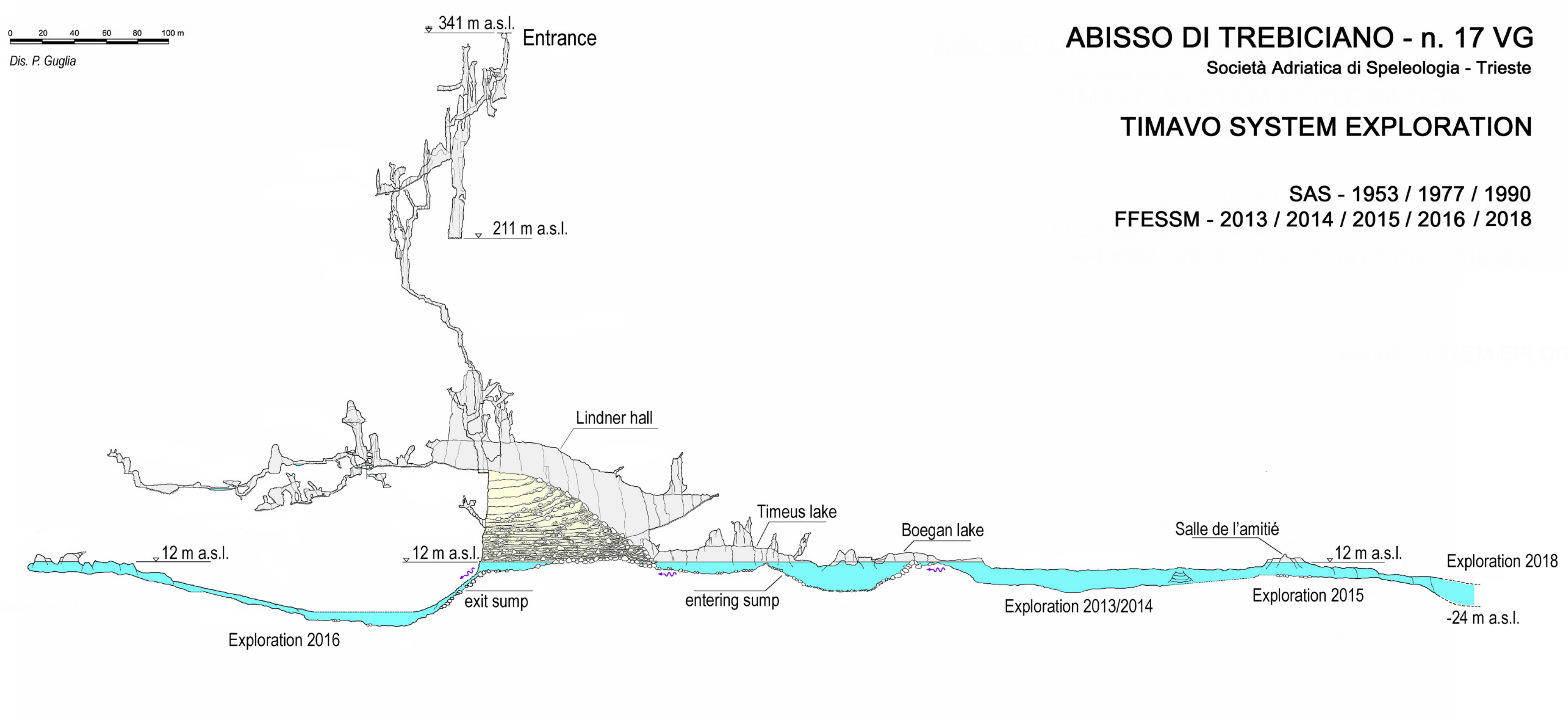


Fig. 26 - The first scuba-diving explorations in the Trebiciano abyss, at the time considered pioneering and risky, began in the 1950s with Walter Maucci and Stefano Bartoli, members of the Società Adriatica di Speleologia (SAS). In 2013, almost 20 years after the last explorations, a new adventure began which in addition to the SAS members involved French divers from the Fédération Française d'Études et de Sports Sous-marins (FFESMM) from Marseille with the support of Slovenian and Italian scuba-divers. So far there have been four complex exploration phases called the Timavo System Exploration, during which increasingly remote portions of the outlet and inlet siphons have been surveyed. The longitudinal profile in the image was updated to 2018.

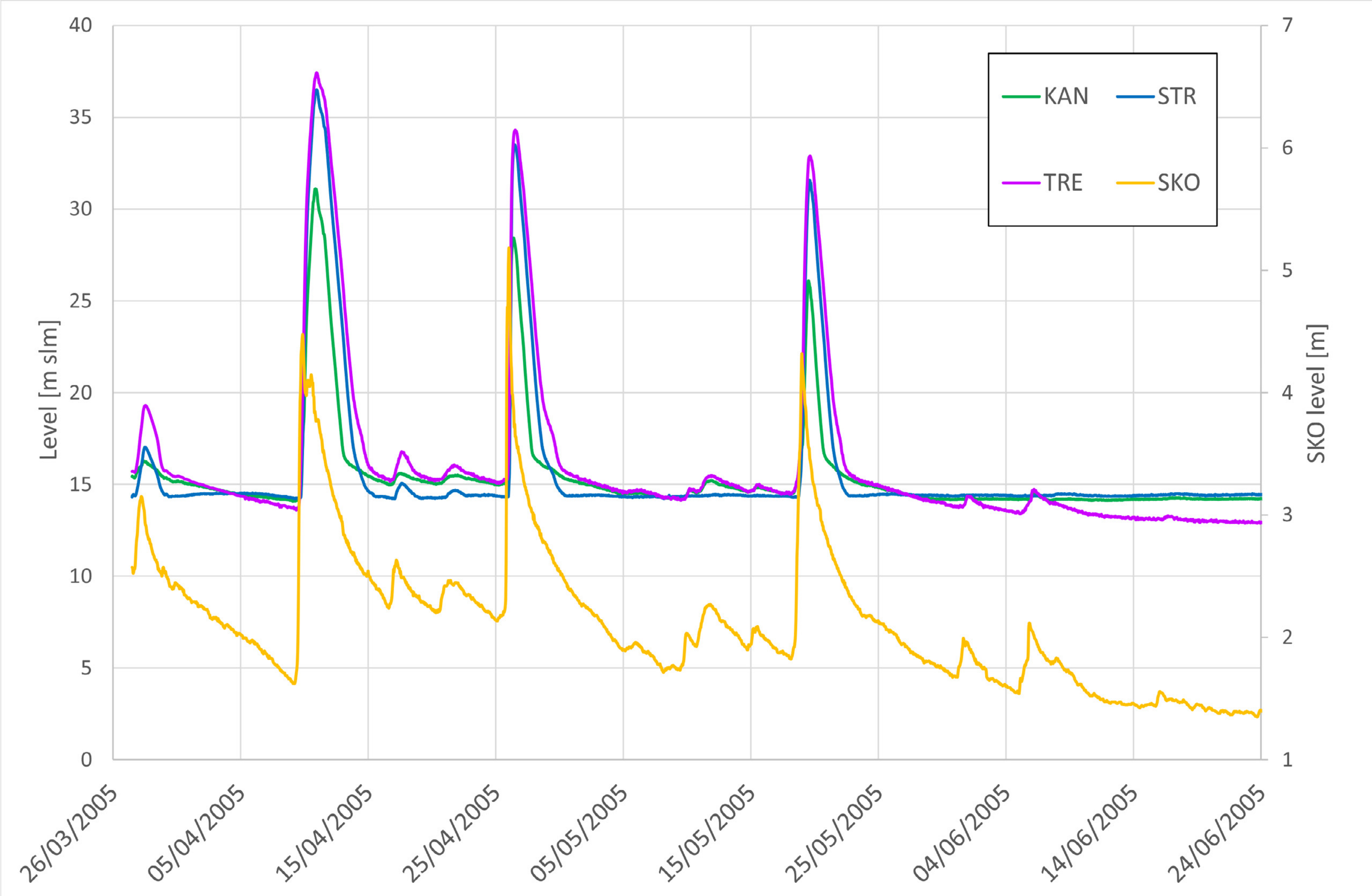


Fig. 27 - Hydrograph of the water levels recorded at the Škocjanske jame (SKO), Jama 1 v Kanjaducah (KAN), Brezno v Stršinkni dolini - Jama Sežanske Reke (STR) and abisso di Trebiciano (TRE). The water level in this sector of the aquifer records strong fluctuations linked to the waters swallowing into the Škocjan caves. In the sector between KAN and LAJ caves, the water level normally rises about 20/30 m, but during exceptional floods, at the Trebiciano abyss, the level recorded can be even higher than 100 m. Dye-tests with artificial tracers confirmed the connection between these caves, but this is also clear from the hydrograph analysis which show similar hydrodynamics.

STOP 2 - Grotta Gigante cave and the other Timavo caves
(45° 42′ 34,76″N – 13° 45′ 53,00″E)

After visiting Slovenia, the group will go back to Italy by bus via the A3-E70, crossing the town of Sežana (SLO), going around Opicina reaching Borgo Grotta Gigante, where it will be possible to find the entrance to the cave and the restaurant (https://www.grottagigante.it/ - https://en.wikipedia.org/wiki/Grotta_Gigante). Just across the border along the road, the *Dolina di Percedol* (a geosite of national importance) and the Lazzaro Jerko cave open to the right, the Trebiciano abyss to the left (see ***STOP 1***). On the hills to the right it will be possible to see the Rocca di Monrupino, a prehistoric castle that became a sanctuary.
After lunch, the tour will continue, visiting the Experimental Station where the lowering of carbonate rocks has been measured since the 1980s, as well as the Speleological Museum. Later on there will be the visit to the cave. The visit takes about an hour. The temperature inside is 11° C, the humidity is close to 100%. The path is only 850 m: about 500 steps lead to a depth of about one hundred meters. Going down you cross the immense hall and then rise to the surface along an uphill artificial path with numerous other steps. If the weather is favourable and there is enough time, the tour will go near the Borgo where on the eastern side of a wide doline, the *"campi solcati"* of Borgo Grotta Gigante extends (Cucchi et al., 2010).
The Grotta Gigante opens in the municipality of Sgonico and is characterised by a hall 167 m long, 76 m wide and 99 m high, for a total volume of 365,000 m^3 (Fig. 28 and Fig. 29).

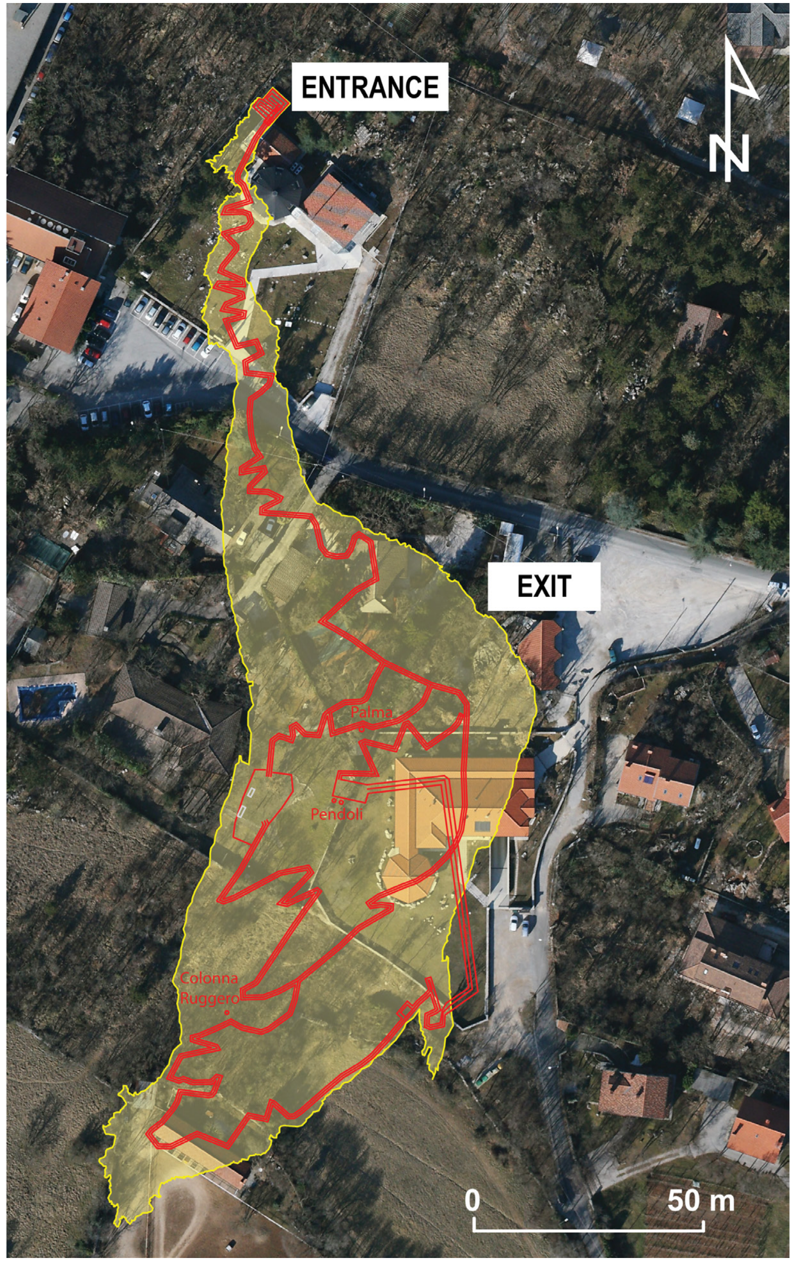


Fig. 28 - Plan of the Grotta Gigante cave. The tourist path is indicated in red.

https://doi.org/10.3301/GFT.2022.03

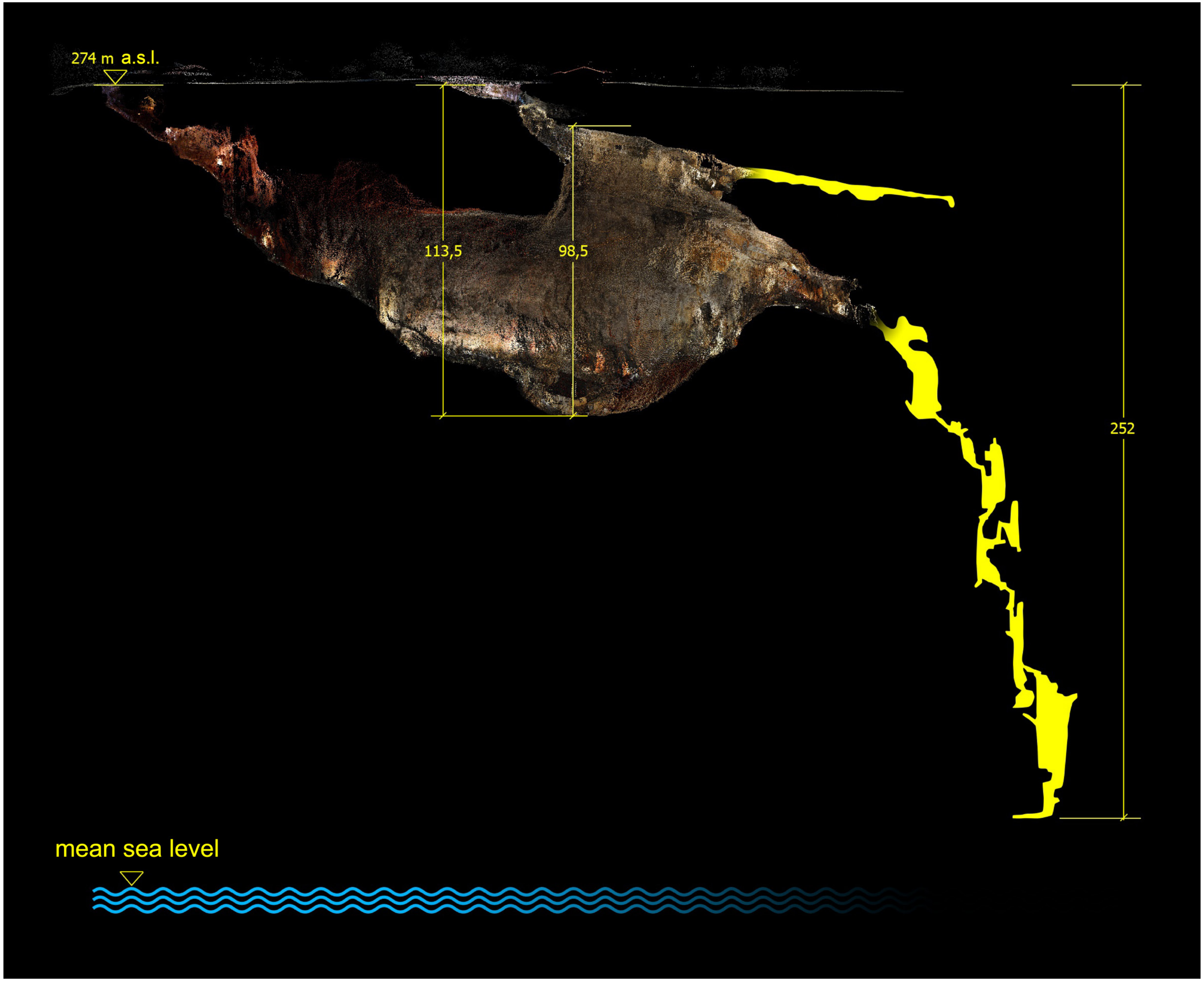


Fig. 29 - Longitudinal profile of the Grotta Gigante; in yellow, the shafts reaching the groundwaters only during floods.

https://doi.org/10.3301/GFT.2022.03

For speleological significance and historical reasons, it is one of the most famous caves of the Classical Karst Region. Given the size of the hall, it has been recorded in the Guinness World Records since 1995 as the largest show-cave in the world. It opens in the Lipica fm. (dating back to the Cretaceous), with a sub-horizontal layering.

The cave was explored for the first time in 1840 by A. F. Lindner, the mining engineer who in the first half of the nineteenth century also discovered the Trebiciano abyss. At that time, the descent on rope ladders in the immense darkness for more than 90 meters was an epic undertaking. Due to technical difficulties, intense explorations started about fifty years later when two other entrances were discovered. The present entrance was enlarged in 1904 and the cave was opened to the public in 1908.

Its morphological characteristics, central position in the Classical Karst as well as the ease of access and the willingness of the owners, have resulted in the placing of monitoring stations within the cave that make it a reference point for the study of natural phenomena.

The cave houses some scientific laboratories: two horizontal pendulums (Fig. 30) and clinometers belonging to the Department of Mathematics and Geosciences (DMG) of the University of Trieste; the seismology station of the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (INOGS); stations for measuring the percolation intensity and growth-rate of stalagmites (Fig. 31); sensors for an *in continuous* monitoring of Radon gas (managed by ARPA FVG) and an archaeological site. Outside the cave there is a weather station which has been managed by Istituto di Scienze Marine (ISMAR) since 1967. At the cave location, gravimetric, seismic and geoelectric investigations were carried out in order to “calibrate” them for the purpose of identifying other caves in the subsoil: only the extremely precise microgravimetric investigations have provided significant results.

Inside the cave, horizontal pendulums installed by Marussi in 1959 can detect the movements of the earth’s crust. These instruments are sensitive to deviations from the perpendicular, rotations and shear strains of the cave. The upper and lower mountings of the pendulums are at a distance of 95 m, which makes this long-base instrument a ultra-broad- band tiltmeter, apt to record the tilt signal on a broad-band of frequencies, ranging from secular deformation rate through the earth tides to seismic waves (Braitenberg and Nagy, 2014).

After several years of excavation, overcoming a series of shafts, in October 2005 speleologists reached a depth of -252 m reaching an altitude of 23 m a.s.l. The final part of the cave consists of a large shaft where very abundant dripping water collects in a rivulet disappearing in a fracture. To assess the rise in the water table, close to this point and to integrate the existing monitoring network, in December 2009 researchers from the DMG installed a datalogger device which measures the level, temperature and electrical conductivity of the

https://doi.org/10.3301/GFT.2022.03

Fig. 30 - The Great Hall which forms the heart of the Grotta Gigante in the Sežana fm. (Jurkovšek et al., 2016, *cfr.* "Aurisina limestone", Consorti et al., 2021). On the right the so-called "Altar", in the background, the artificial tunnel to the exit. In the center, the two tubes protecting the tempered steel cables that support the two horizontal pendulums, which measure inclinations from the vertical according to N-S and E-W (photo courtesy: S. Laburu).

https://doi.org/10.3301/GFT.2022.03

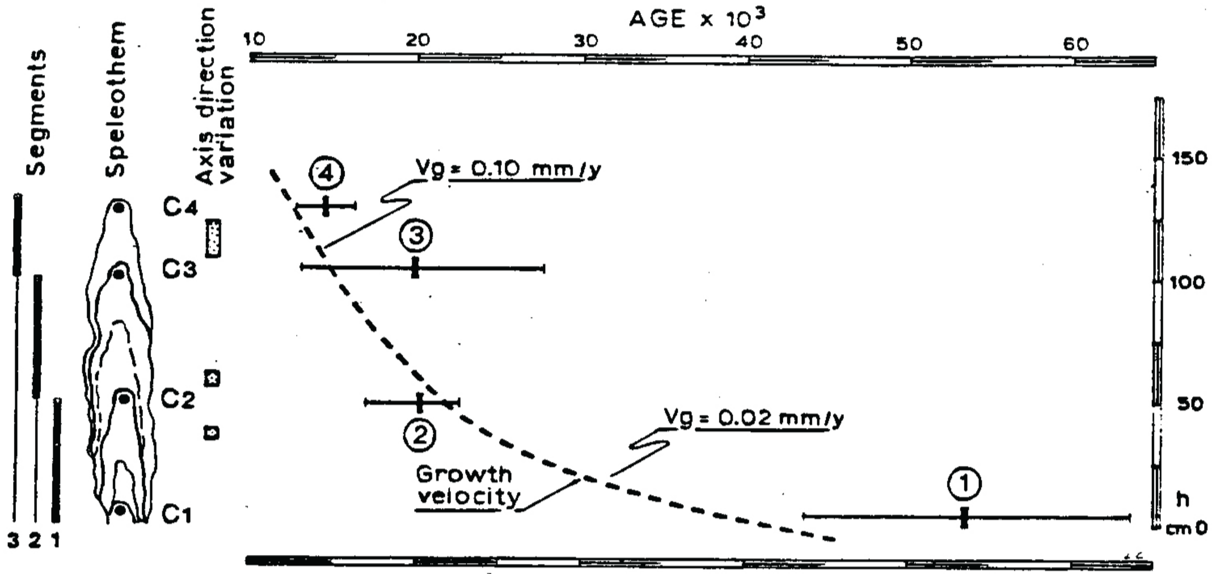


Fig. 31 - THE SPELEOLOGICAL MUSEUM. The stalagmite, which overturned 15,000 years ago, was collected from the hall of the Grotta Gigante. It is 140 cm high and 30 cm wide at the base. The half missing from the photo was used to date the moments of change in the inclination of the growth axis and the growth rate. The analyses using the U/Th method determined that it had formed about 55,000 y B.P. The growth rate is variable from 0.02 mm/y to 0.10 mm/y. The increase in growth rate that occurred around 20,000 years ago may be related to the passage from an open karst to a covered karst with a subsequent increase in the dissolutive power (and therefore of the solute) of the percolating waters (Cucchi and Forti, 1990). A still active stalagmite collected in the Savi cave (Val Rosandra), began to form about 17,000 years ago showing an initial very low growing rate, usually lower than 10 μm/y, up to the end of the cold period. In between 10,700 and 7,600 years ago, higher growing rates were recorded (30-43 μm/y) witnessing a change in the external environmental conditions (Borsato et al., 2005).

water. The station was made accessible thanks to fixed steel stairs installed by speleologists from the CGEB. The datalogger is out of the water most of the time and immersed only when there are significant flood events.

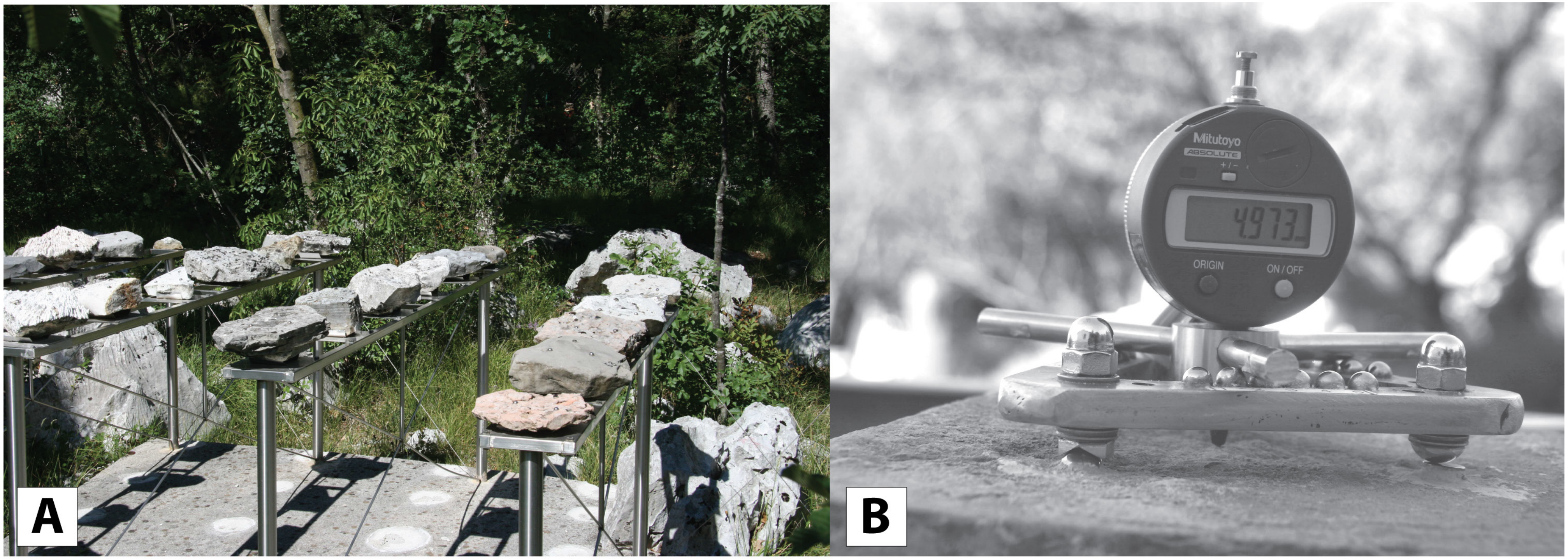
The Limestone Lowering Station (Fig. 32) was initially installed outside the cave in 1979. The number of samples increased in a few years' time. Currently it houses about fifty carbonate and two evaporitic rock samples on which support nails have been fixed in order to measure the progressive surface lowering due to meteoric weathering.

Between the Grotta Gigante and Timavo Springs, there are several caves which reach the groundwaters during floods. One of these is the Skilan cave. Its entrance can be found at Basovizza at 389 m a.s.l. The maximum depth is 378 m and the development is 6.400 m. It was discovered and explored in the nineties by the Gruppo Grotte "C. Debeljak" who then equipped the entering shaft (40 m deep) and partially the initial part of the following shaft, with fixed stairs which lead to the level of the main sub-horizontal conduits. A large 110-meter shaft leads to the bottom of the cave reaching 11 m a.s.l. During extreme floods, groundwaters can rise up to 80 m.

Following the flowing hidden Timavo, in the small town square of Rupingrande, opens the Rupingrande abyss (RUP) which serves as a drain for the waters. It consists of a predominantly vertical cave where the horizontal sections have almost all been artificially excavated by the Club Alpino Triestino in 2012 reaching 308 m depth (9 m a.s.l.). In November 2009 the groundwater level rose to 90 m a.s.l. For a period, the cave was equipped with a datalogger device, and in this place proteus have been sighted on various occasions, testifying to the direct connection with Reka/Timavo waters.

Moving westward, located near Prosecco, the Abisso Massimo was discovered and explored by the Gruppo Speleologico San Giusto. The abyss, consisting of a sequence of shafts almost all following the NNE-SSW direction, is 227 m deep and reaches the water table during floods, at about 3 m a.s.l. Until 1992, during different surveys, the speleologists observed water rises of up to 30 m, but the marks left by mud covering the walls hints at even larger rises. The presence of bottlenecks, powerful clay deposits and landslides make visiting this cave difficult.

A story in itself is the borehole equipped with a piezometer drilled in 2004 (OPI). It was part of the studies for the high speed railway project near Opicina, a town near Trieste, on the plateau. It is a sort of artificial cave 302 m deep reaching an altitude of -12 m a.s.l. Screens are between 44 and -9 m a.s.l. The Opicina piezometer has been considered important as it is representative of the so-called *karst waters*.



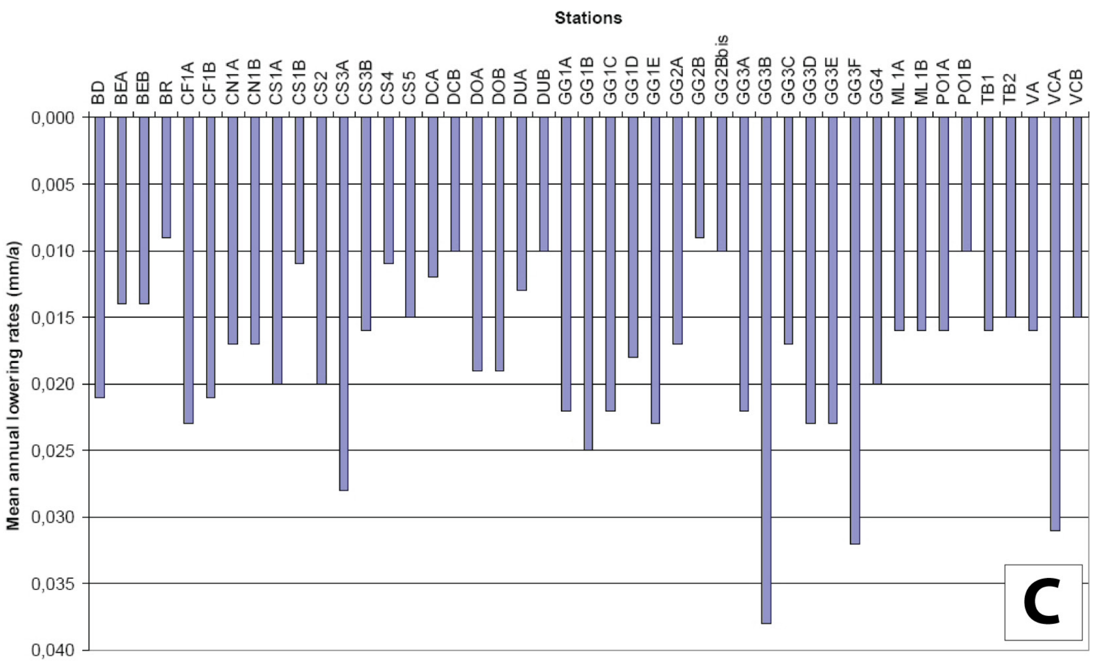
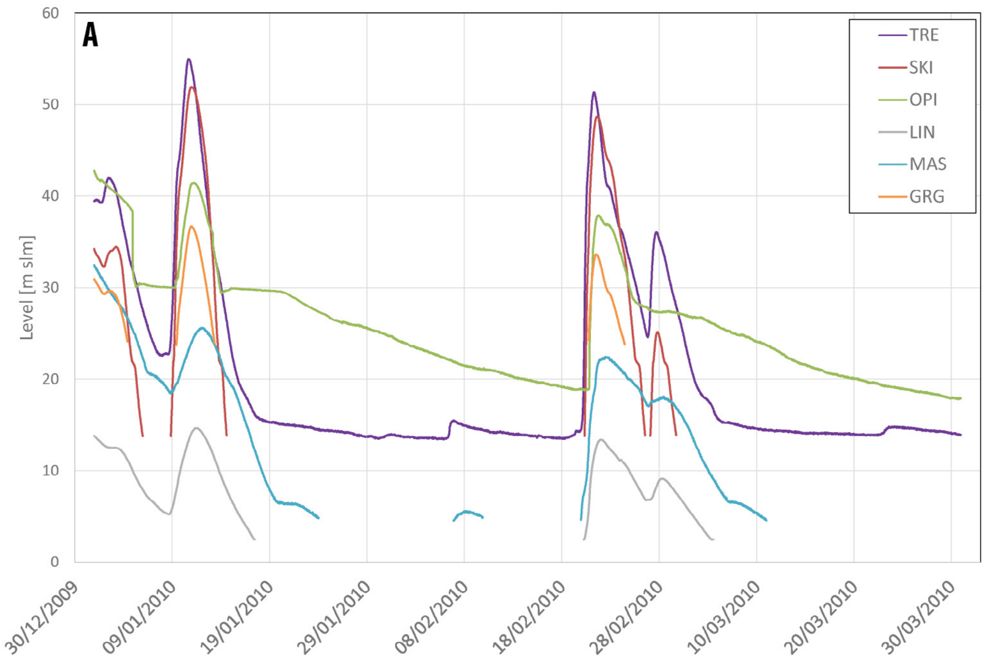


Fig. 32 - A) A detail of the Lowering Station: rock samples are placed on supports, others are on site, such as the limestone of the Lipica fm. (Jurkovšek et al., 2016, *cfr.* "Aurisina limestone", Consorti et al., 2021); B) the Micro Erosion Meter; C) the mean lowering rate of carbonate rocks in the period from 1979 to 2009 is 0.018 mm/y (Furlani et al., 2009).

One of the last caves before the springs is the Antonio Federico Lindner cave (LIN), which opens in Slivia at an altitude of 179 m. It has a development of 825 m consisting of a single descending tunnel, sometimes even very wide which reaches an altitude of 9 m a.s.l. Two lateral sub-vertical branches reach 2 m a.s.l. Normally the cave is dry but both final stretches are affected by water rises during floods related to the water regime at the Timavo Springs, located 6.8 km away. In 1982 the dye-trace injected in the cave was detected at the Timavo Springs after almost 10 days with an apparent velocity of 30 m/h (Gemiti and Merlak, 2005; Casagrande et al., 2005).

Over time, on the Italian side of the Classical Karst Region, the caves where the Timavo waters flowed in the main conduits and those which were usually dry and flooded only during the main flood events were monitored. Figure 33 represents the water level and electrical conductivity behavior of the waters monitored in the central part of the study area. The water level rise is similar in all the points, caves and piezometer (OPI), even if



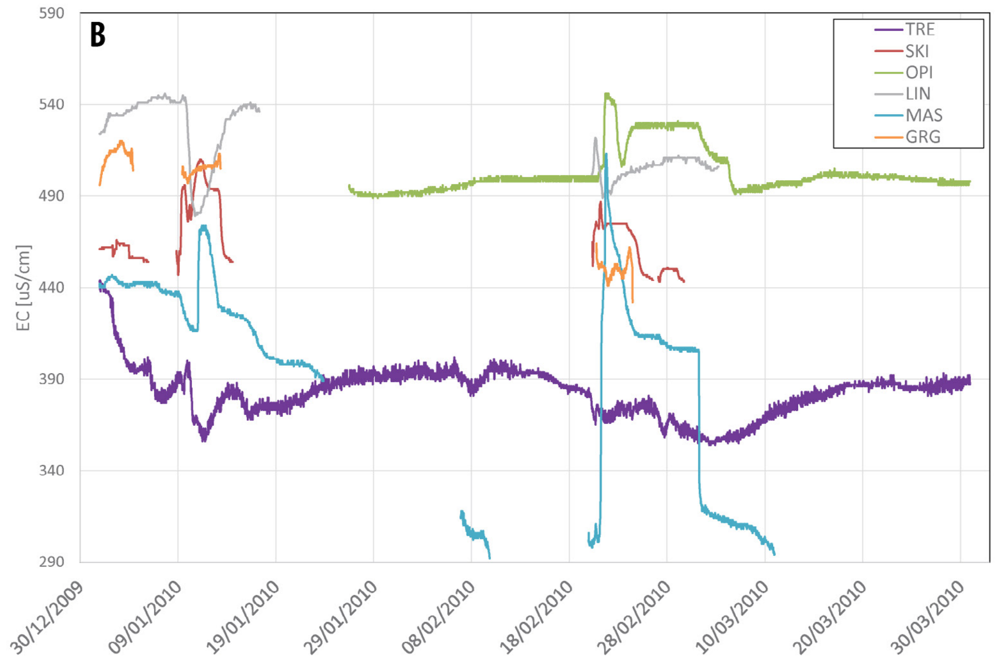


Fig. 33 - Water level (A) and electrical conductivity (B) recorded at the Trebiciano abyss (TRE), Skilan cave (SKI), Opicina piezometer (OPI), Grotta Gigante cave (GRG), Massimo abyss (MAS) and Lindner cave (LIN).

the peak elevation decreases moving from the Trebiciano area towards the springs. All the points also show a similar lowering limb except the piezometer which takes much more time to recover.
From the analysis of the electrical conductivity (EC) emerges the presence of two different behaviors. During floods Trebiciano abyss (TRE) and Lindner cave (LIN) show a clear decrease in the EC values in agreement with the Notranjska Reka influence (lower EC values linked to precipitation and the fast circulation of the waters through the conduits). All the other points show an EC increase which indicates the influence of the *karst waters*, which on average have higher EC values.

https://doi.org/10.3301/GFT.2022.03

STOP 3 – Doberdò Lake and its surroundings
(45° 50’ 30,32’’N – 13° 32’ 52,62’’E)
*From **STOP 2** to **STOP 3** (about 28 km, 25 min)*

To reach ***STOP 3***, Casa Cadorna (Fig. 10) a panoramic view of Doberdò Lake and the Timavo springs area, the bus will follow the SS 202 and quickly travel through the large intensely karstified limestone area located between Opicina and Mt. Ermada. The plateau is bordered towards the sea and inland by two small series of reliefs: those to the N are dolomitic limestone or dolomite with a sub-horizontal dip, those to the S are limestones with an almost completely vertical dip facing the sea. The way to Doberdò passes close to Aurisina, an area where Lipica fm. limestones with high geotechnical characteristics have been quarried since the Roman age, and Sistiana, a bay with structural imprinting. After passing Mt. Ermada, one of the bloody theaters of World War I, the road to ***STOP 3*** passes close to the Timavo Springs (***STOP 4***) and climbs up towards the *polje* which is home to the karst aquifer.
Doberdò Lake is one of the few examples of Karst lakes in Europe and is located in an area of particular value in terms of biodiversity conservation and landscape, so much so that it is part of the Natura 2000 Network site IT3341002 - Karst Areas of Venezia Giulia and Regional Natural Reserve of Doberdò and Pietrarossa Lakes.
Oriented NW-SE, Doberdò Lake is located in an articulated depression limited by the *Colle Nero fault* on the northern side and the *Doberdò fault* on the southern side (Fig. 34). To the N of the *Colle Nero fault* the bottom part of the Sežana fm. (upper late Turonian-lower early Santonian in age) is present. The limestones detectable in correspondence with the Doberdò area belong to Povir fm. dating back to the Albian-Cenomanian.
Doberdò Lake represents the northernmost in a series of depressions which also includes Mucille, Pietrarossa and Sablici Lakes (Fig. 34). These depressions, placed at altitudes between 1 and 4 m a.s.l., are flooded by the waters of the karst aquifer. In correspondence with Doberdò (DOB) and Mucille (MUC) lakes there are permanent spring belts and swallow holes regulating the water regime. During floods while the spring flow rate rapidly increases, the swallow holes are unable to drain all the waters causing a sudden rise in the water levels in a few hours. The water level of the Doberdò Lake, which is on average 4.78 m a.s.l., usually reaches 8 m a.s.l. during floods and during exceptional floods reaches 11 m a.s.l. At Mucille, the average water level is 4.60 m a.s.l. which rises to about 6 m a.s.l. during ordinary floods, but occasionally it can also exceed 8 m a.s.l. Up to the 1960s, similar behavior could also be observed at Pietrarossa and Sablici Lakes. Later began the construction of two channels cutting the natural thresholds present between Pietrarossa and Sablici lakes and between the latter

https://doi.org/10.3301/GFT.2022.03

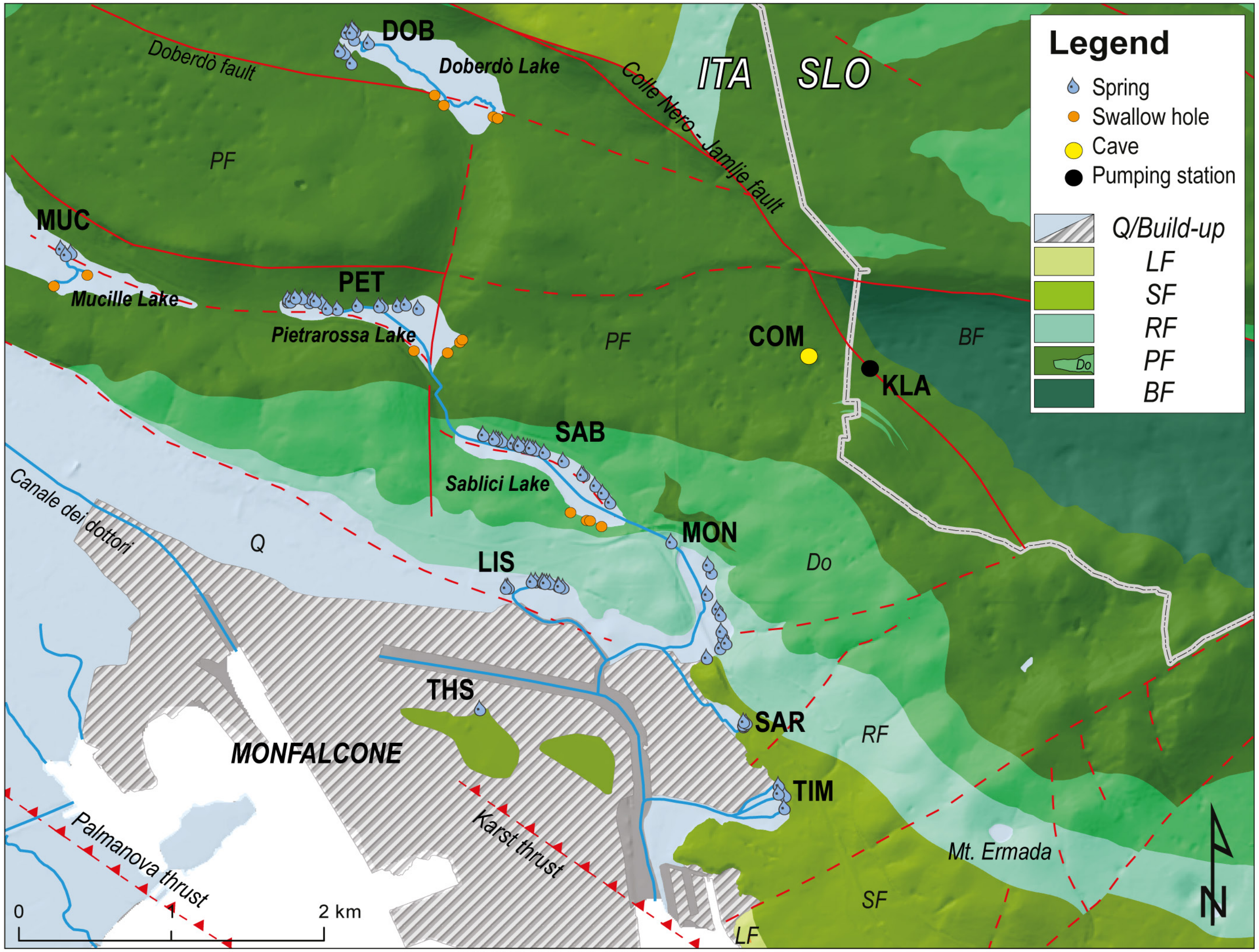


Fig. 34 - Focus on the spring area. Also includes the Klarici pumping station (KLA) of the Kraški Vodovod Sežana water supply (Urbanc et al., 2012) and the thermal springs (THS) of Monfalcone (Petrini et al., 2013). The main faults and thrusts are represented in red. Q (Quaternary deposits); LF (Lipica formation, "Aurisina limestone"); SF (Sežana formation, "Aurisina limestone"); RF (Repen formation, "Aurisina limestone"); PF (Povir formation, "Monte Coste limestone"); BF (Brje formation, no correspondence). The terms in parenthesis refer, the first to Jurkovšek et al., 2016 and the second to Consorti et al., 2021, respectively.

and Moschenizza channel, aimed at draining the area during floods. This project led to a change in the whole hydrogeology causing a general lowering of the piezometric levels in both lakes which is especially notable during periods of low flow, affecting the whole area up to Doberdò Lake. To these modifications, it is also necessary to add climate change and the ever increasing groundwater well withdrawals also affecting these areas (Calligaris et al., 2016). In fact, up to the first half of the 20th century, Doberdò Lake was flooded for most of the year, but presently during droughts, which even last for several months, only a narrow stream connecting the western springs with the eastern swallow holes is present. All this has led to an increase in the vegetation and the progressive burial of the lake which is rapidly transforming from a typical lake environment to a humid forest. An entire ecosystem with a rich biodiversity linked to the presence of water is at risk of total degradation in a short time. For the preservation of this ecosystem researches started, financed by the Friuli Venezia Giulia Region (Servizio Gestione Risorse Idriche) aimed at studying the changes in vegetation as well as the understanding of hydrodynamics. Concerning the waters, a team of researchers from the DMG has implemented a research project aimed at understanding if there is any possibility to restore the hydrogeological conditions of the area recreating the past environment without compromising the general hydrogeology. It was necessary to understand where the waters come from and where they are going. In the case of the Classical Karst Region, electrical conductivity represents a simple but very useful parameter for determining the origin of the waters. The waters flowing in the western sector of the Classical Karst Region are recharged by 2 sources: one due to the influent character of the Soča/Isonzo River which has an average electrical conductivity (25°C) of 270 uS/cm and the other due to the effective infiltration with mean EC values of 530 uS/cm (Calligaris et al., 2019b). A field investigation survey using geochemical sampling and in continuous monitoring with multiparameteric devices allowed for the observation of how the electrical conductivity of the water increases from W to E, confirming the groundwater recharge by the Isonzo waters and the gradual mixing of the latter with the karst ones. During floods, a general increase in electrical conductivity is also observed as a result of the greater influence of *karst waters* on the Soča/Isonzo component due to the increase in the piezometric levels in the karst sector which inhibits the recharge from the Soča/Isonzo (Fig. 35). To integrate continuous monitoring data, dye-tests were carried out from Doberdò Lake swallow holes (Fig. 36). The results were quite striking and showed that most of the tracer flowed unexpectedly to the Timavo Springs (TIM). In lower quantities the tracer was also detected at Sablici (SAB), Moschenizze (MON) and Sardos (SAR) springs. Pietrarossa springs (PET), although the closest from a geographic point of view, are only marginally affected by the waters of Doberdò Lake. The tracer was also detected at Klarici pumping station (KLA).

https://doi.org/10.3301/GFT.2022.03

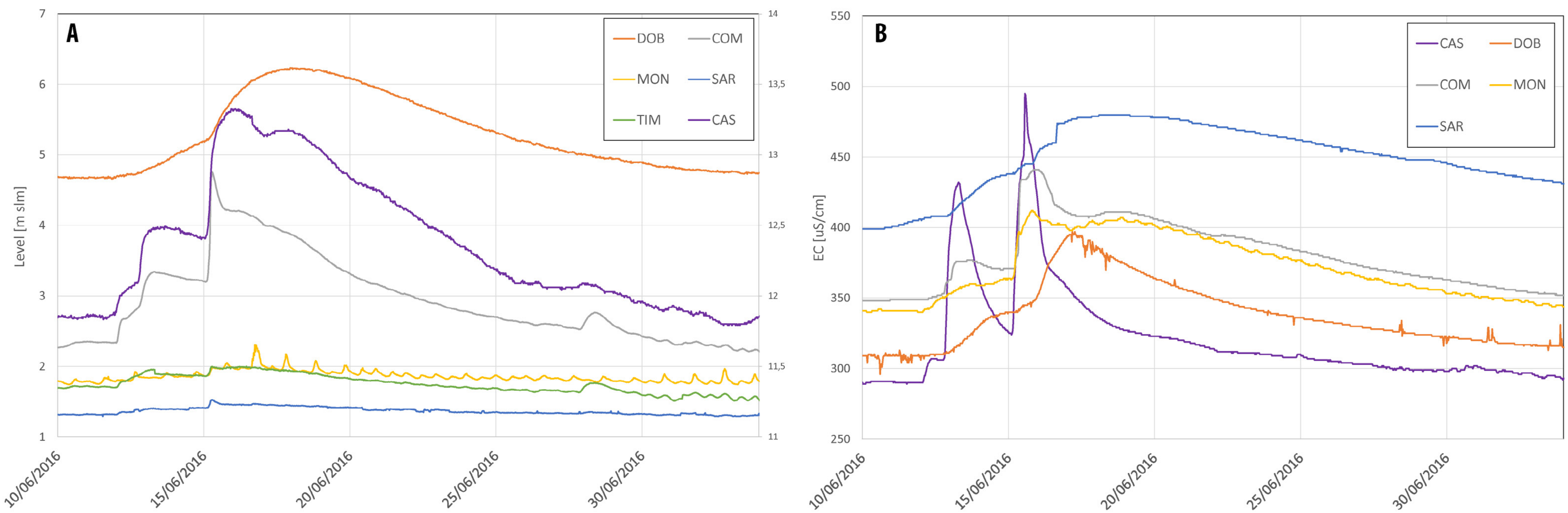


Fig. 35 - Groundwater flow (A) and electrical conductivity (B) dynamics recorded by the multiparametric devices installed in the western sector of the Classical Karst Region at Doberdò Lake (DOB), Comarie cave (COM), Castelvecchio (CAS), Moschenizze Nord spring (MON), Sardos spring (SAR) and the Timavo Springs (TIM).

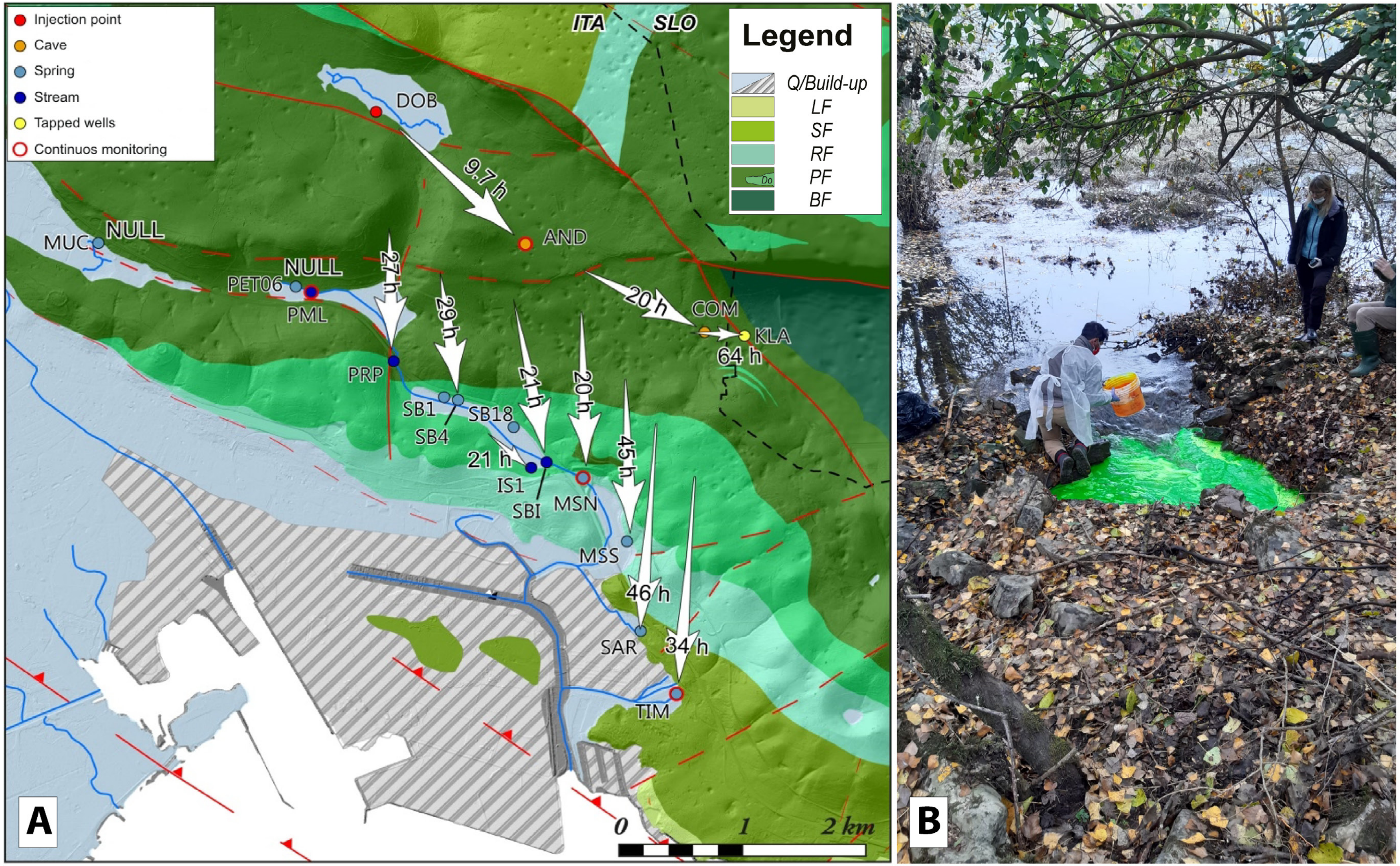


Fig. 36 - A) Uranine dye-test results via injection (autumn 2020 during the recovering limb of a flood) in the southern swallow hole of Doberdò Lake. The arrows indicate the first arrivals of the tracer in correspondence with the monitored points. B) Dye injection in the swallow hole (red dot in Figure 36A). The main faults and thrusts are represented in red. Q (Quaternary deposits); LF (Lipica formation, “Aurisina limestone”); SF (Sežana formation, “Aurisina limestone”); RF (Repen formation, “Aurisina limestone”); PF (Povir formation, “Monte Coste limestone”); BF (Brje formation, no correspondence). The terms in parenthesis refer, the first to Jurkovšek et al., 2016 and the second to Consorti et al., 2021, respectively.

STOP 4 – The outflows: Timavo Springs and other minor springs

(45° 47′ 19,00″ – 13° 35′ 22,02″E)

*From **STOP 3** to **STOP 4** (about 10 km, 10 min)*

From ***STOP 3*** the tour will move back down toward the sea, passing alongside Doberdò, Pietrarossa and Sablici lakes. The latter collects the outflowing waters of the karst aquifer. The bus will stop at a parking lot close to the churches of San Giovanni in Tuba and San Giovanni Battista, the war memorials of the Brigata Lupi di Toscana and Terza Armata, the water supply plant of Randaccio, the four outflows of the Timavo Springs (Fig. 37), the Pozzo dei Colombi cave, the ancient and recent gate of challenging underwater surveys, the remains of a Roman *mansio* and the road to Aquileia harbor, which connected the lands of the west to the east.

Fig. 37 - 3rd branch of the Timavo Springs during the October 2010 flood.

Timavo Springs (TIM), located in San Giovanni di Duino, represent the main spring system of the Classical Karst Region. They consist of four different outflows collected into three branches. The latter are in turn collected into a single channel which after about 3 km flows into the Adriatic Sea to the Gulf of Monfalcone.

The Timavo and Sardos springs (SAR) were in use as far back as ancient times, but modern water exploitation dates from 1929 on, when a water supply plant was built and later named after Giovanni Randaccio, a World War I hero who died near the spring (Gemiti, 2004). With the increase in the demand for water, the 4 outflows of the Timavo Springs were also used. A series of mobile gates and weirs were built to avoid marine water ingression and to facilitate water withdrawals, in addition to special basins for water collection. The flow rate is definitively remarkable, with average daily values of about 30 m^3/s, minimum of 7.4 m^3/s and maximum of 158 m^3/s (Gemiti, 1995).

If, from a quantitative point of view, the Timavo Springs were an excellent water resource, one cannot say the same from a qualitative viewpoint. These waters were heavily polluted by organic substances discharged in the Notranjska Reka from industrial plants in Ilirska Bistica, and by the turbidity which reached values even higher than 200 FTU during floods. For these reasons, the Timavo Springs were in use up to the 1980s when tapping was suspended and replaced by well withdrawals located in the Soča/Isonzo plain near the Trieste airport. In the meantime, environmental sensitivity and the changed geopolitical structure of Slovenia have led to a series of actions aimed at reducing the risk of polluting the Notranjska Reka, the waters of which are now of excellent quality thus also resulting in higher water quality at the Timavo Springs, which has now taken on a strategic role and is ready to be used as a good quality freshwater resource in case of emergency.

The Timavo Springs represent the central hub of the entire Classical Karst Region hydrogeology, draining most of the waters recharging the entire aquifer. From the three spring branches, a complex and articulated network of large conduits develops. It reaches a depth of -83 m a.s.l. and a development of over 1.500 meters collecting the Reka waters sinking into the Škocjan caves, those of the Soča/Isonzo karst and the effective infiltrations recharging the Italian and Slovenian hinterland.

In the past, the connection of the entire hydrostructure with the spring area was proved by several tracing-tests performed starting from 1599 when the pharmacist Ferrante Imperato tried to link the Škocjan caves with the Timavo Springs by using leaves and straw. Floaters were used several times in the nineteenth century (Grablovitz, 1885) but without results until 1891 when F. Muller obtained his first success by using uranine. In the 1890s a series of further experiments took place using different dye-tests (uranine, rhodamine, ...) or in general, substances such as chemicals (lithium chloride, strontium chloride, cesium chloride ...), radioactive

https://doi.org/10.3301/GFT.2022.03

(uranite), isotopes (tritium), accidental spillage of hydrocarbons and biological tracers (Galli, 2012 and all the references therein). Of particular interest was the experiment proposed by Massimo Sella, head of the Institute of Marine Biology of Rovinj (Istria), who, taking advantage of the natural instinct of eels to go back to the sea, verified the water connection between the Škocjan caves and the Timavo Springs by releasing 362 eels between the Vreme sinkhole and the Škocjan caves (Galli, 2012 and all references therein). New dye-tests are still on-going aimed at increasing the knowledge regarding the territory (Petrič and Kogovšec, 2016; Petrič et al., 2020; Pavoni et al., 2021). The hydrogeological map and a summary of the tracer tests is presented in Fig. 38.

The joint analysis of the flow rate, electrical conductivity and groundwater temperatures allows us to observe how, according to the hydrogeological regime, one recharge area prevails over another. During floods there are generally differentiated water arrivals, with temperature and electrical conductivity trends that differ from episode to episode. These behaviors are due to the overlapping or opposing water impulses conveyed through different drainage paths and at different altitudes, coming from the Notranjska Reka basin, from the influent character of the Soča/Isonzo and Vipacco rivers and from the effective precipitations occurring on the plateau. Figure 39 highlights the intimate connection between the Notranjska Reka and Timavo Springs during high water flow regimes. In the period between mid-February 2006 and mid-March 2006, intense precipitation followed one after another, causing 4 flood events in the Notranjska Reka/Timavo Superiore river basin.

The flood peaks recorded in the Škocjan caves can also be observed at the Trebiciano Abyss, where water rises normally exceeding 30 meters, and at the Timavo Springs the EC trend is definitely of interest. During floods, Notranjska Reka waters record a sharp decrease with values that drop from 350-380 uS/cm to 250-260 uS/cm. These abrupt decreases in EC can also be observed at the Trebiciano abyss and the Timavo Springs, but with a site-to-site delay which also allows for the evaluation of the velocity of the waters between the Škocjan caves and the Timavo Springs (Turpaud et al., 2018). This behavior indicates the clear connection and fast circulation into the conduits connecting the Škocjan caves and Timavo Springs (Fig. 40).

When the precipitation in the Classical Karst Region is higher than in the Notranjska Reka basin, the Timavo Springs are more influenced by *karst waters*. This phenomenon can be clearly observed in the sequence of floods that occurred between January and March 2016 (Fig. 40). Also in this case the EC trend clarifies what happens in the hydrostructure. During the flood event recorded in mid-January 2016, a diametrically opposite behavior is observed at the Timavo Springs and at the Škocjan caves: to a classical EC decrease at Škocjan, there is a corresponding EC increase in Timavo Springs. The Reka flow rates being low, the Timavo conduits

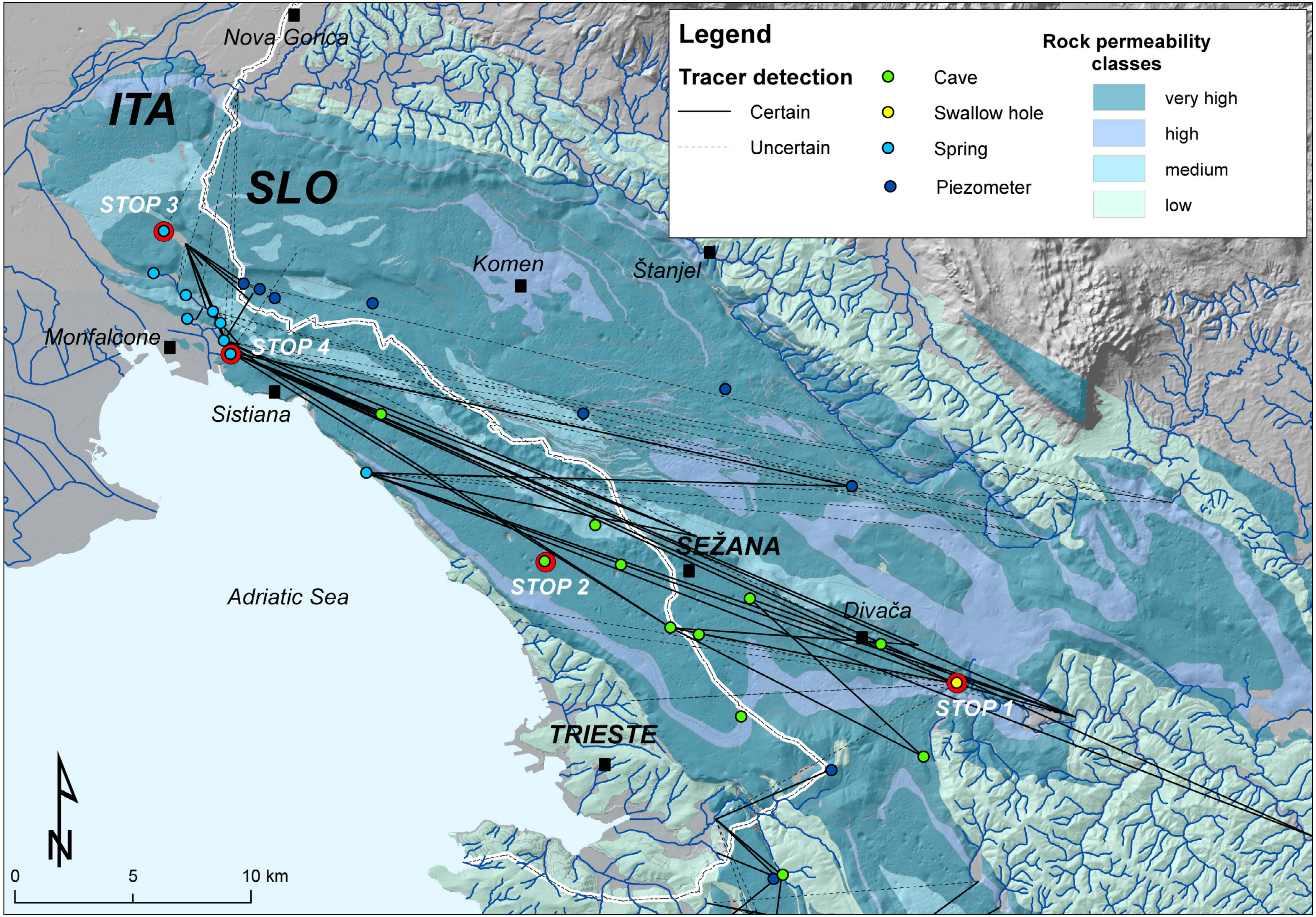


Fig. 38 - Hydrogeological map of the study area. A summary of the tracer tests is presented showing the main connections among the water points.

https://doi.org/10.3301/GFT.2022.03

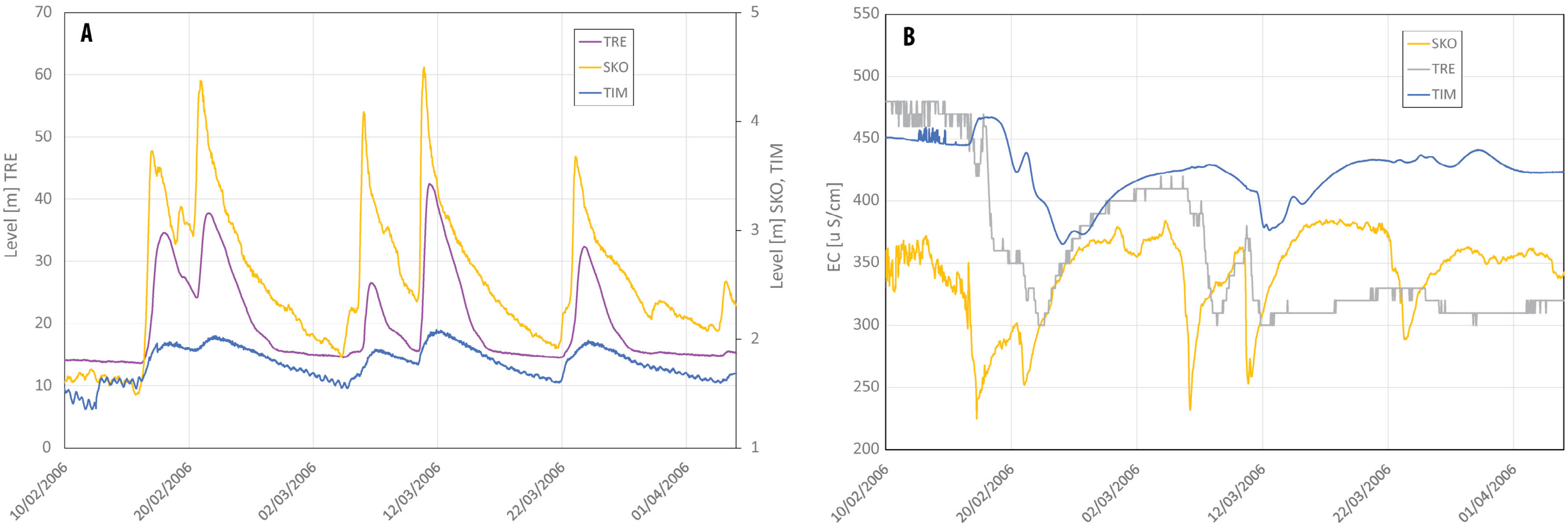
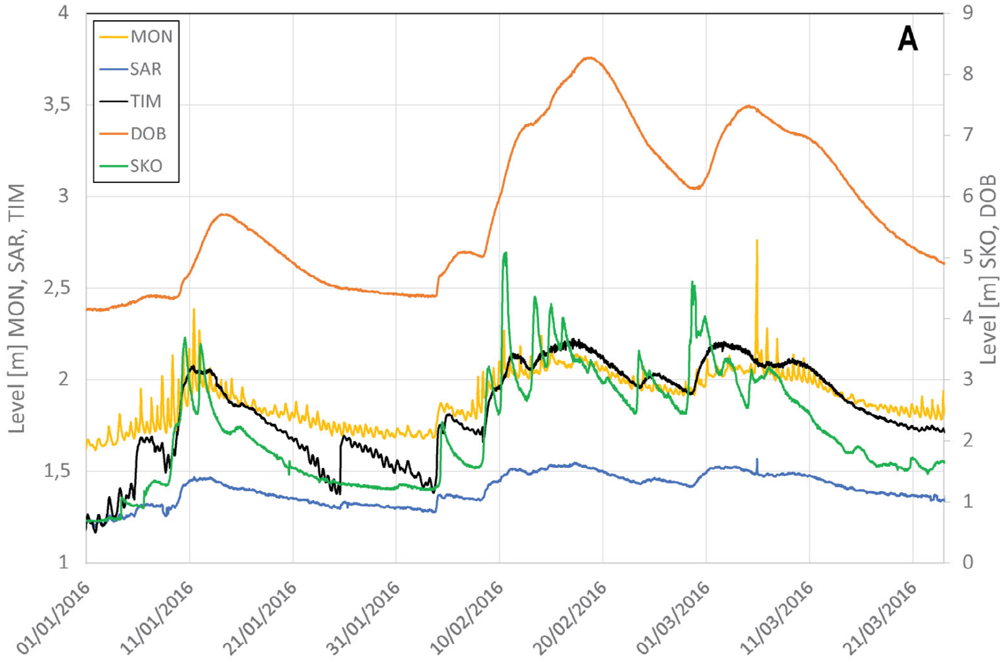


Fig. 39 - Connection between the Reka and Timavo Springs during high water flow regimes. A) water level; B) Electrical Conductivity (EC) recorded in correspondence with the Škocjanske jame, Trebiciano abyss (TRE) and Timavo Springs (TIM) in the period between mid-February 2006 and mid-March 2006.

mainly drain *karst waters*: the signal observed is therefore an EC increase quite similar to that of all the other monitoring points of the western sector of the Classical Karst Region. Figure 41 portrays Sardos spring.

On the other hand, during floods in the period between February and March 2016, an excellent correlation was observed between Škocjan caves and Timavo Springs. The high flow rates of the Reka recorded at the sinkhole create pressure in the conduits inhibiting the *karst water* drainage. The influence of the Reka waters, however, is not felt at any of the other monitored points of the western area (from Sardos spring to Doberdò Lake) which also highlights the transit of more mineralised *karst waters*.

https://doi.org/10.3301/GFT.2022.03



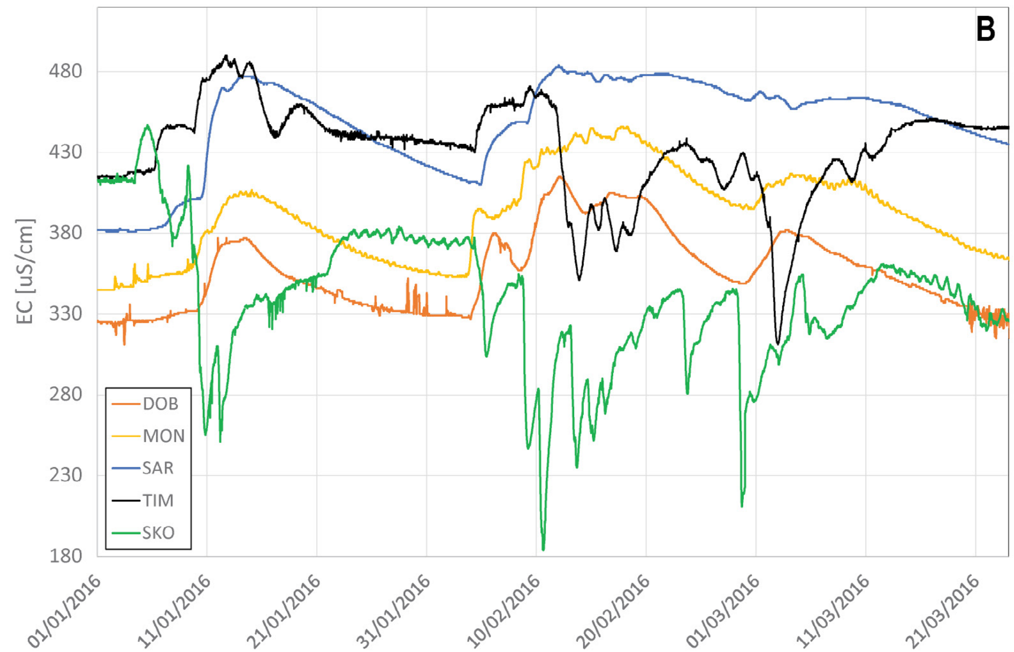


Fig. 40 - Water level (A) and EC (B) values recorded in correspondence with the spring areas compared with the Škocjanske jame.

https://doi.org/10.3301/GFT.2022.03

Fig. 41 - Sardos springs: the outflow inside the Randaccio water supply plant.

Back to Trieste

(about 24 km, 30 min)

The excursion ends by going back following state road no. 14, the *Costiera* which runs along the rocky coast of the Gulf of Trieste: it represents the gateway to Trieste, a panoramic road with breathtaking sweeping views of the coast, of the northern Adriatic Sea and among the vegetation, of the northern part of Istria. The bays of Muggia (ITA) and Koper (SLO), the flysch cliffs of Isola (SLO) and the church of Santo Stefano di Pirano (SLO) are in the background. Moving to Trieste, on the right, the view goes to Villaggio del Pescatore, built almost from scratch to house Istrian refugees but where the famous fossils of dinosaur of “Antonio” and “Bruno” were discovered (https://museostorianaturaletrieste.it), to the Duino Castle which was home to the princes of the Torre Tasso, postmen of the Germanic Empire and its fascinating cliff, the Sistiana Bay, Aurisina springs, Miramare Castle and its park which hosted the Archduke Maximilian of Habsburg-Lorraine before he became Emperor of Mexico (Fig. 42), the Barcola Riviera, a free bathing destination for DOC inhabitants of Trieste.

Acknowledgements

The Authors would like to thank all the reviewers as well as Carolyn Close for the review of the English text.
Comments and corrections by the journal reviewers and by the editorial team Andrea Zanchi and Marta Dalla Seta which sensibly improved the quality of this field guide.

Fig. 42 - “Alveolinid-Nummulitid limestone” olistolites (Jurkovšek et al., 2016, *cfr.* “Miliolid, *Alveolina* and *Nummulites* limestone”, Consorti et al., 2021), huge limestone boulders shaping the Miramare promontory having a gravitative origin which took to their inclusion in the marly areanaceous flysch sequence.

References

Belli R., Frisia S., Borsato A., Drysdale R., Hellstrom J., Zhao J.-x., Spötl C. (2013) - Regional climate variability and ecosystem responses to the last deglaciation in the northern hemisphere from stable isotope data and calcite fabrics in two northern Adriatic stalagmites. Quat. Sci. Rev., 72, 146-158.

Borsato A., Cucchi F., Frisia S., Miorandi R., Paladini M., Piccini L., Potleca M., Sauro U., Sp ötl C., Tuccimei P., Villa I.M., Zini L. (2005) - Ricostruzione climatica degli ultimi 17.000 anni da una stalagmite della Grotta Savi (Trieste, Italia). Studi Trentini Sci. Nat., Acta Geol., 80, 111-125.

Braitenberg C. and Nagy I. (2014) - Illustrating the superposition of signals recorded by the Grotta Gigante pendulums with musical analogues. Acta Carsologica, 43(1), 139-147.

Braitenberg C., Pivetta T., Rossi G., Ventura P., Betic A. (2018) - Karst caves and hydrology between geodesy and archeology: Field trip notes. Geod. Geodyn., 9 (3), 262-269.

Brancelj A., Mori N., Treu F., Stoch F. (2020) - The groundwater fauna of the Classical Karst: hydrogeological indicators and descriptors. Aquat. Ecol., 54(1), 205-224.

Buser S., Grad K., Pleničar M. (1967) - Osnovna geološka karta SFRJ, list Postojna, 1:100.000. Zvezni geološki zavod, Beograd.

Buser S. (1968) - Osnovna geološka karta SFRJ, list Gorica, 1:100.000. Zvezni geološki zavod, Beograd.

Calligaris C., Cucchi F., Zini L. (2016) - Climate changes and piezometric level fluctuations in the Isonzo/Soča River Plain (NE Italy). Rend. Online Soc. Geol. It., 41, 26-29.

Calligaris C., Mezga K., Slejko F.F., Urbanc J., Zini L. (2018) - Groundwater characterization by means of conservative (d^{18}O and d^{2}H) and non-conservative (^{87}Sr/^{86}Sr) isotopic values: the Classical Karst Region aquifer case (Italy–Slovenia). Geosciences (Switzerland), 8, 321.

Calligaris C., Casagrande G., Iervolino D., Lippi F., Olivo P., Ramani M., Treu F., Zini L. (2019a) - Water–budget as a tool to evaluate the sustainable use of groundwater resources (Isonzo Plain, NE Italy). Rend. Online Soc. Geol. It., 47, 7-12.

Calligaris C., Galli M., Gemiti F., Piselli S., Tentor M., Zini L., Cucchi F. (2019b) - Electrical conductivity as a tool to evaluate the various recharges of a karst aquifer. Rend. Online Soc. Geol. It., 47, 13-17.

Cancian G. (1987) - L'idrologia del Carso goriziano-triestino tra l'Isonzo e le risorgive del Timavo. Studi Trentini di Sci. Nat., 64, 77–98.

Carulli G. B. (2011) - Structural model of the Trieste Gulf: a proposal. J. Geodyn., 51, 156-165.

Casagrande G., Cucchi F., Zini L. (2005) - Hazard connected to railway tunnel construction in karstic area: Applied geomorphological and hydrogeological surveys. Nat. Hazards Earth Syst. Sci., 5(2), 243-250.

Civita M., Cucchi F., Eusebio A., Garavoglia S., Maranzana F., Vigna B. (1995) - The river Timavo: an important supplementary water resource which needs to be protected and regained. Acta Carsologica, 24, 169-186.

Consorti L., Arbulla D., Bonini L., Fabbi S., Fanti F., Franceschi M., Frijia G., Pini G.A. (2021) – The Mesozoic paleoenvironmental richness of the Trieste Karst. Geol. F. Trips Maps, 13(2.1), 1-40. https://doi.org/10.3301/GFT.2021.06

Covelli S., Cucchi F., Mosca R. (1998) – Monitoring of percolation water to discriminate surficial inputs in a karst aquifer. Environ. Geol., 36(3-4), 296-304.
Cucchi F. and Forti F. (1981) - La “cattura” del Timavo superiore a Vreme. Atti e Memorie C.G. E.B., 21, 55-64.
Cucchi F., Forti F., Stefanini S., Ulcigrai F. (1985) – Mésures de degradation de roches carbonates et d’accroisement de stalagmites. In: Collin G., Drouin P. (eds.) Spelunca Mémories, Actes XVIe Congrès National de Spéléologie, Nancy-Metz. Université Metz-Nancy, pp.87-90.
Cucchi F., Pirini Radrizzani C., Pugliese N. (1989) - The carbonate stratigraphic sequence of the Karst of Trieste (Italy). Mem. Soc. Geol. It., Vol. XL (1987), Trieste, 35–44. Proceedings of “International Symposium on Evolution of the karstic carbonate platform,” Trieste, 1st–6th June 1987.
Cucchi F. and Forti P. (1990) - Prime datazioni assolute su una stalagmite del carso triestino. Acta Carsologica, 18, 53-64.
Cucchi F., Forti F., Marinetti E. (1996) - Surface degradation of carbonate rocks in the karst of Trieste (Classical Karst, Italy). In: Karren landforms: Proceedings of the International Symposium on Karren Landforms: Sóller on 19-24th of September 1995/ Juan José Fornós Astó (ed. lit.), Angel Ginés Gracia (ed. lit.), 41-52.
Cucchi F., Casagrande G., Manca P., Zini L. (2001) - Il Timavo ipogeo tra l’Abisso di Trebiciano e la Grotta meravigliosa Lazzaro Jerko, Le Grotte d’Italia, serie V, 2, 39-48.
Cucchi F. and Zini L. (2009) - Paesaggi carsici nel Friuli Venezia Giulia. Ed. DiSGAM-Università di Trieste - R.A. Friuli Venezia Giulia, Tipografia Stella Arti Grafiche, Trieste, 112 pp.
Cucchi F., Finocchiaro F., Muscio G., Lizzi G., Ravalico M., Piano C. (2010) - Geositi del Friuli Venezia Giulia. Regione Autonoma Friuli Venezia Giulia, Trieste, pp. 383.
Cucchi F., Riccamboni R., Bandi E. (2012) - Water and life in the caves of the Rosandra valley. LINT editoriale, Trieste, 141 pp.
Cucchi F. and Piano C. (2013) - Carta geologica del Carso Classico (tratta dalla Carta di sintesi geologica alla scala 1:10.000 – Progetto GEO-CGT) e Brevi Note Illustrative della Carta Geologica del Carso Classico Italiano, con F. Fanucci, N. Pugliese, G. Tunis, L. Zini. Direzione centrale ambiente energia e politiche per la montagna, Servizio Geologico, Regione Autonoma Friuli Venezia Giulia, Trieste. Retrieved April 4, 2016, from http:// www.regione.fvg.it/rafvg/cms/RAFVG/ambiente-territorio/ tutela-ambiente-gestione-risorse-naturali/FOGLIA201/FOGLIA9/.
Cucchi F., Zini L., Calligaris C. (2015) - Il Progetto Hydrokarst: Le Acque del Carso Classico. Ed. E.U.T. Trieste. http://www.openstarts.units.it/dspace/handle/10077/10676, pp.181.
Cvijic J. (1893) - Das karstphenomenon. Versuch einer morphologischen Monographie. Geograph. Abhandlungen Band, Wien, V, Heft, 3, 1-114.
D’Ambrosi C. (1953). Carta geologica delle Tre Venezie. Foglio 53° “Trieste”. Uff. Idrogr. Mag. Acque, Venezia.
Doctor D.H., Lojen S., Horvatat M. (2000) - A stable isotope investigation of the Classical Karst aquifer: evaluating karst groundwater components for water quality preservation. Acta Carsologica, 29(1), 79-82.
Forti F., Semeraro R., Ulcigrai F. (1978) - Carsogenesi e geomorfologia dell’abisso di Trebiciano (Carso Triestino). Atti e Memorie della Comm. Grotte E. Boegan, 18, 49pp.

Furlani S., Cucchi F., Forti F., Rossi A. (2009a) - Comparison between coastal and inland Karst limestone lowering rates in the northeastern Adriatic Region (Italy and Croatia). Geomorphology, 104, 73-81.

Furlani S., Biolchi S., Cucchi F., Bensi S., Burelli G. (2009b) - Surveying of a submerged flysch outcrop at Sistiana-Duino (Gulf of Trieste, Italy). Atti e Memorie della Comm. Grotte E. Boegan, 42, 85-94.

Gams I. (1993) - Origin of the term "karst," and the transformation of the classical karst (kras). Environmental Geology, 21(3), 110-114.

Gabrovšek F. and Peric B. (2006) - Monitoring the flood pulses in the epiphreatic zone of karst aquifer: the case of Reka river system, Karst plateau, SW Slovenia. Acta Carsologica, 35(1), 35-45.

Galli M. (2012) - I traccianti nelle ricerche sul Timavo, Trieste, EUT Edizioni Università di Trieste.

Gemiti F. and Licciardello M. (1977) - Indagini sui rapporti di alimentazione delle acque del Carso triestino e goriziano mediante l'utilizzo di alcuni traccianti naturali. Annali Gruppo Grotte Ass. XXX Ottobre, 6, 43–61.

Gemiti F. (1984) - La portata del Timavo alle risorgive di S. Giovanni di Duino. Annali Gruppo Grotte Ass. XXX Ottobre, 7, 23-41.

Gemiti F. and Merlak E. (2005) - Interpretazione dell'esperimento di marcatura con tetracloruro di carbonio delle acque di fondo della Grotta A.F. Lindner (3988 VG). Atti e Memorie della Comm. Grotte E. Boegan, 40, 45-61.

Gemiti F. (2004) - Le sorgenti Sardos e l'approvvigionamento idrico della Provincia di Trieste. Atti e Memorie della Comm. Grotte E. Boegan, 39,67-80.

Gemiti F. (1995) - Portata liquida e portata solida del Timavo alle risorgive di S. Giovanni di Duino. Hydrores., 13, 75-88.

Grablovitz G. (1885) - Sull'idrologia del Carso. Atti e Memorie della Società degli Alpinisti triestini, Trieste 57-62.

Gunn J. (2004) - Encyclopedia of Cave and Karst Science. Fitzroy Dearborn, New York & London, pp. 902.

Jurkovšek B. (2010) - Geološka karta severnega dela Tržaškokomenske planote 1:25 000 = Geological map of the Trieste-Komen Plateau 1:25.000, explanatory book. Ljubljana: Geološki zavod Slovenije, 72 pp.

Jurkovšek B., Biolchi S., Furlani S., Kolar-Jurkovšek T., Zini L., Jež J., Tunis G., Bavec M., Cucchi F. (2016) - Geology of the Classical Karst Region (SW Slovenia–NE Italy). J. Maps, 12, 352-362. http://dx.doi.org/10.1080/17445647.2016.1215941, http://www.tandfonline.com/doi/suppl/10.1080/17445647.2016.1215

Kovačič G. and Ravbar N. (2013) - Analysis of human induced changes in a karst landscape — the filling of dolines in the Kras plateau, Slovenia. Sci. of the Total Environ., 447, 143-151.

Knez M. and Slabe T. (2002) - Unroofed caves are an important feature of karst surfaces: examples from the classical karst. Zeitschrift für Geomorphologie, 46(2), 181-191.

Kranic A. (1997) - Slovene Classical Karst - Kras. ZRC SAZU, Ljubljana, 254 pp.

Kranjc A. (2013) - Scientific Research of Škocjanske Jame Caves (UNESCO World Heritage) – since Antiquity to Modern Times. Conference volume: 5th Symposium for Research in Protected Areas, 10 to 12 June 2013, Mittersill, 415-419.

Laurenti J.N. (1768) - Synopsin Reptilium. J.T. de Trattnern, Viennae, pp. 35-36.

Martinis B. (1951) - Carta geologica delle Tre Venezie. Foglio 40° "Gorizia". Uff. Idrogr. Acque Venezia, Firenze.

Mosetti F. and D'Ambrosi C. (1963) - Alcune ricerche preliminari in merito a supposti legami di alimentazione fra il Timavo e l'Isonzo. B Geofis Teor Appl, 5(17), 69-84.

Nardini A., Petruzzellis F., Marusig D., Tomasella M., Natale S., Altobelli A., Calligaris C., Floriddia G., Cucchi F., Forte E., Zini L. (2021) - Water on the rocks: a summer drink for thirsty trees? New Phytol., 229, 199-212.

Pavoni E., Crosera M., Petranich E., Faganeli J., Klun K., Oliveri P., Adami G. (2021) - Distribution, Mobility and Fate of Trace Elements in an Estuarine System Under Anthropogenic Pressure: the Case of the Karstic Timavo River (Northern Adriatic Sea, Italy). Estuaries Coast., 1-17.

Petrič M. and Kogovšek J. (2016) - Identifying the characteristics of groundwater flow in the Classical Karst area (Slovenia/Italy) by means of tracer tests. Environ. Earth Sci., 75(22), 1-13.

Petrič M., Ravbar N., Zini L., Calligaris C., Corazzi R., Zitko Z., Restaino M., Knez M. (2020) - Determining the directions and characteristics of underground water flow in karst for the purpose of traffic routes construction: The case of the new Divača-koper railway line (SW Slovenia) | Določitev smeri in značilnosti toka podzemne vode v krasu za namen izgradnje prometnih poti: Primer nove železniške proge divača-koper (jz Slovenija). Acta Carsologica, 49(1), 63-80.

Petrini R., Italiano F., Ponton M., Slejko F.F., Aviani U., Zini L. (2013) - Geochemistry and isotope geochemistry of the Monfalcone thermal waters (northern Italy): inference on the deep geothermal reservoir. Hydrogeol J., 21, 1275-1287.

Placer L. (1998) - Contribution to the macrotectonic subdivision of the border region between Southern Alps and External Dinarides. Geologija, 41

Pleničar M., Polšak A., Šikić D. (1973) - Osnovna geološka karta SFRJ, list Trst, 1:100.000. Zvezni geološki zavod, Beograd.

Samez D., Casagrande G., Cucchi F., Zini L. (2005) - Idrodinamica dei laghi di Doberdò e di Pietrarossa (Carso Classico, Italia). Relazioni con le piene dei fiumi Isonzo, Vipacco e Timavo. Atti e Memorie della Comm. Grotte E. Boegan, 40, 13-152.

Savi T., Petruzzellis F., Martellos S., Stenni B., Dal Borgo A., Zini L., Lisjak K., Nardini A. (2018) - Vineyard water relations in a karstic area: deep roots and irrigation management. Agr, Ecosyst. Environ., 263, 53-59.

Semeraro R., Merlak E., Gemiti F., Brun C. (2007) - Chemistry of percolation and base-flow water in the Carso/Kras. 6th Symposium on Karst Protection, 29-30 September 2007 Beograd (Serbia). 6 pp.

Sciuto K., Moschin E., Moro I. (2017) - Cryptic Cyanobacterial Diversity in the Giant Cave (Trieste, Italy): The New Genus Timaviella (Leptolyngbyaceae). Cryptogamie, Algologie 38(4), 285-323. https://doi.org/10.7872/crya/v38.iss4.2017.285.

Stoykova D., Shopov Y., Sauro U., Borsato A., Cucchi F., Forti P. (2003) - High-resolution luminescence speleothem records from Savi Cave, Trieste, NE Italy. Studi Trentini Sci. Nat., Acta Geol., 80, 169-173.

Timeus G. (1928) - Nei misteri del mondo sotterraneo: risultati delle ricerche idrogeologiche sul Timavo 1895–1914, 1918-1927. Atti e Memorie della Comm. Grotte E. Boegan, 22, 117-133.

Treu F., Zini L., Zavagno E., Biolchi S., Boccali C., Gregorič A., Napolitano R., Urbanc J., Zuecco G., Cucchi F. (2017) - Intrinsic Vulnerability of the Isonzo/Soča High Plain aquifer (NE Italy - W Slovenia). J. Maps, 13(2), 799-810.

https://doi.org/10.3301/GFT.2022.03

Turpaud P., Zini L., Ravbar N., Cucchi F., Petric M., Urbanc J. (2018) - Development of a Protocol for the Karst Water Source Protection Zoning: Application to the Classical Karst Region (NE Italy and SW Slovenia). Sustain. Water Resour. Manag., 32(6), 1953-1968.

Ulcigrai F. (1976) - Successione stratigrafica dell'Abisso di Trebiciano. Atti e Memorie della Comm. Grotte E. Boegan, 16, 19pp.

Urbanc J., Mezga K., Zini L. (2012) - An assessment of capacity of Brestovica – Klariči Karst Water Supply (Slovenia). Acta Carsologica, 41(1), 89-100.

Valvasor, J.V. (1689) - Die Ehre dess Hertzogthums Crain. Acta Eruditorum, Leipzig. 529-539.

Vižintin G., Ravbar N., Janež J., Koren E., Janež N., Zini L., Treu F., Petrič M. (2018) – Integration of models of various types of aquifers for water quality management in the transboundary area of the Soca/Isonzo River basin (Slovenia/Italy). Sci. Total Environ., 619-620, 1214-1225.

Velić I. (2007) - Stratigraphy and palaeobiogeography of Mesozoic Benthic foraminifera of the Karst Dinarides (SE Europe). Geologia Croatica, 60(1), 1-113.

Vlahović I., Tišljar J., Velić I., Matičec D. (2005) - Evolution of the Adriatic carbonate platform: Palaeogeography, main events and depositional dynamics. Palaeogeography, Palaeoclimatology, Palaeoecology, 220, 333-360.

Vlahović I., Tišljar J., Velić I., Matičec D. (2002) - The Karst Dinarides are composed of relics of a single Mesozoic platform: Facts and consequences. Geologia Croatica, 55(2), 171-183.

Zini L., Visintin L., Cucchi F., Boschin W. (2011) - Potential impact of a proposed railway tunnel on the karst environment: the example of Rosandra valley, Classical Karst Region, Italy-Slovenia. Acta Carsologica, 40(1), 207-218.

Zini L., Calligaris C., Zavagno E. (2013) - Classical Karst hydrodynamics: a shared aquifer within Italy and Slovenia. In: Evolving Water Resources Systems: Understanding, Predicting and Managing Water-Society Interactions. IAHS Publication 364, 499-504.

Zini L., Calligaris C., Cucchi F. (2015) - The challenge of tunneling through Mediterranean karst aquifers: the case study of Trieste (Italy). Environ. Earth Sci., 74(1), 281-295.

Žvab Rožič P., Čar J., Rožič B. (2015) - Geological Structure of the Divača Area and its Influence on the Speleogenesis and Hydrogeology of Kačna jama. Acta Carsologica, 44(2), 153-168.

Manuscript received 30 June 2021; accepted 18 January 2022; published online 27 April 2022;
editorial responsibility and handling by M. Della Seta.