A karst area shared between carbonate megabeds and siliciclastic units: the example of Mt. Bernadia (NE Italy)

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Rend. Online Soc. Geol. It., Vol. 67 (2025), pp. …-…, 3 figs., 1 tab. https://doi.org/10.3301/ROL.2025.19

Short Note

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Citation: Zini L., Calligaris C., Finocchiaro F., Ponton M., Potleca M. & Manca P. (2025) - A karst area shared between carbonate megabeds and siliciclastic units: the example of Mt. Bernadia (NE Italy). Rend. Online Soc. Geol. It., 67, XX-XX, https://doi.org/10.3301/ROL.2025.19

Associate Editor: Marco Pantaloni

Submitted: 24 January 2025
Accepted: 07 July 2025
Published online: XX August 2025

ABSTRACT

A significant portion (28%) of the entire Friuli Venezia Giulia Region (FVG) (NE Italy) comprises carbonate aquifers, many of which are extensively karstified and exploited for drinking purposes. Ensuring water availability and protection remains a critical priority to meet the rising demand driven by population growth. In pursuit of this goal, according to the FVG Regional Law 15/2016, the Department of Mathematics, Informatics and Geosciences of the University of Trieste and the Geological Survey of the Friuli Venezia Giulia Region started a multi-year project aimed at identifying regional and cross-border karst aquifers assessing their vulnerability. Among the 130 karst areas recognized, one of the most peculiar is the Mt. Bernadia. Sited in the Julian Prealps, it has a particular hydrogeological and karst context where several megabeds of calcarenites and carbonatic breccias alternate within marls and siliciclastic sandstones of the flysch formations (Paleocene – Eocene). The latter lie on Cretaceous limestones. Megabeds are highly karstified, with important sub-horizontal caves draining groundwaters and impressive caprock sinkholes involving siliciclastic materials. The landscape contrast between the characteristic fluvial landforms and the karst features is striking. In order to improve the knowledge of the Mt. Bernadia aquifer, detailed hydrogeological surveys, and, among the others, dye-tracers were scheduled. The present paper details the results of the dye-experiments realized thanks also to the contribution of the speleological associations, in particular to Circolo Speleologico e Idrologico Friulano and Gruppo Speleologico San Giusto. Data acquired evidenced how carbonate megabeds experience a mature karst where caves and conduits often develop at the contact between carbonates and siliciclastic layers giving rise to peculiar features: caves develop both thanks to solutional and erosional processes. The presence of several sinkholes also in correspondence of a siliciclastic cover, allow anyway a fast and concentrated infiltration of the waters reaching quickly the karst hydrostructure in the megabeds. Here the groundwaters are guided by the dip of the strata and the main tectonic features. Being in a mature karst system, travel times are quite short and as consequence the vulnerability is high.

KEYWORDS: karst hydrogeology, tracer test, karst, cave.

INTRODUCTION

Karst aquifers store substantial amounts of water, making them essential water resources worldwide (Stevanović, 2019) even if they are particularly fragile and susceptible to surface human activities. Standard approaches to study them include numerical groundwater modeling, as well as analytical and empirical methods which both require diverse geological and hydrogeological input data, which, in karst environments, are often indirectly obtained and less reliable due to the high heterogeneity of the bedrock. Moreover, the limited availability of such data often introduces significant uncertainty, making predictions about groundwater drainage patterns less reliable (Petrič et al., 2020). To improve understanding and accuracy, tracer tests with artificial tracers are particularly valuable for assessing groundwater flow and drainage patterns (Käss, 1998; Benischke et al., 2007; Goldscheider et al., 2008; Kogovšek & Petrič, 2014; Benischke, 2021; Filippini et al., 2018; Turpaud et al., 2018).

In this framework fits the activities realised by the researcher group coordinated by the Trieste University on the Mt. Bernadia

(NE Italy), an area characterized by the presence of extensive karst features, both epigean and hypogean favoured by the exposure of the peculiar paleogenic siliciclastic sequences with several carbonate embedded megabeds (Pini & Ponton, 2023).

Over the years, passionate scholars and researchers tried to understand the underground water flows in these complex areas. The first approaches occurred on 1897 with Marinelli, and later on continued with Feruglio (1954) which realised tracer tests by using uranine. Following these initial studies, no further tracing tests have been conducted until the present day when new tracer tests gave the possibility to better comprehend the geological constrain on the hydrogeology of the area with a view to the protection of the karst aquifer.

STUDY AREA

The area has a complex geological structure, featuring a carbonate core composed of thick layers of highly karstifiable Cretaceous limestone (LIM, Fig. 1), covered by flysch (*Flysch del Grivò Fm.*) (GRI, Fig. 1). This flysch consists of impermeable siliciclastic sandstone-marl deposits interbedded with highly karstifiable large carbonate beds (ranging in thickness from few to tens of meters) (GRIa, Fig. 1).

According to Feruglio (1925, 1954), 23 were the identified megabed of which the most important bear the name of the site where they are clearly visible as Mt. Ioanaz and Vernasso; the others are simply numbered. Recently Pini & Ponton (2023) published a new map, better distinguishing the sedimentary facies and adding 8 megabeds to Feruglio's list.

In the southwestern sector of M. Bernadia outcrop limestones belonging to the *Calcare del Cellina Fm*. and to the *Calcare del Monte Cavallo Fm*. (LIM, Fig. 1), Jurassic and Cretacic in age. Further south, marls and sandstones belonging to the *Marne ed arenaria di Savorgnano Fm*., outcrops (SVO, Fig. 1) (Zanferrari et al., 2013).

From a tectonic perspective, the area is characterized by a broad, asymmetrical antiform fold connected with a thrust and it is cut from a system of fracture and vertical faults NW-SE in direction. The tectonic structure, the nature of the rocks, and their distribution influence the development of the epigean and hypogean karst features. The Bernadia anticline is deeply incised by two streams: Torre (at its NW) and Cornappo (in the SE), which mainly flow from north to south, receiving contributions from different torrents and several springs. This creates a geomorphological watershed line that accurately describes surface water runoff but, as is common in karst massifs, does not always align with the underground watershed.

The wide variety of geological situations proposed by the area, further complicated by tectonic structures, has created peculiar geomorphological and hydrogeological environments. In the south, where limestones outcrops, it is possible to find the typical karst landscape characterised by the presence of a high density of karst features (dolines, karren, ...). In the northern part, instead, the alternations between siliciclastic deposits and carbonates gave rise to a patchy landscape with sectors where karst features are massively present (areas in which carbonates outcrop) and others in which the latter are totally absent (siliciclastic deposits).

Megabeds are highly karstifiable and several are the caves which development is accordance to them. The longer hypogean systems are represented by Tirfor Cave (7739/4721Fr, Sistema Bernardo Chiappa), Grotta Doviza (13/70 Fr), Grotta di Villanova Cave (938/323 Fr) and Feruglio Cave (3895/2175 Fr) (Ponton, 2019). The Sistema Bernardo Chiappa develops in the megabed numbered 13, Doviza Cave in megabed 14, while Grotta Nuova di Villanova and Feruglio caves in megabed 15. The thickness of the megabed limits the deep of the cave, on the contrary horizontal length vary from more than 8 kilometers for the Grotta Nuova di Villanova Cave to less than 5 kilometers for the Doviza. All the hypogean environment just described have a watercourse flowing inside the megabed and at the inferior passage. Although all the caves are very close, they have quite independent water circulation, due to silicoclastic flysch separating the carbonate megabeds.

Other caves open at the contact between flysch and Cretaceous limestones and develop in the limestones. The best example is the Viganti - Pre Oreak cave system, near Villanova delle Grotte village (Ciarabellini et al., 1999). Rio Tanaholo flows on flysch, at the contact with limestone water it sinks into the Viganti Abyss (110/66Fr), deep 252 m. At its bottom, a submerged gallery joins with Pre Oreak Cave (167/65Fr), a sub-horizontal gallery that opens a few meters above Cornappo Torrent. Other caves open and develop completely in limestones, as Grotta del Partigiano Cave (2125/968Fr).

The surficial geomorphological differences reflect also on the underground hydrogeology of the area. In the southern side, it is possible to find a unique aquifer, while in the northern part, swallow-holes and multiple aquifers can be identified according to the position of the different megabeds.

After the World War II, the discovering of several new caves in the area of Mt. Bernadia, pushed researchers and speleologists to better study the area in order to understand its speleological genesis. In October 1952, after a rainfall during the recession phase, Feruglio (1954) decided to realise a tracing experiment by using uranine inside the Grotta Nuova of Villanova Cave.

The tracer reached Mustig, one of the main springs feeding the Torre River, with a calculated apparent velocity 48 m/h. Comparing the discharge inside the Grotta Nuova di Villanova Cave and the one at Mustig spring, he noticed a significant difference. Therefore, he decided to conduct a second tracer test in February 1953 from the Doviza Cave. The tracer was detected only at the Mustig spring.

MATERIALS AND METHODS

2020 tracer test

Uranine and Tinopal CBS were used to trace water in two caves of the Mt. Bernadia massif (Tirfor Cave and Partigiano Cave). In 2020, tracer injections were conducted in the western sector (Elianto Branch) and the eastern sector (Off Limits Branch) of Tirfor Cave. A total of 17 different points, including springs and watercourses,

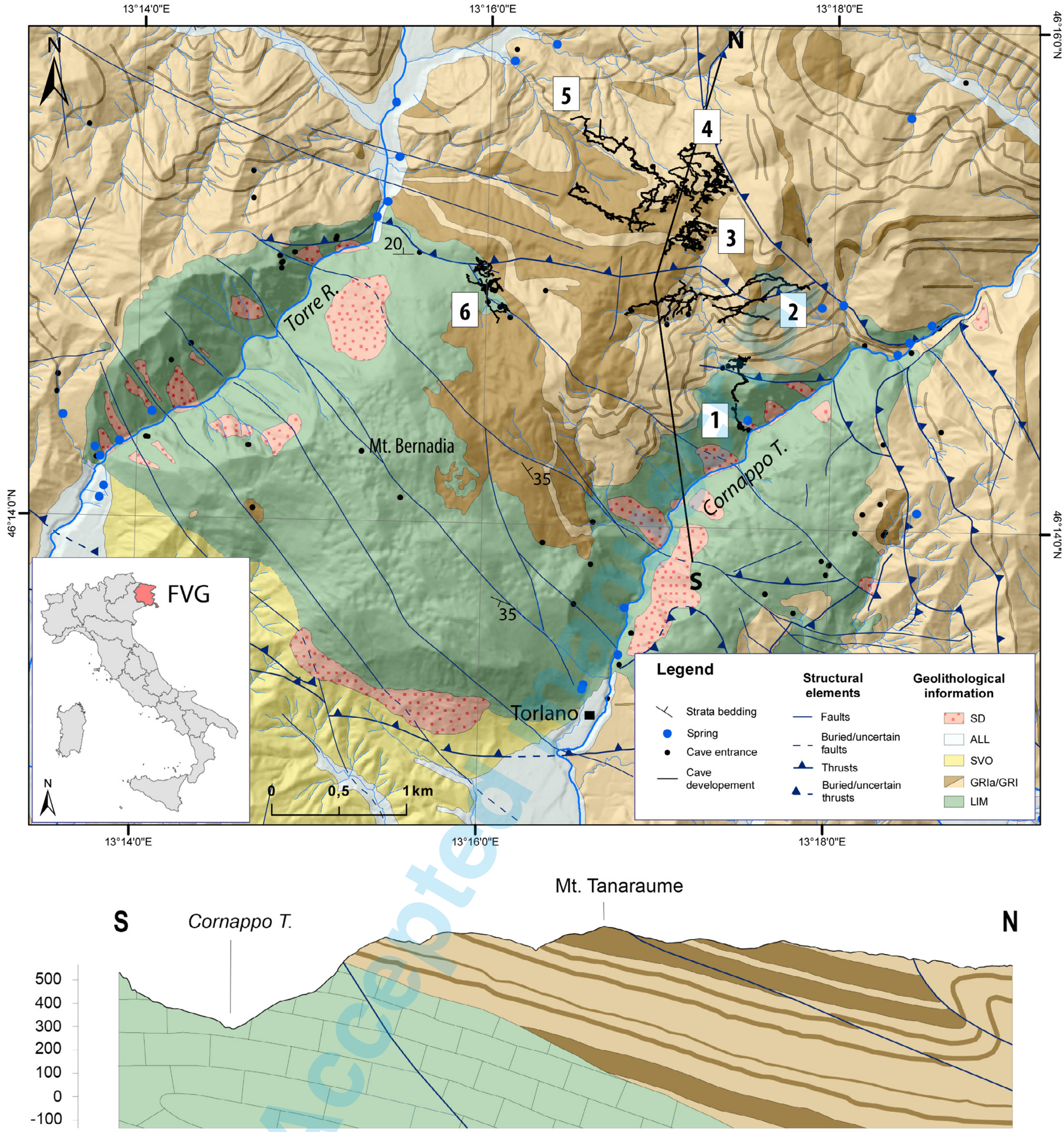

Fig. 1 - Geological map of the study area (modified after Ponton et al., 1996): a1-a3 scree slope deposits; b Alluvial sediments; SVO Marne ed arenaria di Savorgnano Fm; GRIa Carbonatic megabeds; GRI Flysch del Grivò Fm.; LIM Cretaceous limestone. Cave development are numbered: 1) Viganti – Pre Oreak cave system; 2) Tirfor Cave; 3) Doviza Cave; 4) Feruglio Cave; 5) Grotta Nuova di Villanova Cave; 6) Grotta del Partigiano Cave.

were monitored through water sample collection. From February 8 to 11, three samples were collected daily, followed by two samples per day until February 20, and finally, three additional sampling sessions were conducted on February 21, February 28, and March 5, 2020. Three of the 17 points were continuously monitored (sampling rate 15 minutes) using a fluorimetric probe (GGUN-FL24 fluorimeter) from February 7 to March 5, 2020.

2021 tracer test

In 2021, due to the unsuccessful tracing in the Elianto branch of the Tirfor Cave, the experiment was repeated, considering other monitoring points and adding also the tracing of the waters from the Partigiano Cave. A total of 15 different points, including springs and watercourses (in the southern part of the study area

Table 1 - A summary of the main characteristics of the tracer test injection experiments.

Injection point	Date and time of injection	Tracer used	Amount of tracer
Tirfor (Off Limits)	08/02/2020 11:10	uranine	60 g
Tirfor (Elianto)	08/02/2020 12:00	tinopal CBS	1 kg
Partigiano	19/02/2021 15:45	uranine	1 kg
Tirfor (Elianto)	19/02/2021 17:15	tinopal CBS	1 kg

and not present in Fig. 3), were monitored with daily water sample collections from February 20 to March 4. Subsequently, samples were collected once a day until March 8, and finally, one sample every two days until March 17. For specific points, as Mustig (MUS) and Torlano (TOR2), samples continued to be collected until April 1, 2021. From February 18, 2021, to March 19, 2021, two points were monitored in continuous with a sampling rate of 15 minutes, by using a fluorimetric probe (GGUN-FL24 fluorimeter).

The collected water samples were analyzed at the Hydrogeology Laboratory of the Department of Mathematics, Informatics, and Geosciences at the University of Trieste using a Perkin-Elmer LS45 luminescence spectrometer. Calibration curves for each tracer were done using water samples collected at the installation sites. The instrumental detection limit for uranine is 0.001 µg/L, and for tinopal, 0.01 µg/L.

Both tests were conducted under low-flow conditions and in almost total absence of precipitation: in 2020, the first significant rainfall occurred in early March, while in 2021, it only occurred in April.

RESULTS

2020 tracer test

Uranine was detected in a small spring located a few dozen meters upstream from the CPR1 sampling point at an elevation of 380 m a.s.l., at the base of the megabed hosting the Tirfor Cave. The planar distance between the injection point and the spring is approximately 510 m, with a vertical drop of 157 m. The tracer was first detected on February 9, 2020, at 01:04, with a peak recorded at 21:19 at a concentration of about 141 ppb. Being the average flow rate at the monitoring point of approximately 3.7 l/s, a tracer recovery of 82% was calculated. The uranine was detected 13 hours later along the Cornappo Torrent at the Pre Oreak Cave (PRE) and approximately 15 hours later near the small town of Torlano (COR). As for tinopal, it was not detected at any of the monitoring points, despite monitoring continuing for about a month.

2021 tracer test

Uranine was almost accidentally detected by an operator on February 24, 2021, at one of the monitoring points along the Torre stream (TOR 2). The operator, who was sampling the water, noticed that both on the left and right banks of the river, upstream and downstream from the monitoring point, there were springs (previously unknown) of greenish water that immediately lost their colour as they mixed with the water of the Torre River, which on that day had a discharge of approximately 3.8 m^3/s.

From February 24 onward, two additional monitoring points were added on the left bank of the river in correspondence of the two of the six identified springs. At these points, the concentrations recorded between February 24 and 26 reached values exceeding 170 ppb.

The fluorimeter, located 980 m from the injection point, was positioned on the left bank in an intermediate location between the newly identified springs. For this reason, it was only able to sample

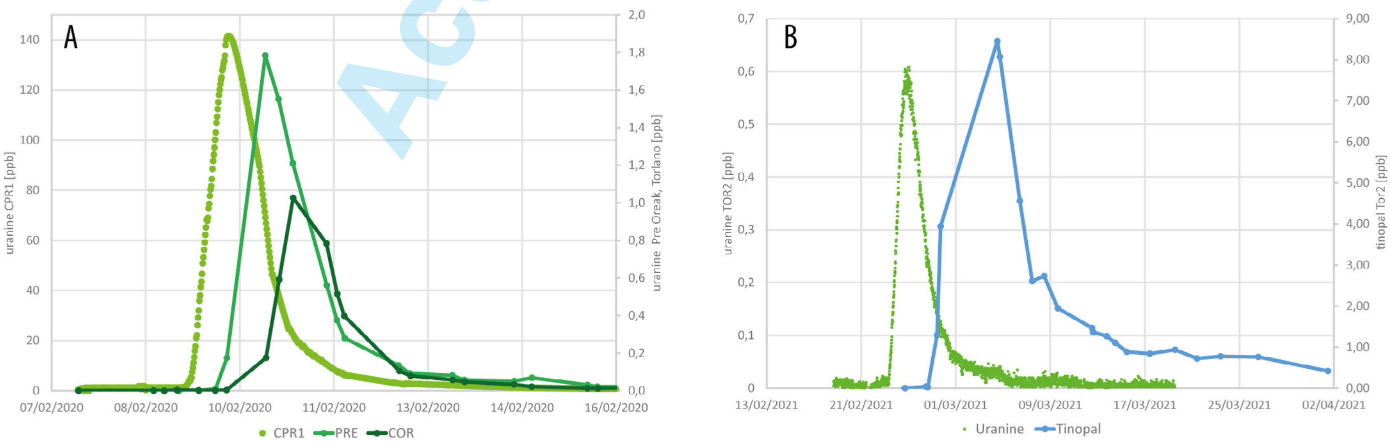

Fig. 2 - Tracer breakthrough curves. A) 2020 tracer test results; B) 2021 tracer test results.

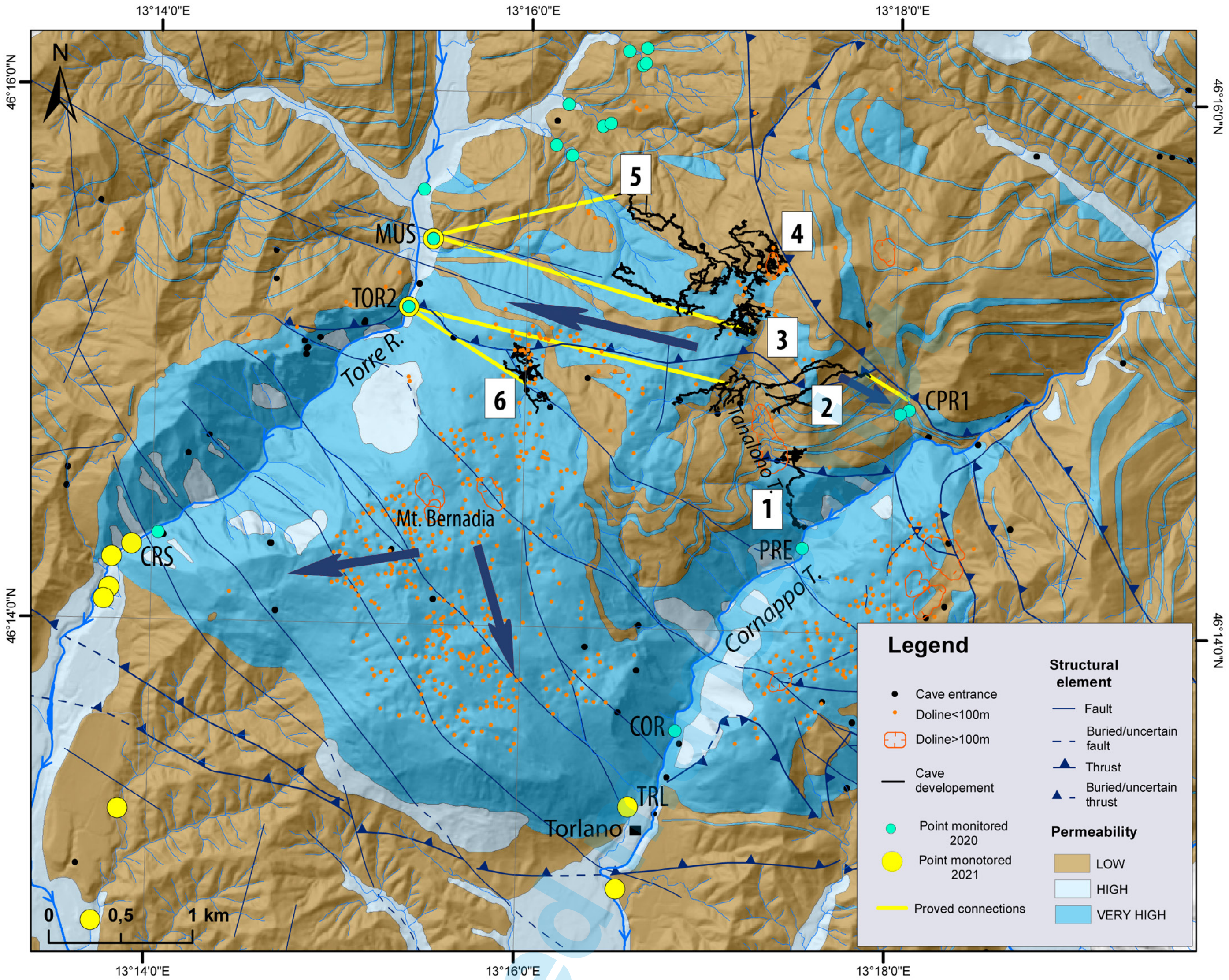

Fig. 3 - Hydrogeological map of the investigated area.

a portion of the tracer that flowed into the Torre River. The first positive sample was recorded on February 23 at 9:15 AM (estimated velocity of approximately 11 m/h), with the peak occurring on February 25 at 1:15 AM (estimated velocity of approximately 7.6 m/h) and a concentration of 0.6 ppb. Calculations performed at the TOR2 sampling point indicate that approximately 60% of the tracer injected into the Partigiano Cave was recovered. However, this value is certainly lower than the real amount passed through the Torre River, as additional springs draining the tracer were present downstream of the monitoring point and on the opposite bank.

As for tinopal, it was also detected in the springs near the TOR2 monitoring point. The first positive sample was recorded on February 27 at 9:53 AM, with concentrations of 1.3 ppb. Peak values were recorded on March 4, reaching approximately 8.5 ppb. The continuous fluorimeter was unable to detect the passage of tinopal because the springs near TOR2 point had flow rates of just a few liters per second, while the Torre River had flow rates exceeding 3000 l/s in early March. As a result, the tracer concentrations fell below the detection threshold of the instrument.

DISCUSSION

The recent dye-tests realised allowed to better understand the connections between the megabeds and the carbonates as well as among the different megabeds and the rivers. The results obtained from the tracer test conducted in 2020, indicated that waters flowed in the megabed and at the contact between the megabed itself and the siliciclastic units thus defining a lithological constrain. Analysing the results of the tracer tests conducted in the fifties, the lithological constrain is clear. Even if the geological structures dip towards north, the groundwaters flowed westerly due to the presence of the siliciclastic deposits in the northern part of the study area. Even if this is generally confirmed, there are specific situations in which there is a connection between megabeds as verified by Feruglio's tracer test: the groundwaters flowing in the 14 and 15 megabeds both outflow in correspondence of Mustig spring (MUS).

The tracer test realised in the 2021 highlighted the presence of a groundwater divide in correspondence of Tanaloho torrent. The waters from Elianto branch, following the megabeds and one of the main tectonic structure present in the area, outflowed to the Torre River. The role of this tectonic structure is also highlighted by the tracer test conducted from Partigiano Cave which develop in the limestones (LIM). The groundwaters from Partigiano Cave do not reach the main spring downstream Torre River (Crosis - CRS and Torlano springs - TRL), but outflows at TOR2 point. In adjoint, interesting is that the uranine outflowed on both sides of the Torre River in correspondence of the springs placed close to TOR2 monitoring point. This means that there is a conduit passing underneath the river connecting the springs.

CONCLUSIONS

The findings from all tracing efforts conducted recently, and in the past, have highlighted the geological-structural constraint of the Mount Bernadia hydrostructure. To the south, a thrust fault blocks the flow through the carbonates, while to the north, the siliciclastic formation restricts the aquifer, channeling all the water into a fairly narrow sector toward the northwest, between Vedronza small town and TOR2 monitoring point. Furthermore, a significant portion of the water infiltrating the massif is drained by the Torre River and, to a lesser extent, by the Cornappo Torrent.

The results obtained contribute to expand the knowledge about karst aquifers integrating and updating the hydrogeological maps of the Friuli Venezia Giulia region (https://catastogrotte.regione.fvg.it/webgisacquiferi). This tool is essential for visualizing hydrogeological data, monitoring aquifers, and supporting land-use planning, water resource management, and the protection of the karst environment.

ACKNOWLEDGEMENTS

This research was funded by Servizio Geologico of the Friuli Venezia Giulia Region in the framework of the projects: "*Individuazione e delimitazione degli acquiferi carsici del Friuli Venezia Giulia*" and "*Vulnerabilità degli acquiferi carsici del Friuli Venezia Giulia*" (CUP: J92F20000950002); scientific coordinator Prof. Luca Zini. The authors are grateful to the two reviewers for their valuable input, which helped improve the manuscript.

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