MONTE LAGO POLJE, A CASE STUDY REGARDING THE INFLUENCE OF GEOLOGIC STRUCTURE AND DEGREE OF KARSTFICATION ON GROUNDWATER DRAINAGE IN THE CENTRAL APENNINES (ITALY)

KRAŠKO POLJE MONTE LAGO, ŠTUDIJA VPLIVA GEOLOŠKE ZGRADBE IN STOPNJE ZAKRASELOSTI NA TOK PODZEMNE VODE V CENTRALNIH APENINIH (ITALIJA)

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Abstract   UDC 551.444(450.5/.6)
Sandro Galdenzi: Monte Lago polje, a case study regarding the influence of geologic structure and degree of karstfication on groundwater drainage in the Central Apennines (Italy)
Research on the cave and karst water in the area of Monte Lago polje (Central Apennines) has revealed an articulate drainage pathway, influenced by the karstfication degree and geological setting. A fast drainage occurs from the ponor in the polje to the main temporary resurgence in the valley of San Giovanni, impeding the karst water in achieving thermal equilibrium with the rock. The water temperature in the resurgence decreases to very low values (~3 °C) during the winter, and the daily thermal cycles are clearly recognizable. These inputs of vadose water from the ponor have only a minor influence on the chemo-physical characteristics of San Giovanni spring, the largest emergence in the area, located a few hundred meters downstream in the same valley and fed by the main basal aquifer. The two nearby springs are recharged by different hydrostructures divided by low permeability levels in the Jurassic carbonate succession. This reduces the cross-formational communication mainly for the descending vadose fluxes. The fast drainage of karst water in the transfer vadose zone is due to a high karstfication, confirmed by the typology and distribution of the karst caves. A more regular discharge in the springs fed by the basal aquifer is probably related to a minor karstfication in the lower part of the limestone massifs.
Key words: Monte Lago, Central Apennines, Karst, Groundwater monitoring.

Izvleček   UDK 551.444(450.5/.6)
Sandro Galdenzi: Kraško polje Monte Lago, študija vpliva geološke zgradbe in stopnje zakraselosti na tok podzemne vode v Centralnih Apeninih (Italija)
Raziskave jam in kraške vode na območju kraškega polja Monte Lago (Centralni Apenini) so razkrile obstoj drenažne mreže, na katero vplivata stopnja zakraselosti in geološka zgradba. Med ponorom na polju in glavnim občasnim izvirom v dolini San Giovanni se pojavlja hiter tok, ki preprečuje uravnoteženje temperature vode s temperaturo kamnine. Pozimi ima voda v izviru zelo nizko temperaturo (~3 °C), jasno so vidni dnevni temperaturni cikli. Ti dotoki vadozne vode iz ponora imajo le majhen vpliv na fizikalno-kemijske značilnosti izvira San Giovanni, največjega izvira na tem območju, ki je lociran nekaj sto metrov dolvodno v isti dolini in se napaja iz glavnega spodnjega vodonosnika. Dva sosednja izvira se napajata iz različnih hidrostruktur, ločenih s plastmi slabše prepustnosti v jurskem karbonatnem zaporedju. To zmanjšuje prehajanje predvsem navzdol tekočih vadoznih vod skozi formacije. Hitro pretakanje kraške vode v vadozni coni je posledica dobre zakraselosti, ki jo potrjujeta tipologija in razpored kraških jam. Bolj enakomeren pretok izvirov, ki se napajajo iz spodnjega vodonosnika, je verjetno povezan z manjšo zakraselostjo v spodnjem delu apnenčastega masiva.
Ključne besede: Monte Lago, Centralni Apenini, kras, monitoring podzemne vode.

INTRODUCTION

Research on the hydrology of the Umbria-Marche limestone ridge already evidenced the co-existence of different flowpaths for the groundwater. A fast drainage results in spring hydrographs (Ciancetti *et al.* 1991; Nanni *et al.* 2006; Tamburini & Menichetti 2017) and also from the study of active cave systems (Galdenzi 2013a). The main linear springs in the river valleys however have more regular characteristics due to a significant contribution from the basal flow of regional aquifers (Boni *et al.* 1986; Tazioli *et al.* 2007). The geological structure, with folds and overthrusts displaced by different types of fault systems, complicate the study of the groundwater circulation and the relations between the different hydrogeological complexes. The probable existence of hydraulic connections between the different aquifers notwithstanding the presence of aquicludes was already suggested in regional and local studies (Boni *et al.* 1986; Nanni & Vivalda 2005; Aquilanti *et al.* 2106).

Knowledge of the groundwater drainage has both a scientific and practical interest because the karst aquifers represent the most important reserves of potable water in the region, largely used for important aqueducts. The present research analyzes the groundwater flowpath together with deep karst in the Monte Lago area and represents an in-depth analysis of the relationship between the ponor of the Piani di Monte Lago and the main emergences in the surroundings.

Piani (i.e., plains) is the Italian word used in the Apennines to indicate groups of poljes formed in structural depressions partly filled by alluvial sediments. These are the most important surface karst features of the Umbria-Marche Apennines, and a few examples of them are in the southern part of the region. The amount of sediment filling impedes a direct exploration of the ponors, therefore the underground pathway of the sinking water is not directly known. The existence of an active ponor in the Monte Lago polje provides natural pulses which facilitate the study of the hydrographs of the springs. The propagation of the natural pulses is widely used to study the water drainage in karstic aquifer (e.g., Halihan *et al.* 1998; Gabrovsek & Peric 2006; Ford & William 2007; Mayaud *et al.* 2013).

METHODS

The study utilized different methods: the existing geologic surveys (Calamita & Pierantoni 1993; Regione Marche 2010) were revisited in detail with new field work at 1:10,000 scale in the area of the poljes and San Giovanni valley to define the hydrogeological setting. A morphological analysis of the caves provided information on their development, evolution and hydrologic role.

The characteristics of surface and groundwater drainage were monitored thanks to remote data loggers (Eijkelkamp, Netherlands) which measured temperature, level and conductivity of the sinking stream and water emergences. The water temperature and conductivity were also verified with periodic *in situ* measurements using probes (WTW, Germany) to exclude loggers' malfunction. The water level readings were corrected for barometric pressure changes. The acquisition interval was fixed at one hour for all the loggers.

The registration of water parameters was integrated with chemical analyses of the waters which were carried out every two months in the laboratories of the Camerino University utilizing Standard Methods for the Examination of Water and Wastewater (21th Edition). All the data were related to meteoric precipitation in the station of Sorti village, inside the study area.

After a first monitoring period, as the very stable characteristics of the San Giovanni spring did not agree with the supposed role of emergence for the polje water, the monitoring was extended to the temporary emergences in the upper part of the same valley.

GEOLOGICAL BACKGROUND

STRATIGRAPHY AND TECTONIC
The Umbria-Marche Apennines consists of a northeastern verging fold and thrust structure (Deiana & Pialli 1994), involving the mainly calcareous Meso-Cenozoic Umbria-Marche succession (Minetti *et al.* 1991, with references therein).
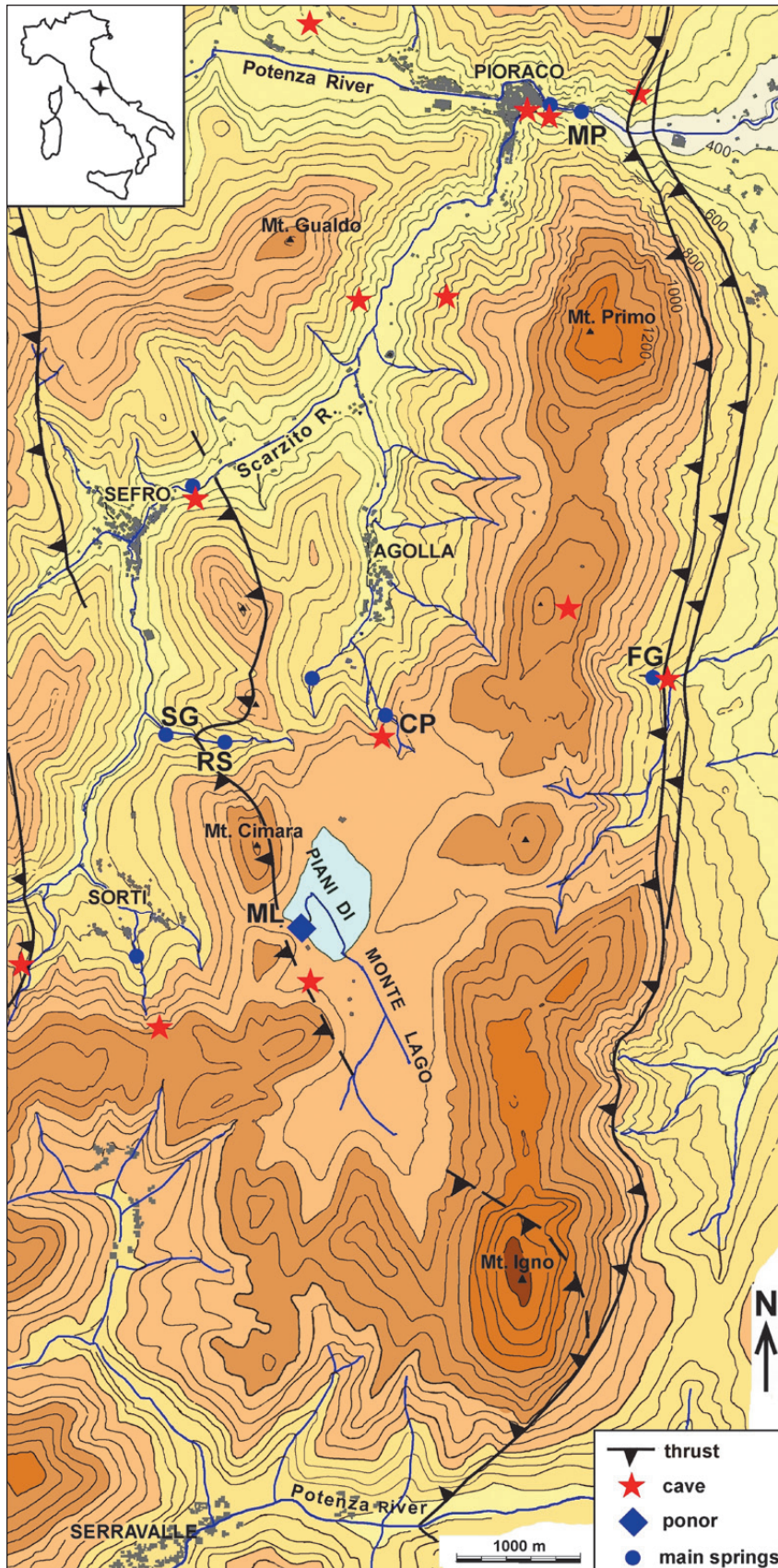
Fig. 1: Location of the investigated area, with the main karstic, hydrographic and tectonic features. Legend: SG) San Giovanni spring; RS) resurgence; CP) Caprelle caves and spring; FG) Figareto caves and spring; ML) Monte Lago ponor; MP) Monte Primo springs.
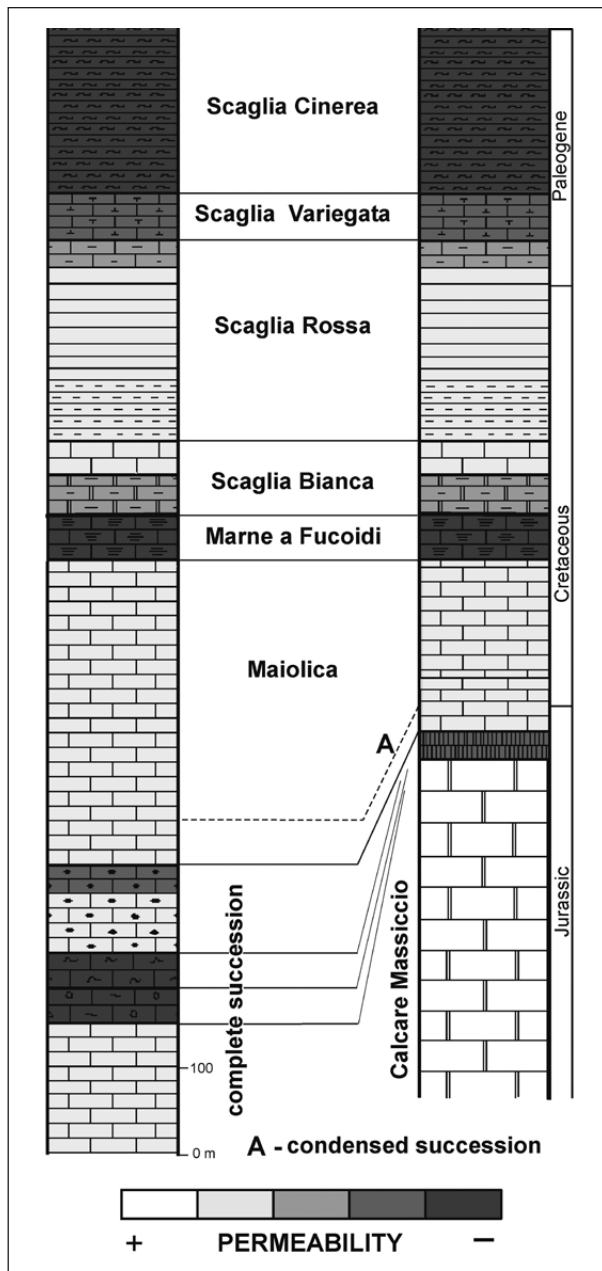
Fig. 2: Schematic stratigraphic succession, with qualitative permeability of the different units.

The Piani di Monte Lago are located in the inner ridge, 60 km west from the Adriatic Sea. This sector of the chain is a part of a regional anticline structure, overthrusting the Miocene terrigenous units of the foothill zone to the East (Fig. 1). The major tectonic contact between the Meso-Cenozoic carbonates and the Miocene units crops out along the foot of the ridge (Mt. Primo-Mt. Cavallo thrust, Calamita & Pierantoni 1993). Inside the chain, some minor asymmetric anticlines overthrust, with a minor throw, the carbonate units of the interposed synclines.

The lower part of the outcropping succession is a Lower Lias epicontinental carbonate platform (Calcare Massiccio Fm., over 700 m thick), overlain by a hemipelagic, mainly carbonatic succession that was deposited during the entire period from the Middle Lias to the Oligocene, with a total thickness that varies from 700 to more than 1500 m (Fig. 2).

The Jurassic hemi-pelagic rocks are highly variable in thickness and lithology, due to the extensional tectonic that drowned the platform. A few tens of meters of mainly nodular carbonatic beds were deposited in small areas at the footwall of the faults (condensed succession), while the basins were filled by cherty limestone, chert and marls (complete succession, up to 500 meters thick). Cretaceous and Cenozoic deposits have a more uniform lithology, although differences of thickness remain. They mainly consist of cherty limestones (Maiolica, Scaglia Bianca and Scaglia Rossa Fms.) and include significant marl units (Marne a Fucoidi, Scaglia Variegata and Scaglia Cinerea Fms.).

HYDROGEOLOGY

Inside the carbonate succession (Fig. 2) three main permeable hydrogeological complexes (Calcare Massiccio, Maiolica and Scaglia group) can be distinguished, separated by two main aquicludes (Jurassic complete succession and Marne a Fucoidi).

The Calcare Massiccio is highly permeable due to its syngenetic porosity and well-developed network of fractures. This hydrogeological complex also comprises the lower part of the complete succession (Corniola Fm.), and hosts the main hydrostructures of the region. The
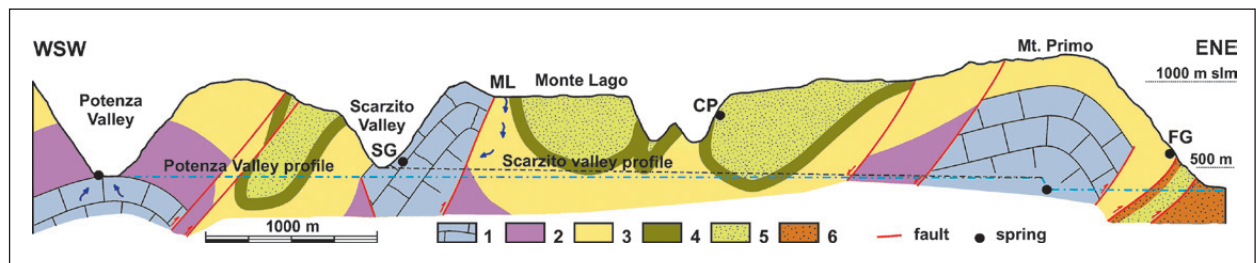

Fig. 3: Hydrogeological scheme of the area. Legend: 1) Calcare Massiccio; 2) Jurassic Fms. 3) Maiolica; 4) Marne a Fucoidi; 5) Scaglia; 6) Oligocene and Miocene marl. SG) San Giovanni spring; ML) Monte Lago ponor; CP) Caprelle spring; FG) Figareto spring.

Maiolica has a middle-high permeability for its secondary porosity, while the Scaglia Bianca and Scaglia Rossa Fms. represent a single complex with a middle permeability due to its secondary porosity, locally decreased by a variable clay content. All these units are widely karstfied in the region (Galdenzi 1988; 1996).

The Calcare Massiccio and Maiolica complexes are in hydraulic continuity in the condensed succession, because the thin and discontinuous poorly permeable Jurassic beds only play a local influence on underground drainage. In the whole region, cross formational communications among the three permeable complexes are favoured by faults and produce hydrostructures with different importance.
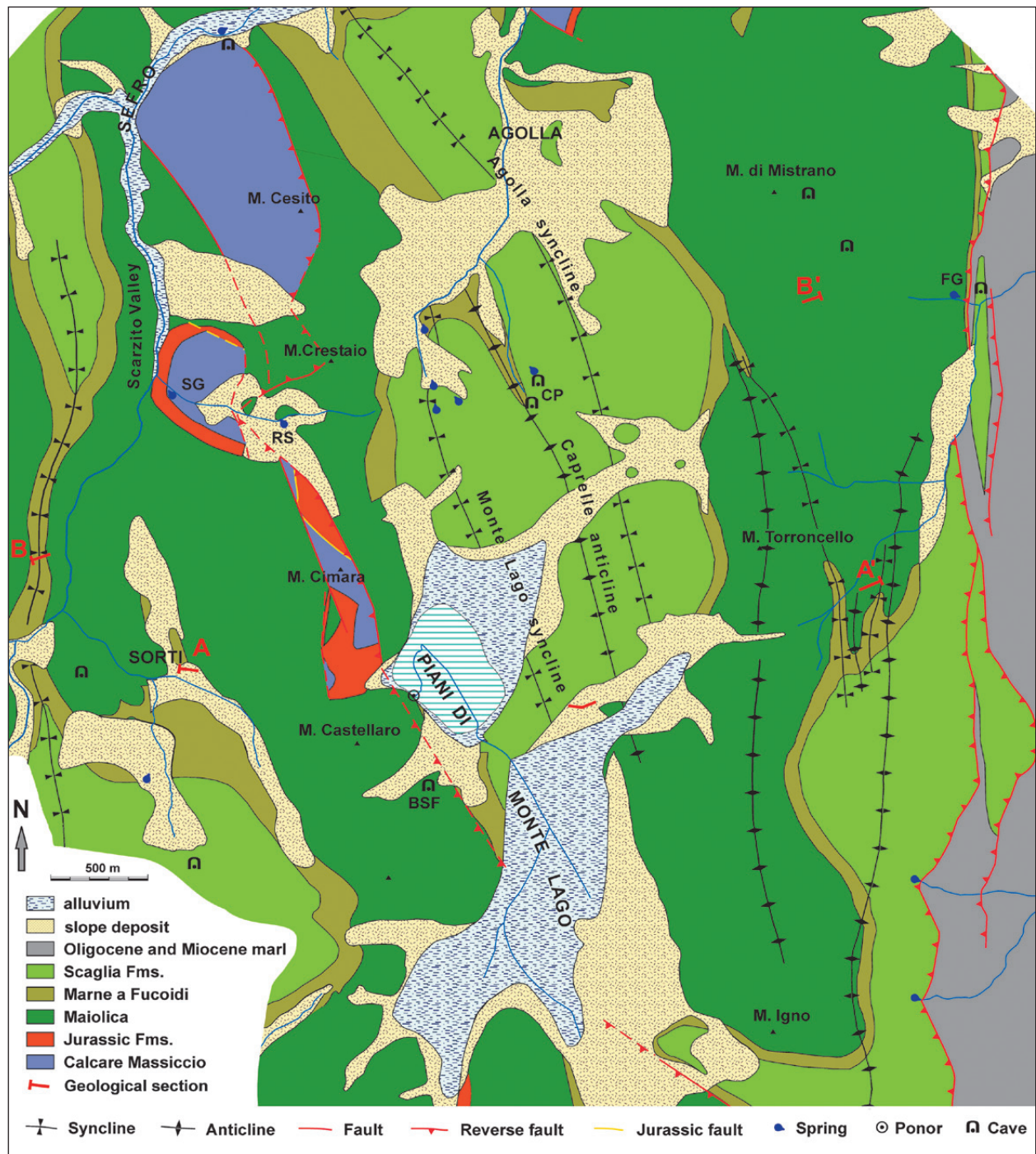

Fig. 4: Geologic map of the study area: SG) San Giovanni spring; RS) resurgence; CP) Caprelle caves and spring; FG) Figareto caves and spring; BSF) Buca di Sasso Freddo.

In the study area, the geological structure heavily influences groundwater circulation (Fig. 3). The main faults and the Miocene aquiclude bordering the karst structure favour a groundwater drainage sub-parallel to bedding direction and fold axes, both for the general and local drainage. This situation is common in the region and has been outlined since the first hydrologic studies (Fossa Mancini 1916) and is confirmed by the pattern of phreatic caves (Galdenzi 1988).

Large linear springs such as the San Giovanni spring in the Scarzito valley near Sefro and the Mt. Primo springs in the Potenza Valley feed the surface rivers. The water originates from the basal aquifer (generally the Calcare Massiccio) at the core of the anticlines crossed by transverse valleys, a situation quite common in the region (Boni *et al.* 1986; Nanni & Vivalda 2005).

Minor hydrostructures develop inside Maiolica or Scaglia aquifers in the limbs of the folds; these aquifers are often perched above the base level and feed non-regular springs or contribute to recharge the basal groundwater circulation (Fig. 3). Many minor springs are known in these aquifers (Dramis & Deiana 1972). Some of them are in the eastern side of the anticline (Figareto spring) in a strongly tectonized zone close to the thrust (Figs. 3 and 4). Springs from the Scaglia aquifers are in the Agolla valley at the core of the Monte Lago syncline and also in the Sorti area at the head of the Scarzito valley (Fig. 4). Small springs are also at high elevations in the slopes due to the marl units in the limestone succession.

Tests with tracers showed a complex flow path for the sinking water of Monte Lago (Fig. 5). A first fluorescein test proved that the main emergence is in the valley of San Giovanni (Deiana *et al.* 1970).

A sequence of quantitative tests carried out between the 2011 and 2016 using either fluorescent dye and DNA tracer studied the recharge mechanism and the groundwater flowpath (Aquilanti *et al.* 2016; Tazioli *et al.* 2016). The research confirmed the possibility of a fast flow of the water from the ponor towards the spring. At the end of the recharge period the water emerged along the Scarzito valley, from the San Giovanni area up to Sefro, and in the Figareto spring. During the recharge period, with a
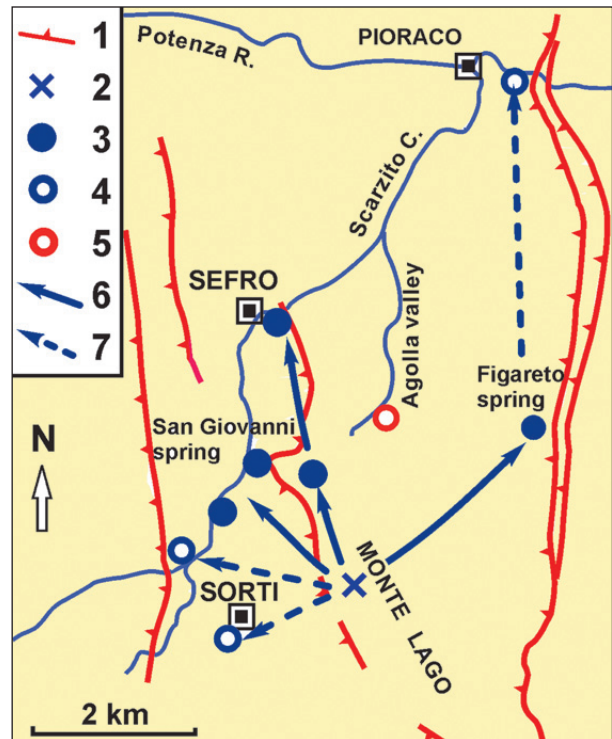

Fig. 5: Sketch of the main results of the tracer tests (simplified, after Aquilanti et al. 2016). Legend:1) Thrust; 2) injection point (ponor); 3) sampling point (positive signal); 4) sampling point (positive signal during high recharge periods): 5) sampling point (permanent negative signal); 6) flow direction; 7) flow direction (only during high recharge periods).

higher flow rate in the ponor, the tracers also reached springs in the Potenza Valley to the north and in the Sorti zone to the east. These results prove the existence of connections among the different hydrostructures. Negative signals were always from the springs in the Agolla valley, at the northern limit of the polje (Fig. 5), and in the Chienti Valley to the South. Quantitative measurements confirmed the location of the main emergence in the San Giovanni valley, but showed that a significant percentage (over 25%) of the tracers reached other springs in adjacent hydrostructures, such as the Figareto spring (10-11%).

KARST

SURFACE FEATURES

Two main anticlines and an interposed complicated syncline can be distinguished in the study area (Figs. 1 and 3). The eastern anticline (Mt. Primo anticline) overthrusts

the Miocene deposits of the Camerino basin (the Mt. Primo–Mt. Cavallo thrust, Calamita & Pierantoni 1993), while the inner one (Mt. Cimara anticline) overthrusts, with a minor throw, the interposed synclines. This cen-

Fig. 6: The Piani di Monte Lago, in the "gentle" landscape at the mountains' summit (Photo: S. Galdenzi).

Fig. 7: The lower plain of Monte Lago. A) The swamp with (1) the main sinking point and (2) the location of the data logger. B) The temporary lake in the wet periods (Photo: S. Galdenzi).

tral structure comprises some minor folds in Upper Cretaceous and Paleogene rocks (the Agolla syncline, the Caprelle anticline and the Monte Lago syncline) (Fig. 4).

The whole area has the typical fluvio-karstic landscape of the Umbria-Marche Apennines. The main surface karst structure are the Monte Lago poljes, which consist of two close areas about 2 km² wide, located inside a structural depression corresponding to the central synclines. In detail, the Piani develop almost entirely in the Scaglia of the Monte Lago syncline, and only the northeastern part of the upper polje extends to the adjacent Agolla syncline.

The Piani di Monte Lago formed in a gentle landscape that existed in the region throughout the Late Pliocene and Early Pleistocene (Fig. 6). Since the end of the Early Pleistocene, steep slopes incised the marginal areas of the Piani after that the regional uplift caused the entrenchment of the river valleys into the pre-existing erosion surfaces (Calamita *et al.* 1982; Ciccacci *et al.* 1985; Bartolini *et al.* 2003). Deepening of the river valleys in the surrounding areas reduced the area of endokarst and favored an increase of hydraulic gradient between sink points and springs.

Thin sediments carried by surface water have formed two small plains, respectively located at an altitude of 918 and 891 m. The upper polje is wider and is wholly cultivated for hay thanks to small drains that prevent stagnation of the water. This upper polje was joined to the lower one through a deep artificial trench
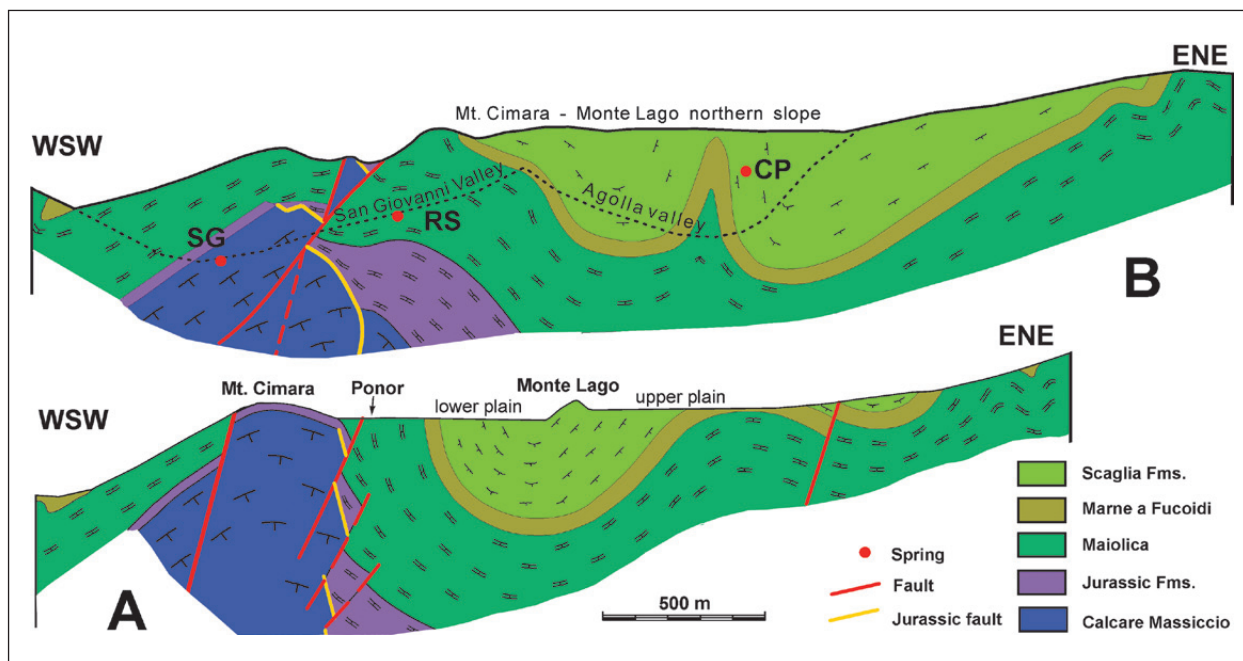

Fig. 8: Geologic sections in the Monte Lago area. A) southern slope of Mt. Cimara, in the ponor area; B) northern slope of Mt. Cimara, in the resurgence area; the dashed line represents the profile of the valleys. CP – Caprelle spring; RS – Resurgence; SG – San Giovanni spring.

dug in 1458 to facilitate drainage (Falaschi 1987). A small swamp is on the floor of the lower polje, and after intense rain and snowmelt, a wide temporary lake floods a large part of the plain (Fig. 7). The lower polje is drained by an active ponor, located at 891 m asl. in the vertical beds of the Maiolica, at the footwall of the reverse fault of the Mt. Cimara anticline (Fig. 8a). The attempts to explore the underground course of the water through digging by speleologists have been unsuccessful so far.

Aside from the Monte Lago polje, typical surface karst landforms such as dolines are uncommon. The rock surface, when exposed, can be highly karstfied, with fissure and holes, but generally the bedrock is covered by thin soils or thick periglacial debris on the slopes. The high permeability of the epikarst zone impedes a significant drainage on the mountain surface and favours the direct infiltration of meteoric water. Therefore, with the exception of the polje, the karstic circulation is mostly fed by autogenic recharge.

CAVES

The deep karst in the area is represented by a few small caves in the Maiolica and Scaglia Fms., with the same general characteristics of the epigenic caves in these units (Galdenzi 1988; 1996). No caves develop in the highly permeable Calcare Massiccio. Although the caves are quite superficial, their morphology indicates a relatively long evolutionary history. Their development was highly influenced by structural conditions, such as the bedding and fault attitude, the spatial distribution of aquicludes, while the absence of allochthonous deposits and erosional features suggests a limited or insignificant role of allogenic water.

A few shaft caves open directly on the gentle slopes of the mountain summits or were cut off by erosion in the steep slopes of the valleys. These caves consist of sequences of a few pits which reach depths of up to a few tens of meters and develop along the limestone bedding in the sub-vertical limbs of the folds or in the correspondence of faults. Most of these caves consist of wide passages, and breakdown rubbles are the most common deposit. They are not connected to active sinking points or surface streams and are temporarily active during rainy periods and snowmelt, when a water sheet or small ephemeral streams flow inside. A different morphology characterizes the Buca di Sasso Freddo, a 45 m-deep narrow vertical cave, entirely developed in a crack corroded by water dissolution.

The outflow caves have different locations and characteristics. Two caves near the Figareto spring represent good examples of the phreatic outflow caves that develop in the limbs of the anticlines in this region (Galdenzi 1988). They consist of single, small tubes a few tens of meters long in the limestone of the Scaglia complex, sandwiched between two aquicludes at the foot of the mountain. One of them is an active emergence, horizontal and partly flooded. The other is a relict tube with an irregular profile, ascending towards the surface.

Outflow caves are also found on the upper part of the slopes more than 200 m above the local erosion base level. The location of these caves is not related to the poorly permeable units in the carbonate succession (Fig. 9). They probably are remnants of an old drainage system that formed before the base level lowered as a consequence of the deepening of the river valleys. A few narrow relict caves are located at the head of the Sorti valley, while the Grotta Piccola di Caprelle is a wide,100-m-long passage that feeds a permanent spring in the steep head of Agolla valley, at the northern margin of the Piani.

The Grotta Piccola di Caprelle and the nearby Grotta di Caprelle, represent the most significant cave system in the area (Fig. 9). The two caves are very close, but not directly connected (Galdenzi 1983; 2013b). The 76 m deep Grotta di Caprelle has primarily a vertical structure. A sequence of three pits reaches a lower sector, formed by some sub-horizontal passages at different heights, close to the Grotta Piccola. Both caves develop in the vertical beds of the Scaglia Bianca Fm. (Fig. 9).
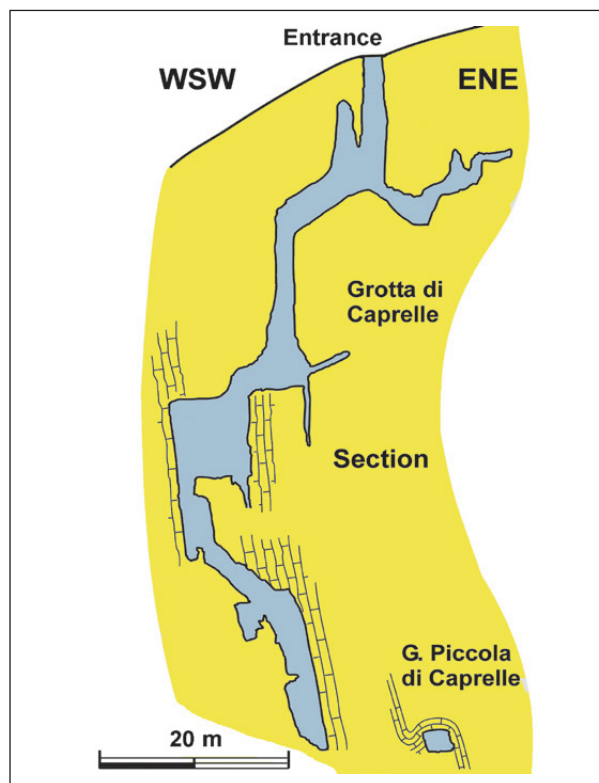

Fig. 9: Geologic section through Caprelle caves. The permanent stream in the Grotta Piccola is perched above the local erosion base level in the vertical beds of limestone.

Direct evidence of the first speleogenetic phases were not preserved in these caves, while breakdown and deposition of calcite speleothems are the prevailing active processes. Dating with uranium series (ages up to 92.5 ± 3.4 ka BP) has revealed that calcite speleothems were forming throughout the Late Pleistocene and Holocene (Galdenzi *et al.* 2014). Relict, partially corroded sheets of calcite may have been formed during a large-scale deposition event. Dating of the sheets revealed an age of 28.4 ± 1.2 ka BP in the Caprelle caves (Galdenzi *et al.* 2014), 31.3 ± 1.5 ka BP in the Pozzo di Fonte Fragola, a shaft cave close to the study area (Galdenzi 1996).

Sediment transport by infiltrating vadose water pro-duced thin muddy wall coatings and fine-grained floor deposits with a minor sand content. The well-preserved pollen content suggests that the sediment transport occurred in a cool/cold climate, probably during the Late Pleistocene, based on the depositional setting and dating results (Galdenzi *et al.* 2014).

In the Late Pleistocene, the cave passages already had the present structure, volume and morphology, and it was argued that the first phases of their development had begun before the deepening of the hydrografic surface (Galdenzi *et al.* 2014), an event that is in general referred to as the end of the Early Pleistocene.

THE GROUNDWATER MONITORING

THE SPRINGS: CHARACTERISTICS AND GEOLOGICAL SETTING

The Caprelle spring (800 m asl) is a small emergence in the Scaglia Bianca Fm. (discharge of few L s^{-1}), at the head of a steep valley which incises the northern edge of the Piani. The spring is directly fed by the perennial small stream from the Grotta Piccola di Caprelle. The spring and the ponor are located on the western limb of two different synclines in the Scaglia and Maiolica, respectively, impeding a direct hydraulic connection (Figs. 4 and 8).

The largest spring (San Giovanni spring) is situated at an altitude of 530 m in a tributary valley of the Scarzito Creek, close to the confluence (Fig. 4). This transverse valley incises the core and the eastern limb of the Mt. Cimara anticline (Fig. 8b). The water rises from the Calcare Massiccio at the core of the fold and is collected for drinkable use, with a discharge of up to 40 L s^{-1} in the dry season.

Under high recharge conditions a further variable amount of water rises along the upper part of the same valley. The water rises at different elevations mainly from the rubble in the valley floor, with a main emergence (the "resurgence") localized during field research at 640 m asl, in the only place where a part of the water directly emerges from the bedrock as a bedding plane spring (Fig. 10). The discharge decreases and ceases during a low water regime, while downstream in the valley, the water flow is maintained for a slightly longer duration, maybe due to the contribution of buried emergences.

All these temporary emergences are located in the Maiolica at the footwall of the Mt. Cimara thrust and belong to the same hydrostructure of the ponor, while the San Giovanni spring rises from the Calcare Massiccio in the core of the anticline (Fig. 8b). These hydrostructures are separated by the fault of Mt. Cimara, a reverse fault which involves a pre-existing Jurassic normal fault. The possibility that Jurassic extensional structures influenced the Neogene structural setting is a common occurrence in the Central Apennines (e.g., Calamita *et al.* 2011), with possible re-activation and inversion of the Jurassic faults during thrusting.

At the surface, the Calcare Massiccio and Maiolica are in direct tectonic contact along to the reverse fault or can be separated by the interposition of sub-vertical layers of Jurassic cherty limestone, flattened against the fault in the ponor area (Fig. 8a). These layers represent the upper part of a complete succession which underlies the Maiolica in a Jurassic basin, East of Mt. Cimara. Field evidence of the Jurassic fault scarp between the basin and the condensed succession of Mt. Cimara was found

Fig. 10: The temporary resurgence in the valley of San Giovanni (Photo: S. Galdenzi).

in the San Giovanni valley, where beds of the complete succession and collapse megabreccias lye as small bodies strongly unconformable on the Calcare Massiccio (Fig. 4). The existence of the Jurassic fault scarp confirms an abrupt lithological change in the Jurassic deposits along the fault. The low-permeability units of the complete succession overly the Calcare Massiccio along the fault, impeding the hydraulic continuity with the Maiolica of the Monte Lago hydrostructure (Fig. 8).

THE MONITORING

In the first monitoring period (September 2006 – September 2007) the loggers were placed at San Giovanni (SG) and Caprelle (CP) springs and in the Monte Lago ponor (ML). Temperature, water level and conductivity were measured in the San Giovanni and Caprelle springs, and only water temperature and level in the Monte Lago ponor.

In the Monte Lago polje, it was not possible to place the logger directly in the stream at the ponor entrance because of logistic problems and instrument

safety. Consequently the logger was placed in the nearby doline (Fig. 7a) where it did not record the base flow in the stream, instead, it was easily reached by water whenever the stream discharge exceeded the sinking capacity of the ponor. In the San Giovanni spring, the logger was placed inside the springhouse, while in the Caprelle spring it was placed in the cave stream, at ~ 80 m upstream the cave entrance.

Between January and June 2010, monitoring was repeated the same way in the ML ponor and SG spring, extending the measurement of temperature, level and conductivity to the temporary emergence at an altitude of 640 m in the upper part of the valley (the resurgence).

THE 2006−2007 RESULTS

The first monitoring period (September 2006 – September 2007) was droughty in the whole region and a complete flooding of the polje lasted only for short periods of time. As expected, the water level in the polje depended directly on the amount of rainfall and snowmelt. Also,
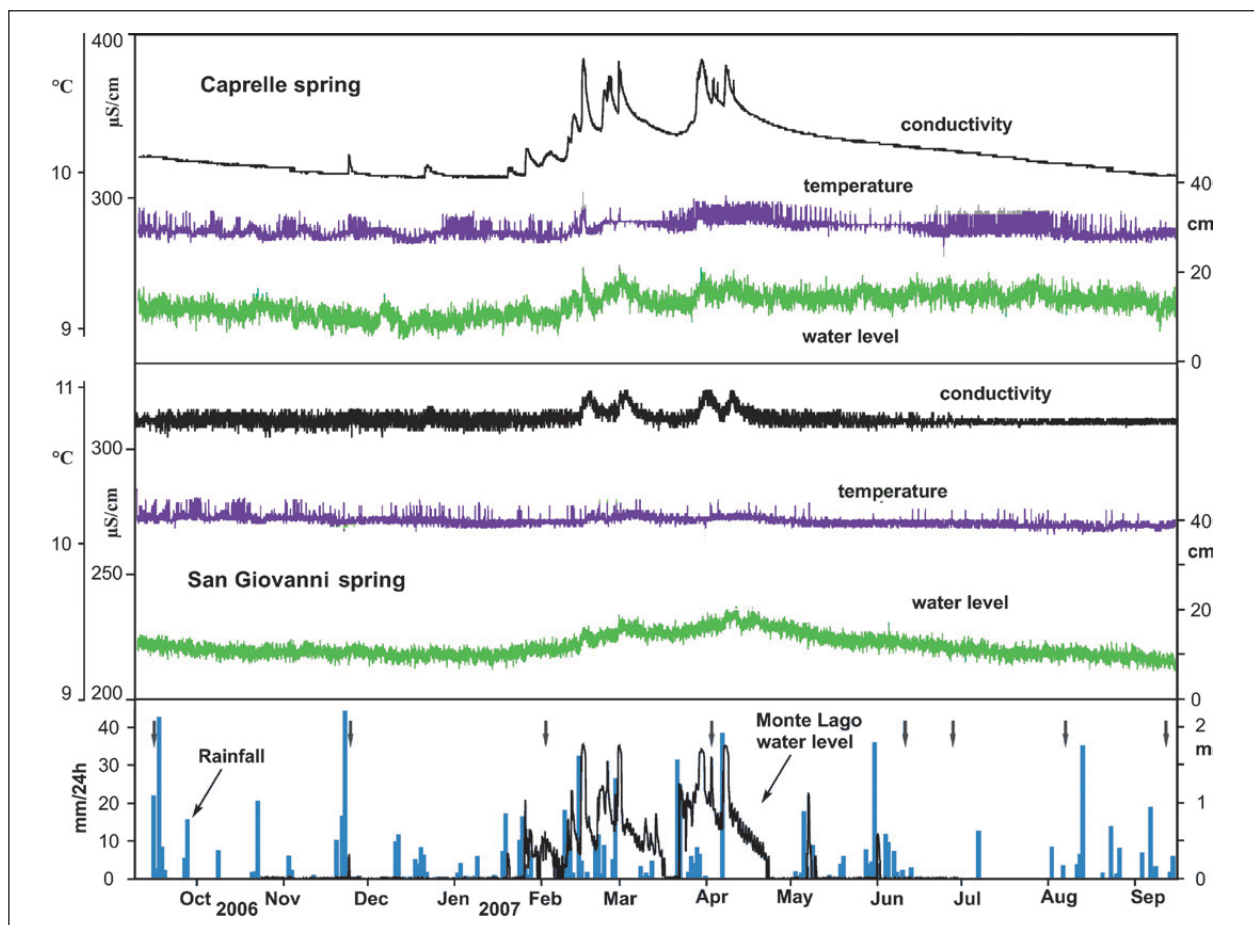

Fig. 11: The hydrographs of San Giovanni and Caprelle springs related to precipitations and water level. The arrows indicate the sampling dates.

the spring water followed the seasonal cycles, as evidenced by the changes of measured parameters (Fig. 11).

The water in the San Giovanni and Caprelle springs is bicarbonate calcic and has a similar content of dissolved ions, even if the SG water has a more stable chemistry and a higher content of minor ions (Tab. 1). In particular, the SG water has a slightly higher content of fluoride and magnesium and contains sulphate (~7 mg L^{-1}), which is almost absent in the CP water. The water in both springs has a low content of nitrates (5.5 and 2.8 mg L^{-1} for CP and SG, respectively). These characteristics agree with the geologic setting: the CP water comes from a minor hydrostructure involving only superficial circuits, while the SG spring represents an emergence of groundwater from the Calcare Massiccio, where groundwater can interact with deep circuits involving the underlying Triassic evaporites.

Thermal seasonal changes were not appreciable in the SG spring and did not exceed 0.2°C in the CP spring, with the lowest values at the end of the winter and the highest ones in the following months during the period of maximum discharge. The water conductivity in the CP spring varied from 310 up to 380 µS cm^{-1}, while it changed only ~10 µS cm^{-1} in the SG spring during the whole year. In both springs, the water conductivity increased during the wet period from late winter to the early spring.

The two springs reacted differently to the main meteoric events (Fig. 12). The CP spring was more directly influenced by the variable recharge of meteoric water, while the changes produced by the meteoric events were smoothed in the SG spring, as the infiltrating water was diluted with a large volume of water already stored in the reservoir.

In the Caprelle spring, the meteoric events caused evident increases of temperature and conductivity due to the mobilization of resident groundwater. These fast changes of conductivity (Figs. 11 and 12) are not closely related to the water level in the polje. Even if many peaks in the two hydrographs are simultaneous, some conductivity peaks are heavily delayed (February 21). Furthermore, some major surface events were not recorded in

Tab. 1: Chemical composition of spring water from Caprelle and San Giovanni springs. Concentration values are in mg L^{-1}.

San Giovanni spring												
	pH	Ca^{2+}	Mg^{2+}	NO_3^-	Na^+	K^+	Cl^-	SO_4^{2-}	HCO_3^-	F^-	Li^+	Sr^{++}
15/09/06	7.49	69.12	3.40	2.90	3.58	0.83	8.66	8.36	212 0	0.40	0.02	0.24
24/11/06	7.52	69.60	3.12	3.04	3.46	0.81	13.34	5.61	204.0	0.42	0.02	0.25
02/02/07	7.56	68.00	7.20	2.79	3.38	1.00	9.72	6.82	228.0	0.43	0.02	0.24
02/04/07	7.58	72.24	4.03	2.70	3.35	0.64	8.87	4.77	230.0	0.42	0.02	0.25
11/06/07	7.45	70.80	3.60	2.65	3.47	0.77	10.22	8.96	218.0	0.53	0.02	0.20
28/06/07	7.54	75.00	5.40	2.79	3.31	0.83	10.43	6.86	238.0	0.43	0.02	0.21
07/08/07	7.56	68.88	3.36	3.01	3.56	0.83	11.57	7.21	210.0	0.44	0.02	0.23
12/09/07	7.36	67.84	3.79	2.66	3.17	0.80	10.15	7.93	215.5	0.42	0.02	0.24
03/06/09	7.00	70.10	3.10	1.52	3.92	0.93	17.22	6.98	204.0	0.47	0.02	0.24
Caprelle Spring												
15/09/06	7.39	72.32	3.16	6.12	2.10	0.60	7.52	1.31	220.0	0.20	<0.02	0.10
24/11/06	7.48	68.84	1.39	5.54	2.69	0.89	11.14	2.46	180.0	0.21	<0.02	0.11
02/02/07	7.60	75.20	4.32	5.31	2.82	0.74	9.65	1.43	228.0	0.17	<0.02	0.11
02/04/07	7.50	83.50	2.73	5.22	2.91	0.44	7.38	0.75	250.0	0.22	<0.02	0.13
11/06/07	7.31	76.72	3.50	5.62	2.76	0.57	8.02	1.98	235.0	0.22	<0.02	0.12
28/06/07	7.37	68.72	2.22	5.80	2.78	0.57	8.30	0.67	200.0	0.21	<0.02	0.12
07/08/07	7.49	70.80	2.73	5.27	2.70	0.57	9.30	1.13	193.0	0.19	<0.02	0.11
12/09/07	7.35	70.40	1.82	5.09	2.71	0.47	7.59	0.69	209.5	0.23	<0.02	0.11

the spring, including those caused by the heavy rains in May and June (Fig. 11).

The SG spring had more stable parameters, and most of the changes in the water level recorded in the polje did not influence the spring at all. The water level in the SG spring rose between March and May as a result of the increase of recharge, but the conductivity remained stable during the year. Only the main events, such as those of February 13 and 26 (Fig. 12), influenced the water conductivity slightly. During these events, a first quick and weak increase of water conductivity (~5 μS cm^{-1}) occurred ~15 hours after the increase of water level in the polje, while the peak values were reached 50–55 hours later.
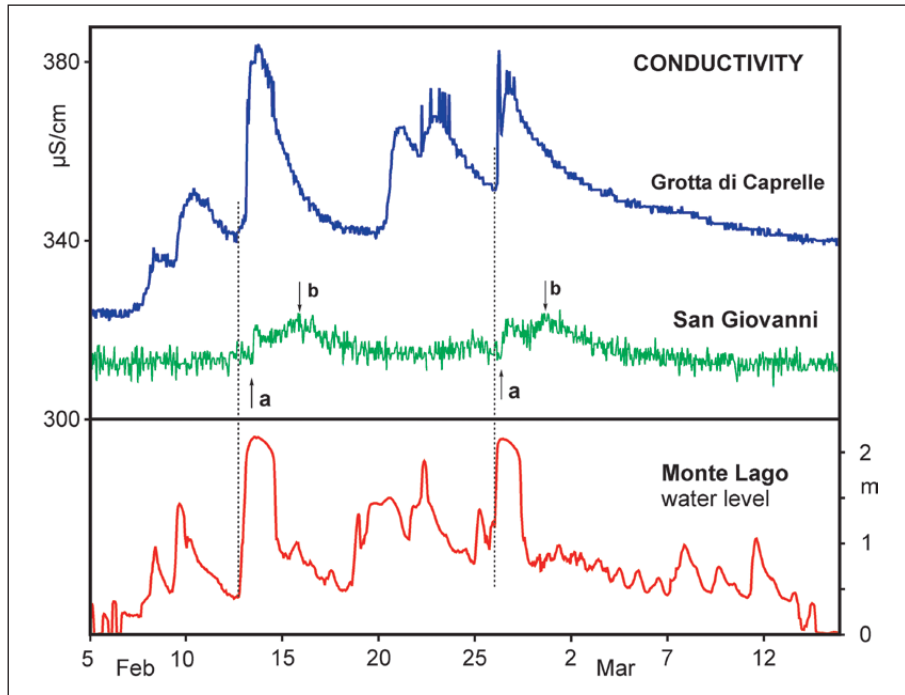

Fig. 12: The hydrographs of San Giovanni and Caprelle springs. Detail on the conductivity changes related to water level in the Monte Lago polje. San Giovanni spring conductivity: a) first increase after the flood events; b) peak value.
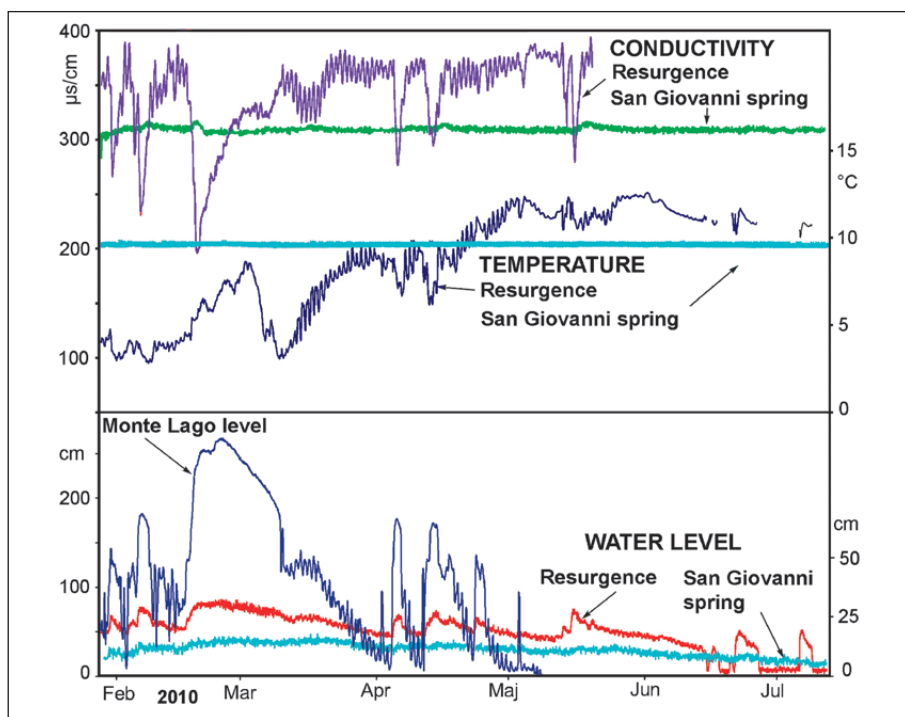

Fig. 13: Hydrographs of San Giovanni spring and resurgence related to the water level of the Monte Lago polje. Note that the monitoring in the polje ceased on May 9.
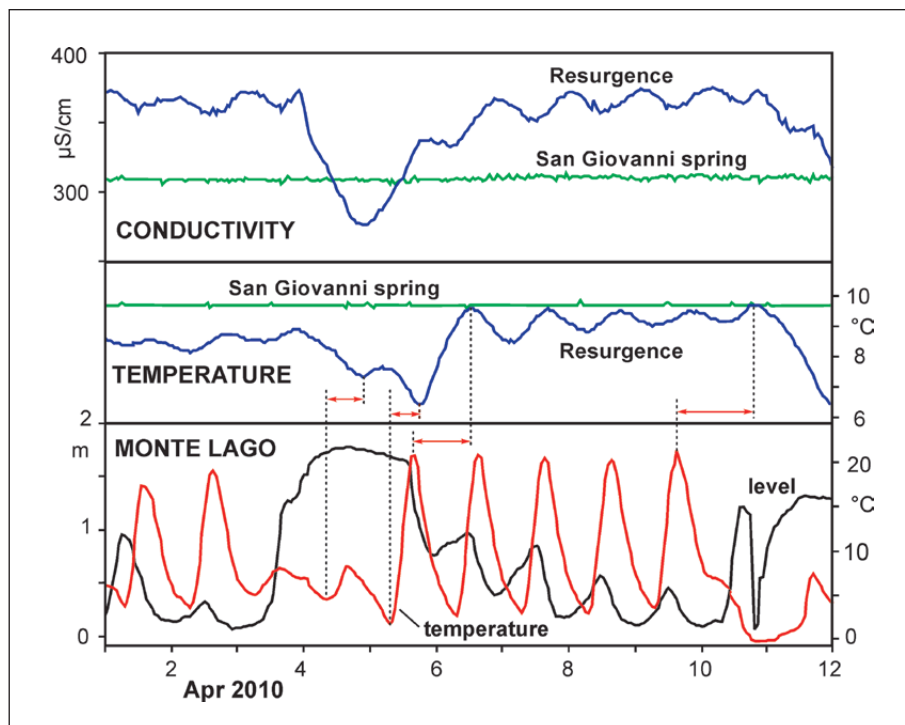
Fig. 14: Daily thermal cycles in the resurgence. The arrows show the delay between the peaks in the surface water and in the resurgence. Note that the time lag increased with low water levels in the polje. The San Giovanni spring maintained stable values in the whole period.

THE 2010 MONITORING OF THE SAN GIOVANNI EMERGENCES

The 2010 monitoring occurred in a favourable period because abundant precipitation maintained a high level in the Piani di Monte Lago for almost one month. The response of the SG spring to the main meteoric events was similar to the former monitored period.

The behaviour of the resurgence was completely different and directly depended on the sinking of water in the polje (Fig. 13). The increased level in the polje resulted in a significant lowering of water conductivity, while the temperature dropped to the surprising values of 3 °C, showing that the cold water descends from the ponor in a few hours, without equilibrating with the rock temperature.

The delay between the events recorded in the hydrographs of the ponor and resurgence indicates that the transit time was 8-10 hours in March, with the polje completely flooded. In March and April, when the daily temperature range increased, the thermal cycle became well evident also at the spring (Fig. 14). The delay between the thermal cycles in the ponor and resurgence indicates a transit time of ~14 hours during the flood of 5 April. The transit time increased to over 24 hours in the following days, with a decreasing water level in the polje.

In May, the water level in the sinking stream decreased below the logger station, which put an end to the acquisition of data. In the same period, the water temperature at the resurgence increased over 12 °C, and the daily cycles became less evident, due the low discharge that favoured heat exchanges with the rock. The discharge in the resurgence became intermittent in June until it ceased to flow at all.

DISCUSSION

The hydrological monitoring and geological survey add new data on the groundwater drainage and on the relationship between the water sunk in the Monte Lago ponor and the most significant springs in the surroundings.

THE CAPRELLE SPRING

The possibility that the Caprelle spring and caves represent an active or past resurgence of karst water from the polje is not supported by the available morphological, hydrological and geological data.

i) The caves are completely void of morphologies or coarse allochthonous deposits that would prove a present or past flow of invasion water from a ponor.

ii) The water parameters in the spring are not strictly related to the water level in the polje. Rainfall capable of producing surface runoff towards the ponor in the warm season (April and May) did not cause any change in the spring water. No direct inlet of low-mineralized surface water was recorded, differently than in the valley of San Giovanni. On the contrary, the fast descent of infiltrating water through the well-karstfied rock is proved by direct observation inside the caves (Galdenzi et al. 2014).

iii) The poljes extend mostly in the Scaglia of the Monte Lago syncline, while the Caprelle spring is in the Agolla syncline, two structures separated by the interposed anticline (Fig. 8). Furthermore, the springs of the Scaglia aquifer in the Agolla valley had always negative results (Fig. 5) after the injection of tracers in the ponor (Aquilanti et al. 2016). The sinking water, infiltrating in the Maiolica complex, should in fact maintain a different pathway due to the interposition of the Marne a Fucoidi aquiclude.

Therefore, the recharge area of Caprelle spring and caves might be in the wide outcrops of Scaglia, near the north-eastern margin of the Piani, where a diffuse infiltration prevails. Only minor contribution from the poljes might be due to cross-formational communication.

THE VALLEY OF SAN GIOVANNI

The hydrologic monitoring confirms the location of the main emergences for the polje water in the valley of San Giovanni, as also verified with the tracer tests (Deiana et al. 1970; Aquilanti et al. 2016; Tazioli et al. 2016). However, the temporary springs that activate along the valley of San Giovanni in high discharge conditions do not represent an overflow of the main San Giovanni spring and their highly variable characteristics derive from a different draining system.

The resurgence is in the same hydrostructure as the ponor, and activates with a high water regime in the polje together with other minor emergences located up and downstream in the rubble-filled valley floor. The fast inflow of cold and low-mineralized water, the lack of thermal equilibrium with the rock and the sensible
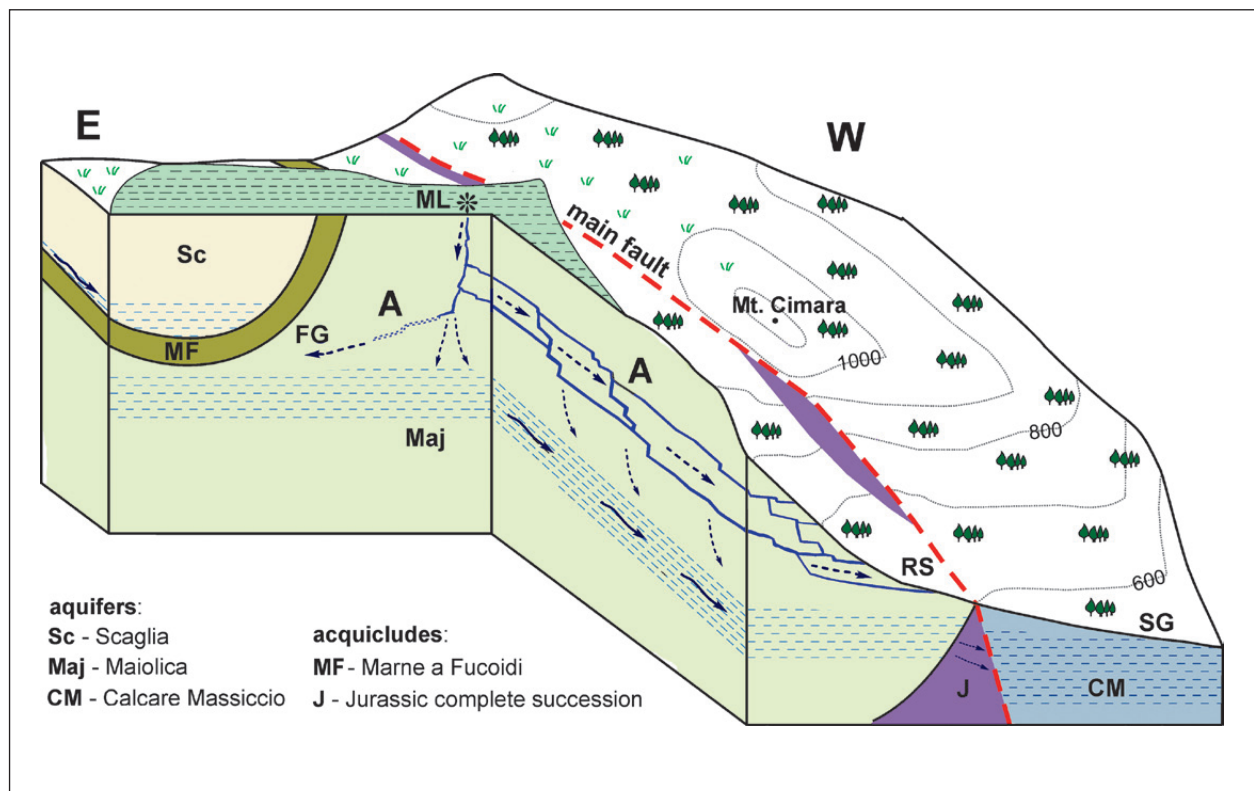

Fig. 15: Scheme for the groundwater flowpath. During high recharge periods vadose water moves in centrifugal directions from the sinking point (A). Most water fast reaches the resurgence in the valley of San Giovanni. The Jurassic aquiclude reduces the drainage towards the San Giovanni spring, mostly fed by the basal aquifer from the Mt. Cimara hydrostructure. Localities: ML) Monte Lago ponor; RS) Resurgence; SG) San Giovanni spring; FG) Figareto spring.

daily thermal cycles in the spring water (Figs. 13 and 14) evidence a highly effective drainage of the water, probably through karst channels. The water moves for over 1.5 km from the ponor to the resurgence in 8-10 hours when the polje is completely flooded, with a longer time, up to over 24 hours, when the amount of sinking water decreases.

Notwithstanding a different sampling site in the same valley, the tests with tracers obtained comparable results (Aquilanti *et al.* 2016). The tracer reached the spring between 15 and 72 hours after the injection with a moderate and low flow rate respectively, and a large percentage of the tracer was recovered in the emergence (31-63% in the different tests).

The stable characteristics, the low content of nitrates, and the scarce influence of the meteoric events on the monitored parameters confirm that the San Giovanni spring represents an emergence of the basal aquifer of the Mt. Cimara anticline, lightly influenced in its chemistry by ions (as Sr^{2+}, Li^+, $SO_4^=$) derived from the underlying Triassic evaporites.

Differently than in the resurgence, a direct inflow of the low-mineralized infiltration water did not occur, and only after the main meteoric events, the pushing caused by the infiltrating water produced a weak rise of conductivity for the mobilization of resident groundwater. The initial rapid increase of the conductivity was probably due to direct infiltration in the area surrounding the spring. The peaks in the water conductivity occurred later, after 52–60 h (Fig. 12), probably with the contribution of sinking water from the ponor. The tracer tests, in fact, verified that a low percentage of the tracer (5-7%) reached also the San Giovanni spring during the recharge periods, with a moderate flow rate in the ponor (Aquilanti *et al.* 2016; Tazioli *et al.* 2016). In those tests, the first arrival of the tracer occurred ~48 hours after the injection, the main peak after ~400 hours.

However, the hypothesis that sinking water could reach the Calcare Massiccio of the Monte Cimara hydrostructure and move through a different pathway to the temporary springs and to the San Giovanni spring, as proposed by Aquilanti *et al.* (2016), is inconsistent with the geological setting. The sinking water moves from the ponor to the resurgence and to the other temporary springs remaining within the same unit (Maiolica). The direct contribution of sinking water to the San Giovanni spring is minor due to the aquiclude interposed towards the Calcare Massiccio (Fig. 15). Furthermore, the sinking water reaches the spring after being diluted into the groundwater.

KARST CIRCULATION

The very different behaviour of the springs derives from a different drainage pattern in the vadose and phreatic zones of the karst aquifers. The rapid response of all the springs to meteoric events is due to the high permeability in the vadose zone, where a well-developed system of open fissures and karst channels facilitates the transfer of infiltration water towards the phreatic zone or directly to the emergences.

On the contrary, the stable chemical characteristics and the high storage capacity of the San Giovanni spring can be related to a lower karstfication in the deep zones of the carbonate massif, in particular in the basal aquifer of Mt. Cimara anticline, with a prevailing flow of groundwater through the fissure system.

These differences on the degree of karstfication are not related to lithology. Fast drainage of vadose water occurs in all the limestone units, and most caves develop in the Maiolica and Scaglia rather than in the highly permeable Calcare Massiccio. The set of active and relict karst channels in the upper part of the massif formed due to a long exposure of the limestone to solutional processes during the Pleistocene. On the contrary, solution processes in the lowest part of the massif significantly increased after the deepening of the river valleys during the Middle and Late Pleistocene as a consequence of the tectonic uplift.

These differences in the karstfication are consistent with the behaviour of the springs. In most springs, the mobilization of resident groundwater due to the pushing infiltration water prevails on the direct inlet of low-mineralized infiltration water causing the increase of T and EC. This effect is weakened in the San Giovanni spring due to the large amount of groundwater stored in the karst aquifer.

In the Monte Lago polje, the direct inflow of a large amount of low-mineralized water through the ponor feeds a pure karst circulation to the temporary resurgences in the valley of San Giovanni. This network of karst channels activates completely only with high water regime. Under this condition, the invasion water exceeds the draining capacity of the karst channels, favouring the dispersion of water towards other springs (Fig. 15). The main route of the sinking water remains separated from the adjacent San Giovanni hydrostructure. The interposed aquiclude, in fact, reduces the possibility of connection for a fast flow of vadose water directly influenced by gravity in highly karstfied rocks.

CONCLUSION

The research evidences an articulate drainage pathway of the groundwater in the Monte Lago area, controlled by the karst solutional processes and geological setting, and influenced by the recharge conditions. The geological setting, and in particular the attitude of bedding and faults, has a primary influence on the large scale groundwater drainage of the basal aquifers, but also influences the vadose water controlled by gravity. The well-developed set of active and relict karst channels facilitates the infiltration of water and its fast drainage in the vadose zone, while karst channels have a minor influence on the groundwater drainage in the basal regional aquifers.

Therefore, the permeability inside the same geological unit does not depend only on the lithological characteristics, but varies locally due to the different degree of karstfication that has been reached over time.

Although the recharge of groundwater from a polje represents an uncommon circumstance in the Umbria-Marche Apennines, the influence of the karstfication on the permeability inside the same geological unit and the different characteristics of vadose and phreatic fluxes represent important conditions to be considered in defining the groundwater circulation pattern of the karstfied structures in the region.

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