Geodesy and Geodynamics 9 (2018) 262–269

Contents lists available at ScienceDirect

Geodesy and Geodynamics

journal homepage: http://www.keaipublishing.com/en/journals/geodesy-and-geodynamics/

Karst caves and hydrology between geodesy and archeology: Field trip notes

Carla Braitenberg [a,*], Tommaso Pivetta [a], Giuliana Rossi [b], Paola Ventura [c], Ambra Betic [c]

[a] University of Trieste, Department of Mathematics and Geosciences, Italy
[b] Istituto Nazionale di Oceanografia e di Geofisica Sperimentale-OGS, Centro di Ricerche Sismologiche, Italy
[c] Ministero dei beni e delle attività culturali e del turismo, Soprintendenza Archeologia, belle arti e paesaggio del Friuli Venezia Giulia, Italy

ARTICLE INFO

Article history:
Received 9 April 2017
Received in revised form
4 June 2017
Accepted 5 June 2017
Available online 10 August 2017

Keywords:
Karst springs
Archeology
Hydrology
Tiltmeter

ABSTRACT

The Geodynamics-Earth-Tides-meeting-2016 was held in the Karst, the origin of geologic karst-formation. Surface-rivers are absent, and water flows in channels over distances of 30 km, forming subsurface caves. Geodetic observations allow detecting caves and sense hydrologic flow. The Karst water had been recognized before Romans as provision for man and livestock. Proto-historic remains near the mouth of the underground river suggest the water outpouring from the Karst was associated with deities to be worshiped. Here the geodetic and cultural aspects of the Karst are summarized, illustrating the field trip that had been offered to the participants.

1. Introduction and field trip summary

The field trip of the meeting was held in one afternoon of June 8, 2016, and included the visit of the Grotta Gigante Karst cave with its geodetic instrumentation and the visit of the mouth of the Timavo river at the base of the Karst Plateau, with its archeological remains. The archeological visit included the remains of an early Christian church and a Roman hostel. The distance from the Grotta Gigante cave, below which the underground river flows to the mouth of the river, is approximately 30 km. In Fig. 1 the itinerary is shown.

The field trip crossed the Karst Plateau, belonging to the so-called "Classic Karst", from which the geological term "karstic", related to the dissolution phenomena in carbonatic rock, took its origin. The plateau is constituted by a thick carbonate succession from Early Cretaceous to Eocene, with a thickness of 2000 m, partially covered by Early-Mid Eocene turbidite flysch deposits [2]. The tectonic setting is an anticlinorium, with altitude a.s.l. decreasing from SE to NW, where the platform disappears, buried below the alluvials of the Friulian plain. The carbonate succession is constituted by limestones, dolomites, breccias and bituminous limestones, with a rich fossil fauna [3]. Karstic features are present in all the formations, from the karren, and sinkholes of the surface to the canyons, chimneys, and caves of the depths. The sinkholes, which are collapsed caves, are well seen in digital terrain models. Fig. 1 shows the alignment of the many round depressions. They range from a few meters to about 300 m in diameter.

The field trip followed one portion of the course of the underground river, which carries the name Timavo, which flows for about 40 km below the surface, hidden by the white rocks and the karstic scrub of the Karst.

The precise path of the river is still unknown: born in Croatia on the southern side of Mount Snežnik, it flows through western Slovenia, and it disappears underground and flows through the Škocjan Caves (location see Fig. 2). In its Italian course, it rapidly deepens, until reaching a level of about 8 m above sea level, at which it gently flows towards the springs at San Giovanni di Duino. In Fig. 3 the river is depicted as it can be seen in the Škocjan Cave. Along its flow it can be seen at the bottom of some of the more than 2000 caves known in the so-called "Classic Karst". Fig. 2 shows the position of all known caves in the Italian Karst. The color code of the

* Corresponding author.
E-mail address: berg@units.it (C. Braitenberg).

Peer review under responsibility of Institute of Seismology, China Earthquake Administration.

Production and Hosting by Elsevier on behalf of KeAi

http://dx.doi.org/10.1016/j.geog.2017.06.004

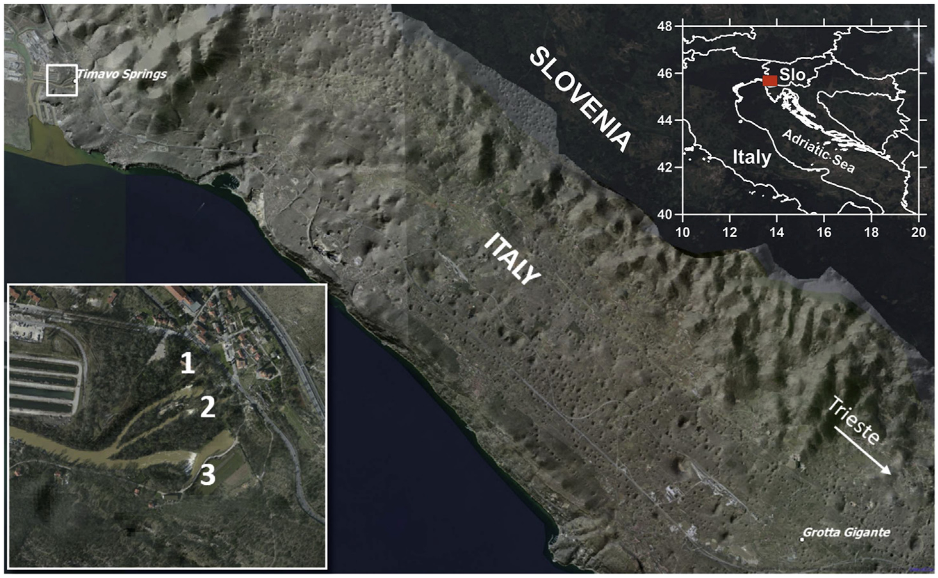

Fig. 1. Map of the itinerary from the Grotta Gigante cave to the mouths of the underground river Timavo (Timavo Springs). The digital terrain model derived from laser-scan data (acquired by Regione Autonoma Friuli Venezia Giulia [1]) is shown together with the satellite images (Microsoft Bing Maps). The many sinkholes are well seen and are presumably aligned with the flow direction of the underground river. The inset displays a detail on the Timavo Springs: the three numbers 1 to 3 refer to the three water mouths shown in Figs. 10–12, respectively.

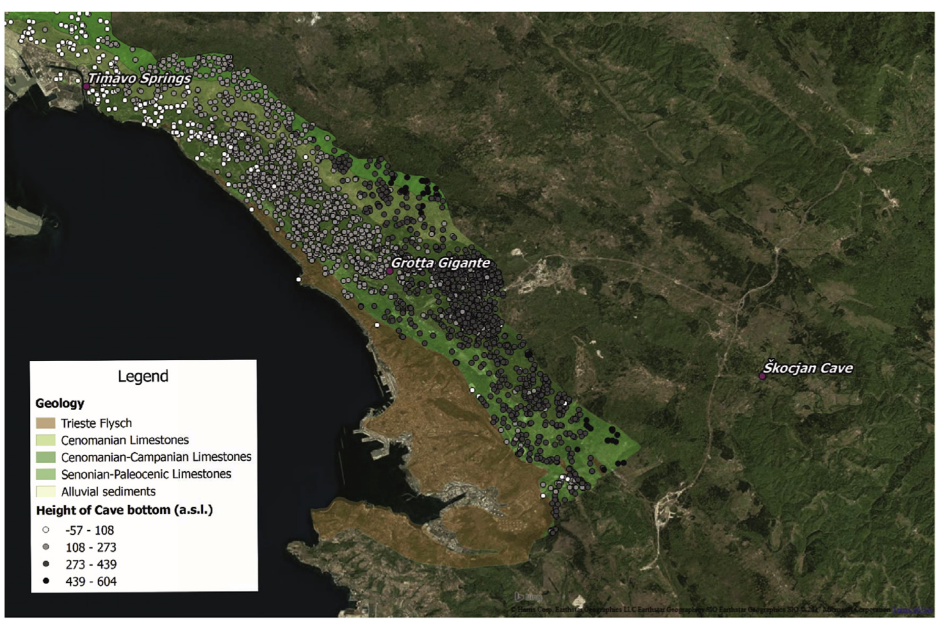

Fig. 2. Map of the Karst showing the outcropping Geological formations in its Italian part [4] and the known caves, reported with circles, according to the Friuli Venezia Giulia (Italy) kadastre catalog [5]. The color of the circle refers to the height of the cave bottom on sea level. A SE–NW trend is evident, that could be interpreted as a general indicator of the flux direction in the Karst system, bound to the tectonic setting of the layers. The increase in water level after strong rainfalls reaches over 100 m. Satellite image from Microsoft Bing Maps.

dots is related to the deepest extension of each cave, which is a proxy for the position of the deepest local water flow. In fact, the extension of each cave is governed by the hydraulic flow. It is seen that the darkest dots are limited to the South-East, then the depth gradually increases, until reaching depths even below sea level close to the Timavo mouths in the North-West. The biggest depth gradient is found in the South-East. In a selection of these caves, the river level is monitored continuously. During river floods, the hydraulic head increases its level by over 100 m, as has been demonstrated by the pressure gauges. The pendulums of Grotta Gigante and the collocated GPS station record the high stands of the underground river through characteristic tilt and displacement, respectively. The underground river appears again through four springs at San Giovanni near Duino, takes an overland course 2 km long, and outflows in the Gulf of Panzano (part of the Gulf of Trieste), 3 km southeast of Monfalcone, into the Adriatic.

2. The Grotta Gigante cave

The Grotta Gigante cave, situated near Borgo Grotta Gigante, in the municipality of Sgonico (Trieste), is the most renowned among the caves in the Italian part of the Classic Karst, the other being in

Fig. 3. Škocjan Caves, where the river Reka starts its voyage below the surface changing its name to Timavo river. **a**. Image of the Timavo river flowing inside the Škocjan Caves. **b**. The caves are open to the public and have an explored length of 6200 m.

Slovenian territory (Postojna, Škocjan, among the others). Open to the public for more than 100 years, the exceptionally large size of its main underground chamber enabled it to enter the Guinness Book of Records as the world's largest show cave in 1995.

2.1. Geological aspects of Karst and Grotta Gigante cave

Approximately 10 million years ago, the rivers flowing on calcareous surfaces gradually began to widen and deepen the fractures in the rocks by the process of dissolution. The surface waterways disappeared underground, creating a complex underground water network. The water erosion inside the rocks gave origin to the cave. Approximately 3 million years ago the ancient Timavo river abandoned the Grotta Gigante, as it had dug a deeper way throughout the cavity, which looked very different from what we see today.

The phase of concretions had already started with the formation of the cave and is still going on. The rainwater percolates throughout the limestone and by chemical reaction, melts the calcium carbonate. Drop by drop, during the course of millions of years, it is re-deposited inside the cave, giving origin to calcium flows, which cover large and small rocks in limestone, stalactites descending from the vault, stalagmites rising from the bottom, columns, created by the fusion of a stalactite with the stalagmite below. Their growth, due to the depositing of calcium carbonate, called calcite, is estimated to be 1 mm every 15–20 years.

The special feature of these stalagmites is their shape: a “stack of dishes” and a “palm tree”. These highly original forms are due to water drops falling from above, which expand as they reach the ground, thus covering a large surface. The variation in the quantity of water, in the course of thousands of years, has led to the differences in the diameter of the dishes.

The different colors one can see on the walls and concretions are due to the presence of mineral salts. White and gray are characteristic of pure calcite, whereas all shades of red, ochre and brown are typical of iron oxides and aluminum salts.

The cave can be accessed through a downhill tunnel; the flights of steps lead down to the main chamber, which is 98,50 m high, 76,30 m wide and 167,60 m long (total volume 365.000 m^3). The floor and the ceiling are covered with stalactites, stalagmites and other speleothems of all sizes, among which it is worth mentioning the most impressive one, Colonna Ruggero, that is 12 m in height.

The Grotta Gigante is also an important underground scientific research center (Geodetic Pendulums, tiltmeters, Seismographic Station, Archeological findings, Flora and fauna research centers, Muon radiography, Radon monitoring) and surface scientific research center (Climatological Observatory of the Karst, Epigean station for the measurement of Karst dissolution). The OGS headquarters and main buildings are located just above the Grotta Gigante cave. The Broad Band seismograph station in the cave links through internet connection directly to the Institute.

2.2. The geodetic aspects of the cave

The Grotta Gigante cave can be seen as a tangible illustration of geodetic measurements in underground exploration. The first is the fact that underground mass changes alter the Earth gravitational acceleration. The gravity field is reduced by up to 1.5 mGal, which corresponds very well to the expectations given by the laser scan survey of its inside [6,7]. In Fig. 4 the free air and Bouguer anomaly are shown, and the more negative values of the gravity field over the cave are well seen (1.5 mGal). The measurement precision of traditional gravimeters is better than hundred times smaller than the signal of the cave.

The second geodetic phenomenon is that underground water flows as those of the Timavo river, shifting great amounts of water at a level 280 m below the cave, deform the overlying rocks in a measurable way. Hence, geodetic observations can be used to sense

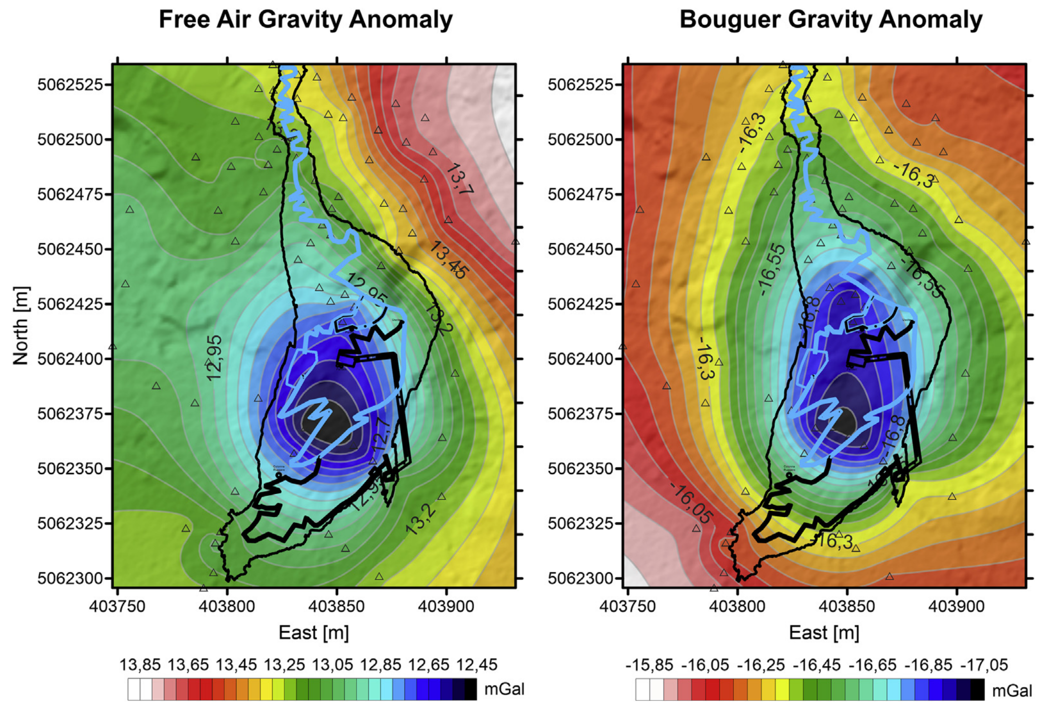

Fig. 4. Free Air and Bouguer gravity field anomaly of the Grotta Gigante cave. The Gravity field diminishes due to the missing mass of the cave. Triangles: measured gravity points. Black: outline of the cave. Blue line: pathway inside the cave done during the visit. The surface topography obtained from a laser scan survey (see Fig. 1) is also plotted.

the presence of underground water flows [8–10]. The cave houses a couple of large scale horizontal pendulums that are mounted on the bottom and top of the cave, as shown in Fig. 5. On the image of Fig. 6, one sees semi-translucent vinyl tubes hanging from the roof of the cave. These are the protection of the upper wire holding the horizontal pendulums. The top mounting is dislocated from the lower mounting by 1 m to give the pendulum the necessary tilting to be able to be sensitive to tilt in the direction orthogonal to the dislocation. This way the pendulum senses either shear between upper and lower mounting or tilting of the entire cave as a whole. The two signals cannot be distinguished.

A typical movement in response to a flood is shown in the cartoon of Fig. 7. The floods of the Timavo river can be quantified by

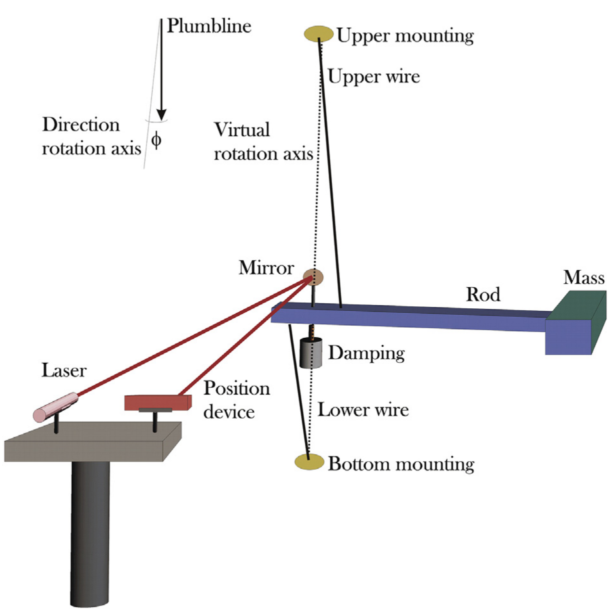

Fig. 5. Schematic drawing of the Marussi Horizontal Pendulums and their mounting in the cave.

Fig. 6. A view of the cave pathway.

the flow rate of the Reka river entering the Karst system at the Škocjan cave in Slovenia and by measuring the flow of water exiting the Karst system at San Giovanni in Tuba near Duino at the four mouths of the river (see position in Fig. 1, and photos in Figs. 8–12). In San Giovanni in Tuba the highest flow rate was measured in 1972 and reached 158 m^3/s. The tiltmeters generally tilt towards SW and return back to their original position during the floods in the time frame of about 7 days.

3. The mouths of the Timavo River

The Timavo River flows underground at the base of the Karst for at least 40 km of its 90 km journey to the sea. It comes to the surface near San Giovanni di Duino, in the Municipality of Duino Aurisina (location is seen in Fig. 1, in the inset of Timavo Springs) with four mouths/springs and a few miles later it outflows into the Gulf of Trieste, in the Adriatic Sea. It receives much of its water through subterranean flow from the Reka River (Slovenia), but tracer studies have shown that other sinking rivers, Vipava, Soča, and Raša also contribute. From modeling results, the Timavo is believed to receive one-third of its flow from the Reka and two-thirds of its flow from infiltration of precipitation into the Karst Plateau, and to a lesser extent from the other sinking river sources. As it leaves the ground at San Giovanni, it is a fast flowing powerful body of water that seemed to indicate the presence of the gods; therefore shrines and votive inscriptions to Diomedes, Hercules, Silvanus and Spes Augusta were placed here. The area has been known since pre-proto-historic times, and these springs (the so-called Risorgive), of great naturalistic and historical importance, were once held to be sacred as confirmed by some Roman stone inscriptions dedicated to

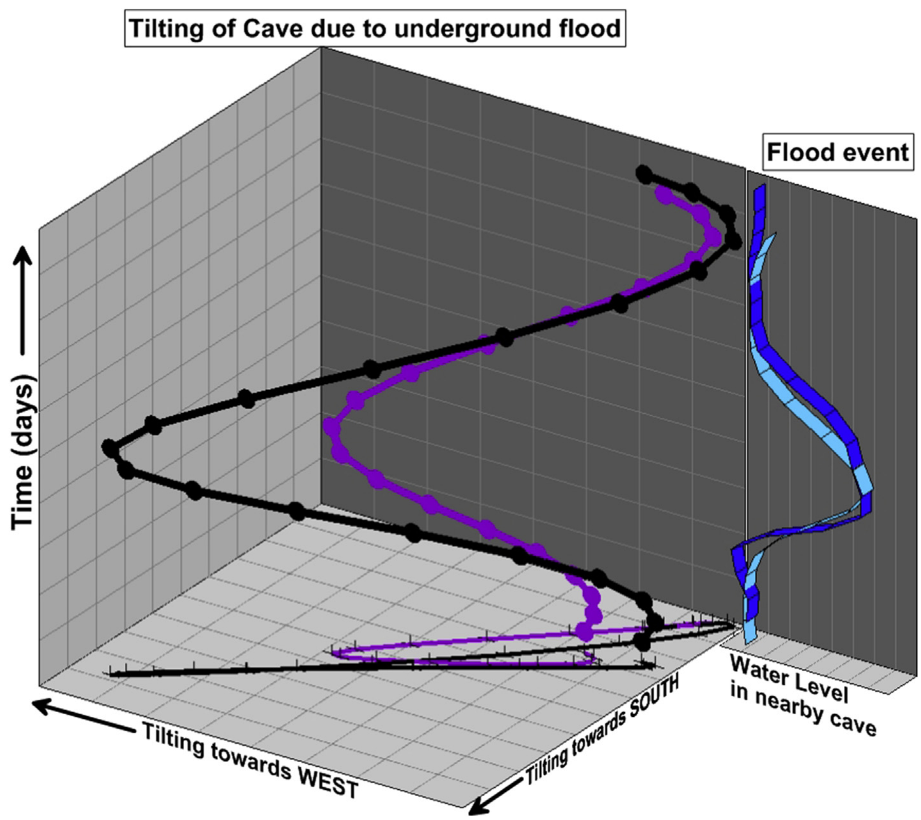

Fig. 7. Characteristic movement of the water induced by tilting.

Fig. 8. View of the church San Giovanni in Tuba from outside: **a**. the artistic ancient building techniques with local stones can be admired; **b**. the beautiful lateral portal.

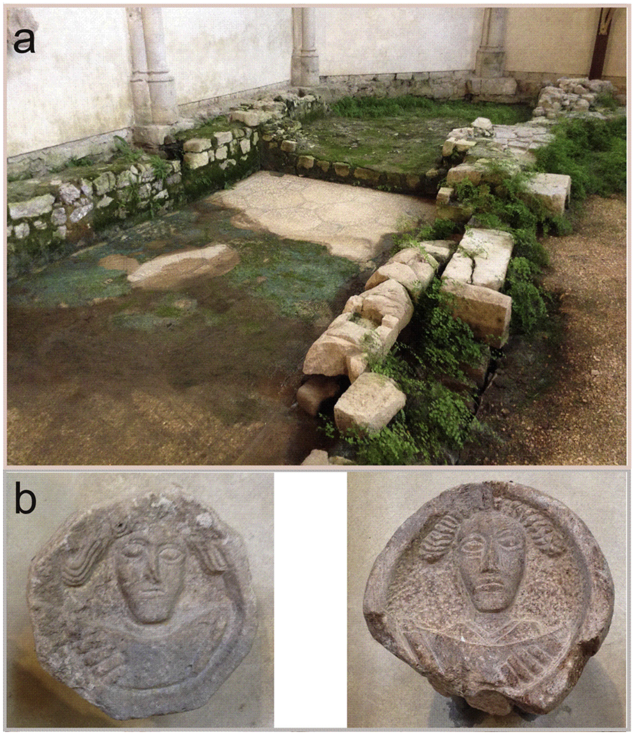

Fig. 9. Composite of interesting features seen in the Duino church. a) Rests of the early Christian basilica walls (5th cent. AD), beneath the present-day pavement. b) Two Medieval sculptures, maybe showing a female and male person. It is not clear what they are presenting in their hands.

the numen Temavus. Ancient historians and poets such as Livy, Strabo, and Virgil described and mentioned its seven (at those times) mouths [11]. Here stands the church of San Giovanni in Tuba, a rare example of Gothic architecture on the Carso, dating back to the XVth century in its present form, but with much older origins, as the Vth century mosaics which can be seen inside, can testify. In the apse, behind the altar, there can be seen the excavations which have brought to light the remains of an early-Christian basilica.

The church has been built around the smaller more ancient rests, the original pieces of stones dating back to Roman times. The

Fig. 11. The second of the Timavo River mouths.

Fig. 12. The Timavo river on its way downwards to the Adriatic sea, the output from the base of the Karst at San Giovanni collecting the outpour from the three Timavo mouths.

Fig. 10. The first of the Timavo River mouths. The arrow shows the flow direction of the water. The water level is a few meters above sea level.

location is characterized by the presence of the underground water, which often penetrates into the church floor from below. The effect is the vegetation that characterizes the older and lower lying church rests, which sometimes are covered with water. Figs. 8 and 9 illustrate this more ancient church of which the floor mosaic and some stone walls remained (Fig. 9a). The interesting bas-reliefs (Fig. 9b) exposed on the wall are maybe Medieval.

The first of the Timavo springs (Fig. 10) lies near to the church, but the thick undergrowth prevents a clear view of the other two branches of the river which are also nearby. These all join together before arriving at the sea, only 2 km away and form a quite big river, as can be seen in Fig. 12.

One hundred meters uphill and towards the left, stands a “mansio”, staging post during the Roman period along an important road (Fig. 13). The archeological area is located inside the park of the aqueduct “Randaccio”, providing water to the city of Trieste. The excavations, conducted in the '80s and '90s of the last century, brought only partially to light (1300 sqm) the ancient building, lying along the slope of the Karstic hills and accordingly divided into three different levels, with 40 rooms. The life of the complex stretches from the beginning of the 1st century BC to the 3rd/4th century AD; during the Augustan epoch (end 1st century BC) many rooms were paved with luxurious mosaics, in the last phases the mansio/villa was converted to productive purposes.

A bit further up of it, there are traces of the ancient Roman road which led from Aquileia over the Karst to Trieste [12,13].

4. Conclusions

The Karst plateau offered privileged living condition since prehistoric times. The caves presented natural shelter, with a constant temperature of 12 °C, which in the winter months is much warmer than the freezing degrees in the open. The hydrologic characteristics of the Karst aquifer are such that caves naturally are provisioned with water, another essential ingredient for mankind. These favorable conditions explain the documented history of at least 3000 years of human presence and relics in the Karst. The participants of the Geodynamic and Earth Tides Symposium 2016 were offered a glimpse into the fascinating Karst world, the river Timavo being the golden thread of the tour. The powerful action of water forms the Karst phenomena, the most prominent of which are the caves and sinkholes well seen on a bird's eye image of the surface. Geodetic measurements offer a modern tool for investigating the Karst phenomena and discover new caves and the underground hydrologic channels. The Laser scan acquisition of the surface has unequivocally mapped the alignment of thousands of sinkholes paralleling the underground water flow. The tiltmeters installed in caves are sensitive to the hydrologic flow and react by transient tilting due to pressure changes in the hydraulic conducts. The time evolution of the tilting is characteristic of the underground pressure buildup and subsequent release. The gravity field measurements are able to detect new caves, if done systematically with the sufficient spatial resolution. The time variable part of the gravity field is sensitive to the integral hydrologic volume. The applications demonstrate the link between geodetic measurements, central to the activities of scientists working in Geodynamics and Earth Tides, and the Karst environment. It is mentioned that history repeats itself: the participants of the Third Earth Tides Symposium in 1959 were lead to the Grotta Gigante cave, to admire the first edition of the long base geodetic pendulums [14], and then visited the ancient Roman city of Aquileia, the fluvial port on the Adriatic, just 20 km from the Duino archeological site the present trip reached.

General information on the area

http://www.grottagigante.it/
https://en.wikipedia.org/wiki/San_Giovanni_in_Tuba
https://en.wikipedia.org/wiki/Timavo
http://www.marecarso.it/da_vedere_timavo.htm (in Italian)
http://www.marecarso.it/da_vedere_sgiovanni.htm (in Italian)
http://www.fvg.tv/WebTV/dettaglio?video.id=496&video.lingua.id=IT (see the chapters: La zona fonti del Timavo; La voce dell'acqua_Lacus Timavi)
http://www.fvg.tv/WebTV/dettaglio?video.id=496&video.lingua.id=IT (Regione FVG, Lacus Timavi, video)
http://www.fvg.tv/WebTV/dettaglio?video.id=3332&video.lingua.id=IT (Regione FVG, The people of Duino, video eng)
http://www2.units.it/adriatic/eng/

Fig. 13. View of the mansio near Timavo springs, a building active in Roman times with 40 rooms and luxurious mosaics.

List of Latin references to the Timavo springs and location: http://www.liceopetrarcats.it/old_site/sperimentazione/sitocarso/timavo.htm#Miti e culti del Timavo

Acknowledgements

The Parrocchia San Marco Evangelista is thanked for access to the Basilica San Giovanni in Tuba. The following institutions are thanked for cooperating in the field trip: University of Trieste, Istituto Nazionale di Oceanografia e di Geofisica Sperimentale – OGS, Karst Research Institute, Research Centre of the Slovenian Academy of Sciences and Arts, Grotta Gigante Touristic cave, Società Alpina delle Giulie – Sezione di Trieste del C.A.I., Ministero dei beni e delle attività culturali e del turismo – Soprintendenza Archeologia, belle arti e paesaggio del Friuli Venezia Giulia. We thank Prof. Gerhard Jentzsch and an anonymous reviewer for their comments.

Photographic credits: Figs. 3 and 4: Grand Site de l'Aven d'Orgnac, La Cité de la Préhistoire, 07150 ORGNAC-L'AVEN, France. Figs. 8–12, Carla Braitenberg. Fig. 13: Soprintendenza Archeologia, belle arti e paesaggio del Friuli Venezia Giulia.

References

[1] Regional DTM data of Friuli Venezia Giulia, http://irdat.regione.fvg.it/CTRN/ricerca-cartografia (Accessed 16 February 2017).

[2] F. Cucchi, C. Pirini Radrizzani, N. Pugliese, The carbonate stratigraphic sequence of the karst of Trieste (Italy), Mem. Soc. Geol. Ital. XL (1987). Trieste: 35–44. Proceedings of "International Symposium on Evolution of the Karstic Carbonate Platform," Trieste, 1st–6th June 1987.

[3] B. Jurkovšek, S. Biolchi, S. Furlani, T. Kolar-Jurkovšek, L. Zini, J. Jež, G. Tunis, M. Bavec, F. Cucchi, Geology of the classical Karst region (SW Slovenia–NE Italy), J. Maps 12 (2016) 352–362, http://dx.doi.org/10.1080/17445647.2016.1215941.

[4] G.B. Carulli, Carta Geologica del Friuli Venezia-Giulia, Regione Autonoma Friuli Venezia Giulia, 2006. Direzione Centrale Ambiente e Lavori Pubblici, Servizio Geologico, Trieste. S.E.L.C.A. Firenze.

[5] Regional cave Kadastre of Friuli Venezia-Giulia, http://www.catastogrotte.fvg.it/ (Accessed 16 February 2017).

[6] C. Braitenberg, D. Sampietro, T. Pivetta, D. Zuliani, A. Barbagallo, P. Fabris, L. Rossi, J. Fabbri, A.H. Mansi, Gravity for detecting caves: airborne and terrestrial simulations based on a comprehensive karstic cave benchmark, Pure Appl. Geophys. 173 (2016) 1–22, http://dx.doi.org/10.1007/s00024-015-1182-y.

[7] T. Pivetta, C. Braitenberg, Laser-scan and gravity joint investigation for subsurface cavity exploration – the Grotta Gigante benchmark, Geophysics 80 (2015) B83–B94, http://dx.doi.org/10.1190/GEO2014-0601.1.

[8] D. Tenze, C. Braitenberg, I. Nagy, Karst deformations due to environmental factors: evidences from the horizontal pendulums of Grotta Gigante, Italy, Boll. Geofis. Teor. Appl. 53 (2012) 331–345, http://dx.doi.org/10.4430/bgta0049.

[9] C. Braitenberg, I. Nagy, Illustrating the superposition of signals recorded by the Grotta Gigante pendulums with musical analogues, Acta Carsol. 43/1 (2014) 139–147.

[10] R. Devoti, D. Zuliani, C. Braitenberg, P. Fabris, B. Grillo, Hydrologically induced slope deformations detected by GPS and clinometric surveys in the Cansiglio plateau, southern Alps, Earth Planet. Sci. Lett. 419 (2015) 134–142, http://dx.doi.org/10.1016/j.epsl.2015.03.023.

[11] V. Vedaldi Iasbez, La *Venetia* orientale e l'*Histria*. Le fonti letterarie greche e latine fino alla caduta dell'Impero Romano d'Occidente, Studi e ricerche sulla Gallia cisalpina, QuasarRome 5 (1994) 160–170.

[12] R. Auriemma, S. Karinja (Eds.), Terre di mare, L'archeologia dei paesaggi costieri e le variazioni climatiche, Atti del Convegno Internazionale di Studi, Trieste, 8–10 novembre 2007, University of Trieste, 2008. ISBN 978 8896940 815, 498 pp., Accessible at: http://www2.units.it/adriatic/files/Terre_di_mare_eBook.pdf.

[13] V. Degrassi, A. Giovannini (Eds.), *Tempus edax rerum*. Roma ed il Timavo – appunti di ricerca, Duino-Aurisina, 2001, p. 88. http://xoomer.virgilio.it/wjerman/appunti/presentazione.htm.

[14] A. Marussi, The University of Trieste station for the study of the tides of the vertical in the Grotta Gigante, in: Proceedings of the third international symposium on Earth Tides, 1960, pp. 45–52.

Prof. Dr. Carla Braitenberg, Ph.D. is Geophysics professor at the University of Trieste, Italy. She fulfilled her Physics and Geophysics education in Germany and Italy. She has found innovative ways to use geodetic measurements to describe geologic features. In a karst environment gravity has proven useful to delineate the extent of caves, and is a tool to detect new ones. The underground karstic water flows were shown to be detectable by their dynamic signal in geodetic measurements of deformation. Underground strainmeters and tiltmeters were shown to be very sensitive to the underground hydrology, and useful in describing the hydraulic characteristics of the subsurface water flows. Exploiting the modern gravity satellite missions GRACE and GOCE she has worked on regional geologic structures and geodynamics, demonstrating how knowledge of the big scale is essential to the interpretation of terrestrial observations at local scale. She develops software methodologies that aim at an intelligent integration of high resolution terrestrial data with satellite observations optimizing investigative tools for natural resource exploration.