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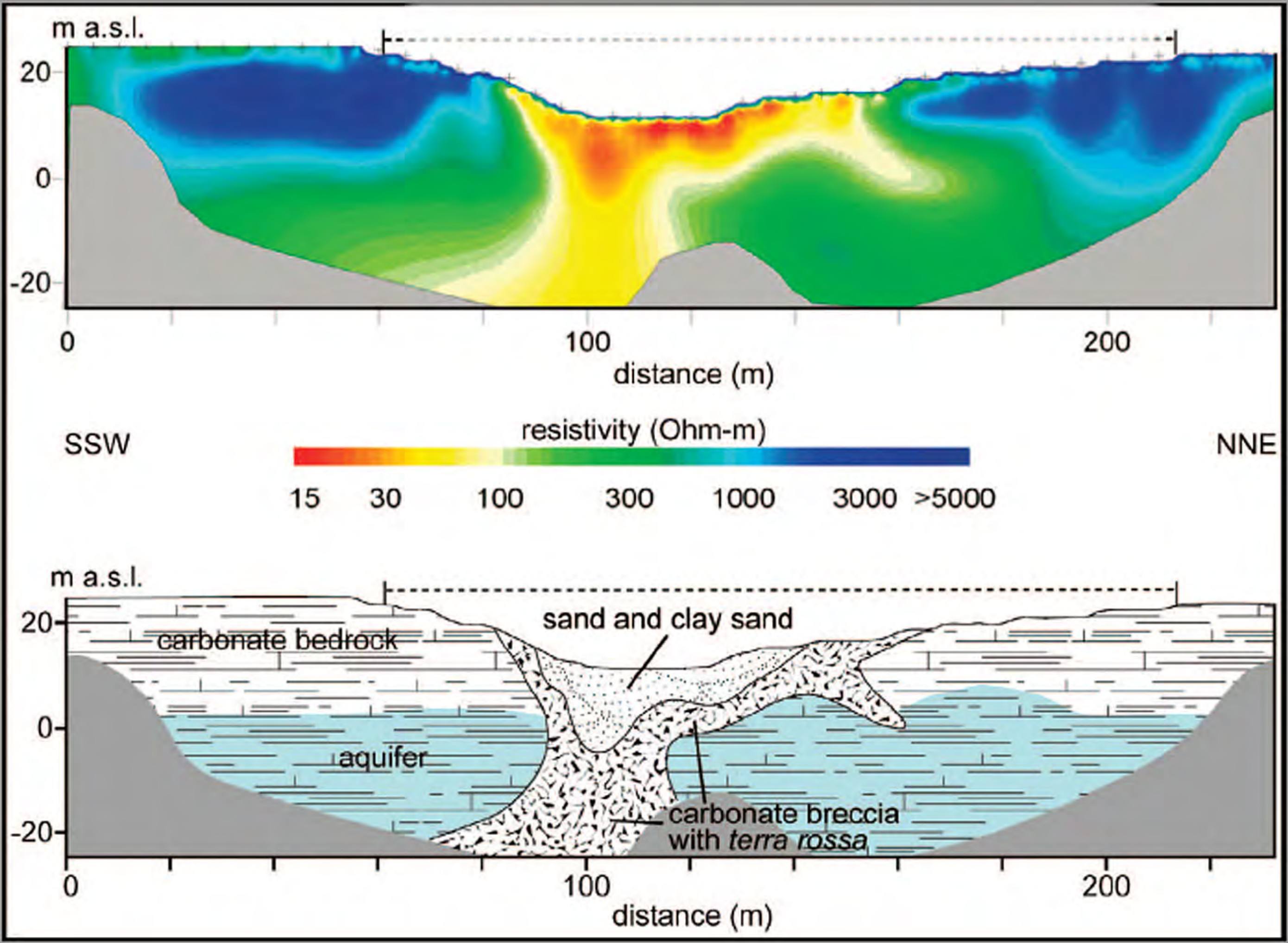

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Front cover: Resistivity cross-section through sinkhole. See Festa et al. in this issue.

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KARST ENVIRONMENTS: PROBLEMS, MANAGEMENT, HUMAN IMPACTS, AND SUSTAINABILITY AN INTRODUCTION TO THE SPECIAL ISSUE

Robert Brinkmann[1] and Mario Parise[2]

Karst systems are extremely complex, and due to a number of geological and hydrological characteristics, they can be included among the most fragile and vulnerable environments in the world. Complexity of karst is expressed by the enormous variations existing in different karst regions (White, 1988). The difficulties inherent in such variability were appropriately described by Beck (1999), who wrote, "Learning to understand the systematics of karst terrain and how to deal with it safely requires serious effort—often a lifetime of study." This means, in other words, that man must make a strong effort to learn to live "in harmony with" karst, rather than to live "on" karst. Many problems we face when interacting with karst environments are best solved through changes in human systems rather than through alterations of karst environments. This is because subtle changes in fragile karst systems change them significantly.

Because karst covers 10 to 20% of the earth's surface and provides 40 to 50% of the world's drinking water (Ford and Williams, 2007), it requires a specific approach to mitigate negative human impacts and allow sustainable development. In this sense, protection of karst groundwater is essential in many countries. Karst hydrologic systems are highly vulnerable to pollution, water withdrawals, and changes in land use (Bakalowicz, 2005; Calò & Parise, 2009). In addition, the dissolution of limestone creates voids in the subsurface that can lead to collapses that directly affect the built environment by inducing severe damage, property loss, and disruptions to daily life. Management of karst environments is a very delicate matter, and how to manage pollution, karst hazards, and human impacts on karst landscapes is a question worthy of discussion (White, 1990; Parise and Pascali, 2003).

Many populated areas of the world obtain drinking water from karst aquifers, and numerous urban areas are underlain by karstified bedrock. Consequently, karst systems pose a number of engineering and environmental problems (Calembert, 1975; Legrand, 1984; Ford, 1993; Williams, 1993; Johnson and Neal, 2003) that are continuously increasing as development extends over these areas. Building on cavernous bedrock and sinkhole-prone areas is a challenging issue for geoscientists and engineers (Waltham et al., 2005; Del Prete et al., 2010); appropriate management of karst areas has to carefully take into account the possibility of the presence of underground voids of both natural and anthropogenic origin in order to mitigate the risk related to sinkholes.

Problems in karst, karst management, and the sustainability of karst environments are receiving growing interest around the world due to the importance of natural resources and the need to protect and properly exploit them. In many karst regions, the human impact on these fragile ecosystems is significant (van Beynen and Townsend, 2005; Calò and Parise, 2006; van Beynen et al., 2007; North et al., 2009). This is especially true along coasts where seasonal increases in population have deleterious impacts. There is, therefore, the need for more work dedicated to understanding human-altered karst landscapes via assessing alterations of natural systems and the repair of karst ecosystems, measuring karst disturbance and sustainability, managing karst lands in urbanized and urbanizing areas, and assessing changes in karst hydrology.

Engineering problems in karst have been the main topic of several conferences and meetings in the last decades that resulted in interesting volumes and special issues. From 1984 to 2011, twelve Multidisciplinary Conferences on Sinkholes and the Engineering and Environmental Impacts of Karst have been organized in the United States (Beck, 1999, 2002). In Europe, since 2004, problems related to karst environments have been the subject of specific sessions at the General Assembly of the European Geosciences Union within the framework of the Natural Hazards Program. In many cases, the most significant outcomes from these sessions have been published as special issues of peer-reviewed journals (Parise and Gunn, 2005; Parise et al., 2008, 2009; De Waele et al., 2011) or as a book (Parise and Gunn, 2007). Notwithstanding these efforts, little attention is given to these issues in karst landscapes, and few regions of the world fully understand or appropriately manage karst areas.

In an attempt to draw the attention of the scientific world on the need to specifically address issues in karst settings, we organized a poster session titled Karst Environments: Problems, Management, Human Impacts, and Sustainability at the Annual Meeting of the Geological Society of America in Denver, Colorado, on November 2, 2010. The session hosted two invited presentations and twenty-three other submissions on a variety of topics and was sponsored by the Karst Waters Institute, the National Cave and Karst Research Institute, and the GSA Hydrogeology and Quaternary Geology and Geomorphology Divisions.

In this special issue, a selection of the papers from that session is presented. The papers explore current research on how humans are interacting with karst, with a distinct focus on management and sustainability. This issue contains eight articles on a number of topics. Mick Day and Bill Reynolds summarize work that they have done at

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Five Blue Lakes National Park in Belize. The changing hydrology of the Belizean karst system greatly impacts the nature of tourism in the region. Along similar investigative lines, Francesco Fiorillo and Gerardo Ventafridda provide evidence from five springs in southern Italy that suggest that the aquifer systems in that region are more complex than originally thought. The authors provide detailed reasoning for understanding how aquifer catchments drain during the dry season. Benjamin Tobin and Benjamin Schwartz detail a fascinating study of marble karst aquifers in Sequoia and Kings Canyon National Parks in the United States. Their work is among a few that provide detailed quantitative data on spring discharge in alpine karst systems. Phil van Beynen and his co-authors discuss a new approach to describing karst using a sustainability index. As karst lands become more threatened, the authors provide a unique way to measure current management conditions.

Vincenzo Festa and his co-authors discuss sinkhole hazards in the Salento Peninsula of Italy, with a case study from Lecce. They provide a historic description of sinkhole formation there to better understand future sinkhole evolution in the region. Maria Asuncion Soriano and her colleagues focused their attention on sinkhole evolution in the Ebro Basin of Spain. Their work examined the geologic history of paleosinkholes and their role in the water supply in the region. Marco Taviani and his colleagues also looked at paleokarst landscapes. Their work took them to the south Adriatic shelf on the Apulian coast of Italy. They offer a better understanding of the complex issues associated with karst-landscape development in the Mediterranean basin. Cipriano di Maggio and his co-authors round out the contributions from Europe by providing a detailed description of the karst of Sicily and how it is managed. They offer several interesting observations about environmental policy and management in the region.

We hope that the readers of the *Journal of Cave and Karst Studies* enjoy these articles and that they advance the understanding of karst and karst management in some way.

ACKNOWLEDGMENTS

We acknowledge the scientists who attended the GSA session in Denver by presenting contributions or simply participating in the discussions. We are also grateful to the Geological Society of America for providing the opportunity to convene the session, and for the International Travel Grant that covered in part the expenses for Mario Parise's attendance. We also thank the session sponsors. Our warmest thanks go to all the referees who undoubtedly improved the quality of the papers. Finally, we are extremely grateful to Malcolm Field for his continuous and invaluable support and guidance during all phases of the publication process.

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V. Festa, A. Fiore, M. Parise, and A. Siniscalchi – Sinkhole evolution in the Apulian Karst of Southern Italy: a case study, with some considerations on Sinkhole Hazards. *Journal of Cave and Karst Studies,* v. 74, no. 2, p. 137–147. DOI: 10.4311/2011JCKS0211

SINKHOLE EVOLUTION IN THE APULIAN KARST OF SOUTHERN ITALY: A CASE STUDY, WITH SOME CONSIDERATIONS ON SINKHOLE HAZARDS

Vincenzo Festa[1], Antonio Fiore[2,3], Mario Parise[4*], and Agata Siniscalchi[1]

Abstract: Sinkholes are the main karst landforms characterizing the Salento Peninsula, which is the southernmost part of the Apulia region of southern Italy. They occur both as evolving recent phenomena and old or relict features testifying to ancient phases of karst processes acting in the area. Most of the sinkholes were formed by karst processes that may be reactivated, a risk to the anthropogenic structures nearby. To highlight such a subtle hazard, an area located a few kilometers from Lecce, the main town in Salento, was the subject of geological, morphological, and geophysical investigations. Historical analysis of multi-year aerial photographs, in particular, allowed identification of several phases in the recent evolution of a particular sinkhole, and demonstrated the need to carefully evaluate the likely evolution of similar features in Salento.

Introduction

Sinkholes are among the most common landforms of karst landscapes worldwide. They occur in a variety of sizes and are morphologically expressed as a function of the mechanisms originating them (Waltham et al., 2005). In many countries, sinkholes are among the most significant geohazards of karst areas, with significant negative consequences for society in terms of economic losses (Galloway et al., 1999; Scheidt et al., 2005).

Sinkhole research has gained wide attention from the Italian scientific community in recent years due to frequent occurrences of sinkholes in several regions of Italy. Among these, Apulia is one of the most important, due to outcrops of soluble rocks in most of the Apulian territory. Salento, the southernmost part of the region (Fig. 1), contains a great variety of sinkhole phenomena that display different typologies and states of activity (Parise, 2008a). They affect all outcropping carbonate rocks, including the Cretaceous limestone, the Oligocene, Miocene, and Plio-Pleistocene calcarenites, and the middle-upper Pleistocene terraced marine deposits. Further, Triassic evaporites in the northern reaches of Apulia are also affected by sinkholes (Fidelibus et al., 2011). In many sectors of Salento, sinkholes are so widespread that they have become the main landform, especially along the low shorelines of both the Adriatic and Ionian seas (Delle Rose and Parise, 2002; Bruno et al., 2008). Sinkholes have often been modified by man to gain land for agricultural practices or to be used as swallet sites to mitigate flood hazards during heavy rainfall. In the latter case, however, lack of maintenance and clogging produced by wastes and vegetation has repeatedly resulted in further flooding events, with severe damage to the surrounding land (Delle Rose and Parise, 2010).

Analysis of sinkholes in Apulia is important not only for understanding the processes at the origin of such events, but also for the protection of society. It is important to understand the past in order to forecast future sinkhole episodes. To achieve the two goals above, we present a case study of the Masseria Forte di Morello sinkhole located a few kilometers north of Lecce that illustrates the likely re-activation of sinkholes, the importance in considering sinkholes in land management, and the need to carry out detailed, dedicated studies aimed at mitigating the risk (Parise, 2008b, 2010).

The investigation was carried out using a multidisciplinary approach. Field mapping and geophysics allowed us to reconstruct the plan view and deep geometry of the sinkhole, as well as to discern the oldest stages of the sinkhole's genesis and evolution. Old aerial photographs, topographic maps, and orthophotos were useful in reconstructing the recent evolution of the sinkhole, especially in relation to anthropogenic activities.

Geological Setting

The Apulian Foreland represents the southern Plio-Pleistocene foreland of the Apenninic and Dinaric-Hellenic orogens (e.g., Ricchetti et al., 1988; Funiciello et al., 1991; Fig. 1A). In Apulia, the exposed foreland is characterized by three main morpho-structural highs. From northwest to southeast, they are Gargano, Murge, and Salento (e.g., Pieri et al., 1997; Del Gaudio et al., 2001; Fig. 1A).

The stratigraphic setting of Salento can be simplified by grouping the different lithostratigraphic units into Cretaceous, Eo-Miocenic, and Plio-Pleistocenic units that are separated by unconformity surfaces (Tropeano et al., 2004, and references therein; Fig. 1B). According to Ciaranfi

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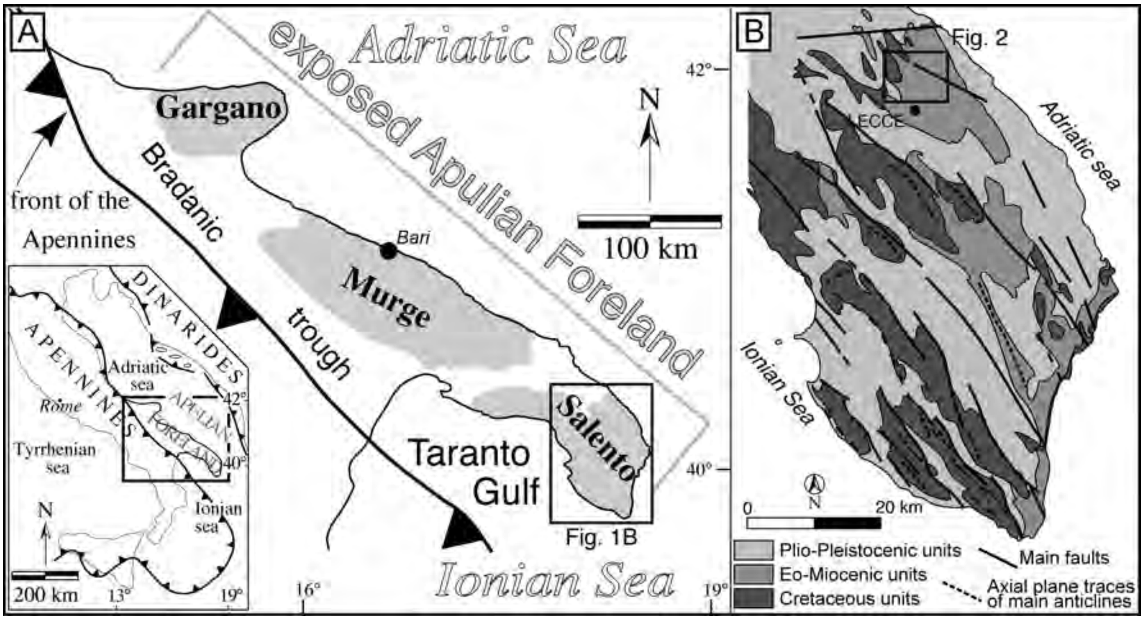

Figure 1. A: The exposed Apulian Foreland (Apulia, southern Italy) in the framework of the Apenninic and the Dinaric-Hellenic orogens (after Festa, 2003, modified). B: Schematic geological map of the Salento area (after Ciaranfi et al., 1988; Tozzi, 1993; and Tropeano et al., 2004).

et al. (1988), the Cretaceous-age Calcare di Altamura formation is the lowest and oldest unit cropping out in the overall area. Recent chronostratigraphic studies by Schlüter et al. (2008) indicate that its age is between 66 and 86 Ma. The formation is mainly characterized by well-stratified limestones, locally represented by dolomitic limestones and dolostones. According to Tulipano and Fidelibus (2002), these Cretaceous rocks constitute the main aquifer in Salento, with water table elevations reaching maximum values of 4 m above sea level.

Rocks belonging to the Calcare di Altamura underlie the zone in which the sinkhole in this case study is located (Ciaranfi et al., 1988; Bossio et al., 1999; Fig. 2). Here the water table of the main aquifer is at about 2 m above sea level, and the Calcare di Altamura rests below both the Eo-Miocenic and the Plio-Pleistocenic units (Tulipano and Fidelibus, 2002). The first are represented by the Pietra Leccese and the Calcareniti di Andrano formations (Fig. 2). The Pietra Leccese consists of thin glauconitic calcarenites with planktonic foraminifera, upper Burdigalian to lower Messinian in age. The Calcareniti di Andrano are characterized by bioclastic calcarenites rich in algae and mollusks that are lower Messinian in age (Bossio et al., 1999; Bosellini, 2006). The Plio-Pleistocenic units are mostly represented by biocalcarenites and biocalcirudites (Bossio et al., 1999) that may belong to the Calcarenite di Gravina formation, middle Pliocene (?) to lower Pleistocene in age (Ciaranfi et al., 1988; D'Alessandro et al., 2004; Tropeano et al., 2004; Fig. 2).

According to Martinis (1962), Palmentola and Vignola (1980), and Parise (2008a), a general correlation between morphology and tectonics is found in the Salento area. The physical landscape is delineated by a set of sub-flat surfaces, variously extended, arranged at different heights, and often connected by small scarps related to faults mainly striking north-northwest—south-southeast and northwest-southeast (Fig. 1B). These faults were active during the Pliocene and Pleistocene and show high-angle planes, with opposite dip directions, along which a maximum extensional offset of about 200 m can be estimated. However, according to Tozzi (1993) and Gambini and Tozzi (1996), a transcurrent component characterizes their kinematics as well. The activity of the faults would be responsible for the formation of open to gentle folds, especially in the Cretaceous and Eo-Miocenic units (Martinis, 1962; Tozzi, 1993; Fig. 1B). The site where the Masseria Forte di Morello sinkhole is located is morphologically an alternation of morpho-structural ridges and depressions elongated roughly northwest to southeast and interpreted as horsts and grabens (Martinis, 1962; Palmentola and Vignola, 1980) or pull-aparts (Tozzi, 1993). In Salento, such ridges are called Serre Salentine and reach a maximum altitude of 199 m above sea level. They are modeled on both Cretaceous and Eo-Miocenic units, while the intervening depressions are generally occupied by Plio-Pleistocenic units (Parise, 2008a, and references therein). This occurs at the study site (Fig. 2), where the Calcarenite di Gravina crops out in structurally depressed sectors produced within the pre-Pliocenic units (Bossio et al., 1999). Recent meso-structural analyses by Di Bucci et al. (2009) indicate that the Salento carbonates have been affected by middle and late Pleistocene extensional tectonics that formed joints that mostly strike northwest-southeast, and subordinately northeast-southwest.

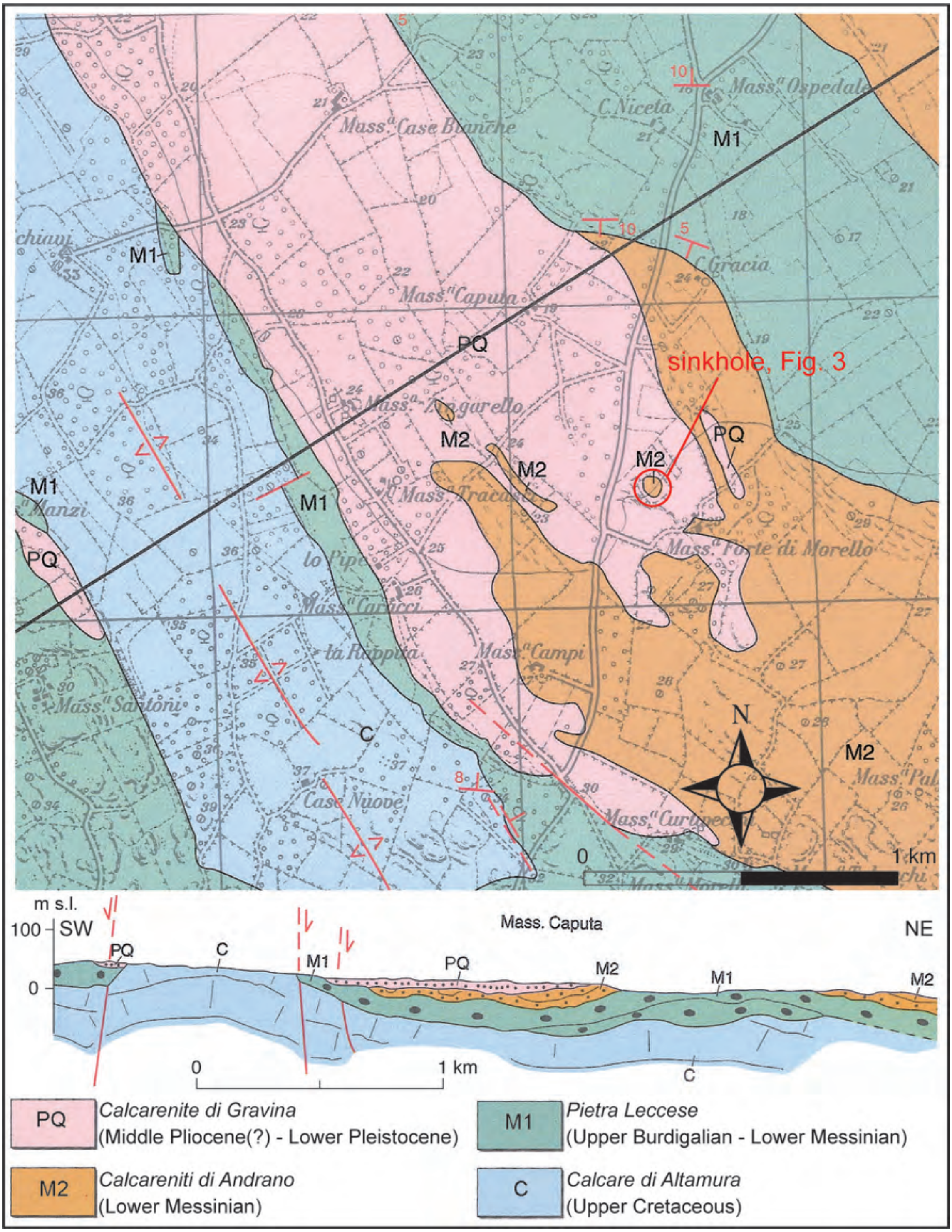

Figure 2. Geological map of the zone around the sinkhole (after Bossio et al., 1999, with modifications according to Ciaranfi et al., 1988; D'Alessandro et al., 2004; Tropeano et al., 2004; and Bosellini, 2006).

Materials and Methods

A combination of geological, geomorphological, and geophysical analyses has been implemented to study the sinkhole at Masseria Forte di Morello. Integration of different approaches is, as a matter of fact, a crucial point in the reconstruction of the local geology of the sinkhole and the understanding of its formation mechanism. The geological survey was conducted over an area of several square kilometers around the sinkhole and in greater detail at the sinkhole. Besides stratigraphic analysis and identification of the lithotypes at outcrops, attention was paid to the structural geology of the different formations to define the likely control of tectonic features on sinkhole formation and evolution.

An important part of the work consisted of the geophysical analysis of site features and morphology. Geophysics provides important non-invasive tools that can be used to predict where and within what limits sinkholes are likely to occur, to determine the underlying cause of an existing or forming subsidence or depression, and to evaluate the success or failure of ground-improvement programs intended to remediate sinkhole conditions (Zhou et al., 2002). Among geophysical methods, electrical resistivity imaging is well suited to mapping sinkholes because of the ability of the technique to detect resistive features and discriminate subtle resistivity variations in karst environments. A number of researchers have used two-dimensional 2D electrical resistivity tomography to examine sinkholes and the underlying weathered bedrock (e.g., van Schoor, 2002; Zhou et al., 2002). The raveling zone is characterized by increased porosity and reduced percentage of fine sediment. Depending on the depth to the local groundwater table, the raveling zone can either be shown as a high-resistivity anomaly (if dry) or a low-resistivity anomaly (if saturated). Deeper void space is typically characterized by a low-resistivity feature that is indicative of carbonate materials being replaced by looser clastic sediments or by water. Of course, an air-filled void would generate a high-resistivity anomaly, but this would not constitute a sinkhole, strictly speaking. ERT sections acquired in a karst area outside an urbanized environment should clearly display the types of anomalies routinely encountered in sinkholes (Dobecki and Upchurch, 2006; Schwartz and Schreiber, 2009).

Many karst features, including the irregular bedrock surface, cavities within the bedrock or in the soil mantle (air-filled, water-filled, or clay-filled), buried sinkholes, raveling zones at the bedrock-overburden interface, and preferential groundwater flow paths can be detected by resistivity investigations, providing electrode configurations are designed for the setting. Zhou et al. (2002) conducted numerical forward-modeling and experimental analysis of dipole–dipole (DD), Schlumberger, and Wenner arrays that produced markedly different anomaly shapes for a conceptual model of a cover-collapse sinkhole. The results from the dipole–dipole array appeared to be better than those from the Wenner and Schlumberger arrays in displaying the sinkhole collapse area. Compared with the DD array, the Wenner and Schlumberger arrays, and their hybrid configuration (Wenner-Schlumberger), have symmetric configurations allowing high data quality, but lower horizontal resolution for identifying vertical and dipping structures, such as those likely characterizing sinkhole features. A dipole-dipole array was therefore chosen for this investigation to ensure a good horizontal resolution.

To complete the study, the geomorphological evolution of the sinkhole was assessed by means of a chronological analysis of the available maps, aerial photographs, and orthophotos. The use of historical data in the analysis of natural hazards is recognized as a fundamental tool for evaluating hazards (Varnes, 1984). Historical data may disclose the timing of events (Calcaterra and Parise, 2001; Glade et al., 2001). Among the many possible sources of historical information, aerial photographs are particularly useful for reconstructing the recent evolution of the landscape. In particular, multi-year analysis of aerial photos, which requires availability of photos from different years and the work of an expert photo-interpreter is a powerful and economical tool (Soeters and van Westen, 1996; Parise, 2001). Comparing several air photos allows detection of the recent evolution of natural phenomena, land use changes, and the efficacy of remediation works to mitigate specific hazards (Parise and Wasowski, 1999). Such an analysis has been performed at the Masseria Forte di Morello sinkhole using eight sets of images covering the time span 1955–2006; the most recent temporal and spatial changes in the study area were assessed through field controls. The stereoscopic analysis of aerial photos was carried out by using a Wild APT2 stereoscope equipped with zoom magnification (maximum 15×). In addition, old maps were also examined (see Table 1 for details).

RESULTS

FIELD SURVEY

Detailed mapping of the geology of the sinkhole area was carried out. In agreement with the stratigraphic setting shown in the geological map (Fig. 2), the bedrock is calcarenites and calcirudites belonging to the Calcareniti di Andrano and the Calcarenite di Gravina formations (Fig. 3). These carbonate rocks, with sub-horizontal bedding, are affected by two main systems of joints (Figs. 4A, 4B) with sub-vertical planes roughly oriented northwest-southeast and northeast-southwest (Fig. 4C). In agreement with Di Bucci et al. (2009), these directions indicate that such joints can be related to extensional tectonics that affected the Salento area during middle and late Pleistocene times. As shown in Figures 4A and 4B, the original joints have been enlarged by karst processes, so that they now appear as flutes and runnels. A scarp rim (I, in Figs. 3A, 3B) on the bedrock surrounds the depressed area where the recent evolution of the sinkhole occurred. It clearly separates the depression from the flat surrounding topography (Fig. 3B) that extends to about 25 m above sea level. In plan view, the scarp rim appears to be very regular in the northern sector, where it is northeast-southwest and north-northwest–south-southeast oriented (Fig. 3A). In contrast, the southern reach has a sub-circular shape. This rim delimits the upper scarp of the sinkhole. The scarp is characterized by a gently-inclined slope that is slightly steeper in its south-western sector (Fig. 3A).

Table 1. Sources used for the historical analysis of the Masseria Forte di Morello sinkhole.

Type	Date	Scale
Aerial photos	June 5, 1955	~ 1:35,000
Aerial photos	July 29, 1972	~ 1:20,000
Aerial photos	July 07, 1987	~ 1:18,000
Aerial photos	July 13, 1996	~ 1:13,000
Aerial photos	May 07, 2003	~ 1:18,000
Topographic maps	1874	1:50,000
Topographic maps	1912	1:100,000
Topographic maps	1954–55	1:25,000
Cadastre maps	1900–10	1:2,000
Orthophotos	1994	1:10,000
Orthophotos	2000	1:10,000
Orthophotos	August 2006	1:5,000

Downslope, a carbonate breccia crops out at the contact with the bedrock, exhibiting an overall thickness of about 4 m (Figs. 3A, 3C). This breccia is composed of calcarenite and calcirudite clasts (Fig. 4D) that reach a maximum size of 80 to 100 cm, with widespread terra rossa between the clasts (Fig. 4E). The larger clasts often show honeycomb features generally infilled by residual clay deposits. Toward the inner depression, the breccia body is exposed along the above-mentioned gently-inclined slope that leads to the intermediate scarp of the sinkhole. This scarp is steeply inclined, with a maximum drop of about 3 m, and surrounds a depression located near the south-southwest margin of the sinkhole area (Fig. 3A). In plan view, the shape of its rim (II in Figs. 3A and C) is ovoid, with the longest axis striking about north-northeast–south-southwest.

The base of this scarp coincides with the contact between the breccia and a succession of siliciclastic

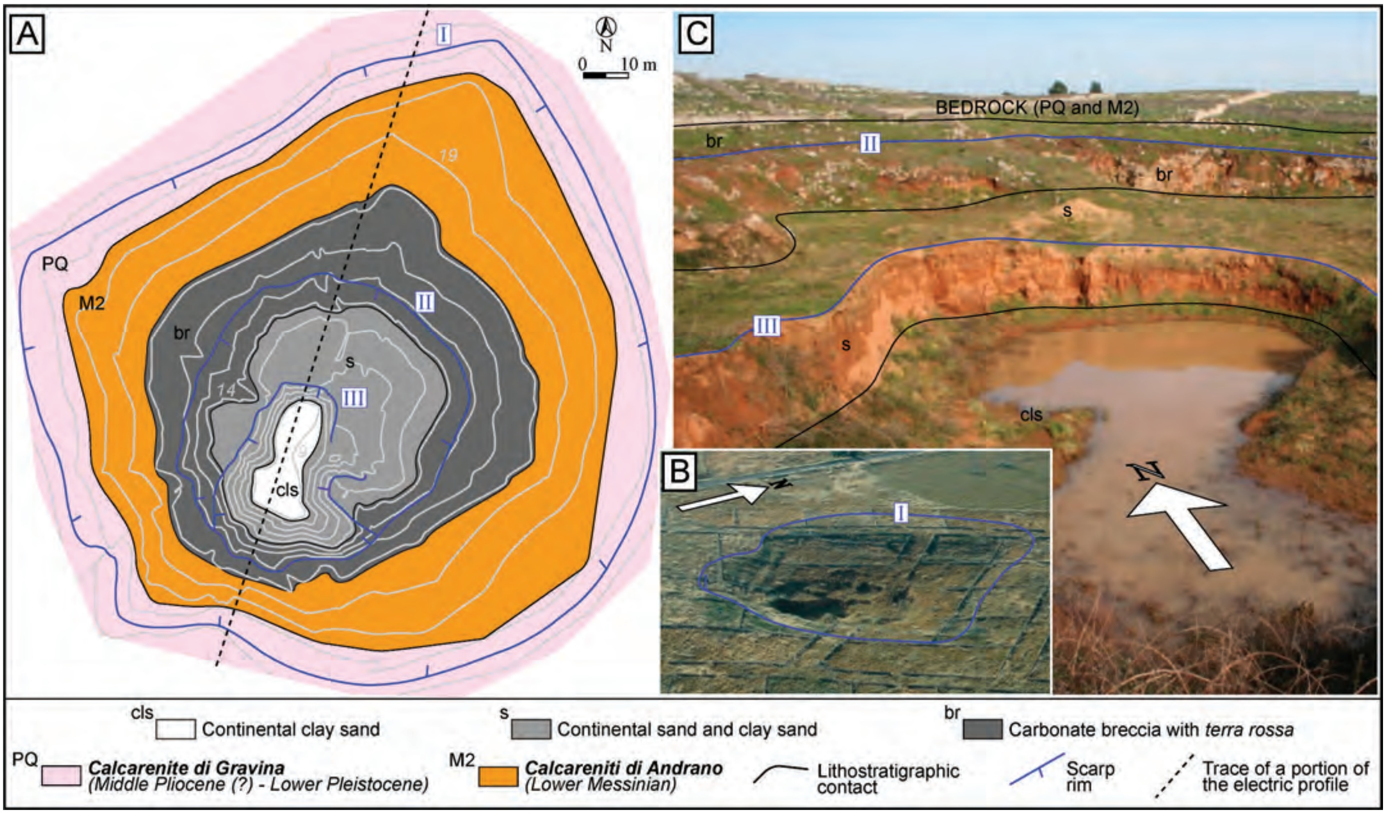

Figure 3. A: Geological map of the sinkhole. B: Aerial photograph of the sinkhole (courtesy of M. Sammarco, Univ. Salento). C: View of the central-northern sector of the sinkhole. Scarps I, II, and III are discussed in the text.

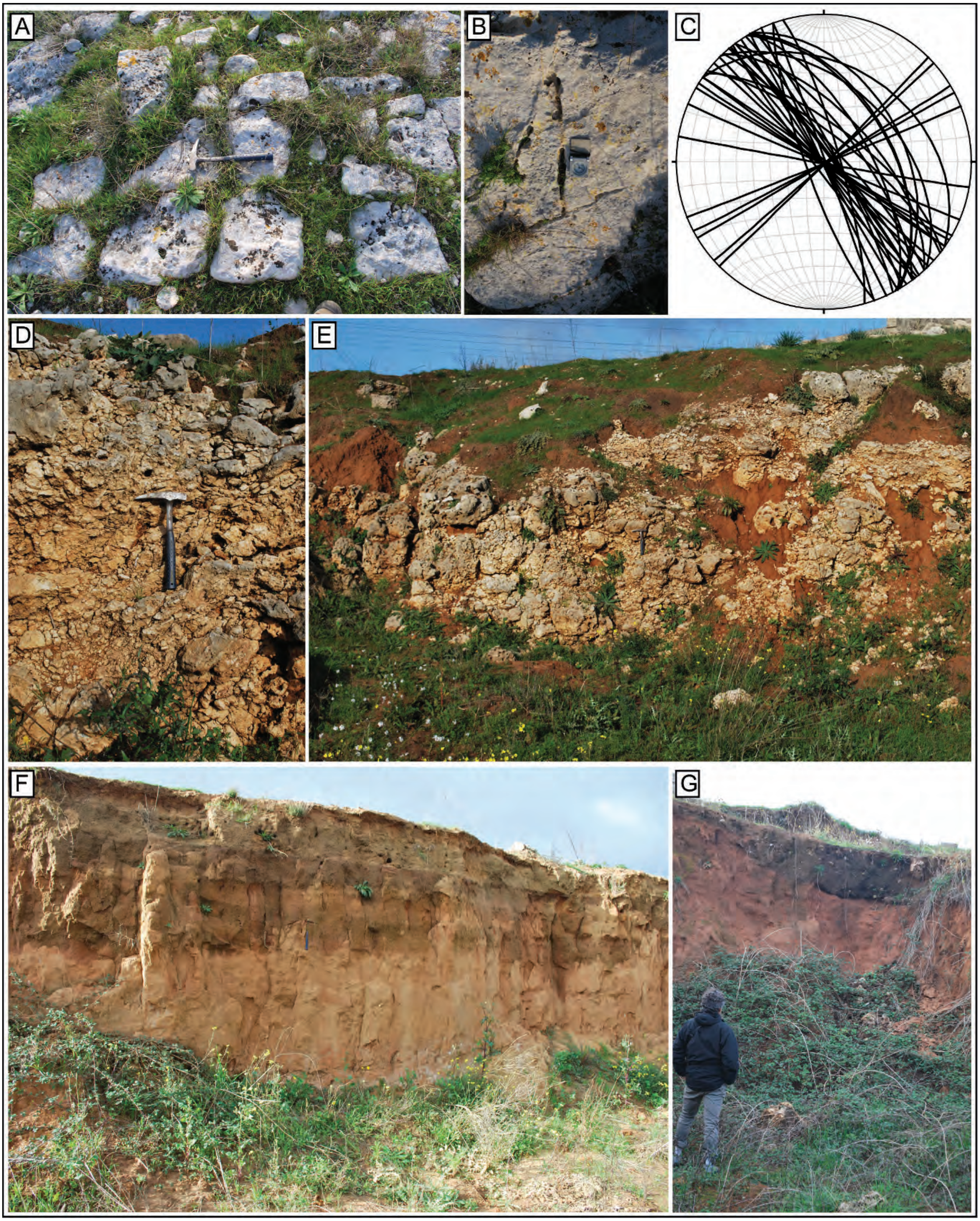

Figure 4. A and B: Tectonic joints in the calcarenite bedrock. Note their flutes-and-runnels appearance. C: Orientation diagram of the joints (n = 39) within the calcarenite bedrock. Equal area projection, lower hemisphere. The data were processed with the software Stereonet 6.3.2X by R. Allmendinger. D and E: carbonate breccia composed of calcarenite and calcirudite clasts with terra rossa. F and G: Siliciclastic continental sands and clay sands. Note the decimeter-thick soil at the top of the succession.

continental sands and clay sands (Figs. 3A and C) that have a maximum thickness of about 5 m. These sediments are generally stratified (Fig. 4F), even though they appear locally massive (Fig. 4G). At the top of the succession, a decimeter-thick soil is present, characterized by dark matrix clay and centimeter-sized carbonate clasts (Fig. 4G). The exposed surface at the top of this succession is sub-horizontal, and its inner edge contains the lower scarp (Fig. 3C). Here, the siliciclastic sediments are well exposed (Figs. 4F and G). The scarp is sub-vertical, reaching a maximum drop of about 4 m, and in its south-western sector represents the downward continuation of the intermediate scarp. Here, a total depth of about 8 m is reached. In plan view, the shape of its rim (III, in Figs. 3A and C) is approximately 8-shaped, with its maximum elongation striking about north-northeast–south-southwest. The bottom of the depression, located about 9 m above sea level, is occupied by thin deposits of clay sands (Fig. 3A) whose sedimentation is still ongoing in a palustrine-type environment (Fig. 3C) strongly characterized by colluvial contributions.

GEOPHYSICS

Electrical resistivity tomography measurements were carried out at the Masseria Forte di Morello sinkhole using a computer-controlled system. Forty-eight electrodes were laid out along a 235 m straight line at 5 m intervals. Each electrode location was surveyed using a Nikon DTM-720 total station and prism in order to include surface topography in the inversion process. The ERT was acquired in a rural setting, ensuring a generally good quality of measurements.

The dipole-dipole ERT was inverted using the method proposed by Oldenburg and Li (1999). A uniform half-space was chosen as the background reference model, and subsequent inversions were made with different values for its resistivity, ranging between 10 Ωm and 10000 Ωm. This procedure allows the depth of investigation (called the DOI index) to be evaluated. In practice, the DOI index, which ranges between 0 and 1, quantifies the change between the models obtained by the different background resistivities. DOI values not exceeding 0.1 for reference resistivities differing by two orders of magnitude indicate that the resulting model is well constrained by the data in that area.

The resulting 2D resistivity model (normalized RMS = 2.1) in the well-constrained area is shown in Figure 5A and has several important features. The higher resistivities (> 1000 Ωm; Fig. 5A) identified the calcarenitic rocks outcropping at both sides of the section (Figs. 3A, 5B). Note the apparent breaches in the bedrock indicated by finger-like projections of lower-resistivity materials into the carbonate rocks (Fig. 5A). An anomalous conductive zone

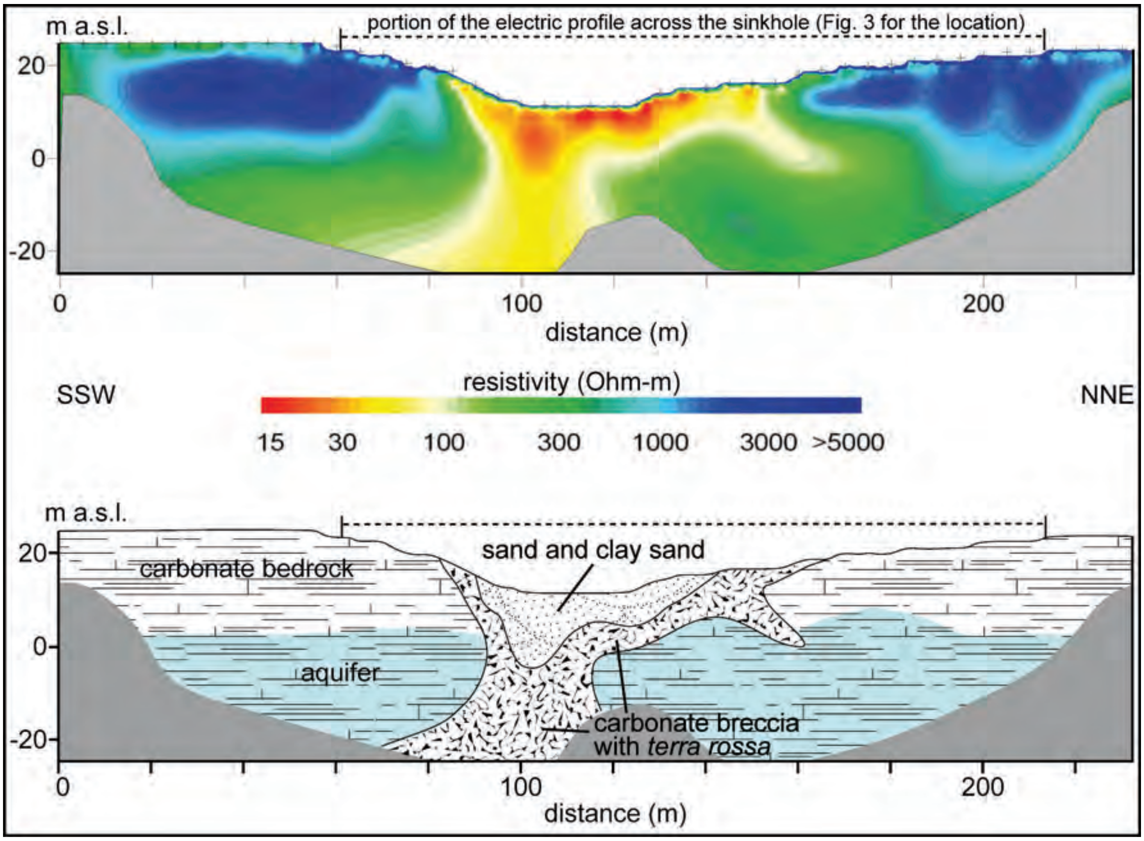

Figure 5. Top: Recovered resistivity model across the sinkhole. Bottom: Geological interpretation of the resistivity model.

is observed sloping toward the south-southwest in the resistivity model, where we can hypothesize penetration of low-resistivity materials into the calcarenites, potentially indicating dissolution features that have been filled by sediments or areas with extensive weathering of the carbonate rocks (e.g., along fractured volumes; Fig. 5A). A second anomalous conductive area is located on north-northeastern half of the resistivity model, but it is shallower (Fig. 5A). Elsewhere, downward from and starting slightly above the 0 m elevation, we recognized an abrupt resistivity lowering (Fig. 5A), which is in agreement with the presence of the aquifer within the carbonate bedrock (Tulipano and Fidelibus, 2002).

The lowest resistivity values (3 to 100 Ωm) are located in the central part of the section in the sinkhole (Fig. 5A). Here, resistivity values between 3 and 30 Ωm are consistent with the siliciclastic continental sands and clay sands (Figs. 3A, 5B), whose depths reach the elevation of about −5 m (Fig. 5B). In agreement with the geological map of Figure 3A, these sediments occupy the uppermost part of a funnel-shaped zone, above resistivity values between 30 and 100 Ωm that are associated with the presence of carbonate breccia with terra rossa to the elevation of about 20 m (Figs. 5A and B). In addition, a belt of fractured carbonate rocks is responsible of the abrupt lateral resistivity lowering recorded in the bedrock near the funnel-shaped body (Fig. 5A).

HISTORICAL DATA ANALYSIS

For this study, a multi-year analysis was performed to gain insights about the evolution of the Masseria Forte di Morello sinkhole over the last 55 years. Five couplets of aerial photographs, three historical topographic maps, ancient cadastre maps, and different sets of orthophotos were used; details of the sources are listed in Table 1. The analysis was associated with periodic field surveys over the last four years.

The sinkhole area is shown in the 1955 air photos (Fig. 6A) as a topographically depressed area bounded on all sides by alignments of limestone rocks. An overall rectangular shape, clearly produced by human activity, characterizes the area. This indicates that the sinkhole, or at least a depression produced by karst processes, was already present in 1955.

The same shape is recognizable on the 1:25,000 topographic maps produced by the Italian Geographic Army Institute in 1952. Blocks are aligned following the first morphological scarp in the landscape, and the lineations are well visible along the southwest-northeast and northeast-southwest, the joint directions. Toward the west, the morphology is less steep than on the other sides. The bottom of the depressed area is flat and regular, with a sub-circular plan.

Surprisingly, the area was considered for building purposes in the late 1960s, and 1 m high walls in calcarenite rocks were placed at the site to delimit a construction zone. The walls partially cover the limestone rock alignments visible in the 1955 air photos. These walls are also visible in the 1972 air photos (Fig. 6B). In 1972 there was no evidence of sinkhole reactivation.

In 1987 (Fig. 6C), the circular depression was again recognizable in the landscape without any particular deformation, but the calcarenite walls, even though not completely disrupted, showed the first signs of irregularity, probably related to deformations in the soil at the NE side of the sinkhole.

The situation strongly changed after 1987. Between July 1987 and late spring or summer 1994 (Figure 6D), the northern sector of the sinkhole collapsed, affecting a significant portion of the walls. The newly-formed sinkhole was encompassed within the boundary of the original depression and showed sub-vertical walls. The shape was circular, a few meters deeper than the surrounding landscape, and bounded at the south-southeastern edge by the spur that would become in the following years the testimony within the sinkhole.

A further collapse occurred between July 1996 (Fig. 6E) and 2000 (Fig. 6F). It affected the southern sector in the original depression, creating an 8-shaped sinkhole that is slightly aligned along a north-south strike. The aforementioned spur separated the areas involved in the two collapses.

Eventually, another event occurred between May 2003 (Fig. 6G) and August 2006 (Fig. 6H), again in the southern sector, thus producing a landform aligned east-west. In the same 2006 orthophotos, at least three other depressions can be recognized not far from the Masseria Forte di Morello sinkhole, disrupting once again the man-made calcarenite walls.

DISCUSSION AND CONCLUSIONS

The present research on the Masseria Forte di Morello sinkhole allowed us to reconstruct the history at the site. We identified five distinct phases of evolution, three of them recent activity over the last twenty years.

Genesis of the sinkhole began with a phase affecting the Miocene and Plio-Pleistocene carbonate bedrock. The collapse produced the carbonate breccia with terra rossa (Figs. 3 and 4D and C) and the funnel-shaped body (Fig. 5). The geological setting likely controlled the sinkhole formation, as shown by the agreement between the limits of the northern sector of the depressed area (Fig. 3A) and the strike of the tectonic joints surveyed in the outcrop of the carbonate bedrock (Figs. 4A to C). The morphological evidence of this first stage is given by the scarp rim I, as shown in Figures 3A and 3B.

The second phase produced a depression in the upper part of the funnel-shaped body (Fig. 5) which was later filled by sand and clay sand deposits (Figs. 3A and C, 4F and G). The depression created scarp rim II (Figs. 3A

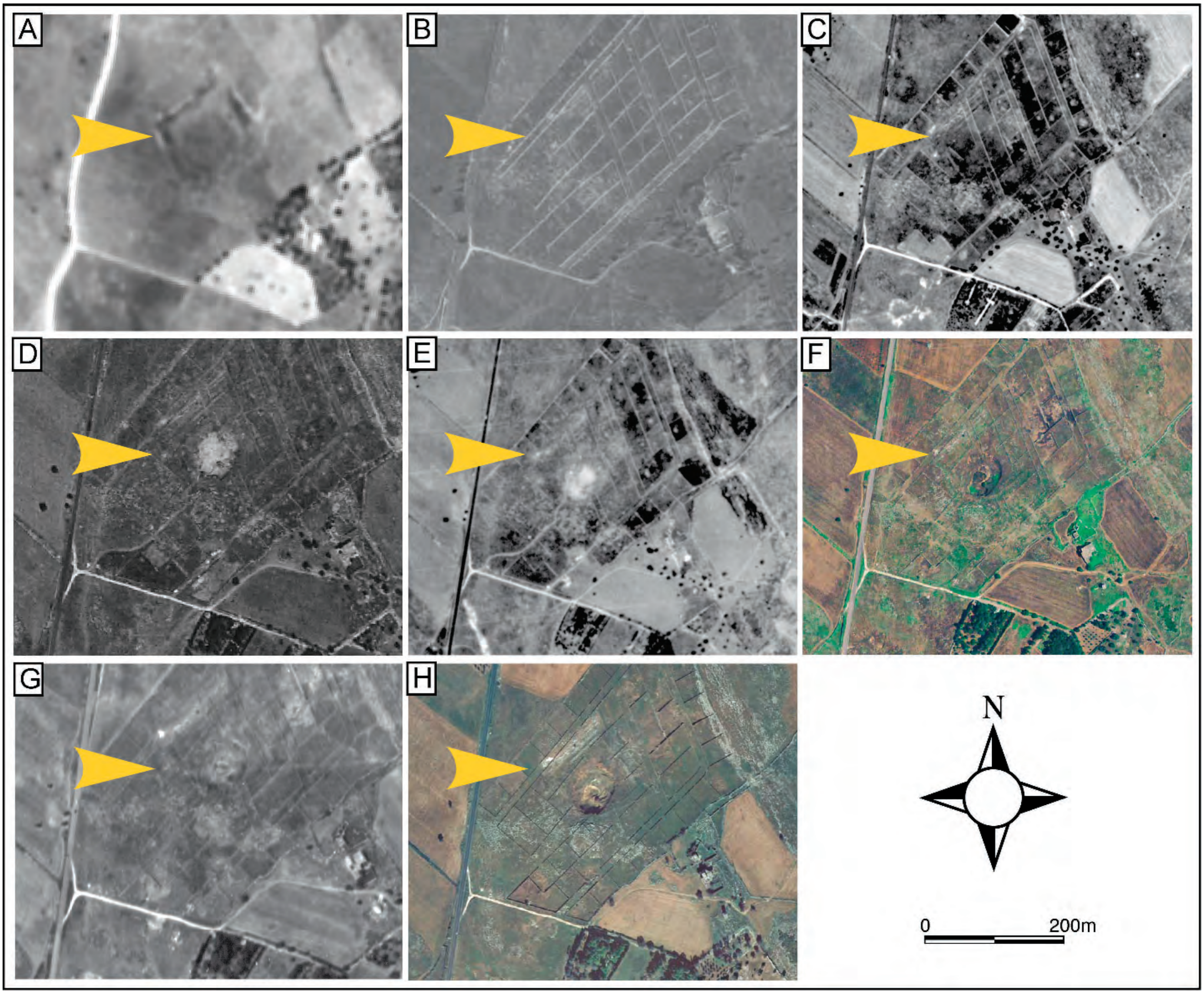

Figure 6. Historical analysis of the Masseria Forte di Morello sinkhole, performed by means of aerial photos and orthophotos. A: 1955 air photo. B: 1972 air photo. C: 1987 air photo. D: 1994 orthophoto. E: 1996 air photo. F: 2000 orthophoto. G: 2003 air photo. H: 2006 orthophoto. Details of the sources are listed in Table 1.

and C) that was likely recognizable in the early twentieth century and is seen on the 1955 topographic map. Since 1955, three re-activation events occurred over the last twenty years, as indicated by aerial photographs and orthophotos (Fig. 6). These events were responsible of the formation of the lowermost scarp rim III (Figs. 3A and C).

The first of these three events, that is, the third in the overall sequence, occurred between 1987 and 1994, with the formation of a circular sinkhole in the northern part of the depression. In the time span 1996 to 2000, another collapse affected the southern sector and created a depression that reached the same depth as in the northern sector to produce an 8-shaped sinkhole. Since 2003, the final phase in the evolution of the Masseria Forte di Morello sinkhole occurred. A collapse in the southern sector formed an elliptical sinkhole with major axis along the east-west strike. Eventually, minor failures along the margins of the sinkhole produced the present shape.

Overall, if the centroids of maximum depth of the three most recent phases are considered (Fig. 7), a migration toward the south-southeast can be observed. The low-resistivity vertical feature in Figure 5 strongly suggests that the greatest potential for further collapse may lie within the southern portion of the depression.

The different phases of evolution identified for the Masseria Forte di Morello sinkhole, with particular regard to those occurred in the last several decades, point out the importance of studying this type of natural phenomena using multiple methods. Until the 1980s, the area was not considered susceptible to any hazard, even though the

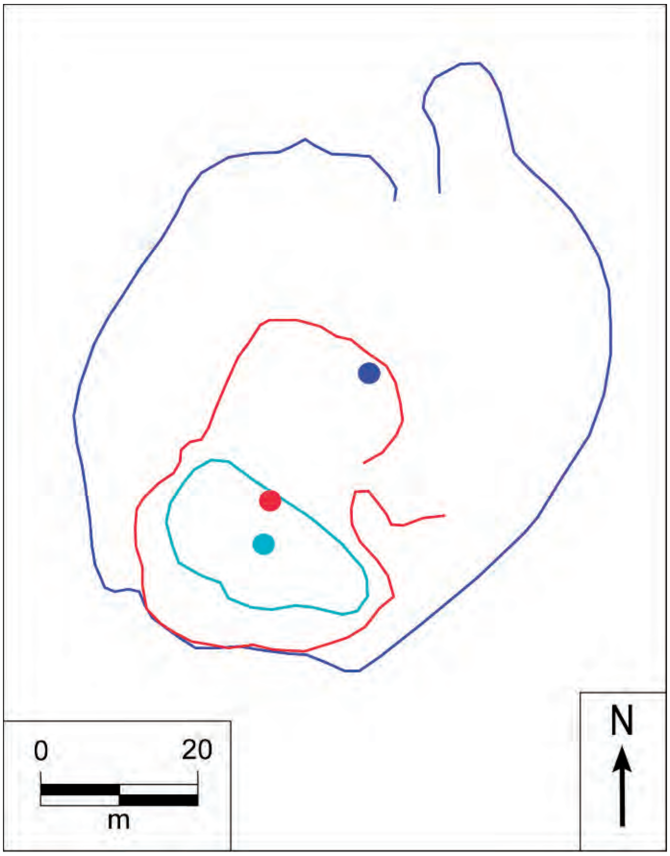

Figure 7. Map showing the centers of the three most recent events of evolution of the Masseria Forte di Morello sinkhole (dark blue, between 1987 and 1994; red, between 1996 and 2000; pale blue, between 2003 and 2006).

depressed area would have brought an expert karst scientist to warn about the site, and a plan for construction at the site was produced. The subsequent evolution, with multiphase re-activation of the sinkhole, clearly shows the danger and the dramatic ways karst landscapes can change. If any buildings had been built, they would have suffered serious damage.

Salento has a great number of sinkholes and depressed areas that are considered very old, inactive karst features. Nevertheless, the case here indicates that it is necessary to perform detailed, site-specific analyses before considering areas inactive and devoid of hazard risk. In particular, the link between the presence of sinkholes and tectonic discontinuities should be properly investigated. Any program devoted to mitigating the sinkhole risk in Salento should therefore start from a careful study aimed at identifying the genesis of the sinkhole and the likely factors that might cause its re-activation.

ACKNOWLEDGMENTS

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KARST AQUIFER DRAINING DURING DRY PERIODS

Francesco Fiorillo[1], Paolo Revellino[1], and Gerardo Ventafridda[2]

Abstract: We analyzed hydrographs of five karst springs in southern Italy during the recession period using ten continuous years of daily discharge measurements and provided conclusions on the aquifer behavior under dry periods and droughts. A straight line was fitted to a semilogarithmic plot (log-discharge versus time), and the recession coefficient (the slope of the line generated from the equation) was calculated for each spring and for each year considered. A deviation from the straight line produced by a simple exponential decay of discharge through time provides information on the actual emptying rate of the aquifer compared to a simple exponential decline. If the recession coefficient decreases or increases, the aquifer is empting more slowly or more quickly than expected, respectively. Water level of a monitored well inside the karst catchment was also assessed and provided information on the water distribution into aquifers. The results describe the hydraulic behavior of karst aquifers during their emptying and provide information for better management of karst springs.

Introduction

Karst aquifers have a fundamental importance for water supply, and large springs are often exploited for commercial and public water supplies (White, 1988; Bakalowicz, 2005; Ford and William, 2007; Goldscheider and Drew, 2007). Spring-discharge data are often used to describe the hydraulic behavior of karst aquifers, especially when other hydrogeological data are missing; in particular, the analysis of spring hydrographs provides information on water storage and the distribution of discharge through time.

The shape of spring hydrographs is controlled by the hydrogeological setting of the catchment area and climate characteristics. Criss and Winston (2003) proposed a simple analytical model to simulate the entire spring hydrograph of small basins and karst springs. During the period of no recharge, spring discharge decreases until the following recharge event. In particular, during the dry season spring hydrographs show a continuous decreasing trend that is know as a recession limb; the nearly flat part at the end of the recession limb is known as baseflow. The traditional approach of recession limb analysis is carried out by using the Maillet formula:

$$Q(t) = Q_0\, e^{-\alpha(t-t_0)}, \qquad (1)$$

where Q_0 is the spring discharge at the beginning of the recession ($t = t_0$), and α is the recession coefficient with dimension $[T^{-1}]$. The recession coefficient is found by plotting the data in a semilogarithmic plot; Equation (1) appears as a straight line with a constant slope independent of the initial Q_0 value (Fig. 1a). Equation (1) is that of a linear reservoir without recharge, where the discharge is proportional at any time to the water volume stored.

Real examples of the recession limb of karst spring hydrographs in the semilogarithmic plot have shown a variation in the angle of the straight line; this indicates the presence of more than one recession coefficient during the entire recession period (Forkasiewicz and Paloc, 1967; Milanovic, 1976; Atkinson, 1977).

An important purpose of karst water management is to assess the behavior of springs under drought conditions that induce a continuous decrease of the discharge, thereby extending the recession limb and providing additional, different recession-coefficient values. A recent editorial (Goldscheider and Ravbar, 2010) highlights the importance of climate change and droughts in future karst hydrogeology research.

Figure 1b shows three main different shapes of the recession limb: Curve 1 shows a simple exponential decrease (Equation (1)), and curves 2 and 3 are characterized by decreasing or increasing recession coefficients during the emptying process. Curve 2 indicates that the discharge decreases more slowly than the simple exponential decay; this behavior of a spring and aquifer system produces the most reliable water supply and is preferable during long dry periods, especially in the Mediterranean area, which is characterized by long and hot dry seasons. Curve 3 indicates that discharge decreases faster than simple exponential decay; this behavior of a spring and aquifer system can cause discharge to fall too quickly during the dry season or under drought conditions, and provides difficult conditions for water management.

Fiorillo (2011) provides a hydrogeological model explaining the behavior of the karst aquifer during emptying and also discusses other models that predict the shape of the spring hydrograph in the semilogarithmic plot, such as those of Forkasiewicz and Paloc (1967), Mangin (1975), Kovacs et al. (2005), and Kovács and Perrochet (2008).

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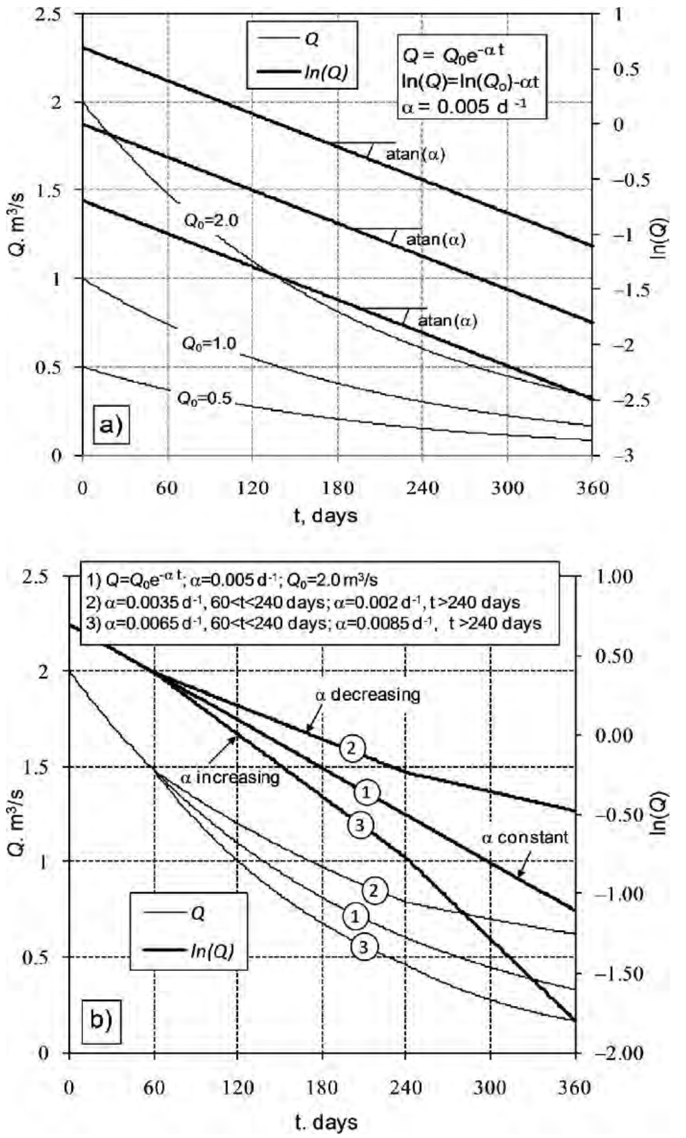

Figure 1. Arithmetic and logarithmic plots of: a) exponential function of Maillet for different initial values of Q_0; b) constant (curve 1) and non-constant (curve 2 and 3) recession coefficient value α during emptying.

On the basis of Fiorillo's model (2011), we analyze daily discharge measurements of karst springs located in Campania, southern Italy: the Caposele springs and the Cassano Irpino springs, plus two individual springs in the Cassano group. We also discuss the monitoring of a well inside the karst catchment that allowed us to check Fiorillo's (2011) model.

HYDROGEOLOGICAL AND HYDROLOGICAL CHARACTERISTICS

The Picentini Mountains constitute a large 600 km² karst system in the Campania region of southern Italy (Fig. 2). In the northeastern sector, over 70% of the catchment lies above 1,000 m a.s.l., up to the top of Mt. Cervialto (1,809 m a.s.l.). In the northwestern sector, 30% of the catchment lies above 1,000 m a.s.l., with the highest point being the top of Mt. Terminio (1,806 m a.s.l.).

Wide areas of closed depressions, such as the Piana del Dragone and Lago Laceno, located inside the Terminio and Cervialto massifs, respectively, favor the infiltration processes.

Outcropping rocks in the area primarily belong to calcareous and calcareous-dolomitic series of the Late Triassic through the Miocene; they are 2,500 m thick, heavily fractured and faulted, and frequently reduced to breccias. The slopes are generally mantled by pyroclastic deposits of Somma-Vesuvius activity, which play an important role in the infiltration of water into the karst substratum below. The calcareous-dolomite series are tectonically bounded by terrigenous and impermeable deposits comprising complex argillaceous (Paleocene) and flysch sequences (Miocene). Further details of geological features of the Southern Apennine can be found in the Geological Map of Italy (1:50,000 scale; ISPRA, 2009).

The region is located in an area with a typical Mediterranean climate characterized by dry, warm summers and a wet period that occurs during autumn, winter, and spring. The monthly rainfall reaches a maximum during November and a minimum in July (Fig. 3). The pattern of potential evapotranspiration, computed using the method described by Thornthwaite (1948), was found to be almost completely opposite to that of rainfall, reaching a maximum in July and a minimum in December–February.

The large springs of the Picentini Mountains belong to three main groups, known as the Serino, Cassano Irpino, and Caposele springs (Fig. 2c). Minor springs are located along the northern boundary of the Mt. Tuoro, in the northern sector of the Terminio massif.

In this study we focus the analysis on the Cassano Irpino and Caposele groups that feed the Acquedotto Pugliese S.p.A., the main aqueduct system in Italy. It supplies water to the Puglia region through a gravity channel about 400 km long. The Caposele group is formed by Sanità Spring (417 m a.s.l.) and several minor springs, all located at the head of the Sele River basin along the northeastern boundary of the Picentini Mountains. The Sanità Spring is fed by the Cervialto karst massif (Celico and Civita, 1976), has a mean annual discharge of 3.96 $m^3\ s^{-1}$ (period 1920–2009), and was tapped in 1920. The Cassano group is located in the Calore River basin along the northern boundary of the Picentini Mountains and consists of the Bagno della Regina, Peschiera, Pollentina, and Prete springs (473 to 476 m a.s.l.). These springs are primarily fed by the Terminio-Tuoro (Coppola et al., 1989) massif and have an overall mean annual discharge of 2.65 $m^3\ s^{-1}$ (period 1965–2009). The Peschiera and Prete spring discharges oscillate slightly during the year, whereas the Pollentina and Bagno della Regina discharges strongly reflect the rainfall regime.

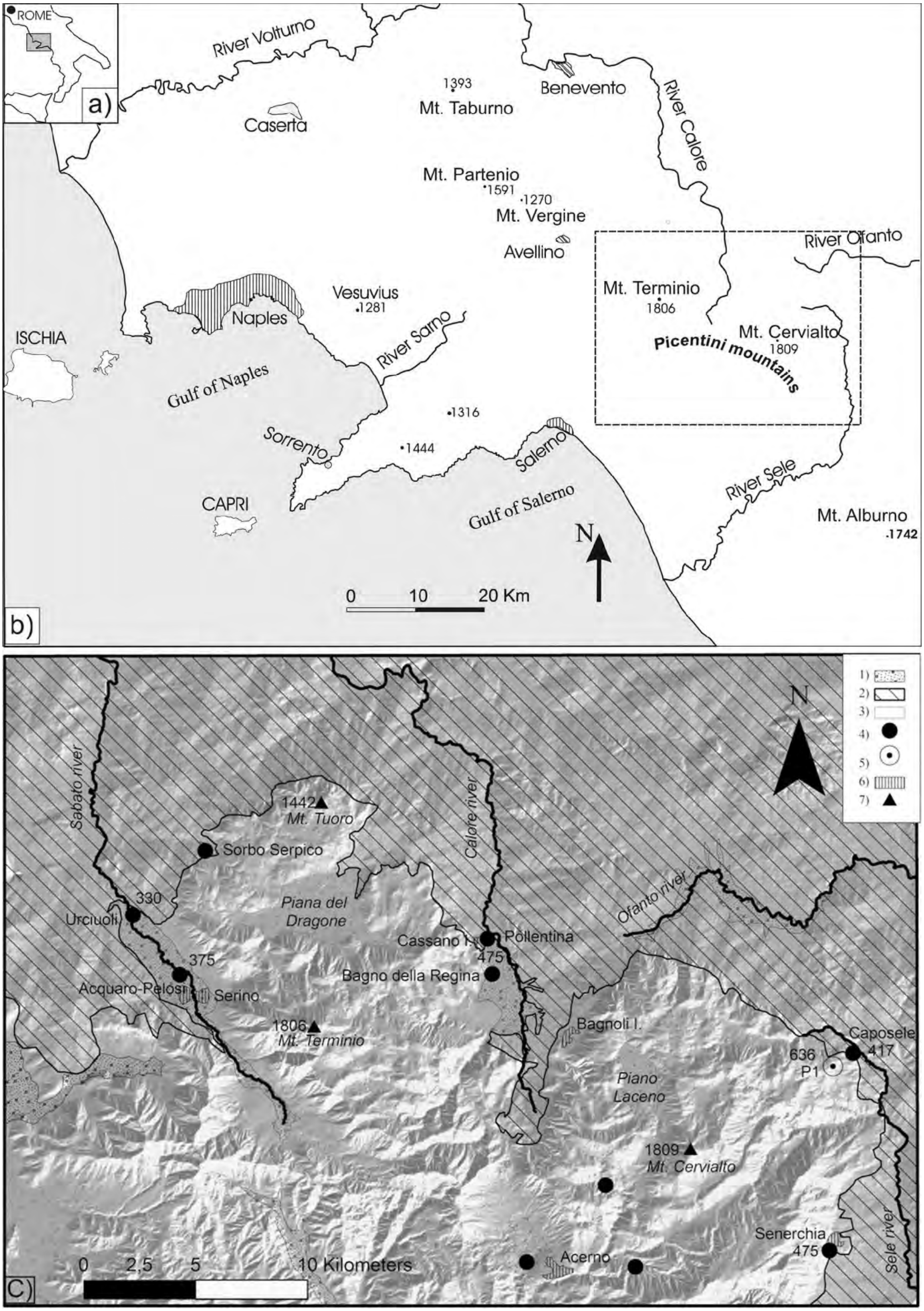

Figure 2. a) Southern Italian peninsula. b) Map of the western Campania region. c) Hydrogeological features of the northern Picentini Mountains outlined in part b. Key: 1) slope breccias and debris, pyroclastic, alluvial, and lacustrine deposits (Quaternary); 2) argillaceous complex and flysch sequences (Paleogene-Miocene); 3) calcareous-dolomite series (Mesozoic); 4) major spring; 5) P1 well; 6) village; 7) mountain peak.

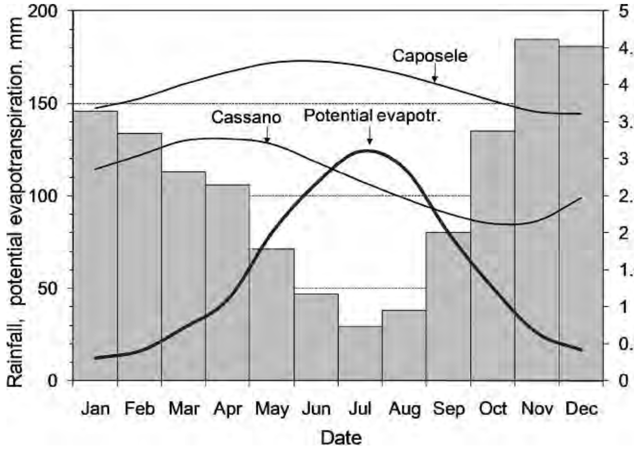

Figure 3. The bars show the mean monthly rainfall and a curve shows the potential evapotranspiration, averages of stations at the Serino (351 m a.s.l.), Cassano (450 m a.s.l.), and Caposele (430 m a.s.l.) springs. Additional curves show the mean discharges of the Caposele and Cassano. Data period is 1921–2006, except Cassano spring discharge, 1966–2006 (modified from Fiorillo, 2009).

The daily spring discharge data cover a 10-year period (January 1, 2000 through December 31, 2009) (Fig. 4). During this period, hydrographs of the wet years are characterized by well-pronounced floods during the spring season, as occurred in 2000, 2006, and 2009, whereas hydrographs of dry years are characterized by slight floods or a continuously decreasing discharge trend during the hydrological year (Fiorillo, 2009). In particular, 2001/02 was one of the most intense hydrological droughts that occurred in southern Italy (Fiorillo and Guadagno, 2010) and caused the historical minimum discharge in many karst springs. After the dry years of 2006/07 and 2007/08, the annual rainfall of the 2008/09 was one of the highest of the historical series, and increased the spring discharges much more than the mean.

Recharge regularly occurs during the autumn-winter season and causes the maximum spring discharge during the spring; during the spring-summer season, due to the high rate of evapotranspiration, recharge can be considered null (Fiorillo et al., 2007; Fiorillo, 2009). Single rain events (daily rainfall) have no direct influence on the spring discharge, and spring hydrographs are characterized by little or no prompt flow, due to a poor development or connection of the karst conduits (Fiorillo 2009). The spring discharge depends on the long term cumulative rainfall; in particular, Fiorillo and Doglioni (2010) analyzed the relation between rainfall and spring discharge by cross-correlation analyses and found that Caposele springs' discharge is shifted up to several months with respect to rainfall and depends mainly on the rainfall accumulated over the preceding 270 days.

Analysis of the Aquifer Draining

Spring discharge data were analyzed to focus on the summer to early-autumn period, during which time a continuous decreasing discharge trend is generally observed and the recharge processes can be considered negligible. During this period, spring hydrographs present a concave shape that follow the previous convex shape connected to the peak or flood earlier in the year.

To evaluate the recession coefficient of the springs, daily discharge data of each hydrological year were plotted in a semilogarithmic graph. Figure 5 shows the case of the Caposele springs, where the plotted period starts generally on September 1 and ends October 31 (61 days); only 2002 starts on April 6 and ends on June 6, because nolinear correlation has been found for the period September 1 to October 31. Table 1 shows the results of all springs. For all the Cassano Irpino group of springs and its individual components Pollentina Spring and the Bagno della Regina spring, the recession coefficients have been computed during the period July 1 to August 31 (62 days). As can be observed from the examples in Figure 5, each plot appears as a straight line, indicating that the aquifer behaves as a linear reservoir without recharge (Equation (1)). However, the

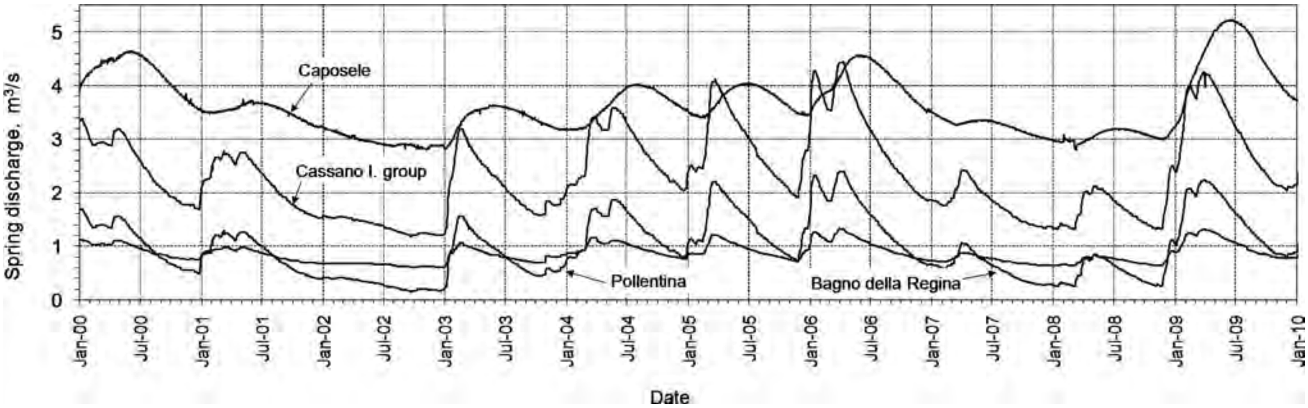

Figure 4. Daily spring discharge data from January 1, 2000, through December 31, 2009. These are totals for the Caposele and Cassano spring groups and individual records for the two major members of the Cassano group.

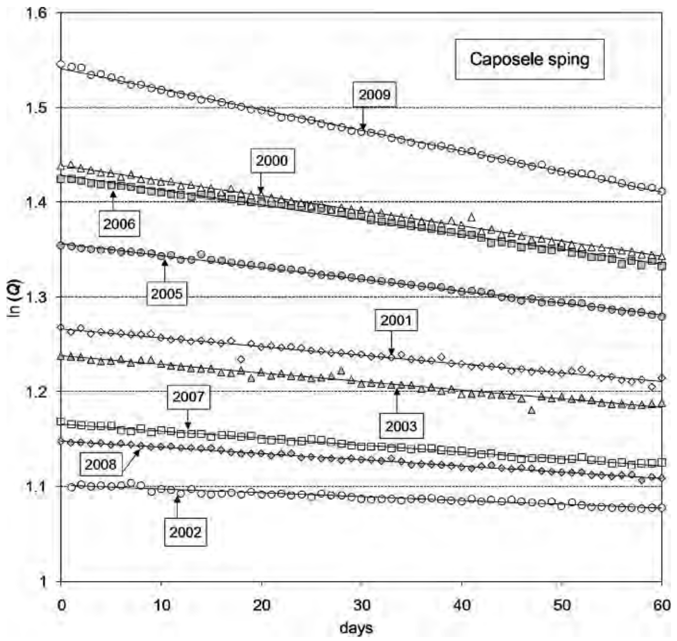

Figure 5. Natural logarithms of the Caposele group daily discharges during linear periods. Day 0 is September 1 for 2000–2009 and April 6 for 2002; no data are shown for 2004.

slope of the linear fit (the recession coefficient) changes from one year to another, indicating a dependence on the initial condition of the aquifer, and in particular, on the spring discharge at the beginning of the draining, Q_0 (Fig. 6). The Caposele group and Pollentina Spring show a linear and positive relationship between α and Q_0 (Figure 6); for these springs the recession coefficient is smaller during droughts and higher after wet years. On the other hand, the Bagno della Regina spring shows a negative relationship between α and Q_0. Over a longer period, the tail of the recession curve for the Caposele and Pollentina springs behaves like curve 2 in Figure 1b, showing a decrease of the recession coefficient during the aquifer emptying. The Bagno della Regina spring is different from the Caposele and Pollentina springs, as it shows the discharge decrease similar to curve 3 of Figure 1b. In all cases, a single recession coefficient value seems unable to explain all the draining processes of the aquifer.

The different behaviors can also be observed by plotting the frequency distribution of the daily data (Fig. 7), where the distributions for Pollentina Spring and the Caposele group cut off abruptly and never reach low values, whereas the Bagno della Regina spring distribution shows the possibility of reaching a null spring discharge under intense drought.

The Bagno della Regina and Pollentina springs are very close together (Fig. 2c) and have similar elevations, and the two smaller springs, Prete and Peschiera, in the Cassano group are located close to Pollentina. This and the other results suggest that all these springs are fed by the same groundwater system and during the draining of the aquifer, interference among these springs occurs, so the analyses should be conducted considering the sum of the discharge of all four springs, as the Cassano spring group, in Figures 2 and 6 and Table 1. In addition, the same groundwater system feeds other karst springs located along the northern (Sorbo Serpico springs) and western (Serino springs) boundary of the Terminio-Tuoro massif (Fig. 2c), indicating further interferences during the draining of the aquifer.

The Caposele springs are the only major springs draining the wide catchment of Mt. Cervialto. The minor springs in the basin drain only a few liters per second. Therefore, during the draining of the aquifer, a constant water table area can be considered for the Caposele springs, which helps to explain the simple variation of the recession coefficient during the draining of different years. A useful water level dataset comes from a well located at 635.54 m a.s.l. inside the catchment of the Caposele group (P1, Fig. 2c). The available data are shown in Figure 8a, for the dry year of 2008 and the wet year of 2009, which are characterized by very different initial conditions of Q_0 (Table 1). During October 2009, the decrease in the water level in the P1 well was 0.32 m and the volume discharged by the Caposele springs was 11.3×10^6 m^3 (Figure 8b). During October 2008 the decrease of the water level into well was 0.06 m, and the volume discharged by the Caposele springs was 8.2×10^6 m^3 (Figure 8b). A different behavior can be observed during these two periods: In October 2008 the aquifer discharged a water volume of $V_{w(2008)} = 1.37 \times 10^6$ m^3 for each centimeter of well level lowering, and in October 2009 the water volume discharged was $V_{w(2009)} = 0.35 \times 10^6$ m^3 (Figure 8b). This different hydraulic behavior suggests that the storage conditions increase in depth; in particular, the effective porosity, n_{eff}, has to increase from the high to low water table level, inside the epiphreatic zone. The ratio between these two values could be compared with the ratio of the effective porosity values:

$$\frac{n_{eff(2008)}}{n_{eff(2009)}} \approx \frac{V_{w(2008)}}{V_{w(2009)}} = \frac{1.37 \times 10^6}{0.35 \times 10^6} = 3.91. \qquad (2)$$

This assumes that in the unconfined aquifer the storativity can be approximated by the effective porosity, and its use in the karst aquifer has been discussed by Stevanovic et al. (2010).

During the draining of the karst aquifer, the model of Fiorillo (2011) shows how the variation of the recession coefficient, for example from α^{II} to α^{III}, with $\alpha^{II} > \alpha^{III}$, can be approximated by the change of the effective porosity, from $n_{eff}^{II} \rightarrow n_{eff}^{III}$, with $n_{eff}^{II} < n_{eff}^{III}$, by the following (Fiorillo, 2011):

$$\frac{\alpha^{II}}{\alpha^{III}} \approx \frac{n_{eff}^{III}}{n_{eff}^{II}}, \qquad (3)$$

which is valid only for a constant water table area during the draining. In this case, Equation (3) gives

$$\frac{n_{eff(2008)}}{n_{eff(2009)}} \approx \frac{\alpha_{(2009)}}{\alpha_{(2008)}} = \frac{0.00230}{0.00060} = 3.83. \qquad (4)$$

Table 1. Values deduced from the semilogarithmic plots during linear periods for the Caposele and Cassano spring groups and two component springs of the Cassano group.

Spring	Year	α, d^{-1}	R^2	ln (Q_0)	Q_0, m^3 s^{-1}	$t_{1/2}$, y
Caposele						
	2000	0.0016	0.995	1.438	4.21	1.19
	2001	0.0009	0.971	1.266	3.55	2.11
	2002	0.0004	0.984	1.101	3.01	4.75
	2003	0.0009	0.967	1.237	3.45	2.11
	2004	0.0012	0.989	1.358	3.89	1.58
	2005	0.0013	0.996	1.357	3.88	1.46
	2006	0.0016	0.989	1.429	4.17	1.19
	2007	0.0007	0.987	1.162	3.2	2.71
	2008	0.0006	0.988	1.165	3.21	3.17
	2009	0.0023	0.997	1.540	4.66	0.83
Bagno della Regina						
	2000	0.0057	0.997	0.466	1.59	0.33
	2001	0.0058	0.996	0.163	1.18	0.33
	2002	0.0062	0.987	−1.145	0.32	0.31
	2003	0.0063	0.997	0.035	1.04	0.3
	2004	0.0044	0.997	0.633	1.88	0.43
	2005	0.0051	0.991	0.539	1.71	0.37
	2006	0.0050	0.997	0.609	1.84	0.38
	2007	0.0061	0.988	0.255	1.29	0.31
	2008	0.0065	0.996	0.254	1.29	0.29
	2009	0.0050	0.997	0.624	1.87	0.38
Pollentina						
	2000	0.0021	0.978	0.018	1.02	0.90
	2001	0.0020	0.994	0.078	1.08	0.95
	2002	0.0008	0.885	−0.407	0.67	2.37
	2003	0.0016	0.979	−0.191	0.83	1.19
	2004	0.0022	0.995	0.109	1.12	0.86
	2005	0.0021	0.987	0.008	1.01	0.90
	2006	0.0024	0.994	0.117	1.12	0.79
	2007	0.0015	0.992	−0.235	0.79	1.27
	2008	0.0016	0.995	−0.222	0.80	1.19
	2009	0.0029	0.982	0.134	1.14	0.65
Cassano I. Group						
	2000	0.0034	0.995	1.047	2.849	0.56
	2001	0.0030	0.998	0.946	2.575	0.63
	2002	0.0016	0.934	0.357	1.428	1.19
	2003	0.0031	0.996	0.826	2.284	0.61
	2004	0.0031	0.997	1.281	3.60	0.61
	2005	0.0033	0.993	1.190	3.287	0.57
	2006	0.0034	0.999	1.253	3.50	0.56
	2007	0.0027	0.997	0.700	2.014	0.70
	2008	0.0029	0.997	0.701	2.015	0.65
	2009	0.0036	0.998	1.275	3.579	0.53

α=recession coefficient; R^2=coefficient of determination; Q_0=spring discharge at time t=0; and $t_{1/2}$=half-time of the spring discharge.

Equations (2) and (4) calculate the effective porosity ratio by different approaches, but indicate that the two values are very close, verifying that Equation (3) is well founded.

Discussion and Conclusions

Based on the shape of the spring hydrograph during the recession period and, in particular, on the value of the

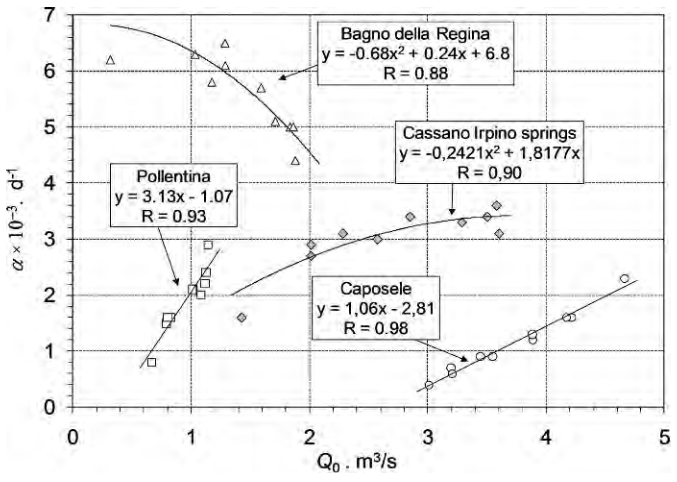

Figure 6. Relation between the recession coefficient α and spring discharge at the beginning of the draining Q_0 for the years 2000–2009 (Table 1). The Bagno della Regina spring and Rollentina Spring are components of the Cassano Irpino group.

recession coefficient, the hydraulic behavior of the aquifer can be outlined during dry periods and droughts.

If spring discharge decreases following the exponential decay (linear reservoir) model, a single value of the recession coefficient α is able to explain the entire draining of the aquifer. This condition appears to be rare in nature, especially under drought conditions, which provide the possibility to investigate the lowest part of the recession limb of spring hydrographs. Under such conditions, hydrographs tend to be as curve 2 or 3 of Figure 1b, indicating non-constant α during the emptying. Many karst springs show a typical variation of the recession coefficient during aquifer draining, especially if several continuous years are considered, including droughts. Fiorillo (2011) has explained that the variation in the recession coefficient is due to non-constant geometric or hydraulic characteristics during the emptying process. In particular, the recession coefficient appears to be strongly controlled by the product of the effective porosity along the water table

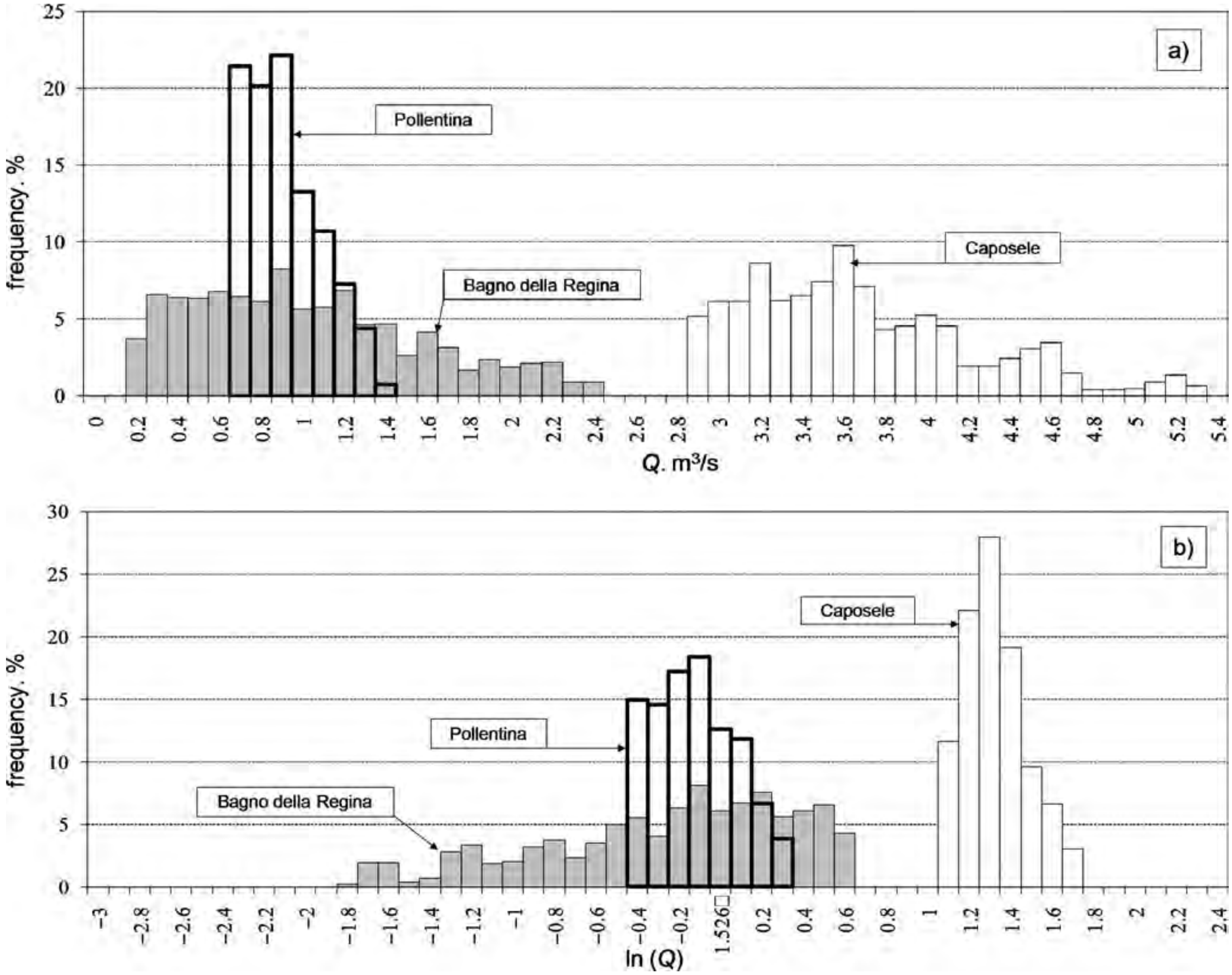

Figure 7. Spring discharge frequency distributions for the Caposele and the two major springs in the Cassano group, period January 1, 2000, through December 31, 2009: a) normal plot, b) logarithm plot.

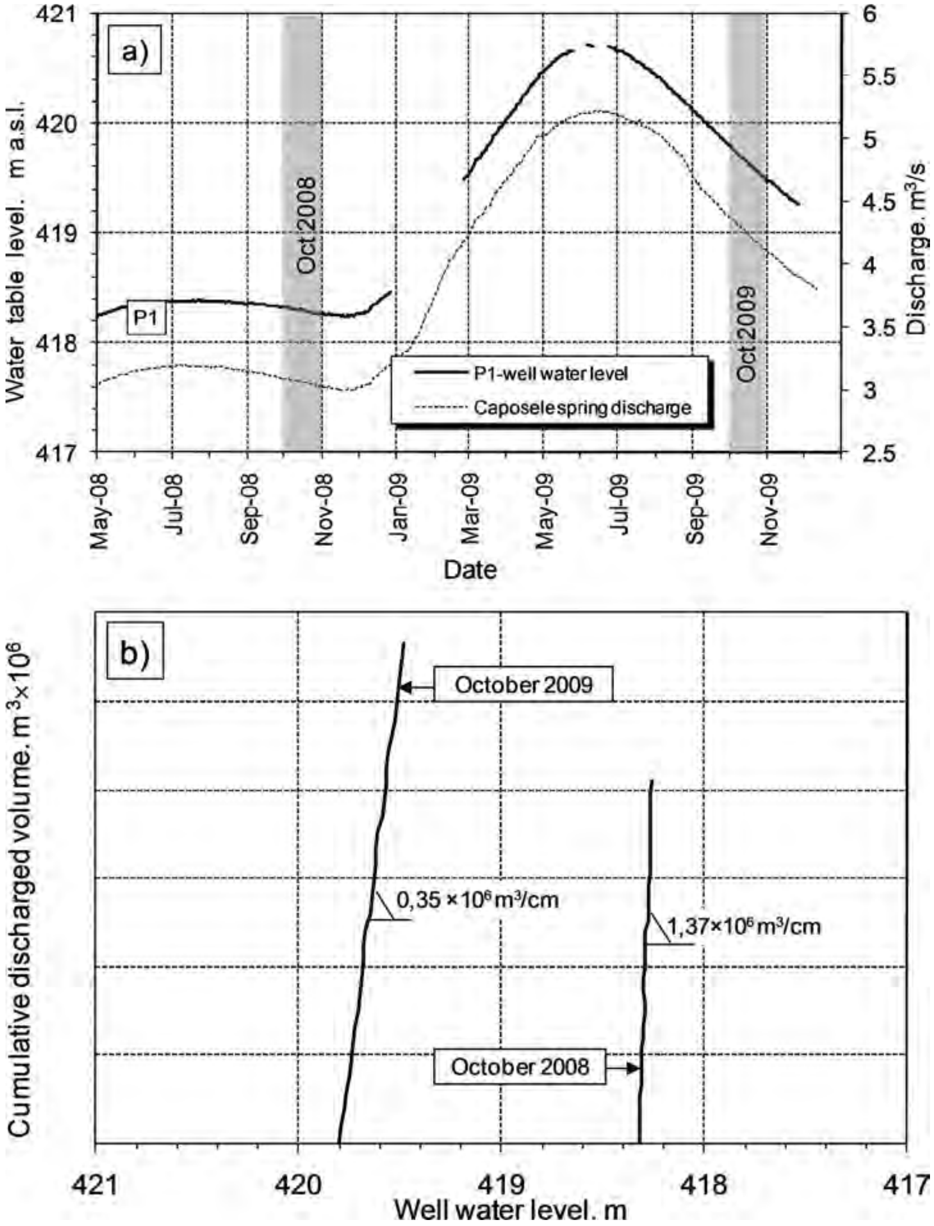

Figure 8. a) Caposele spring discharge and water level monitored in well P1, May 1, 2008, through November 30, 2009. b) Total discharged water volume in relation to the level in the well P1, during the periods October 2008 and October 2009, based on the data in part a. (Note that the horizontal axis is reversed.) The calculated water volume per centimeter of lowering is shown.

and the area occupied by the water table. This product has been called the discharge area, because it expresses the area of the aquifer filled by free-flowing water along the water table. Both parameters can vary during the emptying process, and they control the shape of the hydrograph on the semilogarithmic plot (Fiorillo, 2011).

A hydrograph as in curve 3 of Fig. 1b occurs when the area occupied by the water table decreases during draining, causing a reduction in the discharge area. This reduction can occur when the water table is drained by other springs at lower elevations, as occurs for the Bagno della Regina, or due to the hydrogeological setting of the catchment (see Fig. 8 in Fiorillo, 2011). The reduction of the discharge area can lead to no spring discharge during a dry period, and it characterizes the springs as drought-vulnerable. Hydrographs as in curve 2 of Fig. 1b occur when the effective porosity increases in depth inside the epiphreatic zone, causing an increase in the discharge area (see Fig. 5 in Fiorillo, 2011), as found by Equation (2) for the Caposele aquifer. These springs generally guarantee water during the long dry period in the Mediterranean areas and can be considered drought-resistant. For these springs, an increase in the water table area during the draining, given constant effective porosity, would also produce a similar effect, but it appears less likely, from a geometrical point of view, to justify an increase in the discharge area of about four times for Caposele Spring (Equations (2) and (4)). For this spring, the water level data of the P1 well have allowed us to investigate the hydraulic behavior of the aquifer during draining. It has been found that the ratio of the effective porosity evaluated by Equation (2) is very similar to that of Equation (4), verifying the hypothesis of Fiorillo's (2011) model.

These results indicate that a change in the effective porosity inside the epiphreatic zone has to be connected to different developments of caves, conduits, and voids that favor increasing water storage from a high to low water table. Numerical models have shown how mixing corrosion causes the development of conduits and porosity just below the water table of an unconfined aquifer (Gabrovšek and Dreybrodt, 2010; Dreybrodt et al., 2010). As a consequence, just below the water table there is a strong variation in void distribution (Fiorillo, 2011) that can be observed by the shape of curve 2 in Figure 1b. These hydraulic characteristics probably are more common in basal springs, where a saturated karst aquifer extends well below the spring elevation and the water table area remains constant during the emptying. In the case of aquifer behavior as curve 3 of Figure 1b, a change in the effective porosity inside the epiphreatic zone cannot be ascertained.

Our data and analyses suggest that the common and diffuse computation of the water stored into an karst aquifer obtained by integrating Equation (1), the Maillet equation, over the time interval t_0 to infinity, should be used with caution in the evaluation of the water resources, as no-homogenous hydraulic and geometric conditions may occur during the draining of an aquifer, especially under drought conditions.

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KARST OF SICILY AND ITS CONSERVATION

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Abstract: In Sicily, karst is well developed and exhibits different types of landscapes due to the wide distribution of soluble rocks in different geological and environmental settings. Karst affects both carbonate rocks, outcropping in the northwest and central sectors of the Apennine chain and in the foreland area, and evaporite rocks, mainly gypsum, that characterize the central and the southern parts of the island. The carbonate and gypsum karsts show a great variety of surface landforms, such as karren, dolines, poljes, blind valleys, and fluvio-karst canyons, as well as cave systems. Karst areas in Sicily represent extraordinary environments for the study of solution forms. In addition, they are of great environmental value because they contain a variety of habitats that hold species of biogeographic significance. Unfortunately, karst areas are increasingly threatened by human activity, mainly in the form of grazing and other agricultural practices, wildfires, quarrying, urbanization, building of rural homes, and infrastructure development. The value of karst features has been recognized by the Sicilian Regional Government since 1981 when it enacted laws to create several nature reserves to preserve the peculiar karst landscapes, including caves. At present, the state of conservation of karst areas in Sicily may be considered to be at an acceptable level, yet numerous issues and difficulties need to be overcome for the effective protection and enhancement of karstlands.

Introduction

Sicily is the largest island in the Mediterranean Sea with an area of 25,468 km^2 and increases to 27,708 km^2 when the minor islands are included. About 10% (2650 km^2) of its total land is contained in four Regional Parks and seventy-six Nature Reserves created by the Sicilian Region Government starting in 1981 to conserve geological or landscape features of particular interest; a further five Marine Nature Reserves, covering an area of some 760 km^2, were established to conserve marine life and geomorphological aspects (Dimarca, 2004).

Parks and nature reserves preserve areas of scientific importance or outstanding environmental and aesthetic value. Some areas are of geological, paleontological, geomorphological, or archaeological interest; other provide refuge for different species of flora and fauna and are often important staging points and wintering grounds for many migratory birds. Many protected areas are designed specifically to conserve karst features; others include karst landscapes (Table 1).

Karst in Sicily is widespread and exhibits a great variety of surface and underground landforms related to the wide distribution of soluble rocks. About 20% (more than 6000 km^2) of the land area consists of carbonates and evaporites, primarily gypsum. Carbonate karst lies mainly in the northwestern and central sectors of the Apennine chain and the foreland area in southeastern Sicily; gypsum karst is chiefly in the central and southern areas of the island, though evaporite landscapes are also present in the northern and western parts of Sicily (Figs. 1 and 8).

The designation of karst landscapes as nature reserves was possible, in part, because of several research studies that highlighted the significance of gypsum and carbonate karst areas.

In addition to the first reports by Marinelli and Gemmellaro dating back to late 1800s and early 1900s (Marinelli, 1896, 1911, 1917; Gemmellaro, 1915), gypsum karst was investigated starting in the 1980s. Distribution of gypsum karst areas of Sicily and their geomorphological and speleogenetic features have been described in several articles (P. Madonia et al., 1983; Agnesi et al., 1986; Mannino, 1986; Agnesi and Macaluso, 1989; Biancone et al., 1994; Agnesi et al., 2003). In the last fifteen years detailed studies were carried out on gypsum karren (Macaluso and Sauro, 1996a, 1996b; Macaluso et al., 2001; G. Madonia and Sauro, 2009), genesis of weathering crust and associated forms (Macaluso and Sauro, 1996b, 1998; Ferrarese et al. 2003), natural and anthropogenic sinkholes (Di Maggio et al., 2010), speleogenesis and evolution of karst systems (Panzica La Manna, 1995; Vattano, 2004, 2008, 2010; Buscaglia et al., 2010; G. Madonia and Vattano, 2011), and the role of speleothems in paleoclimate analysis (Calaforra et al., 2008).

Studies on classic karst are less numerous. Some research was performed on the geomorphological setting of the main carbonate-karst areas (Hugonie, 1979; Ruggieri and Grasso, 2000). Many speleological explorations surveyed more than seven hundred caves (P. Madonia et al., 1983; Mannino, 1986; Biancone, 1994; Ruggieri, 2002; Perotti, 1994). This large amount of information prompted studies on the speleogenetic evolution and the

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Table 1. Natural protected karst areas of Sicily (numbers correspond to those on Fig. 8).

No.	Name of Natural Protected Area	Designation	Karst Heritage	Surface Area, ha	Management
1	Grotta di Carburangeli	INR	Carbonate cave	0.96	Legambiente
2	Grotta Conza	INR	Carbonate cave	12.34	C.A.I.[a]
3	Capo Gallo	ONR-SCI	Carbonate caves	585.83	DRAFD[b]
4	Grotta dei Puntali	INR	Carbonate cave	15.3	G.R.E.[c]
5	Grotta Molara	ONR	Carbonate caves	40.2	G.R.E.[c]
6	Serre della Pizzuta	ONR-SCI	Carbonate caves	414.37	DRAFD[b]
7	Pizzo Cane, Pizzo Trigna e Grotta Mazzamuto	ONR-SCI	Carbonate cave	4641.43	DRAFD[b]
8	Serre di Ciminna	ONR-SCI	Gypsum karst landscape	310.625	Palermo Province Administration
9	Grotta di Santa Ninfa	INR-SCI	Gypsum cave system	139.37	Legambiente
10	Grotta di Entella	INR-SPA-SCI	Gypsum cave	19.8	C.A.I.[a]
11	Monte San Calogero (Monte Kronio)	INR	Hypogenic karst system	52.25	DRAFD[b]
12	Grotta di Sant'Angelo Muxaro	INR	Gypsum cave	2.25	Legambiente
13	Monte Conca	INR-SCI	Gypsum karst system	245	C.A.I.[a]
14	Lago Sfondato	INR	Karst lake	43.7	Legambiente
15	Contrada Scaleri	INR	Gypsum karren field	11.875	Caltanissetta Province Administration
16	Lago di Pergusa	SNR-SPA-SCI	Karst lake	402.5	Enna Province Administration
17	Villasmundo-Alfio system	INR	Carbonate cave system	71.66	Catania university
18	Grotta Palombara	INR	Carbonate cave	11.25	Catania university
19	Grotta Monello	INR	Carbonate cave	59.16	Catania university
20	Complesso Immacolatelle e Micio-Conti	INR-SCI	Volcanic caves	69.9	Catania university
21	Zingaro	ONR-SPA-SCI	Carbonate caves	1600	DRAFD[b]
22	Monte Pellegrino	ONR-SCI	Carbonate caves	1016.87	Rangers d'Italia
23	Madonie Geopark	Regional Park	Karst landscapes and caves	39941	Madonie Park Authority
24	Mount Etna Park	Regional Park	Volcanic caves	58095	Etna Park Authority
25	Lago Preola e Gorghi Tondi	INR-SCI	Karst lakes	335.62	W.W.F.[d]
26	Torre Salsa	ONR-SCI	Gypsum karst landscape	761.62	W.W.F.[d]
27	Lago Soprano	ONR-SCI	Karst lake	59.79	Caltanissetta Province Amininstration
28	Pantalica, Valle dell'Anapo e T. Cavagrande	ONR	Fluvio-karst canyon	3712.07	DRAFD[b]
29	Cavagrande del Cassibile	ONR-SCI	Fluvio-karst canyon	1059.62	DRAFD[b]

[a] Italian Alpine Club.
[b] Regional Forest Department.
[c] Ecological Research Groups.
[d] World Wildlife Fund.
Note: INR=Integral Nature Reserve, ONR=Oriented Nature Reserve, SNR=Special Nature Reserve, SCI=Sites of Community Importance, SPA=Special Protection Areas.

physical deposits in selected caves (Messana, 1994; Aricò and Vattano, 2007; G. Madonia and Vattano, 2010), as well as paleoenvironmental and paleoclimatic reconstructions through speleothem analysis (Frisia et al., 2006). Macaluso et al. (1994) focused their attention on the safeguarding and sustainable use of karst geo-ecosystems.

All these studies highlighted the importance of gypsum and carbonate karst in many areas of Sicily as extraordi-

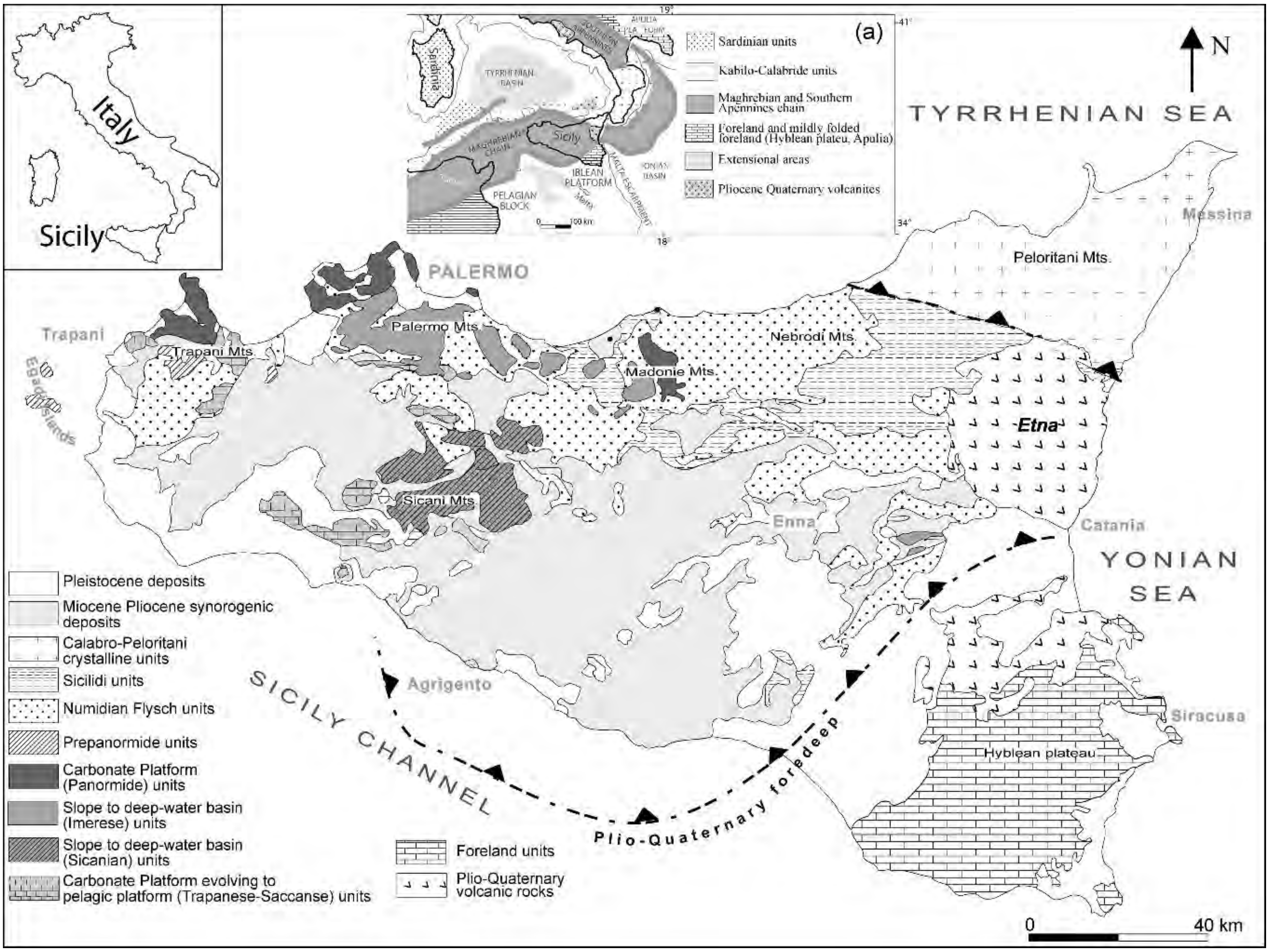

Figure 1. Structural map of Sicily (modified after Catalano et al., 1996, and Avellone et al., 2010). The inset (a) shows the tectonic map of the central Mediterranean area (after Catalano et al., 2000).

nary environments of diverse and peculiar landscapes for the study of solution forms. Nevertheless, these areas are subject to human activity. The main pressures on karst result from grazing and other agricultural practices, wildfires, quarrying, urbanization, building of rural homes, and infrastructure developments such as road and waste dumps. To preserve the peculiar surface landforms and caves, the Sicilian Regional Government designated some karst areas as nature reserves.

The goal of this paper is to illustrate the main features of the karst landscapes in Sicily in different geological and lithological settings and to describe the main conservation measures adopted for their protection.

Geological Setting of Sicily

Sicily is a segment of the Alpine collisional belt along the Africa-Europe plate boundary that links the African Maghrebides to the west and southwest with the Calabria and the Appennines to the east and northeast (Catalano et al., 1996, 2000; Avellone et al., 2010; Fig. 1). The geological setting of Sicily is characterized by three main structural elements: a foreland Hyblean Plateau located in southeastern Sicily, made up of Triassic-Liassic platform and scarp-basin carbonates overlain by Jurassic-Eocene pelagic carbonates and Tertiary open-shelf clastic deposits; a northwest-dipping foredeep located north of the foreland, consisting of Plio-Pleistocene pelagic marly limestones, silty mudstones, and sandy clays overlying Messinian evaporites; and a complex chain composed of several embricate units geometrically arranged in a thrust pile verging toward the east and the southeast, including the Calabro-Peloritani Units, located in northeastern Sicily, formed of Hercynian crystalline units with a Mesozoic terrigenous cover and Plio-Pleistocene clastic and pelagic sediments and the Sicilian Maghrebian Units consisting of Meso-Cenozoic siliceous rocks, basin pelagic turbiditic carbonates, and platform and pelagic carbonates. These units are tectonically overlain by a roof thrust formed of Oligo-Miocene turbiditic successions, or Lower-Middle Miocene glauconitic calcarenites and pelagic mudstones, or Lower-Pleistocene foreland or satellite basin deposits, deformed and detached from the substratum (Catalano et al., 1996, 2000). The Maghrebian Units crop out along the northern Sicily belt in the Madonie, Palermo, and Trapani Mountains and in the western and southwestern sectors of the island. Southern and central Sicily are characterized by the presence of Cretaceous-Lower Pleistocene clastic-terrigenous deposits and Messinian evaporites.

KARST IN CARBONATE ROCKS

Karst in the carbonate rocks of Sicily occurs mainly in the Meso–Cenozoic platform limestones and, subordinately, the Mesozoic slope to basin dolomitic limestones with intercalations of marls and siliceous rocks.

The main and best-developed karst forms are in the northwestern Apennine chain (Trapani, northern Palermo, and eastern Madonie Mountains), where large platform limestone bodies, several hundred meters thick, crop out. To the northeast and south of the chain, karst forms are fewer and less significant, due to less extent and thickness of platform limestones in the Nebrodi, Peloritani, southern Palermo, and northern and southern Sicani Mountains, and to lower solubility of slope to basin dolomitic limestones in the central Trapani, central-southern Palermo, central Sicani, and western Madonie Mountains. In the Hyblean Plateau foreland, deep fluviokarst canyons formed as a consequence of the Quaternary uplift, while horizontal caves are due to the presence of thin horizontal intercalations of limestones between the marl and siliceous levels (Figs. 1 and 8).

Areas marked by thick and extensive platform limestones show a great variety of surface karst forms, ranging from small (karren) to large (dolines, poljes, valleys, and karst planation surfaces), as well as cave systems.

Karren are very widespread, with different typologies according to lithology, topographic setting, structural conditions, presence of soil, and micro-climatic and other geographic factors (Figs. 2a, 2c). Furthermore, large areas made up of densely fractured rock may be characterized by ruiniform reliefs with 0.5 to 3 m high angular pinnacles, and there are rare rock cities made up of remnant blocks and knobs of rock, separated by more or less linear corridors.

Solution dolines are less numerous in the Trapani (a few tens) and Palermo (fewer than a hundred) Mountains, while they are numerous (several hundreds) in the Madonie Mountains, mainly due to the presence of a wide summit tableland, made up of planation surfaces, in the Carbonara Massif area (Fig. 3a). On the large planation surfaces, the larger depressions (up to 400 to 900 m in diameter) are elongated due to the presences of joints, fractures, or faults, and often originated by the coalescence of two or more dolines. Smaller depressions (diameters between 10 and 400 m) have a sub-circular perimeter if located on flat planation or horizontal structural surfaces, while they show an elongated contour if sited at the bottom of dry valleys (Fig. 3c), along structural discontinuities, or on slopes. In the first two cases it is also possible to observe alignments of closed dolines, while in the last case, the dolines are generally open and single.

Four poljes, with steep sides and flat bottoms, have been recognized. They have maximum widths between 2 and 5 km, cover areas of 3 to 8 km^2, and present relief of some hundreds of meters. Poljes are present in the Trapani (Purgatorio polje), Palermo (Falconeri polje, Piano San Nicolò polje), and Madonie (Piano Battaglia polje, Fig. 3b) Mountains. These large depressions are sited in complex tectonic depressions due to E-W (Purgatorio polje), ENE-WSW and NNW-SSE (Falconeri polje), E-W and NE-SW (Piano San Nicolò polje), and ENE-WSW and NW-SE (Piano Battaglia polje) extensional or reverse/strike-slip faults, as evidenced by geological (anomalous contacts among litostratigraphic units, kinematic indicators along fault planes) and geomorphological (faults or fault-line scarps) data. Generally, the faults have a passive role in the development of poljes. Their genesis seems to be influenced mainly by selective erosion of clays at the bottom of the poljes stratigraphically or tectonically interposed between the limestone rocks that form the steep slopes identified as fault-line scarps or inclined structural surfaces. The presence of two fault scarps, ten of meters high, along the north-northwest and east-northeast margins of the Piano Battaglia polje suggests an active tectonic control in the development of this depression (Fig. 3b).

In the platform carbonates of Sicily, the fluviokarst valleys are dry valleys and canyons, with maximum lengths of 1 to 3 km. Dry valleys are mainly located in the Palermo and Madonie Mountains; canyons also may be found in the Trapani Mountains. Dry valleys are often set along structural lines. In particular, in the Carbonara Massif area they seem to be controlled by the northwest-southeast and northeast-southwest fault systems (Fig. 3c). In consequence of lowering of the karst base level, these valleys have been abandoned and now are seen as hanging valleys.

Planation surfaces are present in small patches at various heights between 200 and 1950 m a.s.l., both at the tops of ridges and along slopes. They are often karstified and well preserved in areas made up of carbonate bedrock. Generally, their genesis seems to be linked to several stillstand phases of the general base-level erosion. In some cases, their origin is due to marginal corrosion that affected the footslopes along the polje bottom during flood events. Subsequent relief inversion owing to dismantling of the margins is the cause of the current arrangement of the karst planation surfaces located in summit areas or along the mountainsides. Finally, several hundred horizontal and vertical caves are indicative of a well-developed deep karst network (Fig. 4b and 4d).

In the platform limestones outcropping in the Madonie Mountains, the best developed caves are the Abisso del Gatto and the Abisso del Vento (Biancone, 1994; Macaluso et al., 1994). The first is actually the deepest cave of Sicily,

Figure 2. a. Runnels in platform limestones (Madonie Mountains; photo V. Culotta). b. Large solution pans in slope to basin dolomitic limestones (Palermo Mountains). c. Limestone pavement with rectangular patterns of clints and grikes (Madonie Mountains; photo V. Culotta). d. Ruiniform relief in slope to basin dolomitic limestones (Palermo Mountains).

reaching 320 m of depth. It is a temporary sink cave, with narrow and meandering galleries connected by a sequence of shafts (Fig. 4b), and its sink entrance absorbs waters flowing only during prolonged rainfall. The Abisso del Vento, 220 m deep and about 2 km long, consists of several superimposed tiers of galleries and big rooms joined by vertical shafts and is strongly controlled by tectonics. This cave is characterized by terra rossa deposits rich in hematite, siderite, and goethite and the presence of a large variety of carbonate speleothems (Aricò and Vattano, 2007).

The Trapani Mountains are characterized by a large number of caves with a mainly vertical trend. The deepest cavities, located in the Purgatorio polje area, are the Abisso Purgatorio, 194 m deep, and the Abisso delle Gole, 120 m deep (Ruggieri, 2002). In the eastern sector of the Trapani Mountains and in the platform carbonates of southwestern Sicily, some well-developed, deep hypogenic caves linked to thermal groundwater, such as Grotta dell'Eremita, Abisso dei Cocci (Fig. 4a), and the cave complex of Kronio Mountain, occur (Messana, 1994; Perotti, 1994).

Areas characterized both by small surfaces of platform limestones (southern Palermo, Sicani, Nebrodi, and Peloritani Mountains) and by slope to basin dolomitic limestones (central-southern Palermo, central Trapani, and western Madonie Mountains) show less development of karst.

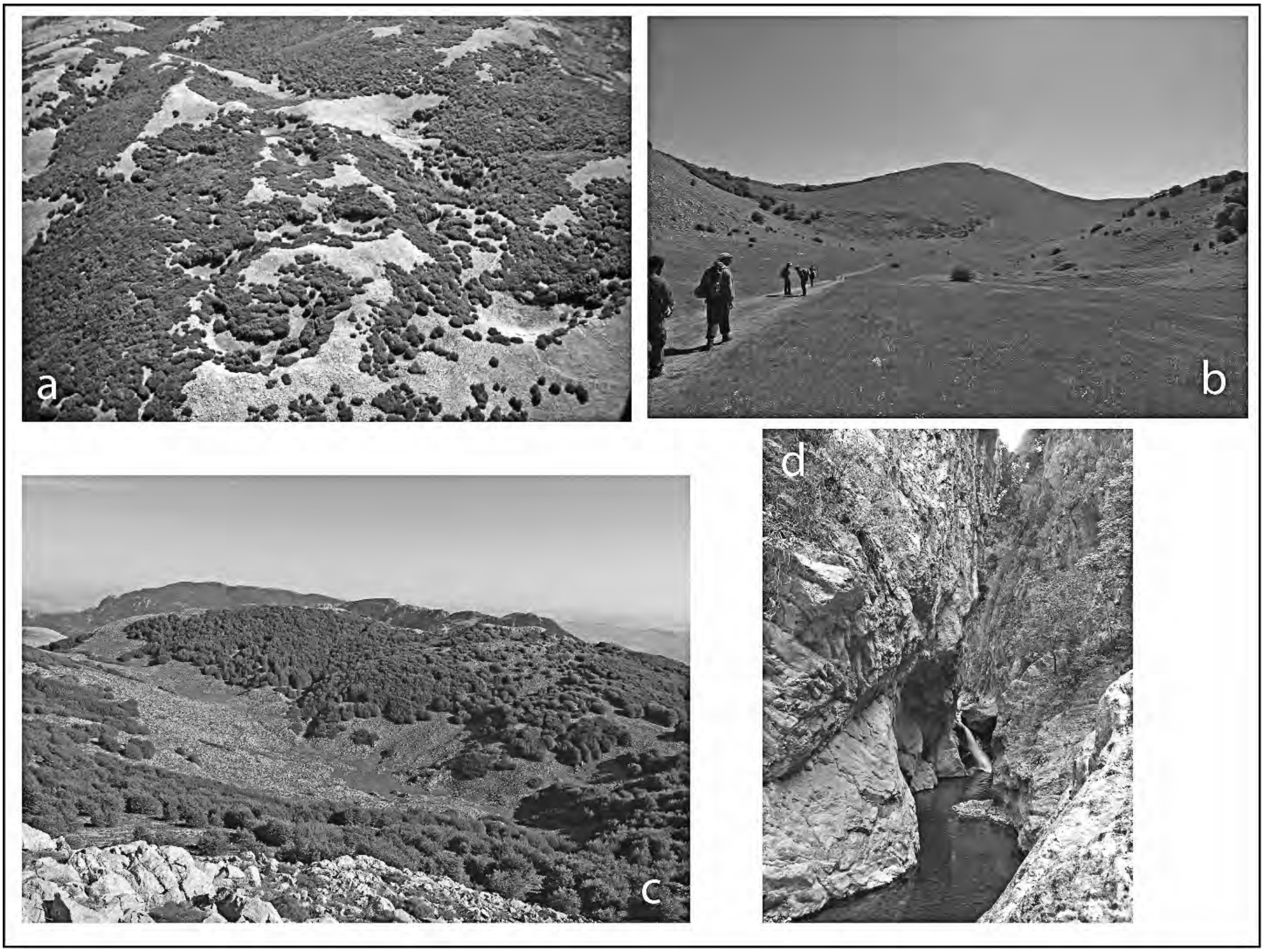

Figure 3. a. Doline alignment following major tectonic lineaments, in the summit area of Carbonara Massif (Madonie Mountains); b. The Piano Battaglia polje (Madonie Mountains). c. Dry valley on the highest reaches of Carbonara Massif; at the bottom alignments of dolines are recognizable (Madonie Mountains). d. Fluvio-karst canyon cut in dolomitic limestones (Nebrodi Mountains).

Platform limestones are marked by a great variety of karren, a few tens of dolines, and some short superimposed canyons. Dolines are generally elongated along E-W, WNW-ESE, NE-SW, and NW-SE fault lines; they exhibit maximum diameters ranging from 10 to 150 m and minimum diameters between 1 and 30 m. Canyons generally are from 400 to 800 m long and between 70 and 100 m wide and may reach up to 100 m in depth (Fig. 3d).

In dolomitic limestones, the main karst landforms are the Pianetto polje and the Piano della Stoppa polje in the Palermo Mountains, with maximum width of 4 to 6 km and located along grabens bounded by NNE-SSW (Pianetto polje) or E-W and NW-SE (Piano della Stoppa polje) fault slopes and systems of hanging dry valleys in Monte Speziale in the Trapani Mountains and Monte dei Cervi in the Madonie Mountains. These valleys, between 1 and 3 km long, host elongated dolines developed along depressions due to rock spreading or tectonic depressions controlled by NNW-SSE (Monte Speziale) or E-W, NE-SW, and N-S (Monte dei Cervi) faults.

In addition, it is possible to distinguish large elongated and sub-circular dolines with maximum diameters ranging from 200 to 700 m, dozens of smaller dolines with diameters between 1 and 100 m, dozens of short fluviokarst canyons a hundred meters long and deep set along faults or maximum-slope lines, and rare karren fields mainly made up of ruiniform reliefs (Figs. 2b, 2d).

The cave systems are not very developed. There are only some tens of cavities, with horizontal and/or vertical development strictly influenced by tectonic features. They are generally controlled by faults and characterized by narrow passages, deep shafts, breakdown rooms, and an abundance of carbonate speleothems (G. Madonia and Vattano, 2010; Fig. 4c).

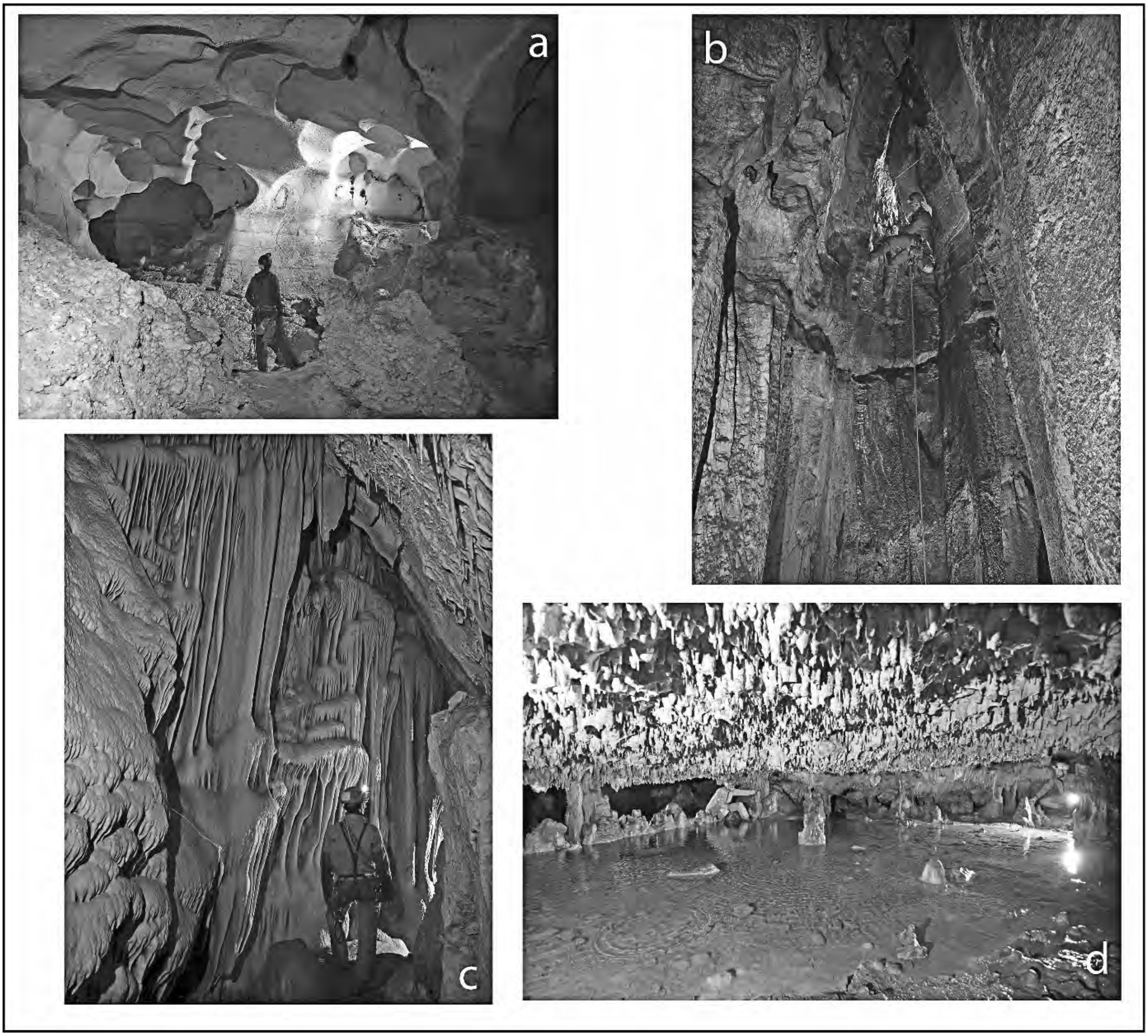

Figure 4. a. Abisso dei Cocci (Trapani Mountains), hypogenic sub-horizontal passage with cupolas in the ceiling. b. Abisso del Gatto (Madonie Mountains), 19m deep shaft connecting two tiers of galleries. c. Pozzo Fiandra (Palermo Mountain), fault-guided passage with large carbonate speleothems on the walls. d. Grotta di Carburangeli Nature Reserve (Palermo Mountain), a small pool in the main passage of the cave, rich in carbonatic speleothems.

The Hyblean Plateau, where platform and basin limestones crop out, is characterized by long and deep fluviokarst canyons that strike along the main regional gradients. The streams flow from the top of the plateau and develop in northwest-southeast and southwest-northeast (toward the Ionian Sea) or northeast-southwest (toward the Sicily Channel) directions. In particular, they are superimposed streams formed after lowering of the general base level as a consequence of uplift of the area. Genesis of these canyons is mainly due to fluvial downcutting. Karst dissolution is considered to be less important because of the widespread occurrence of impure limestones containing a siliceous component and alternating with marl and clay layers. In fact, other large or small surface karst forms are almost absent or not well developed. Due to the presence of only thin horizontal layers of limestone between marl and siliceous levels, caves in this sector have a predominantly horizontal development.

On the whole, both structurally controlled karst forms (fluviokarst valleys, dolines, shafts, ruiniform relief, and rock cities developed along structural lines, as well as poljes developed in depressions produced by tectonics or selective erosion) and karst forms not controlled by structure (karst planation surfaces, superimposed canyons on the Hyblean

Plateau, and some dolines mainly sited along slopes) occur in carbonate rocks of Sicily. Furthermore, the larger forms can be classified as karstified tectonic depressions, depressions controlled by selective erosion where clays are intercalated between carbonate rocks, karst valleys or elongated depressions developed along faults or fractures, depressions developed in areas with strongly fractured rocks, and karst planation surfaces and small depressions that cut structures.

Finally, two different karst processes can be recognized, the first linked to phases of stillstand of the karst base level that produced horizontally developed forms (e.g., karst planation surfaces, horizontal caves, and depressions with breadth more developed than depth), and the second to lowering of the base level, which created deeply developed forms (e.g., fluviokarst canyons, pits, and deep depressions).

KARST IN GYPSUM ROCKS

In Sicily, the gypsum karst is well developed and shows different kinds of surface and subsurface landforms with over 1000 km^2 of Messinian evaporites, outcropping mainly in southern and central Sicily. Additional small gypsum outcrops occur in the northern and western parts of the island. Evaporites are composed of a succession of evaporitic limestone, gypsum, and salt, with many intercalations of clays, marls, and carbonates (Decima and Wezel, 1971; Catalano, 1986). The gypsum units are made of branching selenite, banded selenite, massive selenite, and detrital gypsum, arranged in centimeter to meter thick beds separated by thin marl and carbonate layers. Thick, massive evaporitic carbonates are, in some places, intercalated between the gypsum beds. The gypsum units lie on clay, marly-clayey, and sandy-clayey formations of the Lower Messinian-Middle Serravallian, and are overlain locally by Pliocene calcarenites and marly clays or Pleistocene clays and arenites. The evaporitic successions were generally affected by the Plio-Pleistocene tectonic phases that generated south-trending fold-and-thrust belts and high-angle faults that produced lateral contacts between the Messinian gypsum units and the older marly-clayey deposits.

Several types of landscape characterize the gypsum karst of Sicily. From the morpho-structural standpoint, the most common styles are tabular plateaus, homoclinal ridges, fault scarps, folded relief, and isolated large gypsum blocks floating on clays. In addition, slope, fluvial, lacustrine, coastal, and hypogean geo-ecosystems can be distinguished (Sauro, 2003a; G. Madonia and Sauro, 2009).

Transitions between fluvial and karst processes are evident in many gypsum areas (Marinelli, 1917; Agnesi and Macaluso, 1989). These are the consequences of contact karst, due to a vertical transition from impervious rocks to soluble rocks, a lateral tectonic contact between soluble and insoluble rocks, or thin, discontinuous clastic covers of different permeability intercalated with the gypsum outcrops. The coexistence of fluvial and karst forms exemplifies the progressive transition from a surface hydrographic network to an underground circulation (Forti and Sauro, 1996). The surface karst landforms exhibit a large variety of types ranging from micro (karren) to very large (polje).

Gypsum and small salt outcrops, with solubilities respectively of 2.5 and 360 g L^{-1} (Klimchouk, 1996; Ford and Williams, 2007), are characterized by several types of karren. The karren are widespread and show a variety of shapes due to the large extent of the outcrops, the different lithofacies, and the climate. Karren features are commonly present in all kinds of evaporites, macrocrystalline selenitic gypsum, detrital gypsum with various grain sizes, microcrystalline gypsum (Figs. 5a, 5b), and salts such as halite and kainite. Both the origin and evolution of karren are controlled by several processes such as solution and recrystallization, granular disintegration, carbonation, and phenomena linked to biological activity (Macaluso and Sauro, 1996a, 1996b; Macaluso et al., 2001; G. Madonia and Sauro, 2009). The karren features vary from nano- and micro-forms to very large forms and develop both on the exposed surfaces and under permeable covers. Karren are present on extensive outcrops, such as denuded slopes and hilly summits, and even on the exposed faces of little stones and isolated blocks. Particular environments where some specific types of karren have been recognized are the fluvial and coastal geo-ecosystems (Fig. 5c) and some artificial and semi-artificial geo-ecosystems, such as quarries, mine tailings, and dry walls. Generally, similarities can be seen between the gypsum and limestone karren in Sicily, despite important differences (G. Madonia and Sauro, 2009).

On bare gypsum surfaces gypsum bubbles (*tumuli*) are widely diffused (Macaluso and Sauro, 1998; Calaforra and Pulido-Bosch, 1999). These are dome-like bulges made up of a thin layer of rock, ranging in thickness between a few centimeters and some decimeters, enclosing an underlying void. Gypsum bubbles develop mainly on selenitic gypsum and show diameters between 1 and 6 or 7 meters (Fig. 5d; Macaluso and Sauro 1996b, 1998; Ferrarese et al., 2003).

Among the medium and large landforms, dolines are the best-developed forms in Sicilian gypsum-karst areas, both in number and typology, though blind valleys and poljes occur as well. The dolines have shapes that vary from regular conical, truncated-conical, or hemispherical to irregular and asymmetrical (Fig. 6a). The latter are generally elongated according to the slope and show a significant difference between maximum and minimum depth; sometime these indicate the transition to blind valleys. Complex forms deriving from the merging of simpler features occur as well. Dolines vary from a few meters to several hundreds of meters in average diameter and from a few decimeters to tens of meters in depths.

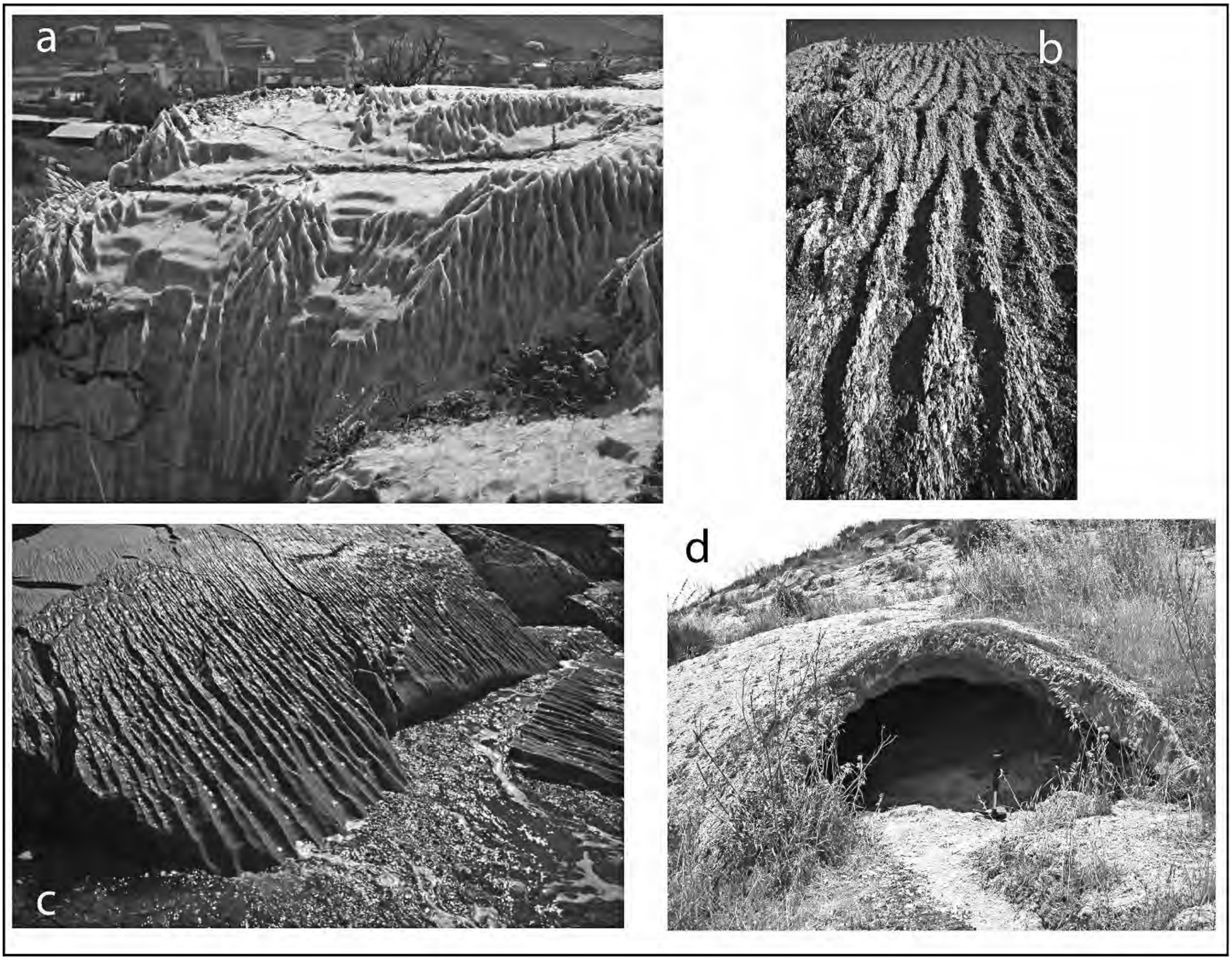

Figure 5. a. Karren in microcrystalline gypsum (southern Sicily). b. Solution runnels on steep slope of macro-crystalline selenitic gypsum (Grotta di Santa Ninfa Nature Reserve). c. Coastal solution runnels and scallops in pelitic gypsum due to wave splashing and surf erosion (southern Sicily). d. Gypsum bubble in macro-crystalline gypsum (southern Sicily).

The dolines are caused by normal solution (mainly point recharge), collapse, suffosion, or subsidence (Sauro, 2003b; Ford and Williams, 2007). In some areas of Sicily, chains of aligned point-recharge dolines, formed as a consequence of an upstream migration of the swallets of small blind valleys, follow the pattern of old fluvial networks that developed on the impermeable cover. Dolines often are grouped in a well-defined karst unit, where they occupy the entire karstifiable area to form a honeycomb karst type, as in the Grotta di Santa Ninfa and Serre di Ciminna nature reserves (Fig. 8; Agnesi and Macaluso, 1989; Sauro, 1996, 2005).

Where gypsum is covered by pervious but not soluble rock, several karst lakes have formed in small subsidence dolines, as in the Lago Preola and Gorghi Tondi, Lago di Pergusa, and Lago Soprano nature reserves (Figs. 6d, 8). These lakes change rapidly in dimensions, depth, and shape due to subsidence, and erosion, and changes in rainfall (Di Maggio et al., 2010).

In southern Sicily, some kilometer-long polje-like depressions linked to folded relief are recognizable, among which the most developed is the Pantano, near Agrigento (Fig. 6c). This polje consists of a flat and nearly horizontal floor 2.5 km long and 900 m wide, bounded by steep slopes, and formed in a tectonic depression linked to a northwest-southeast thrust.

The karst valleys are generally blind valleys that may be entirely cut in gypsum, often assuming a gorge shape, or they may be cut in insoluble sediments and end blindly at a gypsum threshold. Sometimes they have their upstream part on insoluble rocks and the downstream end incised in the gypsum (Fig. 6b; Macaluso et al., 2003).

In Sicily, over two hundred gypsum solution caves are known. Generally, they open at the end of a blind valley

Figure 6. a. Example of truncated-conical solutional drawdown doline in gypsum karst (northern Sicily). b. Blind valley feeding the Grotta di Santa Ninfa gypsum cave; this valley has the upstream part in insoluble rocks and the downstream side incised in gypsum (Grotta di Santa Ninfa Nature Reserve). c. The Pantano, a polje formed at a tectonic depression linked to a northwest-southeast oriented thrust (Torre Salsa Nature Reserve). d. Subsidence doline developed in Pleistocene calcarenites overlying gypsum rocks and hosting a small karst lake (Lago Preola e Gorghi Tondi Nature Reserve).

or at sink points located at doline bottoms. Gypsum caves in Sicily reflect the features of classic gypsum karst systems under unconfined conditions, consisting of a main drainage tube, characterized by rapid flowing water, with generally inactive tributaries locally filled by alluvial or breakdown deposits (Forti and Sauro 1996; Forti and Rossi, 2003). Usually the caves are composed of low-gradient galleries at different elevations connected by shafts related to stillstands and lowering of the local base level (Figs. 7a, 7c, 7d; Vattano, 2004, 2008; G. Madonia and Vattano, 2011).

Solution caves have several different relations to surface hydrology: through-caves, sink caves (e.g., Inghiottitoio di Monte Conca and Inghiottitoio di Sant'Angelo Muxaro), spring caves (Risorgenza di Monte Conca), active caves with streams flowing underground but with no explorable connection to either sink or spring system (Grotta di Santa Ninfa), and finally relict, inactive caves (Grotta di Entella and Inghiottitoio delle Serre) (Forti and Sauro, 1996). Actually, the longest and deepest cave in the Sicilian gypsum is the Monte Conca system that is composed of a sink cave, an active resurgence, and a relict one, reaching more than 2.3 km in length and 132 m in depth (Vattano, 2004, 2008; G. Madonia and Vattano, 2011).

Many caves show large amounts of physical and chemical filling. The first consists of well-stratified alluvial sediments of various grain size (gravel, sand, clay, and silt) and breakdown materials. Chemical deposits are mainly gypsum and carbonate speleothems, plus secondary minerals such as sulfur, opal, phosphates, oxides, and metallic minerals (Hill and Forti, 1997). Gypsum speleothems over carbonate ones occur in many gypsum cavities (Fig. 7b); this alternation can be a powerful instrument in paleoclimate studies, as demonstrated by Calaforra et al. (2008) using samples from the Grotta di Entella.

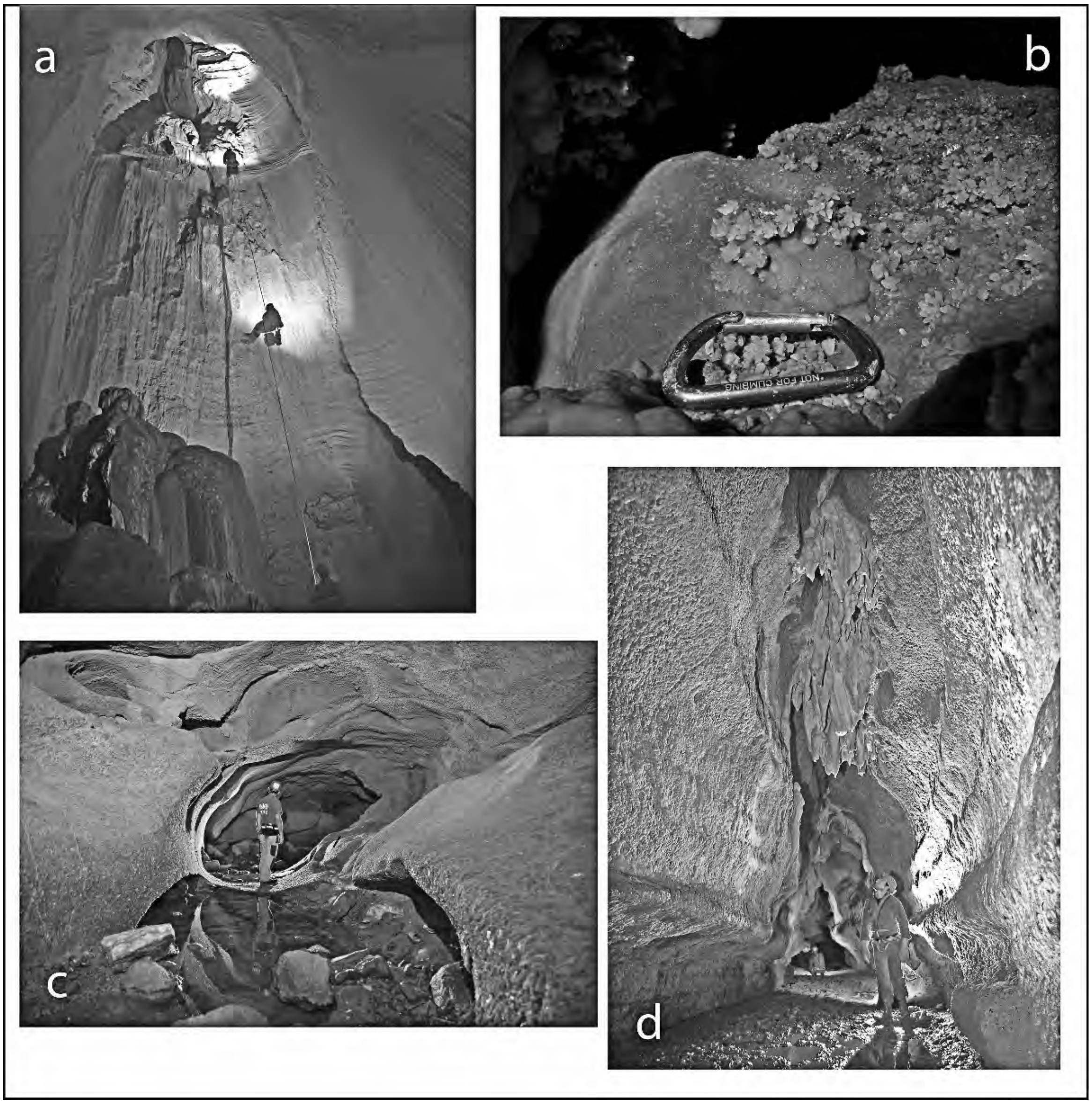

Figure 7. a. Waterfall shaft 26 m deep in the Inghiottitoio di Monte Conca; carbonate flowstones cover breakdown blocks at the bottom and the wall where water flows (Monte Conca Nature Reserve). b. Gypsum crystals on carbonate speleothems (Grotta di Santa Ninfa Nature Reserve). c. A horizontal passage with elliptical section linked to overflow episodes in the Vallone Ponte gypsum karst system (central Sicily). d. Subhorizontal gallery in gypsum cave; on the walls, notches due to selective solution are recognizable, and massive carbonate speleothems grow from the roof (Grotta di Santa Ninfa Nature Reserve).

Protected Karst Areas in Sicily

Since 1981, the Sicilian Regional Government has enacted several laws for the creation of parks and nature reserves to preserve areas of scientific importance or outstanding environmental beauty. The most important steps were the "Norms for the establishment of parks and nature reserves in Sicily" (Regional Laws No. 98/1981 and No. 14/1988), approval of the "Parks and Nature Reserves Regional plan" (Regional Decree No. 970/1991), and the establishment of parks and nature reserves and assignment of management of the protected areas (several regional decrees between 1984 and 2008; Dimarca, 2004). Although there is no specific legislation for the protection of karst landscapes, as many as nineteen of the nature reserves were established for the conservation of karst features because of their intrinsic value (Fig. 8, Table 1). Of these, twelve reserves provide for the protection of gypsum or carbonate caves. Some caves are of great speleological, geological, and hydrological interest, and others contain important paleontological remains. In addition, many of these caves are of biological interest for the presence of significant

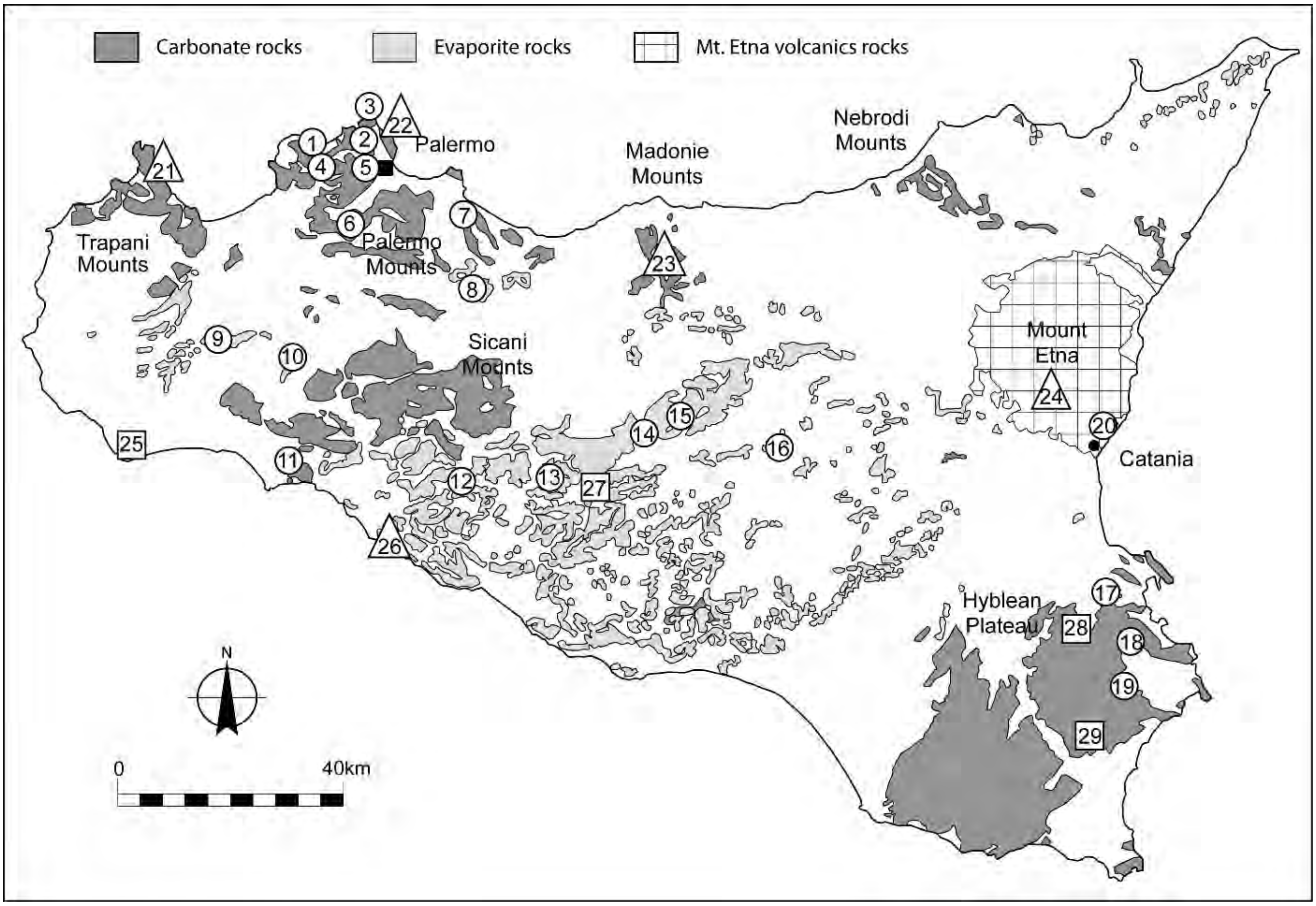

Figure 8. Location map of carbonate and evaporite rocks and natural protected karst areas of Sicily (modified after Catalano, 1986, and Macaluso et al., 2001). Numbers correspond to the list in Table 1. Although volcanic caves are not karst features in the strict sense, they are included in this list. Circles indicate karst areas designated as nature reserves for their intrinsic karst value; squares indicate important karst areas designated as nature reserves for the protection of other environmental heritages; and triangles indicate important karst features developed within regional parks or nature reserves established for the conservation of other environmental features.

subterranean fauna. Besides carbonate and gypsum subsurface cavities, a complex of eight volcanic caves at Mount Etna was declared a nature reserve for the conservation of lava tubes.

Two protected areas were designed to conserve gypsum karst lakes of interest from the geological, hydrological, and biological point of view. Other reserves preserve karst landscapes such as gypsum karren fields, dolines, and swallow holes. In some cases, such as numbers 6 and 7 in Table 1, the protected areas include both karst and important biological features.

Many of these areas contain special habitats of interest and species of biogeographic and preservation importance and have therefore been included in Sites of Community Importance under the Council Directive 92/43/EEC on the conservation of natural habitats and wild fauna and flora or as Special Protection Areas designated in accordance with the Council Directive on the conservation of wild birds, 79/409/EEC. Moreover, there are important karst areas and volcanic caves that are found within regional parks (e.g., the Madonie Geopark includes the carbonate karst of the Madonie Mountains) or nature reserves designated for the conservation of other environmental heritages. For example, several significant caves are located in the nature reserve of Monte Pellegrino (Palermo), which was established for the conservation of its rupestral features and the protection of some bird species. An important karstland in gypsum, marked by karren, dolines and a polje, is encompassed in the nature reserve Torre Salsa in Agrigento province, designated for its environmental and biological interest. At the same time, there are significant protected karst areas that were not established because of their intrinsic value as karst features but for different reasons. Among these, some gypsum karst lakes were designated as nature reserves only for their biological resources and because they represent important staging points for many migratory birds, while fluvio-karst canyons were declared nature reserves for the presence of significant associations of flora and fauna.

Most of the protected karst areas are listed as Integral Nature Reserves (INR in Table 1). Each reserve is divided into two areas, Zone A and Zone B, with different land use and protection rules relating to the environmental features and management goals (Casamento et al., 2004). Zone A is the area of maximum protection, where only scientific studies are authorized and tourist access is subject to more restrictive rules. Zone B is a buffer zone between the maximally protected area and the surrounding territory. In this area, appropriate actions to promote the enhancement of the local economy are permitted, with special focus on traditional, zootechnical, and farming or forestry activities, as well as recreation, tourism, and sports. For example, in the reserves established for cave protection, Zone A includes the cave and a 5 m radius area around its entrance, while Zone B surrounds Zone A, though generally covering only part of the catchment area of the cave.

Eleven protected karst areas are designated as Oriented Nature Reserves (ONR) and one area is a Special Nature Reserve (SNR). These are also divided into Zone A and Zone B, but the maximum protection area rules are less restrictive than described above.

Management of the nature reserves was assigned by the Sicilian Regional Government to environmental associations such as the World Wildlife Fund, the Italian Alpine Club, and Legambiente or to universities, provincial administrations, or the Dipartimento Regionale Azienda Foreste Demaniali (Regional Forest Department) of Sicily. Their overall goals are to work for the protection and improvement of the natural resources, promote scientific research, and disseminate knowledge of the natural heritages of the reserves. For many protected areas, however, the strategic aim is the integration of the need to protect unique karst landscapes and their natural heritages with the promotion of forms of sustainable development (Dimarca, 2004).

Each nature reserve should have a specific management plan for the karst features and regulations about prohibited and allowed activities in relation to the resources to be protected. But these areas are protected under general environmental legislation, because specific laws for protection of karst are lacking.

Protection and conservation measures are carried out to minimize human pressure on karst. The main threats and issues are infilling of swallow holes and dolines, inappropriate use of fertilizers, unsuitable agricultural and zootechnical practices, grazing, quarrying, wildfires, building of rural homes, waste dumps, dumping of effluent, poaching, water extraction, and unauthorized caving activities. Daily vigilance is maintained in the reserves and the surrounding areas to reduce threats and address illegal activities. Some management staff cooperate with landowners in the protected areas to promote agricultural practices in compliance with sound karst conservation.

To avoid inappropriate speleological activities, access to the caves is possible only after authorization and under the guidance of management staff. In some cases, visitation is controlled to minimize disturbance of the environmental conditions and to protect subterranean fauna.

Restoration of degraded or abandoned areas is carried out to conserve and enhance karst areas. In some reserves, illegally-built structures were demolished, native shrubs and trees species were planted, and degraded zones were changed into areas with native vegetation, educational information, and park amenities.

Scientific research is one of the most important objectives in the nature reserves, as it increases understanding of their values and provides the information needed to preserve them. Interdisciplinary investigations are carried out in close collaboration with universities, research institutes, and freelance researchers. Many students in these areas conduct studies for the preparation of graduation theses, doctoral dissertations, or they perform training activities as part of degree courses. In some reserves, geological, geomorphological, and hydrogeological studies are carried out to increase understanding of the surface and underground karst (Favara et al., 2001; Macaluso et al., 2001; Frisia et al. 2006; Vattano, 2008; G. Madonia and Vattano, 2011). Biological studies have documented the wildlife and vegetation features, creating the conditions for their inclusion in Sites of Community Importance and Special Protection Areas (Pasta and La Mantia, 2001). In the caves, climate monitoring programs are carried out both to increase knowledge and to devise visitor policies (P. Madonia, 2001a, 2001b, 2008). Studies on subterranean fauna documented new species and contributed to the safeguard of the underground habitat.

Much publicity about protected karst areas is advanced in order to create a conscious environmental awareness: participation in exhibitions, conferences, and local and regional trade shows; publication of brochures, calendars, hiking maps, and multi-languages DVDs; and development of environmental education programs that focus on local communities and students of all ages, from primary school to university. Some reserves diligently promote ecotourism and development based on conservation and enhancement of the natural resources, perpetuation of traditional activities, maintenance of cultural identities, and improvement of the local economy. For these purposes, networks of trails and interpretive visitor centers were constructed, some in renovated old buildings. Management bodies cooperate with institutions and local authorities to develop common cultural initiatives. Local businesses and farmers operating in the reserve areas are engaged to promote rural development and traditional agriculture compatible with the maintenance regime.

At present, the state of conservation of karst areas in Sicily may be considered to be at an acceptable level.

Nevertheless there are numerous issues and difficulties that should be addressed for effective protection and enhancement of karstlands. One of the main problems is the boundaries of the reserve areas. They are often not adequate to safeguard the karst features; for example, the reserves designated for cave protection frequently do not include the entire catchment. Sometimes the cave extends partially outside the boundaries of the reserve, with obvious risks for its conservation; additional important surface landforms and caves may be located outside the protected area. These problems arise mainly because the delineation of the reserves was done on maps at an inappropriate scale (1:25,000) for accurate representation of karst features. Further, many important natural resources have become better-known through studies carried out after the establishment of the reserves.

The main stewardship difficulties, however, are linked to lack of special legislation for protection of karst areas and to structural problems in the regional conservation policy. The state of conservation of karst areas frequently depends entirely on the efforts made by the management staffs, and only some reserves have achieved the good results described above. Coordination, planning, and control by the Sicilian Regional Government do not occur (Dimarca, 2004; Casamento, 2004). Policies lack continuity due to frequent changes of administration. Also, bureaucratic procedures are often slow and farraginous, leading to serious problems of management effectiveness.

The financial resources assigned annually by the Sicily Region, amounting to about €50,000, are clearly insufficient for all management activities. There are no funding sources to develop infrastructure or manage and acquire areas of natural and/or management interest. Most of the activities conducted by the management bodies, such as scientific research, environmental rehabilitation, and construction of footpaths, are carried out within projects funded by the European Union. Measures for the support of traditional activities and for the reorientation of existing ones have not been implemented, causing serious problems for the maintenance of the traditional agricultural landscape and the promotion of rural development (Casamento, 2004).

Unfortunately, a good relationship between conservation activity and local communities is not always achieved. Protected areas were often frequented by hunters, used for inappropriate grazing, or subject to fires. This issue is very complex. In a somewhat simplistic way it can be argued that the conflicts may be linked to several factors. On one hand there are the lack of sensitivity of local populations to the protection of the karst environment and the mistrust of farmers towards new land uses and management. On the other hand, communication by some management bodies is weak, involvement of people and local authorities in management activities is lacking, prohibitions are too rigid in some places, and the needs of the local people are sometimes discounted.

CONCLUSIONS

Karst areas in Sicily represent extraordinary environments in their variety and peculiarity and for the study of various solution forms. Carbonate and gypsum karst exhibit a considerable variety of surface and underground landforms and are important habitats for many vegetal and fauna species. The system of protected karst areas of Sicily is one of the most important in Italy, due to the number of nature reserves, the conservation of bio- and geo-diversity, and the number of institutional authorities and environmental associations involved. Despite this, many karstlands of special scientific and environmental significance are not covered by any conservation measures, resulting in severe risks for their maintenance and preservation.

For a better conservation and enhancement of karst areas, specific legislation taking into account the high complexity and vulnerability of karst systems is needed. Greater political and economic efforts by the responsible authorities are required, and the conservation policy needs unified strategy and planning for all Sicilian karstlands. Adequate funding should be dedicated to the management, research, and sustainable development of these unique landscapes. Management bodies should have greater planning and execution autonomy and limited bureaucratic obstacles. Measures for the support of traditional activities and agricultural practices compatible with karst terrains are needed for acceptance in the local communities. Greater efforts by the management bodies both in stewardship activities and in relationships with the local population are crucially important.

Finally, it should be emphasized the uniqueness of the Sicilian gypsum karst areas, which exhibit unique features in the Mediterranean basin due to the size and thickness of the Messinian evaporite successions and the number and variety of karst landforms. As repeatedly recommended by several scholars and environmental associations, the establishment of a nature-reserve network, or an evaporite geopark, that includes both the protected areas and currently unprotected areas of great scientific and environment significance, is crucial for a comprehensive conservation of evaporite karst in Sicily.

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QUATERNARY ALLUVIAL SINKHOLES: RECORD OF ENVIRONMENTAL CONDITIONS OF KARST DEVELOPMENT, EXAMPLES FROM THE EBRO BASIN, SPAIN

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Abstract: The central Ebro Basin is an exceptional region for studying karstification through time and under different environmental conditions, as sinkholes have been developing since the Early Pleistocene. Knowledge of active sinkholes is complemented with research on paleosinkholes and contemporary deposits. Sedimentological, mineralogical, geomorphological and structural approaches permit interpretation of the natural environmental conditions that favored karst in the past and the main genetic mechanisms involved. The sedimentary features of Pleistocene terraces indicate that they were deposited by a gravel braided fluvial system characterized by higher water and sediment availability than today, probably related to meltwater flows coming from glaciated source areas, mainly in the Pyrenees. Genesis of paleosinkholes was mainly linked to this high water supply. Some of them acted as small lakes where fine sediments are exceptionally well conserved to give clues about environmental conditions. The neoformation of palygorskite and sepiolite suggests arid to semiarid climatic conditions, in agreement with the idea of cold glacial episodes. During Pleistocene times, development of sinkholes was influenced by tectonics. Currently, the genesis and evolution of numerous sinkholes are also influenced by water supplies from human activities such as irrigation or urbanization, sharply changing the nearly steady state exhibited in the past.

Introduction

Karstification requires soluble rock, favorable climatic factors, and a hydraulic gradient that facilitates water mobility (White, 1988). Karst environments have different characteristics than others, in particular, the role of water circulation. Environmental changes cause variations in karst development, owing to the great sensitivity and vulnerability of karst areas to modifications in water availability and gradient (van Beynen and Townsend, 2005). This can even cause ending of karst development in some areas, giving rise to paleokarst (Shunk et al., 2006; Chow and Wendte, 2011). The environmental modifications can be of either natural or human origin, with the latter being more rapid (Ford and Williams, 2007) and also shown by several significant historical examples (Jia and Yuan, 2004; Beach et al., 2008; Closson and Abou Karaki, 2009 and references therein).

Evaporite karst in the central Ebro Basin has been broadly studied for decades since high solubility of evaporites and the heavy human occupation of the karst evaporite zone (around 700,000 inhabitants) increase the risk. The morphology of sinkholes and their genetic mechanisms, spatial distribution, and associated risks are well known (Soriano, 1992; Soriano and Simón, 2002 and references therein; Lamelas et al., 2008; Galve et al., 2009 and references therein).

Sinkholes in this area are not only recent, but also paleosinkholes affecting Quaternary sediments can be observed in artificial outcrops in the whole area (Luzón et al., 2008; Gutiérrez et al., 2008; Benito et al., 2010). This indicates that karstification occurred before human influences and makes the Ebro Basin an exceptional place to study sinkholes through time and under different environmental conditions.

As a consequence, the study of present-day sinkholes should be integrated with research about paleosinkholes and their related deposits to better understand the natural environmental conditions that favored karst in the past. Moreover, the study of paleosinkholes permits a wider time window for the study of sinkholes, a direct access to their inner structure and, consequently, to the main genetic mechanisms involved. It allows us to characterize the main stages in a sinkhole's evolution, as well as to constrain its period of development. The main purpose of this work is the study of present-day and ancient sinkholes and the environment, both natural and anthropogenic, in which they developed. These include natural settings under a cold Pleistocene climate and human-influenced conditions under present-day semiarid climate. To achieve these objectives, a multifaceted

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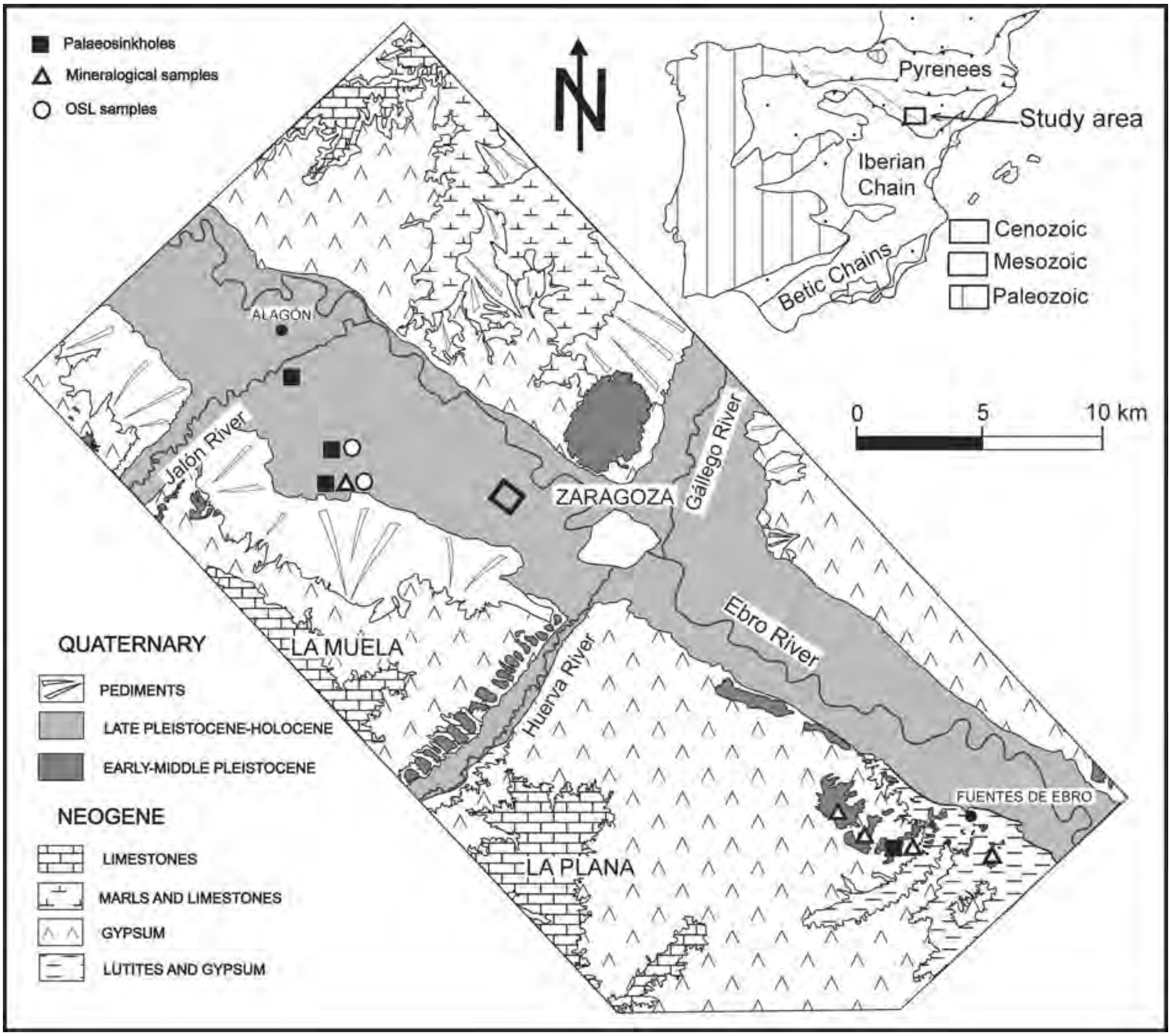

Figure 1. Location of the studied area in northeastern Spain and geological map of the central Ebro Basin. An open square indicates location of Figure 3.

approach has been carried out, including sedimentological, mineralogical, geomorphological, and structural studies.

GEOLOGICAL AND GEOGRAPHICAL SETTING

The study area (Fig. 1) is located in the central part of the Ebro Basin in northeastern Spain, which is the foreland basin of the Pyrenean alpine orogen. This basin is bounded by the Iberian Range to the south and the Catalonian Coastal Range to the east, and is crossed by the Ebro River that flows towards the Mediterranean Sea to the east. The basin was endorheic from the Late Eocene to the Middle-Late Miocene (García-Castellanos et al., 2003) and alluvial fans sourced in the surrounding mountains interfered with central saline or carbonate lakes (Muñoz et al., 2002; Pardo et al., 2004). Due to this paleogeographical distribution, the stratigraphic succession in the central part of the basin is characterized mainly by thick, nearly horizontal carbonate or evaporite rocks. In the study area, the outcropping Miocene units are mainly composed of evaporite rocks with interbedded marl, the Zaragoza Formation. A regional disconformity separates the Miocene rocks from the Quaternary deposits. The latter have been traditionally considered to be fluvial terraces belonging to the Ebro River and its main tributaries, and pediments. Soriano (1990) recognized eight stepped terrace levels in the area, as well as six pediment levels. Thickness of the terrace levels is variable, the three youngest being the best-preserved. Fluvial deposits are mainly composed of polygenic gravels with interbedded sands and very scarce lutites. Thickness of the pediments, consisting of sands, lutites, and angular to sub-angular gravels, is also variable.

The Miocene beds usually lie nearly horizontal, although gentle folds and faults have been recognized. The Quaternary deposits have been affected by tectonic, gravitational, diapiric, and dissolution processes (Simón and Soriano, 1986; Benito and Casas, 1987; Arlegui and Simón, 2000). As previously mentioned, karstification is currently the most active geological process in the central Ebro Basin caused by dissolution of Miocene evaporite rocks and their subsequent collapse, subsidence, and suffosion of the Quaternary detrital cover.

Climate in this area is semiarid, with mean annual precipitation between 200 and 300 mm irregularly distributed over the year and a mean annual temperature of about 15 °C. Precipitation reaches some 400 to 500 mm during occasional humid years and, exceptionally, almost 700 mm, as in 1990. At present, the Ebro River shows a meandering pattern and a wide flood plain, densely occupied by human settlements.

METHODS

In this work, different traditional geologic methods have been utilized to analyze the characteristics of sinkholes, especially those developed during the Pleistocene.

In the study of recent sinkholes, analysis and comparison of aerial photographs from various years (1927, 1946, 1957, 1970, 1982, 1986, 1988, 1993, 1999, and 2006) with scales ranging from 1:43,000 to 1:5,000 allow us to identify depressions larger than 10 m in diameter and to determine spatial variations through time. Fieldwork facilitates the identification of smaller depressions, the corroboration of the presence of the larger ones, and the study of damage in urban areas at a detailed scale (Simón et al., 1998).

To study paleosinkholes and to characterize the environmental conditions under which they developed, a sedimentological analysis was carried out in the Pleistocene succession through the application of facies analysis (Miall, 1978). The studied sections mainly occur on Middle-Late Pleistocene and Early Pleistocene terraces, as well as pediments. Multiple survey lines were analyzed along quarry faces and artificial slopes of roads and railways, with a total length of about 30 km. Typical sections are several tens of meters long and 10 to 20 meters high, providing a good view and sufficient samples. Four paleosinkholes were selected for detailed study, based on evidence of synsedimentary deformation, the size and quality of the sections, and the presence of a non-deformed sedimentary cover.

The sedimentological and paleoenvironmental analysis was completed with the mineralogical study of five sediment filled paleosinkholes (Fig. 1). A total of thirty-three marl and sand samples (thirteen from Early Pleistocene and twenty from Middle-Late Pleistocene deposits) were analyzed to determine their mineralogical composition and texture. Mineralogical compositions of whole samples, as well as air-dried and ethylene glycol treated and dimethyl sulfoxide-treated oriented samples of the finer fractions (2 to 20 μm and < 2 μm), were determined by X-ray diffraction. In addition, the absolute intensity ratio of the smectite and illite 001 reflections (I_{Sm}/I_{Il}) was calculated from the glycoated oriented samples. Microtextural and morphological observations were performed by scanning electron microscopy observing gold-coated fragments of selected samples using secondary electron imaging. Chemical analyses and morphological studies of phyllosilicate particles from the < 2 μm fraction of selected samples were carried out by transmission electron microscope equipped with an EDX analytical system.

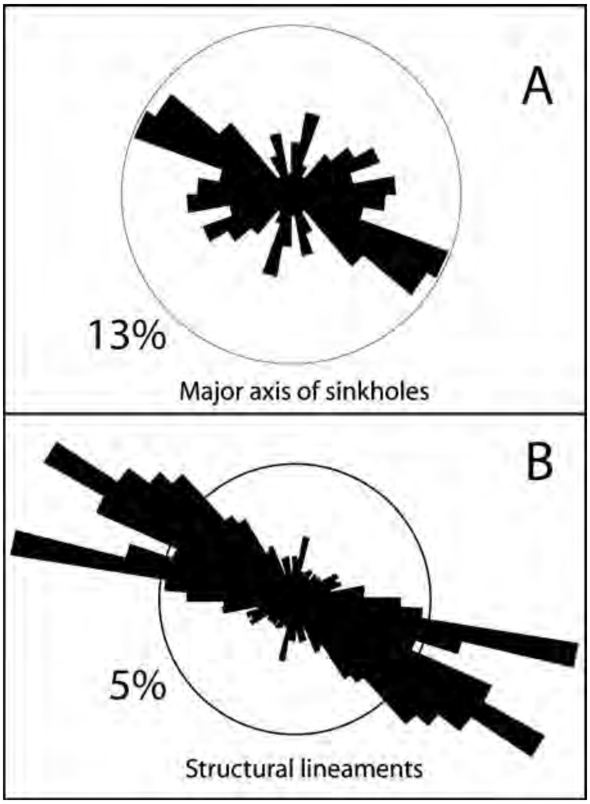

Figure 2. Rose diagrams. A, Major axis orientation of recent sinkholes. B, Lineaments of the central Ebro Basin after Arlegui and Soriano (1998).

Four samples were collected from two quarries (Fig. 1) for dating by the optically stimulated luminescence (OSL) method, following standard procedure to avoid light exposure. The preparation and pre-treatment of the samples for OSL dating was carried out in the Laboratorio de Datación y Radioquímica of the Universidad Autónoma de Madrid, using the additive dose method for fine grain size. OSL measurements were performed using a Risø TL/OSL-DA-10 device.

To determine the mechanisms of sinkhole development, deformational structures were studied by means of standard field surveys and analyses including recording detailed cross-sections on quarry faces where such structures are well exposed, exhaustive compilation of data on faults, joints, and folds in both Pleistocene deposits and Tertiary rocks, and retrodeformational analysis directed toward kinematical reconstruction of structures and discrimination of deformational mechanisms.

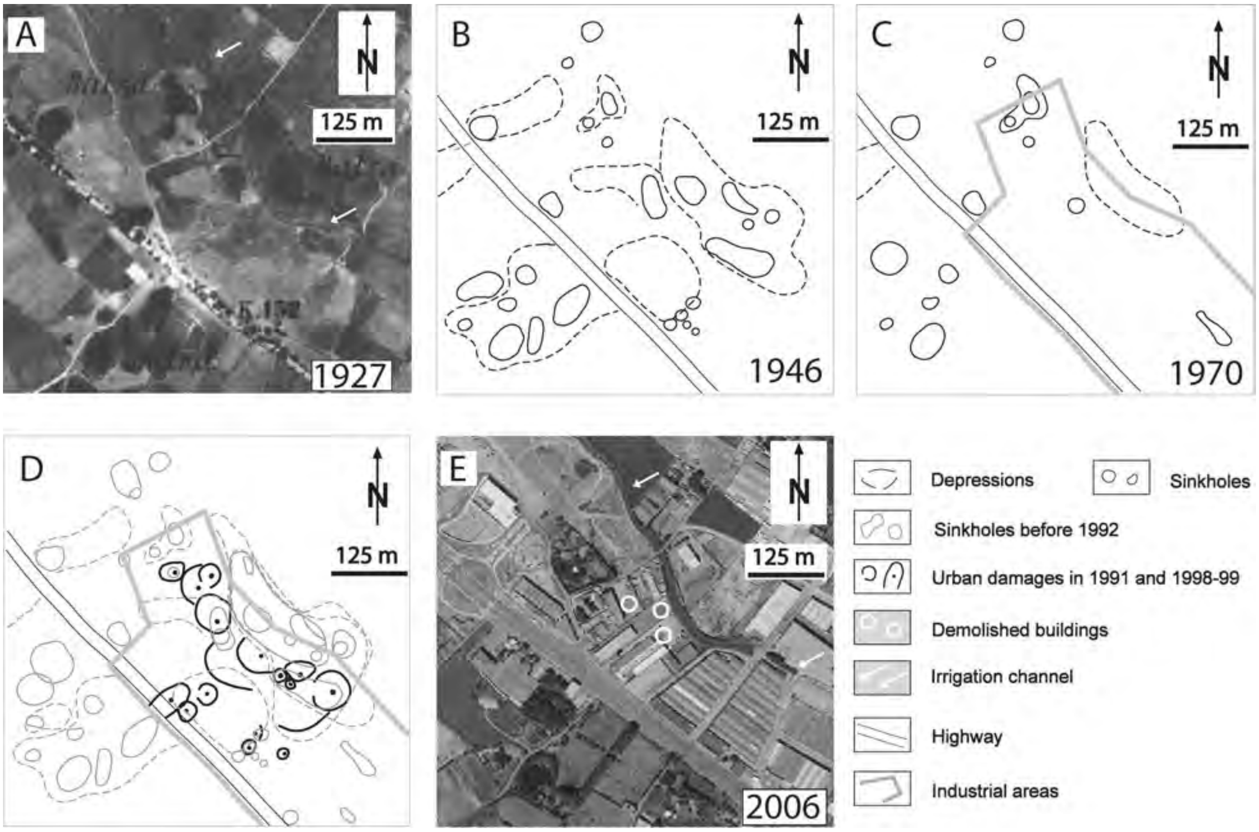

Figure 3. Aerial photographs and geomorphological maps of sinkholes near Zaragoza (see location in Fig. 1). A, aerial photograph of 1927. B and C, geomorphological maps based on aerial photographs of 1946 and 1970, respectively. D, damages in urban zones (in black) allow to map present sinkholes and to monitor their activity; comparison with sinkholes mapped from aerial photographs before 1992 (in gray) shows a spatial relation between them. E, aerial photograph of 2006; in this zone three buildings had to be demolished due to severe damage caused by sinkhole activity.

Results and Discussion

Modern Sinkholes

More than three hundred sinkholes have been recognized (see Figure 1 in Soriano and Simón, 2002) between Alagón and Zaragoza (Fig. 1). Most of them are circular or subcircular, attaining up to 1200 m in diameter and 20 to 25 m in depth. Major axes of sinkholes show an average trend N 130° E (Soriano, 1992; Gutiérrez-Santolalla et al., 2005b) that is parallel to the central Ebro Basin main lineament set determined by Arlegui and Soriano (1998) (Fig. 2). This points out the structural control that favored the circulation of water and the subsequent dissolution of evaporites.

Other natural factors, mostly related to water availability, influence the development of sinkholes in the region. Generation and subsidence of sinkholes clearly increase after heavy storms and in years with higher precipitation than usual (Soriano and Simón, 2002; Gutiérrez-Santolalla et al., 2005a). Nevertheless, the control that land use exerts on karst evolution is noteworthy, as discusssed below.

Analysis of aerial photographs indicates that prior to 1970 most of the land surface was dedicated to agriculture. Sinkholes were numerous (Fig. 3A and B) and coexisted with farming activities. An almost steady state could be inferred for that time; comparison of sinkholes identified in aerial photographs of different years shows that their total number remained approximately constant (Simón et al., 2008). Strong differences between the number of sinkholes in irrigated (mean density 5.8 sinkholes per km^2) and non-irrigated fields (mean density = 1.47) were observed, as well as a high number of sinkholes, about half of them, (Soriano, 1992 and references therein) developed in connection with irrigation channels (Fig. 3). Human influence continues at present, since irrigation techniques in this zone mostly follow very old practices consisting in field flooding. In fact, groundwater recharge by natural precipitation is estimated in 9×10^6 m^3/y, while irrigation supplies 171×10^6 m^3/y (Confederación Hidrográfica del Ebro, 2010). The large amount of irrigation contributes to increased variation in water level, hydraulic gradient, dissolution of evaporites in the subsoil, and mobilization of detrital material through the voids, with subsequent generation of sinkholes (Currin and Barfus, 1989; Simón et al. 2008; Mancini et al., 2009).

By 1970, although large areas of land remained dedicated to agriculture, important changes in land use had occurred

Figure 4. Damage in urban areas northwest of the city of Zaragoza resulting from karst subsidence. A, fractures in walls. B, strong deformation of a fence.

in the areas surrounding both the urban settlements and the main roads. Some agricultural lands had become urban and industrial areas. Many sinkholes were filled (Fig. 3C), mainly with aggregates, concrete, building rubble, and other waste. Consequently, marked spatial changes took place, with a clear decrease in the number of visible sinkholes (Simón et al., 2008).

In spite of sinkhole filling, dissolution and suffosion processes are still active. Subsidence reappears over a period of time as the source of water from irrigation continues (Soriano and Simón, 2002 and references therein). The consequences in urbanized areas are damages to buildings and infrastructures (Fig. 3D and E and Fig. 4). Study of cracks in walls, floors, and roofs, the subsidence of pavements, breaks in water supply systems, and the collapse of roads or railways allows us to identify subsidence centers (Fig. 3D) and establish the scale of damages (Cooper and Calow, 1998; Soriano and Simón, 2002; Pueyo-Anchuela et al., 2010). Frequently, migration of subsidence centers occurs (Soriano and Simón, 2002 and references therein; Pueyo-Anchuela et al., 2010), probably due to changes in the groundwater flow and gradient caused by artificial fill. Observing the sinkholes in the urban areas allows us to study spacial and temporal variations in their development, as well as the overall rate of subsidence, which in the central Ebro Basin ranges from 1.7 to 11 cm/yr (Simón et al., 2008 and references therein). In summary, human action has modified the almost steady sinkhole development existing before 1970.

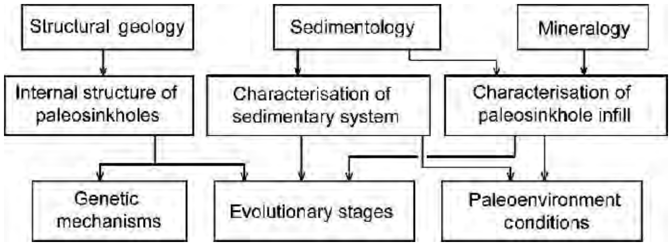

Figure 5. Schematic diagram showing the multifaceted approach to the study of paleosinkholes.

PALEOSINKHOLES

The previous section discusses the human influence on the generation of present-day sinkholes. However, the presence of Pleistocene paleosinkholes reveals that karstification occurred by natural causes in past epochs. Sedimentological, mineralogical, and structural studies help to reach insights into these phenomena (Fig. 5). The studied sections mainly correspond to low and high terrace levels. Dating by OSL indicates that the low terraces are Late Pleistocene, while the higher terraces are considered, by their stratigraphical position and magnetostratigraphical data, to be Early Pleistocene in age (Benito et al., 1998; Marqués et al., 1998; Colomer et al., 2006). Paleosinkholes are exposed, mainly on quarry faces and road slopes. The observed sedimentary infilling usually ranges from 2 to 25 m in width and from 2 to 15 m in height, although several sinkholes are only partially exposed and might continue at greater depths into the subsoil.

Sedimentological Data

Thick successions of gravels with interbedded sands and lutites are predominate in the Pleistocene terrace deposits. Clast-supported, well-sorted, rounded to subrounded gravels are the most common lithofacies, whereas lutites are only locally present. Gravels usually show imbrication and form thick tabular or subordinately channeled bodies with horizontal stratification and cross-stratification. Sands show different types of sedimentary structures (e.g., horizontal and cross-lamination). These deposits represent tractive processes and testify to the development of longitudinal bars, transverse bars, and channels in a gravel braided setting (Luzón et al., 2008). This scenario (Fig. 6A) strongly contrasts with the current meandering flow of the Ebro River and suggests greater water availability during the Pleistocene in a clearly different climate setting than present. Intercalated in these deposits, ancient sinkhole fillings are found in some zones (Figs. 7 and 8). They consist of lutites laterally passing to

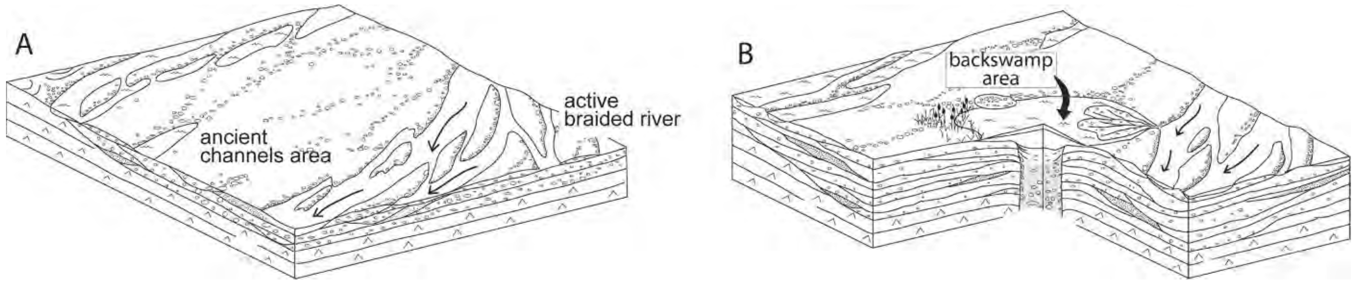

Figure 6. A, schematic diagram showing the sedimentary environment during the Pleistocene in the area and its relationship to the evaporite substratum. B, paleosinkholes often developed close to active channels and backswamp areas generated.

marginal gravel lobes, all making a U-shaped or basin-form deposit (Fig. 7). In many cases, gravels form a progressive unconformity that indicates synsedimentary deformation (Fig. 8A). Less often, the U-shaped filling consists of well-sorted sands with trough cross-stratification and lamination. In some cases, several laterally connected U-shaped lutite bodies have been preserved (Fig. 8B). Among of the most interesting facies associated with paleosinkholes are disorganized gravels and gravels with vertical A-axis.

Taking into account the climate during the Pleistocene (García Ruiz and Martí Bono, 1994), the water availability was related to the existence of glaciers in the surrounding source areas, mainly the Pyrenees. The high and very variable water discharges due to ice melting in highlands create ideal conditions for braided-plain development (Boothroyd and Ashley, 1975; Miall, 1978; Rust, 1978; Maizels, 1997; Zielinski and Van Loon, 2003). Moreover, this provided the necessary water for karst development. Therefore, the genesis of sinkholes in the area was due to different conditions than those working at present, primarily those high natural water discharges.

Considering that fine deposits are usually eroded in gravel braided fluvial settings, as demonstrated by the very

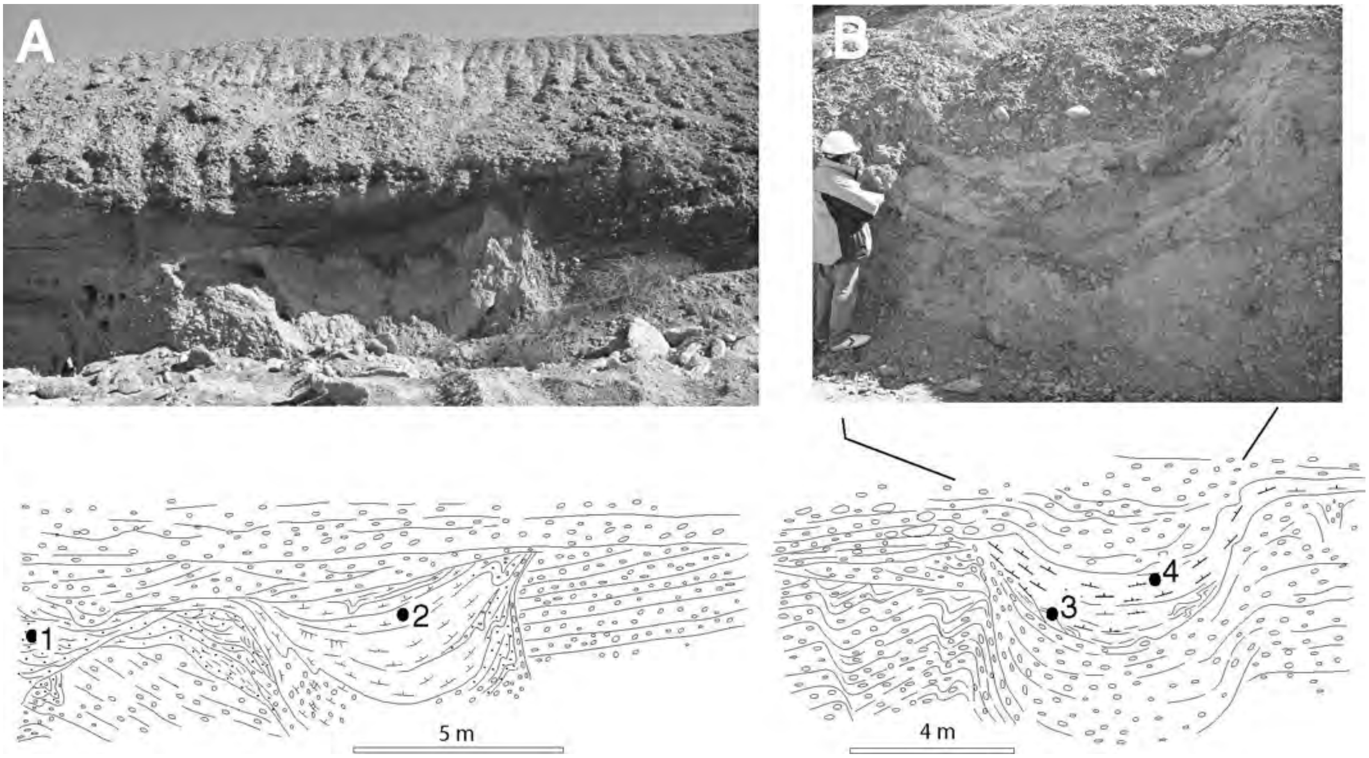

Figure 7. Photographs and cross-sections of two paleosinkholes filled with lutites and marginal deformed gravels. They are U-shaped deposits intercalated in tabular gravel beds where fine sediments were exceptionally well preserved in the fluvial context. A, the uppermost gravel levels are non-deformed and date the end of karstification. B, the uppermost gravels are still deformed. Samples taken for dating by optically stimulated luminescence are indicated. 1: 57, 880 ± 4,411; 2: 49, 876 ± 5,434; 3: 112,293 ± 10,059; 4: 111,662 ± 9,745 yr BP.

Figure 8. A, Early Pleistocene paleosinkhole with U-shaped sandy deposit; gravels in the right border show a progressive unconformity evincing synsedimentary deformation. B, a mainly tabular lutite bed with local thickenings interpreted as laterally connected small paleosinkholes.

rare presence of mudstones from flood-plain zones in the area, the negative relief of paleosinkholes made them excellent sites where fine sediments could be exceptionally preserved. This permitted us to analyze paleoenvironmental information that otherwise would have been lost.

When sinkholes developed in areas far from active flows but with high phreatic levels, they acted as small lakes in which lutites with rare marginal gravel lobes were deposited (Fig. 6B). During subsequent erosive episodes, the fine deposits could be preserved (Fig. 7). Wider lutite bodies such as those in Figure 8B are interpreted as flood-plain deposits preserved in extensive subsiding areas with different local subsidence rates, a feature that we have also recognized in present-day sinkhole fields (Figs. 3A and B). Moreover, when the phreatic level was almost coincident with the sedimentary surface, aeolian sands (Fig. 8A) were preserved within the sinkholes (Luzón et al., 2011). When sinkholes developed in active fluvial areas, disorganized gravels were deposited. Disorganized gravels and gravels with vertical A-axis clasts can also be generated by dissolution of the substratum, gravitational processes affecting previously deposited gravels, and dragging of the latter into the depressions.

Paleosinkholes also allow an approach to the duration of sinkholes development. OSL dating of two paleosinkholes (Fig. 7) indicates that they were filling for thousands of years. Assuming that deformation was synsedimentary, gives a rate of subsidence that ranges from 0.04 to 1 mm/yr.

Table 1. Mineralogical composition (%) of the whole sample and finer fractions of the Early Pleistocene samples.

	Early Pleistocene																			
	Whole sample						< 2 μ							20–2 μ						
Sample	Qtz	FK+Pl	Cal	Sid	Gyps.	Phyll.	Ilt	Sm	Chl-Kln	Kln	Sepiol.	Palyg.	I_{Sm}/I_{Ilt}	Ilt	Sm	Chl-Kln	Kln	Sepiol.	Palyg.	I_{Sm}/I_{Ilt}
1	22	3	32	2	...	41	71	11	18	✓	...	ev.	0.7	68	12	20	✓	...	...	0.8
2	29	3	31	...	...	37	73	8	19	✗	...	ev.	0.5	75	8	17	✗	...	...	0.5
3	15	4	35		...	46	72	15	13	✗	...	ev.	0.9	73	16	11	✗	...	ev.	1
4	21	4	32	2	...	41	75	10	15	✗	...	ev.	0.6	69	13	18	✗	...	ev.	0.9
5	28	4	37	ev.	...	30	74	12	14	✓	...	ev.	0.7	74	12	14	✓	...	ev.	0.7
6	10	4	48	...	...	37	72	17	11	✗	...	...	1.1	73	16	11	✗	...	...	1
7	9	2	60	...	...	29	76	16	8	✓	...	ev.	1	77	15	8	✓	...	ev.	0.9
8	21	4	12	...	28	35	68	23	9	✓	...	...	1.5	66	22	12	✓	...	...	1.5
9	18	2	48	...	2	30	72	19	9	✓	...	...	1.2	74	18	8	✓	...	ev.	1.1
10	27	3	14	ev.	23	33	78	22	0	✗	...	ev.	1.2	76	24	0	✗	...	...	1.4
11	38	4	23	...	...	38	69	19	12	✗	ev.	...	1.2	72	16	12	?	ev.	...	1
12	25	6	3	...	...	66	66	23	10	✓	...	...	1.6	69	20	11	✓	...	...	1.3
13	22	2	40	...	...	36	70	14	17	✓	...	...	0.9	73	10	17	✓	...	ev.	0.6
Mean	22	3	32			38	72	16	12				1	72	16	12				1

Notes: Qtz: quartz, FK: K-feldspar, Pl: plagioclase, Cal: calcite, Sid: siderite, Gyps.: gypsum, Phyll: phyllosilicates, Ilt: illite, Sm: smectite, Chl:chlorite, Kln: kaolinite, Sepiol.: sepiolite; Palyg.: palygorskite, ev.: evidences, ✓: presence, ✗: absence, ?: doubtful.

Mineralogical Data

When water flooded paleosinkholes, accumulation of lutites was frequent (Fig. 7). In these deposits, a detailed mineralogical study has been achieved.

X-ray diffraction analysis (Tables 1 and 2) showed that the samples consist of phyllosilicates, calcite, and quartz, with accessory plagioclase and K-feldspar and occasionally siderite and gypsum. In the finer fractions, illite is the main phyllosilicate, accompanied by chlorite+kaolinite and smectite. Evidences of palygorskite and, to a lesser extent, sepiolite have been observed, although they could not be quantified. Some differences in clay mineralogy can be seen if age of the paleosinkholes is taken into account. Early Pleistocene samples (Table 1) show on average higher smectite content than Middle-Late Pleistocene ones (Table 2) and, accordingly, the intensity ratio I_{Sm}/I_{Ilt} in the early samples is about twice as high. On the other hand, kaolinite is present in almost all the Middle-Late Pleistocene samples (Table 2), mainly in the 2 to 20 μm fraction, indicating that kaolinite crystals are frequently larger than 2 μm. Kaolinite is lacking in several Early Pleistocene samples and, in general, the chlorite+kaolinite content is lower (Table 1).

Scanning electron microscope observation of selected samples revealed the presence of fibrous phyllosilicates, mostly interpreted as palygorskite based on the X-ray diffraction data. These fibers are less than 3 μm long and appear as cement coating other grains and developed on the edges of planar particles (Fig. 9A). In samples where XRD patterns showed evidence of sepiolite, delicate sinuous fibers have been observed filling pores and again at the boundaries of planar particles (Fig. 9B).

Transmission electron microscope analyses supported the presence of illite, chlorite, Al-smectite (mainly beidellite and minor montmorillonite), and palygorskite. No evidence of kaolinite has been found, confirming the XRD data that indicate kaolinite grain sizes larger than 2 μm. Illite and chlorite occur very frequently as rounded anhedral-subhedral plates, while Al-smectite shows anhedral morphologies with irregular outlines or ragged edges. Palygorskite appears as single and double fibers, sometimes very small in size (0.1 μm).

The mineralogical differences between the Early and Middle-Late Pleistocene samples shown by XRD can be interpreted in different ways. The textural and morphological features mentioned above indicate that illite, chlorite, kaolinite, and Al-smectite are detrital constituents of the studied materials. Taking into account the distance between the location of the studied paleosinkholes, differences among sampled areas may be related with distinct relative influence of source areas during the Pleistocene. This hypothesis is supported by the fact that the only sample of Middle-Late Pleistocene age where kaolinite is clearly lacking (as in the Early Pleistocene samples), was collected at a geographic location close to the Early Pleistocene ones, so the absence of this mineral could be

Table 2. Mineralogical composition (%) of the whole sample and finer fractions of the Middle-Late Pleistocene samples.

	Middle-Late Pleistocene																			
	Whole sample						< 2 μ							20–2 μ						
Sample	Qtz	FK+Pl	Cal	Sid	Gyps.	Phyll.	Ilt	Sm	Chl-Kln	Kln	Sepiol.	Palyg.	I_{Sm}/I_{Ilt}	Ilt	Sm	Chl-Kln	Kln	Sepiol.	Palyg.	I_{Sm}/I_{Ilt}
1	52	3	31	⋯	⋯	13	66	13	20	✓	ev.	ev.	0.9	71	10	19	✓	⋯	ev.	0.6
2	59	3	28	⋯	⋯	10	71	10	21	✓	ev.	ev.	0.6	70	9	22	✓	⋯	ev.	0.5
3	26	3	32	⋯	⋯	39	77	9	13	?	ev.	ev.	0.5	76	7	17	✓	⋯	ev.	0.4
4	33	2	32	⋯	⋯	33	75	10	15	✓	⋯	⋯	0.6	73	7	20	✓	⋯	⋯	0.4
5	39	2	39	⋯	⋯	21	71	11	18	✓	ev.	⋯	0.7	67	11	22	✓	⋯	ev.	0.7
6	39	2	35	2	⋯	22	74	8	18	✓	⋯	⋯	0.5	74	7	19	✓	⋯	ev.	0.4
7	36	2	35	⋯	⋯	26	72	10	18	✓	ev.	ev.	0.6	75	8	17	?	⋯	⋯	0.4
8	37	2	30	⋯	⋯	31	76	9	15	✓	⋯	⋯	0.5	73	6	20	✓	⋯	⋯	0.4
9	30	2	31	2	⋯	34	69	9	22	?	ev.	ev.	0.6	74	5	21	✓	⋯	ev.	0.3
10	31	3	33	2	⋯	32	73	11	16	?	⋯	ev.	0.7	73	7	19	✓	⋯	ev.	0.4
11	27	1	33	⋯	⋯	39	71	10	20	?	⋯	ev.	0.6	73	8	19	✓	⋯	ev.	0.5
12	15	3	31	⋯	⋯	50	78	9	13	?	⋯	ev.	0.5	76	7	17	✓	⋯	⋯	0.4
13	21	3	26	⋯	⋯	49	78	8	14	?	⋯	ev.	0.4	77	6	18	✓	⋯	⋯	0.3
14	26	2	34	⋯	⋯	38	72	9	19	✓	⋯	ev.	0.5	74	10	16	✓	⋯	⋯	0.6
15	20	3	30	2	⋯	45	80	7	13	?	⋯	⋯	0.4	80	6	14	✓	⋯	⋯	0.3
16	30	3	32	2	⋯	33	86	7	8	?	⋯	⋯	0.4	80	7	13	✓	⋯	⋯	0.4
17	28	4	28	⋯	⋯	40	75	8	17	✓	⋯	⋯	0.5	79	5	16	✓	⋯	ev.	0.3
18	42	4	41	⋯	⋯	14	75	11	14	✓	⋯	⋯	0.7	76	9	15	✓	⋯	ev.	0.5
19	47	3	33	⋯	⋯	17	71	11	18	?	⋯	ev.	0.6	79	6	15	✓	⋯	ev.	0.3
20	41	6	4	2	⋯	47	78	11	11	✗	⋯	ev.	0.6	77	11	12	✗	⋯	⋯	0.6
Mean	34	3	31			32	74	10	16				0.6	75	8	18				0.4

Notes: Qtz: quartz, FK: K-feldspar, Pl: plagioclase, Cal: calcite, Sid: siderite, Gyps.: gypsum, Phyll: phyllosilicates, Ilt: illite, Sm: smectite, Chl:chlorite, Kln: kaolinite, Sepiol.: sepiolite; Palyg.: palygorskite, ev.: evidences, √: presence, ✗: absence, ?: doubtful.

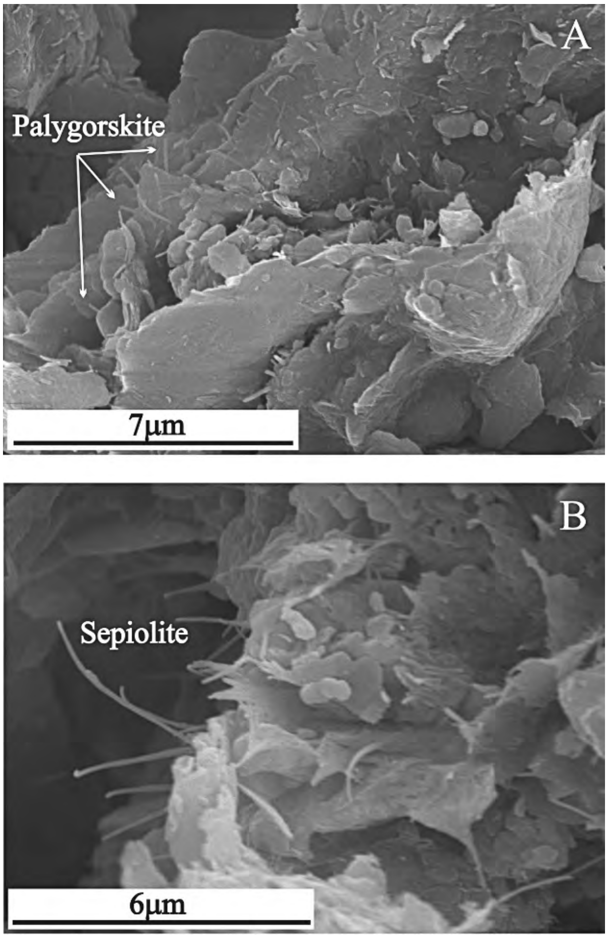

Figure 9. A, small fibers of authigenic palygorskite on the edge of planar phyllosilicates; in the lower right area, palygorskite fibers are covering other mineral grains. B, delicate fibrous sepiolite of authigenic origin.

related with its scarcity in the main source area that fed this site. However, if mineralogical differences were detected in the samples with different ages for the whole area, climate could be proposed as the main cause of such variations. In that case, the lower smectite contents and the widespread existence of kaolinite in the Late Pleistocene samples would be related to a change towards more humid conditions in the source areas, favoring the formation of kaolinite over smectite.

On the other hand, palygorskite and sepiolite show features indicative of authigenesis in both the early and later Pleistocene samples, in some cases, through the transformation of precursor clay minerals, probably smectite. The formation of these minerals would indicate arid to semi-arid environments during the Pleistocene, since the occurrence of palygorskite and sepiolite in continental lacustrine deposits, such as these, is indicative of those environments (Jones and Galán, 1988). This is in agreement with the possibility of repetitive glaciations during the Pleistocene.

Structural Data

Deformation of the Quaternary cover is an essential attribute of paleosinkholes, since normal and reverse faults, fractures, folds, and tilted beds are commonly observed either within or near them. Nevertheless, in the central Ebro Basin, not every deformation structure is genetically associated to karst subsidence and a detailed structural study is necessary to determine their origin from regional tectonics, karst activity, or occasional diapirism (Simón and Soriano, 1986; Arlegui and Simón, 2000). Karst subsidence usually produces local extensional structures (concentric normal faults and fractures), although contractional structures (reverse faults and reverse kink-bands) can appear as well if the sinking material shows high internal cohesion and low external cohesion with respect to the surrounding rock. Tectonic faults can be identified because they usually form conjugate systems striking parallel to the regional major horizontal stress trajectories, N-S to NNW-SSE, in our case.

Interaction between tectonic and karst deformation is also common. Many paleosinkhole boundaries are controlled by faults that show regional trends and suggest strong control by the existing structural pattern (Soriano et al., 2010). Although the structure of Figure 8A has been characterized as a paleosinkhole, it is bounded by NNW-SSE–striking faults that controlled the location of the sink's center by creating discontinuities that favored water infiltration and modified the mechanical properties of the Quaternary cover.

Besides discerning the possible relationships between karst and tectonics, the structural techniques provide information on the development stages of karst landforms. As an example, a paleokarst structure 3 km southwest of Fuentes de Ebro (Fig. 1), one of the many observed along the high-speed railway between Zaragoza and Barcelona, has been analyzed. The materials involved in the collapse are Neogene gypsum and marl, together with Quaternary gravel and sand (Fig. 10). The zone of maximum deformation involves partly folded and unstructured Quaternary gravel overlying fragments of gypsum and marls. High-angle reverse faults with opposite dips bound the collapsed zone and separate it from Neogene layers that are steeply tilted towards the center of the paleosinkhole. Far away, Neogene layers become horizontal. Analysis of the cross-section (Fig. 10B) points out that a part of the subsidence recorded by bed tilting occurred before deposition of the Quaternary deposits, since the latter lie unconformably on gypsum and marl beds dipping centripetally in the vicinity of the collapse. The restored cross-section (Fig. 10C) highlights this fact. When the beds are relocated to their original positions, a Neogene sequence would be placed in the vertical of the collapse zone; no such sequence is actually present beneath the Quaternary disconformity in the surrounding area. Fluvial activity continued after the collapse, as the thickening of gravel on top of the paleosinkhole indicates.

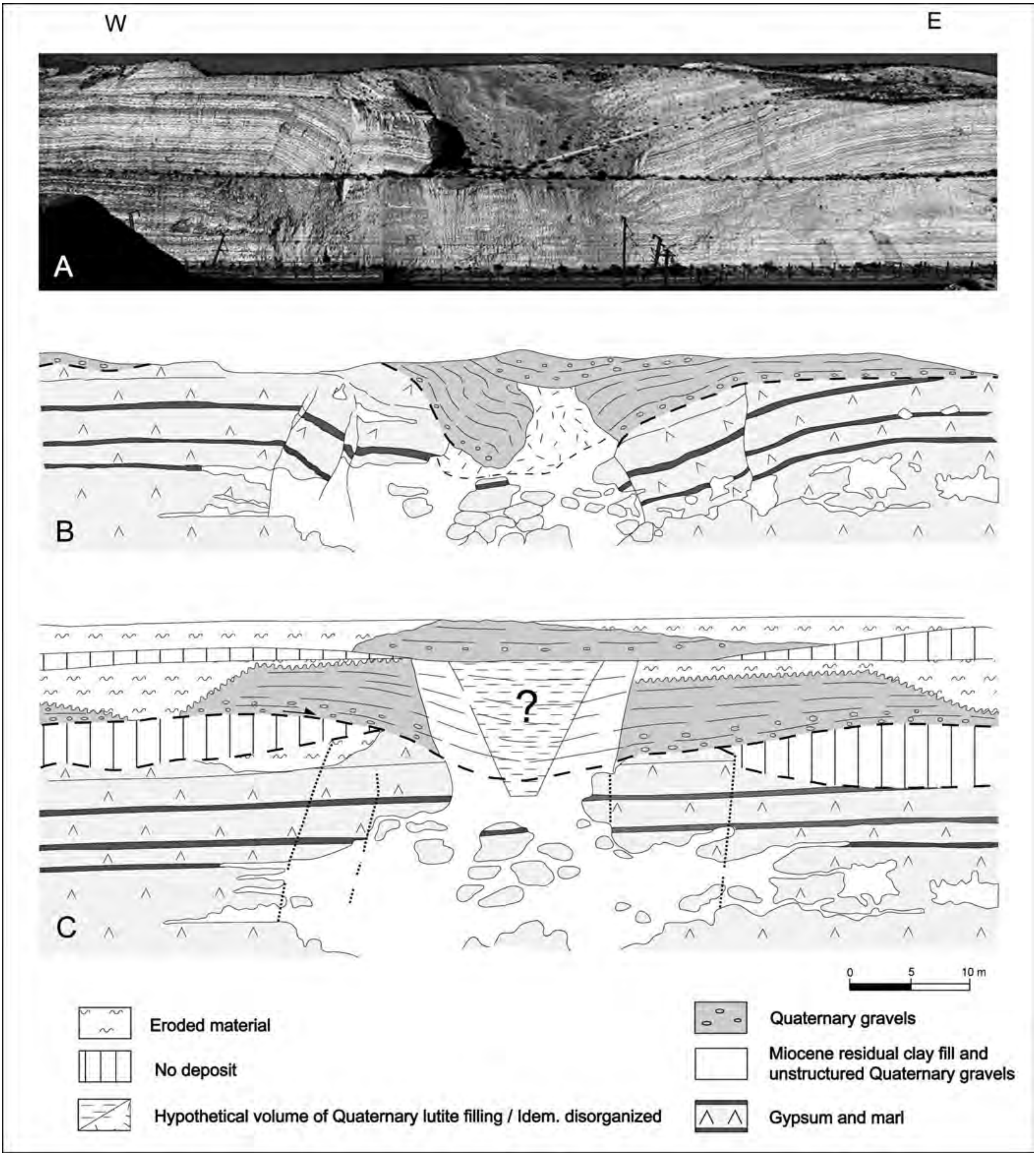

Figure 10. A and B, photograph and cross-section of a paleocollapse exposed on a slope of the high-speed railway, southwest of Fuentes de Ebro. In the lower right, several karst conduits can be seen. In the lower part of the collapsed area, blocks of Neogene materials appear, and in the upper part there are Quaternary gravels. The limiting Neogene beds are tilted and affected by reverse faults. C, restored cross-section that shows the occurrence of karstic subsidence previous to Quaternary sedimentation.

From the analysis of sedimentary and structural data, several evolutionary episodes of collapse, subsidence, and suffosion in the development of the paleosinkholes were recognized (Luzón et al., 2008). The sedimentological and geomorphological context determined the height of the phreatic level and whether the sinkholes were flooded.

CONCLUSIONS

The abundance of sinkholes and paleosinkholes in the central Ebro Basin indicates that karstification has been active since the Early Pleistocene. The development of Pleistocene sinkholes was only conditioned by natural factors. Their study reveals data that can not be obtained from the present-day sinkholes.

The access to the inner structure of paleosinkholes shows that, very often, tectonic faults conditioned the location of sinking centers where preferential dissolution and later suffosion took place. In addition, evolutionary episodes in which collapses and progressive subsidence took place can be inferred using structural and sedimentological analysis. Dating of paleosinkholes infillings indicated that synsedimentary filling took thousands of years.

The study of sedimentary features of Early Pleistocene and Late Pleistocene terraces in the Ebro Basin indicates that they were deposited in a gravel braided fluvial system, with high water volume and sediment availability, a situation that clearly differs from the present-day hydrological conditions. The braided pattern could have been favored by melting of ice in surrounding glaciated source areas, with fluctuating water discharges reaching the central part of the Ebro Basin. Genesis of sinkholes at that time was probably related to higher water supply.

Some of the studied paleosinkholes were flooded and acted as small lakes where fine sediments accumulated, recording the regional paleoenvironmental conditions. Widespread evidence of palygorskite and sepiolite neoformation suggests arid to semi-arid climatic conditions in agreement with glacial episodes. The mineralogical differences between distinct sampled areas were probably related to different source areas.

In spite of the present-day semi-arid climate of the central Ebro Basin, active development of sinkholes continues due to the irrigation at almost twenty times the quantity of water provided by natural precipitation in the zone. Infiltration of this causes variations in the water table, a high hydraulic gradient, dissolution of evaporites, and mobilization of detrital materials.

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B. Tobin and B. Schwartz – Quantifying concentrated and diffuse recharge in two marble karst aquifers: Big Spring and Tufa Spring, Sequoia and Kings Canyon National Parks, California, USA. *Journal of Cave and Karst Studies,* v. 74, no. 2, p. 186–196. DOI: 10.4311/2011JCKS0210

QUANTIFYING CONCENTRATED AND DIFFUSE RECHARGE IN TWO MARBLE KARST AQUIFERS: BIG SPRING AND TUFA SPRING, SEQUOIA AND KINGS CANYON NATIONAL PARKS, CALIFORNIA, USA

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Abstract: To improve water management in mountain systems, it is essential that we understand how water moves through them. Researchers have documented the importance of porous-media aquifers in mountain river systems, but no previous research has explicitly included mountain karst as part of conceptual models. To do so, we used discharge and geochemical parameters measured along upstream-to-downstream transects under high- and low-flow conditions in 2010 to assess storage characteristics and geochemical properties of two mountain marble-karst systems, the Big Spring and Tufa Spring systems in Sequoia and Kings Canyon National Parks, California. During both high- and low-flow conditions, we quantified the relative contributions of concentrated and diffuse recharge in both karst systems, and we used a simple linear mixing model to calculate specific conductance in unsampled diffuse sources that ranged from 34 μS cm^{-1} to 257 μS cm^{-1}. Data show that the Big Spring system has a much higher seasonal storage capacity than the Tufa Spring system, and that diffuse sources dominate discharge and geochemistry under baseflow conditions in both aquifer systems. Baseflow in Big Spring was 0.114 m^3 s^{-1} and in Tufa Spring it was 0.022 m^3 s^{-1}. Snowmelt-derived allogenic recharge dominates both systems during high discharge periods, measured at Big Spring as 0.182 m^3 s^{-1} and Tufa Spring as 0.220 m^3 s^{-1}. A conceptual model is proposed that explicitly includes the effects of karst aquifers on mountain hydrology when karst is present in the basin.

Introduction

Understanding how water enters and is stored in karst aquifers is essential to characterizing storage properties, as well as assessing the vulnerability of an aquifer to contamination (Scanlon et al., 2003). In mountain aquifer systems, little is known about storage and vulnerability relative to our understanding of larger aquifers that are more intensively used and studied. For example, the Edwards Aquifer in central Texas is intensively utilized for municipal and agricultural water, and many studies have been performed to assess its storage properties and vulnerability (Scanlon et al., 2003; Musgrove and Banner, 2004; Slade et al., 1986). In mountain aquifers, however, an individual aquifer is rarely utilized directly, and it is often relatively small and difficult to access for study. Despite this, the combined effects of many small mountain aquifer systems can be important because they contribute significant amounts of water to mountain river systems (Clow et al., 2003) that may be heavily or entirely exploited for municipal, agricultural, and industrial uses as they leave the mountain range. In most cases, although small mountain aquifers can be vitally important to the surface water system, especially during dry seasons after snowmelt, they are not well characterized or studied because snowmelt dominates annual discharge. As a result, little is known about how storage varies spatially along an elevational gradient, as a function of rock type or other geologic materials, or how vulnerable these smaller aquifers are to contamination and climate change.

Clow et al. (2003) built a conceptual model of groundwater systems in mountain ranges that describes their importance in storing water and influencing biogeochemical processes. They found that aquifers in unconsolidated porous media in the Colorado Rockies, USA, play a significant role in storing water over seasonal timescales. Although they were able to quantify the roles these aquifers play in contributing to the stream systems, the systems they focused on did not include karst aquifers. Karst aquifers are often conceptualized as a network of conduits that are surrounded by and connected to a matrix, each having its own continuum of properties (Bakalowicz, 2005). To better understand storage properties and potential flow paths in a karst aquifer, it is important to quantify how the conduit and matrix components, as well as any associated porous media such as soils and glacial sediments, contribute to controlling discharge and geochemistry at a spring. The relative importance of each of these components depends on a variety of geological variables, such as matrix

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porosity, fracture frequency and aperture, epikarst thickness, soil thickness, and phreatic storage, that ultimately affect both water storage and contaminant movement in an aquifer (Ford and Williams, 2007).

In the Sierra Nevada in Sequoia and Kings Canyon National Parks (SEKI), California (Fig. 1), karst aquifers, formed in numerous long and narrow bands of marble in the Kaweah River basin, contribute substantially to

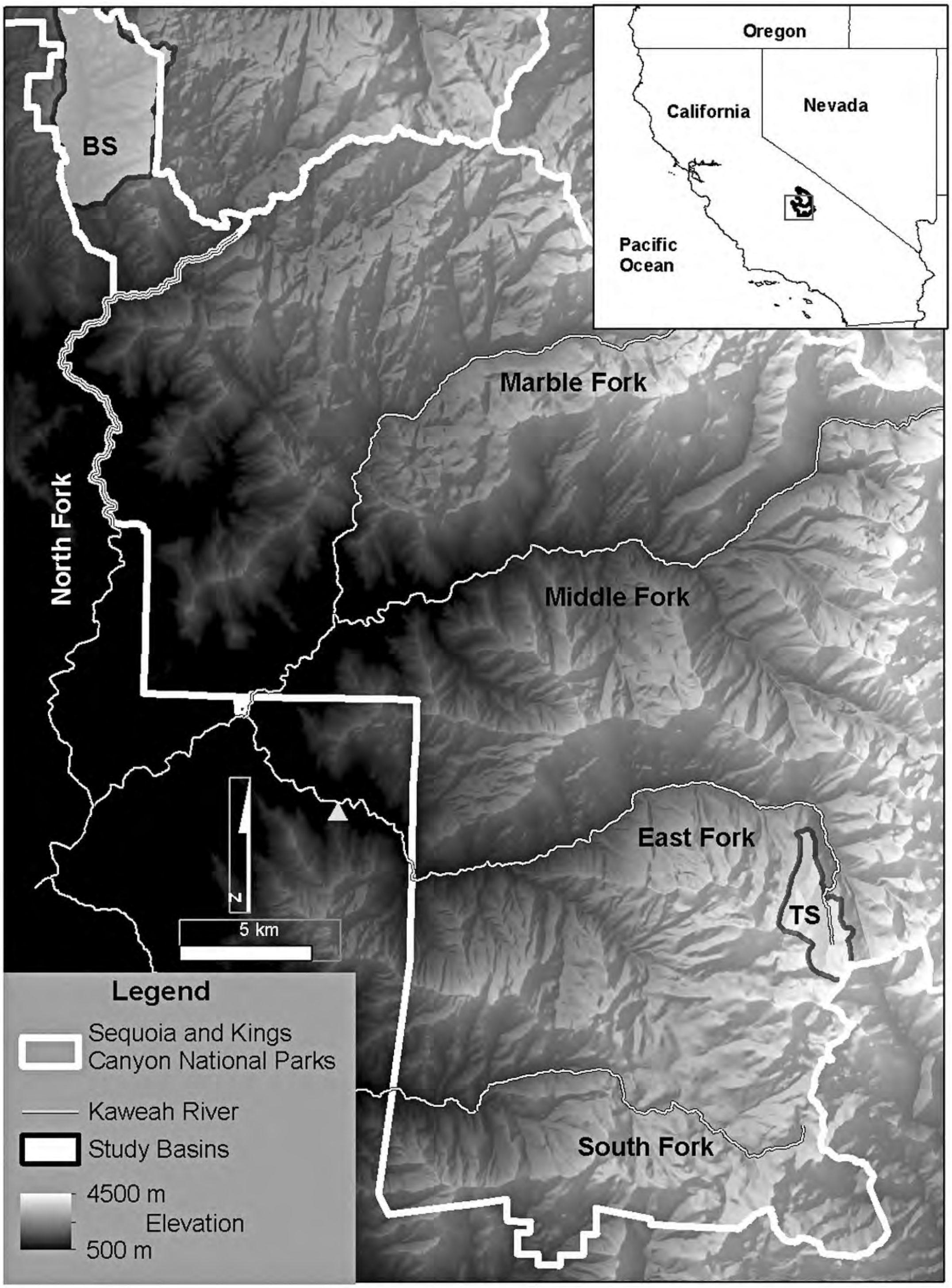

Figure 1. Drainage basin locations. Inset map shows Sequoia and Kings Canyon National Parks and the study location (rectangle) in the state of California, USA. Groundwater systems studied are noted by letters BS for Big Spring and TS for Tufa Spring. USGS gauging site 11208731, on the East Fork, is noted by a gray triangle.

maintaining river flows during the dry season (Despain, 2006; Tobin and Doctor, 2009). However, with only a few exceptions, even the most basic quantitative data describing how, how much, where, and when water enters and moves through these groundwater systems, and what their geochemical properties are, is nonexistent.

Six of the karst aquifers in the Kaweah River basin provide the only known habitat for two endemic aquatic species, an isopod (*Bomanecellus sequoia*) and an undescribed flatworm. Recent applications of fire-retardants in one of these watersheds highlighted the need for at least a basic understanding of how the systems function before management strategies can be implemented. However, to develop realistic and effective management strategies for both the surface and subsurface systems associated with these and other aquifers in SEKI, resource managers first require the development of conceptual models that describe how water and mobilized contaminants move through the aquifer systems.

Flow dynamics and pollutant type have been shown to play major roles in determining the overall impact a contaminant has on a karst ecosystem. For example, Loop and White (2001) documented that if contaminants enter the karst system via concentrated recharge, they remain primarily in the conduit systems. Conversely, if contaminants enter a system via diffuse infiltration, they are likely to behave more similarly to contaminants in typical porous media and fractured aquifers. While SEKI karst systems contain both rapid and slow flowpaths, the systems are additionally complicated by the fact that they may include flow derived from multiple karstic sources, as well as from adjacent non-karstic groundwater sources and varying amounts and types of overlying porous media such as glacial deposit. In Indiana, Iqbal and Krothe (1995) documented multiple flow paths in a flat-lying mantled karst, where movement through overlying unconsolidated materials is typically dominated by laminar flow and transport in the karst bedrock is usually through conduits with turbulent flow. Although their study occurred in a different geologic setting, it showed that karst systems overlain by porous media may have substantial amounts of water stored in an overlying, perched aquifer, whether this is part of the epikarst or not.

SEKI receives airborne contaminants of local, national, and international origins. Significant amounts of lead, cadmium, mercury, and other heavy metals, as well as currently and previously used pesticides, have been documented in snow, lake sediment, and both wet and dry atmosphere samples collected in SEKI (Landers et al., 2010). The negative effects of these contaminants on aquatic ecosystems have been repeatedly documented (Hafner et al., 2007; Schwint et al., 2008), and research in the Kaweah River basin in SEKI has shown that pollutants deposited on the land surface are easily mobilized and transported into aquatic systems via seasonal precipitation runoff and snowmelt (Engle et al., 2008). In certain areas, contaminants are transported into and through karst aquifers before being discharged into the larger river system (Despain and Tobin, 2010).

One of the major issues hindering our understanding of how potential contaminants enter and move through small mountain karst systems is the lack of a generalized conceptual model describing storage and flow in these systems. Consequently, there is a need for a conceptual hydrogeologic model that can be used as a foundation for additional work in SEKI and elsewhere. Clow et al. (2003) provide a starting point by describing storage and recharge in non-karstic mountain aquifer systems. Besides the lack of karst in their study system, a difference between their system and those found in the Kaweah River basin is the significantly lower quantities and thicknesses of unconsolidated glacial and landslide deposits in the Kaweah. Without extensive unconsolidated deposits, dry-season baseflow should be extremely low in the Kaweah. However, the opposite has been documented. Peterson et al. (2008) found that, relative to basin size, baseflow was higher in the Kaweah than in surrounding river basins with more substantial glacial deposits. This finding strongly suggests that different storage components must be supporting baseflow. In the Kaweah Basin, the most likely candidate is karst.

Because of their diversity and distribution across a large elevation gradient, the karstified marble aquifers in SEKI provide ideal study systems for adapting the conceptual model of mountain aquifer systems to include the effects of karst on storage, baseflow, and stream chemistry. To achieve this, we measured upstream-to-downstream variations in water quantity and chemistry in two aquifer systems, the Tufa Spring system (Fig. 2) and the Big Spring system (Fig. 3). These systems are typical of karstic systems in the Kaweah Basin in that they include narrow bands of marble bedrock that are at least partially mantled by overlying unconsolidated glacial and landslide materials. These unconsolidated deposits add another layer of complexity to storage, flow, and recharge processes already known to occur in the karstic portion of the aquifer systems. By measuring all concentrated recharge sources in both stream-aquifer systems and by measuring changes in chemistry as water moves from upstream sink-points, through multiple sections of the karst aquifer, and eventually rises at a spring, it is possible to calculate the contributions of concentrated and diffuse recharge components to spring discharge, as well as to constrain both the potential source areas and the basic geochemistry of diffuse recharge.

The primary goals of this research were to determine the source locations for and quantify amounts of water in two marble karst systems, to determine the proportions derived from diffuse karst and unconsolidated sources versus concentrated sources of recharge such as sinking streams during both high- and low-flow conditions, and to adapt

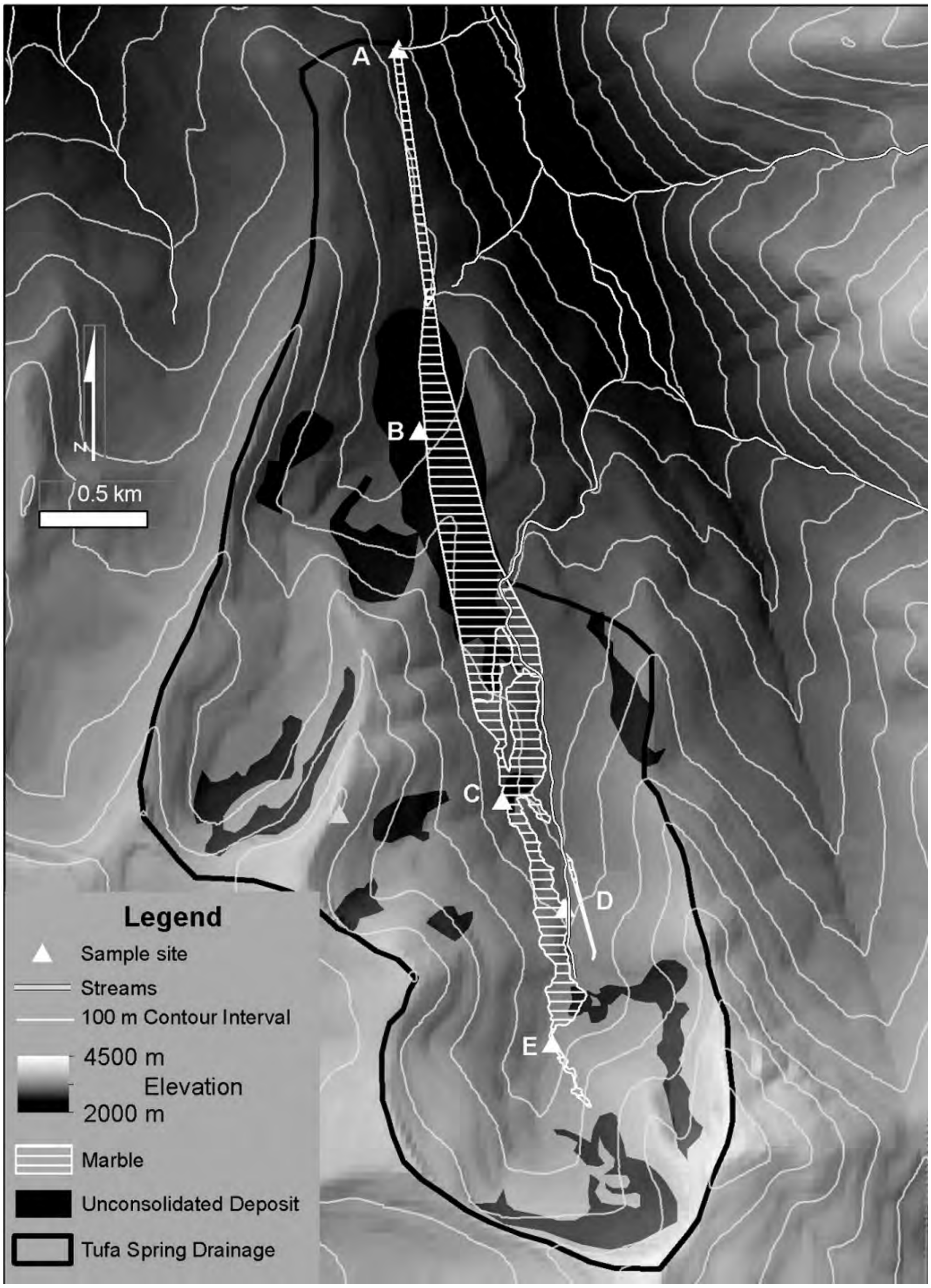

Figure 2. Tufa Spring geology showing the spatial relationship between the marble bedrock and unconsolidated deposits. Sampling locations are marked: A, Cirque Stream; B, White Chief Spring; C, White Chief Lake; D, Eagle Sink; and E, Tufa Spring, the outlet of the system.

and modify the mountain aquifer conceptual model to include the effects of karst.

Although it is a concern to resource managers in SEKI and elsewhere, this study does not specifically address the fate and transport of contaminants in mountain marble karst aquifers. Instead, this study focuses on seasonal changes in groundwater contributions from the two largest karst aquifers in the Kaweah River basin to provide insight into aquifer properties such as storage, concentrated versus diffuse sources, relative residence times, and generalized flow paths in the aquifer. In doing this, the study provides a hydrogeological and geochemical framework upon which future studies about fate and transport of contaminants, monitoring protocols, and management strategies can be built.

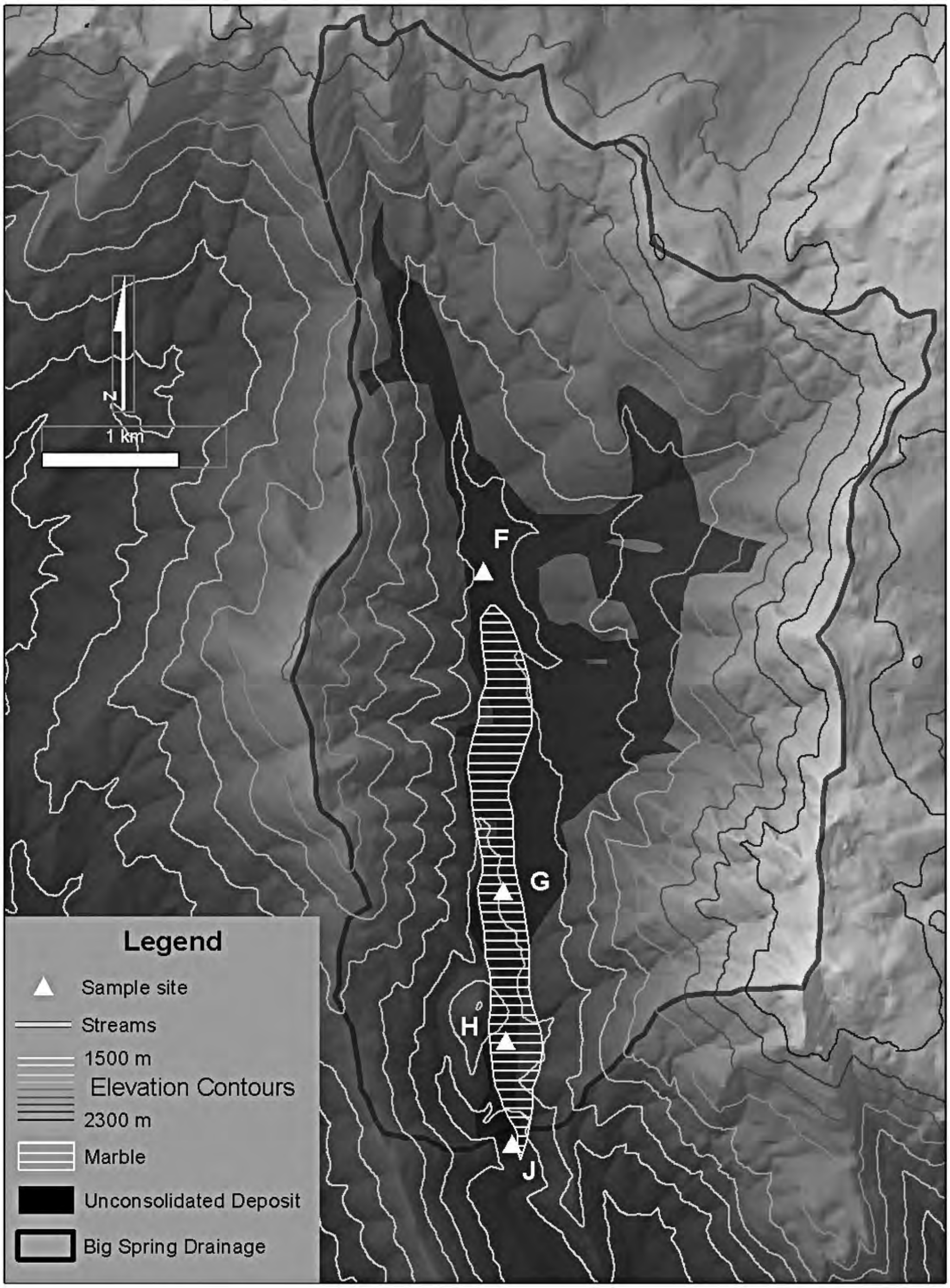

Figure 3. Big Spring geology showing the spatial relationship between the bedrock marble and unconsolidated deposits. Sampling locations are marked: F, Redwood Creek; G, White Rapids (Lilburn Cave main conduit); H, Z-Room (Lilburn Cave main conduit); and J, Big Spring, the outlet of the system.

STUDY LOCATION

SEKI, in the southern Sierra Nevada of California, contains approximately fifty documented karst aquifers, primarily in the Kaweah River basin (Fig. 1). The river basin has a catchment of 1080 km^2 and ranges in elevation from approximately 300 m at the base of the Sierra Nevada, to over 4,000 m in the upper reaches of the drainage. Spring discharge from karst aquifers is a significant source of baseflow into all forks of the Kaweah River during the dry season. Despain (2006) documented that Tufa Spring contributed approximately 30 percent of the discharge of the entire East Fork, as measured at the USGS gauging station near the confluence with the Middle Fork, during low-flow conditions in 2003.

The region experiences a Mediterranean climate, with most precipitation falling during winter months. Precipitation varies along an elevational gradient, with an annual average of 35 cm at 500 m elevation and 100 cm at 2000 m. At elevations above 2000 m, precipitation is primarily in the form of snow that begins melting in late spring and supplies large amounts of melt water to the river system during early summer. The wet season is followed by a long dry period through the summer months and into the fall. As snowmelt decreases throughout the summer, discharge from karst aquifers in the park supplies an increasingly larger proportion of water in the rivers (Despain, 2006).

Surface geology in the Kaweah River basin is dominated by the granite to grano-diorites of the larger Sierran Batholith (Sisson and Moore, 1994). A series of northwest-southeast trending bands of schists, quartzites, and marbles along the western edge of the mountain range are derived from Mesozoic-aged marine sediments. The highly karstified marbles are bounded by relatively insoluble non-karstic rocks and are excellent examples of marble-stripe karst as described by Lauritzen (2001). Unlike karst drainage basins developed in regions with extensive horizontally bedded carbonates and substantially less topographic relief, the contributing areas associated with stripe-karst aquifers have distinct boundaries. Typically, each band of marble is exposed in only one or two surface drainage basins, which constrains the areas of potential karstic and contributing drainage.

Water emerging at Tufa Spring is derived from two high-elevation basins (Despain, 2006). More than forty caves have been documented in these basins, the longest of which are White Chief Cave, with approximately 1.6 km of mapped passage, and Cirque Cave, with approximately 1 km. The Big Spring system drains a larger basin in a mid-elevation coniferous forest and contains the longest known cave in California: Lilburn Cave, with over 32 km of mapped passage.

Many karst aquifers in SEKI are mantled by significant deposits of unconsolidated material such as alluvium, talus, and glacial or landslide deposits. The Big Spring and Tufa Spring aquifers are both mantled to varying degrees by these deposits. More than half of the marble that contains the Tufa Spring system is exposed in outcrops, with the remainder mantled by talus, alluvium, or glacial moraines (Fig. 2). The Big Spring system is almost entirely mantled by a series of mature landslide deposits, with only a few small surface outcrops of marble exposed in the basin (Fig. 3).

Methods

In 2010, water samples and discharge measurements were collected during high-flow (July–August) and low-flow (September–October) conditions at a series of points along the Big Spring and Tufa Spring stream-aquifer systems. Previous dye-trace studies at Tufa Spring (Despain, 2006) and Big Spring (Tinsley et al., 1981) documented the flow routes used in the analyses and discussion of this paper.

Water samples (125 mL) were collected from all surface streams and springs, as well as from a number of sites in caves. Sample collection and preservation in the field followed published USGS protocols (Shelton, 1994) for major cation, major anion, and nutrient analyses. Field protocol included on-site measurement of specific conductance, dissolved oxygen, pH, and temperature. Each sample was filtered through a 0.45 μm syringe filter. Samples were refrigerated and analyzed as soon as possible on Dionex ICS-1600 ion chromatographs at Texas State University to measure Ca^{2+}, K^+, Mg^{2+}, Na^+, NO_3^-, PO_4^{3-}, SO_4^{2-}, Cl^-, Br^-, and F^-. Alkalinity was measured by titration in the same lab using the inflection-point method (Rounds, 2006).

Discharge measurements were collected using either a pygmy meter or a turbine flow-meter (a Global Water hand-held flow meter). Springs and streams were gauged at sites having as uniform a cross-section and flow as possible, and with minimal riffles. In rocky streams, whenever possible, the most consolidated section of a stream channel having the fewest flow routes around boulders was used to minimize errors. However, due to the steep and rocky nature of nearly all stream channels and spring runs, the accuracy of discharge measurements is estimated to be ± 10%.

In the Big Spring system, surface water samples were collected upstream of the karst system, at each known surface tributary upstream of where it recharges the karst system, and at Big Spring. Samples were collected at two locations along the main stream in Lilburn Cave (sites G and H on Fig. 3) and at each known subsurface tributary to the main stream in the cave. Due to low flows in each surface tributary during the August sampling and no flowing water at these sampling sites in September, data from these sites could not be included in our analyses.

The Tufa Spring system is a more complex system in which water flows sequentially through a series of karst aquifers and short surface streams before finally emerging at Tufa Spring. Additionally, there are two non-karstic surface streams, White Chief Creek and Eagle Creek, flowing directly into the aquifer via sink points. Samples were collected at sinkpoints upstream of each karst segment, at each known infeeder into the system, and at each spring (Fig. 2).

To quantify the relative importance of diffuse flow to discharge at any given point along the aquifer transect, a mixing model, modified from Lackey and Krothe (1996), was used that incorporates discharge (Q), and geochemical parameters: either specific conductance or ion concentration. With this method, geochemical properties can be determined for water that is added between two measured points in a system. In more detail, a measured geochemical parameter (specific conductance or any major ion can be used in these chemically undersaturated systems) at an upstream site (C_U) is multiplied by the flow measured at the upstream site (Q_U) and then subtracted from the geochemical parameter measured downstream (C_D) multiplied by the flow at the downstream site (Q_D). This value is then divided by the difference in measured discharge between upstream and downstream sites ($Q_D - Q_U = Q_{dif}$) to calculate the geochemical parameter of interest that is added to the flow system between two measured locations. The entire expression can be written as $C_{dif} = [(C_D Q_D) - (C_U Q_U)]/Q_{dif}$. Because we have measured all concentrated recharge sources, the additional water is assumed to be from diffuse sources. To calculate values for each diffuse input (1 and 2 on Fig. 4 and 3, 4, and 5 in Fig. 5), the measured values for the site(s) immediately upstream were used for the upstream values, and the site immediately downstream was used for the downstream values.

The model assumes that measured sink-point discharge values represent all concentrated recharge locations and that any additional water measured at a downstream site is from diffuse inputs. Due to the limited extent of the marble karst in the basins, we believe that we identified and quantified most, if not all, surface tributaries. Additional assumptions of the model are that minimal chemical evolution is occurring along the main flow path of the system and that additional solutes entering the system are derived from the diffuse recharge and flow components. In support of these assumptions, flow times through the aquifers are fast, with water traveling the length of the system in approximately one day (Despain, 2006; Tobin and Doctor, 2009). Additional evidences that minimal dissolution is occurring along the main conduit in both systems is that there is almost no change in the saturation index along the main stream conduit in Lilburn Cave and there are negligible changes in measured conductivity and calcium, bicarbonate, and other ions along the main stream conduit during both sampling periods, indicating minimal dissolution along the main conduit.

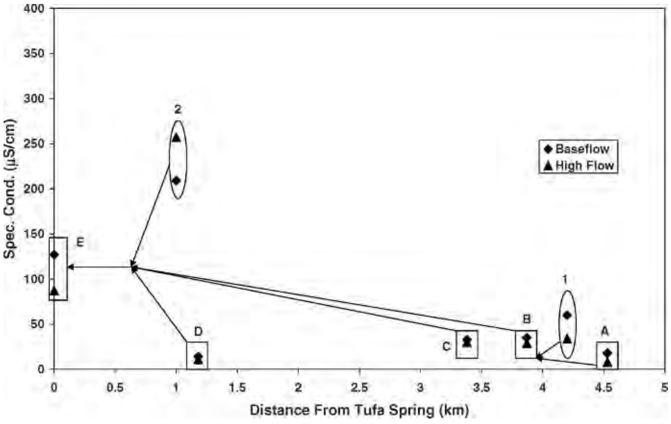

Figure 4. Downstream change in specific conductance values in the Tufa Springs system measured at surface infeeders (A, C, D) and springs (B, E) and calculated for diffuse inputs (1, 2), showing assumed mixing scenarios. Data are derived from values in Table 1.

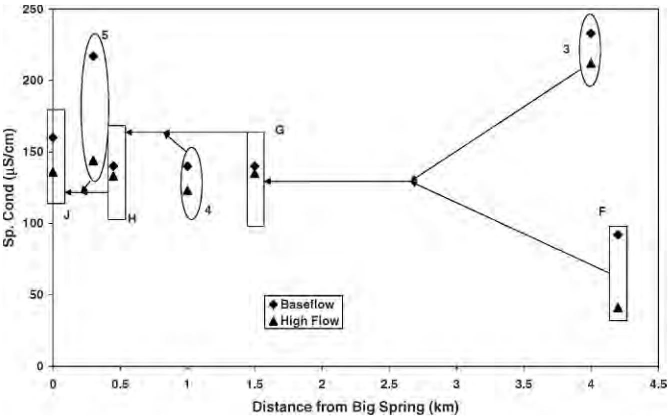

Figure 5. Downstream change in specific conductance values in the Big Spring system measured at the main surface infeeder (F), two cave stream sites (G, H), and Big Spring (J) and calculated for diffuse inputs (3, 4, 5), showing assumed mixing scenario. Data are derived from values in Table 2.

RESULTS AND DISCUSSION

Tufa and Big Springs exhibit different responses during the dry season. Tufa Spring discharge decreased by an order of magnitude, while Big Spring discharge decreased by less than 50%. Tufa Spring also showed much larger differences in the proportions of discharge derived from concentrated and diffuse flow under different flow regimes. Mixing-model results show that the proportion of diffuse water in the Tufa Spring system was 41% during high flow and 68% during baseflow (Table 1). The magnitude of the change in discharge values in the system, however, suggests that, although a large portion of the discharge was derived from diffuse recharge under both conditions, the average residence time in the Tufa Spring system is relatively low. Discharge decreased from 0.22 $m^3\ s^{-1}$ to 0.02 $m^3\ s^{-1}$ between high flow and baseflow periods. Calculated values in the Tufa Spring system show high conductivity and ionic concentrations for diffuse input source 2 in Figure 4, between points D and E in Figure 2, which is consistent with values from other karst springs in SEKI that are dominated by diffuse contributions; small karst springs without any known concentrated recharge have conductivity values ranging from 350 µS cm^{-1} to 650 µS cm^{-1}). Low conductivity values calculated for diffuse source 1, located between points A and B, indicate that these waters are likely flowing quickly through high-permeability, younger deposits and have less time for water-rock interaction. These results are supported by geologic

Table 1. Mixing-model results along the Tufa Spring transect. Letters and numbers in parentheses correspond to locations shown on Figure 4. Diffuse flow sampling site rows are calculated values.

	July						October					
Sampling Sites	Discharge ($m^3\ s^{-1}$)	Proportion of Total Flow	Spec. Cond. ($\mu S\ cm^{-1}$)	Ca^{2+}	Mg^{2+}	HCO_3^-	Discharge ($m^3\ s^{-1}$)	Proportion of Total Flow	Spec. Cond. ($\mu S\ cm^{-1}$)	Ca^{2+}	Mg^{2+}	HCO_3^-
Cirque Cave	0.0389	0.18	8.00	1.70	0.11	4.92	0.0023	0.13	18.00	4.74	0.30	12.32
Diffuse Flow	0.0291	0.13	34.00	11.46	0.28	30.85	0.0028	0.10	60.00	22.23	0.42	59.31
White Chief Spring[a]	0.0681	0.31	29.00	5.89	0.18	16.01	0.0051	0.23	35.00	11.91	0.35	32.75
White Chief Lake	0.0451	0.20	30.00	5.95	0.17	14.17	0.0004	0.03	33.00	9.96	0.16	9.86
Eagle Sink	0.0468	0.21	11.00	2.53	0.14	8.00	0.0042	0.19	14.00	3.48	0.27	11.09
Diffuse Flow	0.0605	0.27	257.04	71.42	5.90	174.30	0.0079	0.55	209.00	58.91	5.69	217.21
Tufa Spring[b]	0.2204	1.00	87.00	22.89	1.74	56.68	0.0221	1.00	127.00	36.10	3.26	129.40

[a] Cirque + Diffuse.
[b] White Chief Spring + White Chief Lake + Eagle Sink + Diffuse.

observations in these two areas. Diffuse source 2 water is derived from thick and poorly sorted glacial deposits lying directly on marble, while source 1 water flows through more recent, primarily granitic talus deposits. During the high-flow period, source 2 had generally higher calculated values than during low flow. Although we have minimal evidence in support of this, one explanation is that this water may be recharging via piston flow through the glacial deposits. Under this scenario, there may be a perched longer-term (annual) storage component in the system that is displaced as recent snowmelt water infiltrates and flushes it out. Then, during low-flow conditions, all the older water has been displaced and only more recent low-conductivity snowmelt waters remain and are recharging the system.

Big Spring responds differently to seasonal changes in the proportions of discharge derived from diffuse and concentrated recharge. Using only the difference between concentrated recharge and spring discharge to quantify diffuse recharge, the high-flow period in August appears to be dominated by diffuse flow, accounting for 72% of the discharge at Big Spring (Table 2). However, during September the percentage actually decreased to 52%, which is surprising because the diffuse contribution would be expected to increase as rapid recharge, dominated by snowmelt, decreases throughout the dry season. Calculated values for specific conductance and chemical concentrations in diffuse source 5 in Figure 5 during August high-flow conditions are lower, in some cases substantially, than might be expected for diffuse flow in this system, which are approximately the values found during September. For example, the specific conductivity was 144 μS cm^{-1} during high flow versus 217 μS cm^{-1} during low flow. This likely reflects the contributions of undetected and unmeasured sources of concentrated recharge into the system. In reality, the apparent decrease in the proportion of diffuse contribution to Big Spring between high flow and low flow is likely related to hidden sources of concentrated recharge, which violates the first assumption of the mixing model, that all unaccounted-for discharge is derived from diffuse sources. The lower specific conductivity and ion concentrations (Table 2) for August supports this, and subsequent field observations found that a series of small but unmeasured surface infeeders were likely still flowing during the August sampling, but were sinking upstream from our previously established sampling sites. If this was the case, then water was following unseen rapid flowpaths through and under landslide deposits before directly recharging the karst aquifer. During low-flow conditions in the Big Spring system, calculated specific conductance values for all three diffuse sources (3, 4, and 5) are relatively high, which is consistent with what is expected for water flowing slowly through overlying weathered unconsolidated materials and small fractures in the karst. Calculated values are also consistent with the specific conductivity of drip waters in Lilburn Cave (measured between 160 and 200 μS cm^{-1}), which are slightly higher

Table 2. Mixing-model results along the Big Spring transect. Letters and numbers in parentheses correspond to locations shown on Figure 5. Diffuse flow sampling site rows are calculated values.

	August						September					
Sampling Sites	Discharge ($m^3\ s^{-1}$)	Proportion of Total Flow	Spec. Cond. ($\mu S\ cm^{-1}$)	Ca^{2+}	Mg^{2+}	HCO_3^-	Discharge ($m^3\ s^{-1}$)	Proportion of Total Flow	Spec. Cond. ($\mu S\ cm^{-1}$)	Ca^{2+}	Mg^{2+}	HCO_3^-
Redwood Creek (F)	0.0520	0.28	41.00	5.51	0.64	27.70	0.0541	0.48	92	5.92	0.7	30.81
Diffuse (3)	0.0624	0.34	212.00	58.32	2.21	201.48	0.0282	0.24	233	102.4	3.88	344.88
White Rapids (G)[a]	0.1145	0.62	135.00	34.56	1.50	123.00	0.0823	0.72	140	38.72	1.78	135.50
Diffuse (4)	0.0210	0.12	123.00	29.72	1.15	123.00	0.0023	0.02	140	27.06	0	135.50
Z-Room (H)[b]	0.1355	0.74	133.00	33.78	1.45	123.00	0.0846	0.74	140	38.37	1.7	135.50
Diffuse (5)	0.0466	0.26	144.00	35.13	1.45	73.00	0.0297	0.26	217	38.53	1.69	135.53
Big Spring (J)[c]	0.1821	1.00	136.00	34.14	1.45	110.00	0.1143	1.00	160	38.41	1.7	135.50

[a] Redwood Creek + Diffuse.
[b] White Rapids + Diffuse.
[c] Z-Room + Diffuse.

than the calculated high-flow, diffuse sources at points 4 and 5 in Figure 5 and Table 2.

In both the Tufa Spring and Big Spring systems, ion concentrations and total solute load increase as water moves from the headwater regions toward the springs. This is expected in groundwater systems due to water-rock interactions as water moves through the system. However, this research has shown that the reasons for increased solute loads may have little to do with the length of the primary conduit system and much more to do with inputs from diffuse sources: either small fractures and epikarst sources or overlying unconsolidated materials. In both systems, similar trends occur in ionic concentrations and specific conductance. Upstream tributaries that flow over or through non-carbonates have relatively low concentrations, while calculated diffuse inputs and locations sampled farther downstream have higher concentrations (Tables 1 and 2). While this is consistent with a model of downstream chemical evolution in which solute load increases as a function of residence time, system length, and rates of interactions with geologic materials, measured changes in water chemistry in the Big Spring system indicate that increased solute load is dominated by diffuse inputs along the main flow path rather than by dissolution of marble in the main stream conduit. In accessible portions of the main stream conduit where there is little observed diffuse or other input, specific conductance and ion concentrations stay relatively constant between sampling sites (Fig. 5), and the water is consistently undersaturated with respect to calcite. Only when additional water enters the system between the accessible cave and Big Spring does the chemistry change significantly.

Samples taken at Tufa Spring were also undersaturated with respect to calcite during both sampling periods. Because of the quick flow times in the aquifer, less than one day for storm pulses to move through the system, it is likely that measured changes in the ionic concentrations and specific conductance are due to seasonally variable contributions of diffuse flow into the system, rather than chemical evolution of waters along the main conduit, which is inaccessible.

CONCLUSIONS

Using simple methods and relatively easy to obtain field data, this study quantified the amounts of water derived from concentrated and diffuse recharge sources in the Big Spring and Tufa Spring karst systems. The proportion of flow derived from each type of recharge varies temporally, with concentrated recharge dominating during high flow and diffuse recharge dominating during baseflow conditions. Our data indicate that, although karst aquifers in Sequoia and Kings Canyon National Parks are complex systems with multiple flow paths, storage compartments, and residence times, many of them may be relatively easy to delineate and characterize because of their limited spatial extent and narrow geologic constraints.

This research highlights the importance of quantifying karstic aquifers in mountain hydrologic systems. Currently, karstic groundwater storage in the Kaweah River basin is not included in the conceptual model as described by Clow et al. (2003), nor is it included in any current water management plans or basin models. In addition, high baseflow discharge in the Kaweah River, relative to basin size and the number and size of porous media aquifers in the basin, does not follow the expected trend in which lesser amounts of these aquifer materials correlate with lower dry-season baseflow (Peterson et al. 2008). These findings highlight the importance of and need for modifying the existing conceptual model to include karst, even in settings where the aerial extent of karst may seem insignificant.

In most mountain basins, a substantial amount of water is stored in unconsolidated, porous deposits, as described by Clow et al. (2003). However, karst aquifers also have potentially substantial storage and can contribute significant amounts of groundwater to surface systems during seasonal dry periods, especially in systems such as the Kaweah that contain relatively few unconsolidated aquifer materials and numerous small karst aquifers. Based on our findings in two systems in SEKI, karst aquifers contribute significant amounts of water to the river system and should be included in conceptual models of mountain hydrology whenever karst is present. Karst aquifers are found elsewhere in the Sierra Nevada range and in many other mountain settings, yet because of the importance of snowmelt to annual river discharge, they are often ignored or underappreciated with respect to their contribution during the dry season. In addition, with future changes in climate predicted to result in increasing snowline elevations and less snowmelt discharge, the importance of seasonal or longer karstic storage in maintaining dry season flows will increase.

The susceptibility of any aquifer to contamination is a function of geologic materials, contaminant type, and the transport and flow regime. For a contaminant entering a system via diffuse flowpaths, it is likely that it will be temporally and spatially distributed, which means that it may be detected at the spring in low concentrations for long periods of time. However, if a contaminant enters an aquifer at a concentrated recharge site, it is more likely to be flushed quickly through the conduit system, bypassing most of the smaller fractures and pores, and behaving according to the model proposed by Loop and White (2001). Due to the variability in the retention time and amount of water stored in the two aquifers we studied, the residence time of a contaminant in each aquifer will be different. Higher storage in the diffuse component of the Big Spring system relative to the Tufa Spring system suggests that contaminants are likely to remain in storage for longer periods of time in the Big Spring system. Although this means that a potential contaminant will be spatially and temporally dispersed as it moves through a porous media, sensitive organisms may be exposed to low concentrations for extended periods of time. In the Tufa Spring system, where rapid conduit flow and concentrated recharge dominate, potential contaminants will be flushed quickly through the system. However, if contaminants are deposited aerially and are stored in snowpack, they may also be released over the same time period as the snowmelt occurs.

The major differences in seasonal storage capacity between these two aquifers indicate that overlying unconsolidated materials must contribute substantially more to diffuse flow and storage on annual or shorter time scales than fracture storage does. However, in order to quantify these contributions, additional data are needed. Data presented here are not sufficient to separate matrix and fracture storage in the karst from storage in overlying unconsolidated deposits. Future study is needed to determine if there is a relationship between the proportion of diffuse flow and the amount, type, and maturity of available unconsolidated material. Although a relationship appears to exist in these two aquifers, where more mature unconsolidated materials correlate with larger and longer storage capacity, hydrogeochemical properties of some other karst springs in SEKI indicate much longer average residence times and larger karstic storage capacity. Characterizing recharge, hydrogeologic, and geochemical properties of these springs is the subject of current and future studies.

As SEKI begins planning for mitigation of potential anthropogenic impacts to the aquatic systems in the parks, including spills of toxins, use of fire-retardant or similar chemicals, and deposition of airborne contaminants in the basin, a better understanding of residence times and storage properties is required. Karst aquifers that are supplied by large amounts of water slowly flowing through unconsolidated material prior to entering a conduit system have greater potential for contaminant removal through natural attenuation, bioremediation, or biological uptake of nutrients such as nitrate and phosphate. This is because water moving through the unconsolidated material typically has a longer residence time, and thus, more time to interact and react with the surrounding materials. Water that enters the karst quickly, via larger conduits and fractures, typically has less potential for removal of contaminants from the water, increasing the likelihood that contaminants could leave the system at dangerous concentrations. However, the quick-flow systems also have the potential to flush the contamination through the system rapidly, minimizing potential long-term impacts. In either case, the results of this study contribute to improving our incomplete understanding of how marble aquifer systems in mountains function and will assist managers at SEKI and elsewhere in making scientifically informed and justifiable decisions.

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DROWNED KARST LANDSCAPE OFFSHORE THE APULIAN MARGIN (SOUTHERN ADRIATIC SEA, ITALY)

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Abstract: The south Adriatic shelf offshore of the predominently carbonate Apulian coast is characterized by a peculiar rough topography interpreted as relic karst formed at a time of lower sea level. The study area covers a surface of about 220 km^2, with depths ranging from 50 to 105 m. The most relevant and diagnostic features are circular depressions a few tens to 150 m in diameter and 0.50 to 20 m deep thought to be dolines at various stages of evolution. The major doline, Oyster Pit, has its top at about 50 m water depth and is 20 m deep. It is partly filled with sediments redeposited by episodic mass failure from the doline's flank. Bedrock samples from the study area document that Plio-Pleistocene calcarenites, tentatively correlated with the Calcarenite di Gravina Fm, are a prime candidate for the carbonate rocks involved in the karstification, although the presence of other units, such as the Peschici or Maiolica Fms, is not excluded. The area containing this subaerial karst landscape was submerged about 12,500 years ago as a result of the postglacial transgression over the continental shelf.

INTRODUCTION

Karst landforms resulting from subaerial dissolution of carbonate rocks are distributed almost worldwide in carbonate countries, at places profoundly imprinting the landscape (Sweeting, 1973; Jennings, 1985; James and Choquette, 1988; Palmer, 1990; Ford and Williams, 2007). On modern continental margins, formerly subaerial carbonate karst features (sinkholes, dolines, fluted surfaces, etc.) occur as relics in subaqueous locations as a result of drowning related to continental margin tectonic evolution or sea-level fluctuations (Collina-Girard, 1996; Surić, 2002; van Hengstum et al., 2011). A field of sinkholes identified in the Straits of Florida at depths up to 500 meters is thought to have been formed entirely in a submarine environment in response to the paleohydrology of the carbonate Florida continental margin (Land et al., 1995; Land and Paull, 2000). On the other hand, many sinkholes reported from deep-water submerged locations have been interpreted as collapse structures due to the solution of underground evaporites (e.g., Biju-Duval et al., 1983; Taviani, 1984).

The Mediterranean Sea has a number of limestone coasts subject to karstification along its perimeter (e.g., Herak and Stringfield, 1972; Elhatip and Günay, 1998; Fleury et al., 2006; Mijatović, 2007; De Waele, 2009), but there are only a few records of drowned karst features: emblematic examples are the southern coast of France in the calanques Marseille region (Collina-Girard, 1996) and the northeastern Adriatic coast (Surić, 2002, 2005; Surić et al., 2005; Surić and Juračić, 2010), which represents the seaward expansion of the classical karst area in the Croatian Dinarides (Cvijić, 1893).

Here we report the identification of a drowned karst landscape in the south-western Adriatic Sea in the submarine topography just offshore the prevalently carbonate coast of the Gargano Promontory (Fig. 1).

MATERIALS AND METHODS

The study area was surveyed during cruise CNR002 in March 2002 on board RV *OdinFinder* and cruises ARCO and ARCADIA of RV *Urania* in December 2008 and March 2010, respectively. The region containing karst features was mapped by means of multibeam bathymetry, and the superficial geology was imaged through a chirp-sonar profiler and sidescan sonar. Swath-bathymetry data were acquired using a Kongsberg Simrad EM3000 multibeam echo-sounder with a nominal sonar frequency of 300 kHz and angular coverage sector of 127 beams per ping of 1.5°. Chirp-sonar profiles were obtained using a hull-mounted sixteen-transducer source with a sweep-modulated 2–7 kHz outgoing signal equivalent to a 3.5 kHz profiler. Sidescan sonar profiles were obtained by a towed LG1000 EG&G 260 sidescan sonar with a frequency of 100–500 kHz. Water-column attributes were measured with a Conductivity/Temperature/Depth profiler (CTD) using a Seabird SBE 11 PLUS using the SEASAVE V5.33 software.

Bottom sampling was performed using 1.2 ton gravity corer, large-volume grab, chained geological dredge, and epibenthic hauls (Table 1). Visual inspection of the main doline was conducted using the ROV *Prometeo* equipped

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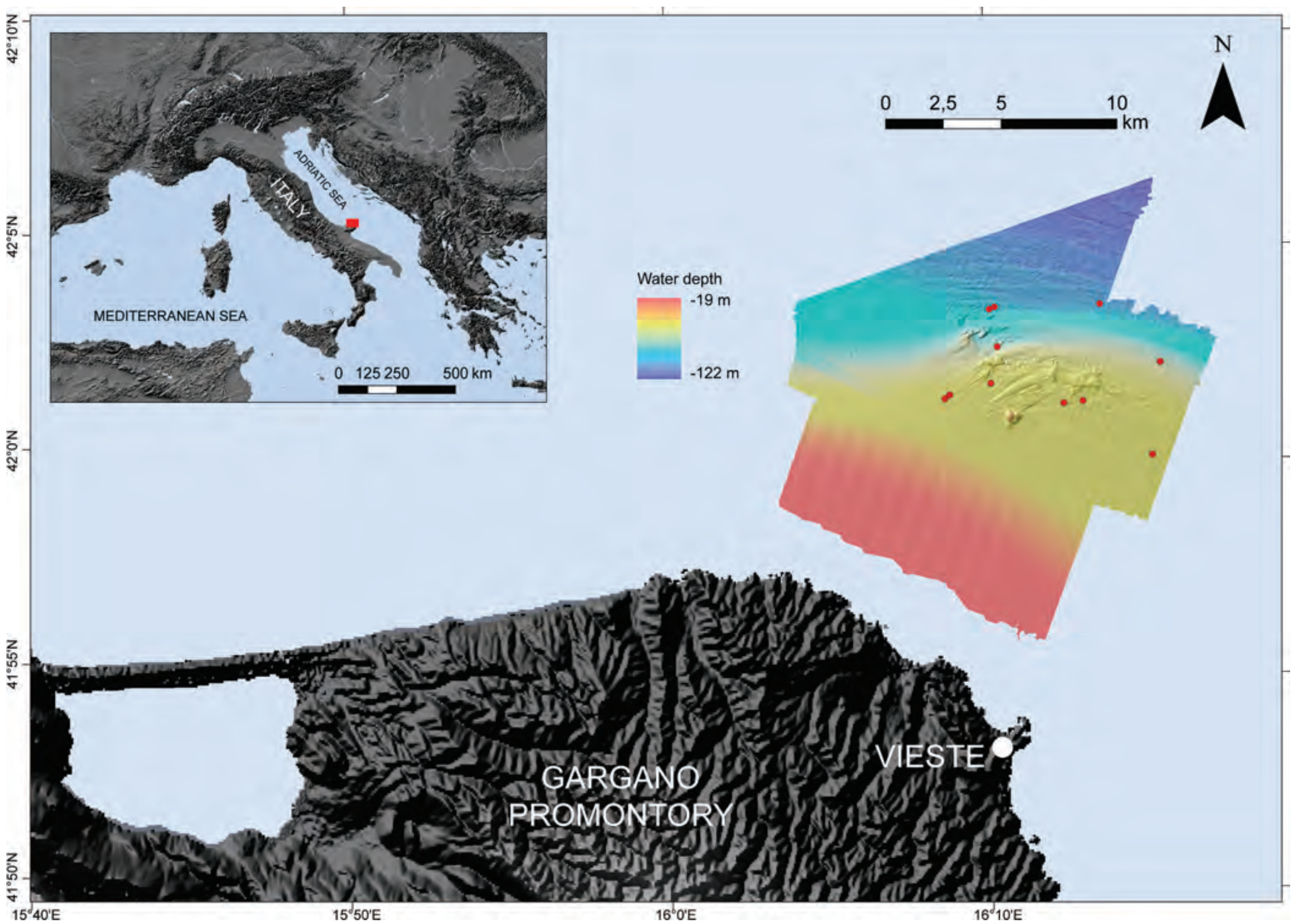

Figure 1. Map showing the location of the drowned karst area offshore the Gargano Promontory in the southern Adriatic Sea discussed in this article (red spots = dolines); inset, the Mediterranean basin with rectangle showing the same area magnified in the figure.

with a Panasonic 1/3 in. CCD camera and ROV *Pollux* (Global Electric Italiana) equipped with a Nikon D80 10-megapixel digital camera and a SonyHDR-HC7 high-definition camera. ^{14}C-AMS dating of mollusk shells was carried out at the Poznán Radiometric Laboratory, Poland. Radiocarbon results in Table 2 are reported as raw ^{14}C ages given in ^{14}C years BP, and as calendar year estimates (cal yrs BP) after calibration; BP refers to AD 1950.

Results

Morphology of Drowned Karst Features

The continental shelf offshore northeast of the Gargano Promontory is characterized by a relatively flat erosional surface at between 45 and 60 m water depth. Landward of this area, a mass of late Holocene deposits reaches a thickness of 25 m and displays a clinostratified internal geometry (Cattaneo et al., 2003). At water depths greater than 70 m, late-Holocene muddy deposits are draped on the pre-existing erosional morphology of the area (Cattaneo et al., 2003). Between the two areas of deposition, the flat area is barren of modern muddy late-Holocene sediment, suggesting that, in this region, the Adriatic Coastal Current accelerating around the Gargano Promontory does not allow permanent deposition of mud, as predicted by oceanographic models (Magaldi et al., 2010). The barren area is characterized by the presence of shell gravel, bioclastic sand, rhodoliths, live oyster aggregates, and by an area of outcropping cemented rocks with a high backscatter on sidescan sonar and a rugged topography suggestive of differentially cemented or differentially eroded stratified rocks.

The study area with karst morphology is located on the Apulian continental shelf about 6 nautical miles (10 km) offshore the Gargano Promontory (Fig. 1). The area covers about 220 km^2, with water depths ranging from approximately 50 to 105 m. The detailed bathymetric map reveals a complex, rough sea-bottom topography, strongly sculptured by small (1 to 5 m) grooved relief, often striking

Table 1. Samples described in the text.

		Location						
Station	Date	Start Lat., °N	Start Long., °E	End Lat., °N	End Long., °E	Start Depth, m	End Depth, m	Type
ARCO66	20 Dec 2008	41°59′01.2″	16°16′03.6″	41°58′48.6″	16°16′04.2″	50.00		Sidescan Sonar
ARCO67	20 Dec 2008	41°59′36.0″	16°15′09.6″			65.60		Grab
ARCO68	20 Dec 2008	41°59′37.2″	16°15′09.0″			73.20		Grab
ARCO69	20 Dec 2008	41°59′37.2″	16°15′09.0″			73.60		Gravity corer
ARCO70	20 Dec 2008	41°59′37.0″	16°15′08.4″			73.80		ROV
ARCO71	20 Dec 2008	41°59′39.6″	16°15′04.2″	41°59′47.4″	16°14′57.0″	73.80	52.80	Epibenthic trawl
ARCO72	20 Dec 2008	41°51′37.2″	16°15′09.0″			73.30		Grab
ARCO73	20 Dec 2008	42°01′13.8″	16°11′13.8″			48.00	48.00	Heavy Dredge
ARCO74	20 Dec 2008	42°01′24.6″	16°12′12.6″			54.00		Grab
ARCO75	20 Dec 2008	42°01′13.8″	16°12′40.8″	42°01′13.2″	16°12′23.4″	50.50	52.00	Epibenthic trawl (lost)
ARCO76	20 Dec 2008	41°59′36.6″	16°15′09.0″			68.00		CTD
ARCO77	20 Dec 2008	42°00′51.6″	16°13′01.8″			52.00		Grab
ARCADIA104	27 Mar 2010	41°59′37.0″	16°15′07.9″			73.90		Grab
ARCADIA105	27 Mar 2010	41°59′36.9″	16°15′08.0″			73.40		Gravity Corer
ARCADIA106	27 Mar 2010	41°59′35.8″	16°15′06.1″			54.00		Grab
ARCADIA107	27 Mar 2010	41°59′35.8″	16°15′06.1″			54.00		Grab
ARCADIA108	27 Mar 2010	41°59′36.6″	16°15′08.7″			70.00		CTD
ARCADIA109	27 Mar 2010	41°59′37.0″	16°15′07.9″	41°59′35.9″	16°15′10.2″	67.00		ROV
ARCADIA110	27 Mar 2010	41°59′33.2″	16°15′08.2″			53.00		Grab
ARCADIA111	27 Mar 2010	41°59′36.1″	16°15′08.4″			71.00		Grab

Table 2. Radiocarbon data from the Poznán Radiocarbon Laboratory in Poznán, Poland. Radiocarbon years (^{14}C-yrs) correspond to the true half-life. Calibrated age ranges reflect the 95.4% probability window (2σ-error) and were calculated with Calib6.0.1, using the surface marine calibration curve MARINE 09 by Reimer et al., 2009.

Code #	Species	Samples	Radiocarbon Age (^{14}C-yrs BP)	Delta R (yrs)	Two-σ Ranges (yrs cal BP)	Age Cal BP (yrs cal BP)	Calibration Data
Poz-29335	*Cerastoderma glaucum*	ARCO72	42,200 ± 1,200	121 ± 60	43,332–47,710	45,521 ± 2,189	Marine/No.Hem09
Poz-30018	*Cerastoderma glaucum*	ARCO69	42,000 ± 2,000	121 ± 60	42,431–49,213	45,882 ± 3,391	Marine/No.Hem09
Poz-30019	*Cerastoderma glaucum*	ARCO69	41,000 ± 1,000	121 ± 60	42,961–45,883	44,422 ± 1,461	Marine/No.Hem09
Poz-30020	*Solen marginatus*	ARCO71	41,000 ± 1,000	121 ± 60	42,806–45,707	44,257 ± 1,451	Marine09
Poz-30021	*Gibbula albida*	ARCO71	10,950 ± 60	121 ± 60	12,524–12,748	12,636 ± 112	Marine/No.Hem09
Poz-30023	*Hydrobia acuta*	ARCO71	10,620 ± 50	121 ± 60	11,978–12,402	12,190 ± 212	Marine/No.Hem09
Poz-30024	*Lymnaea stagnalis*	ARCO71	10,890 ± 50		12,624–12,917	12,771 ± 147	IntCal09

NE-SW and ENE-WSW, and punctuated by circular depressions (Figs. 2, 3, 4). This topography is in our view related to former karstification, and arguments to support this view are discussed below.

Dolines

One of the main morphologies identified on the Apulian shelf is circular depressions interpreted as dolines at various stages of evolution (Figs. 2, 4; Table 3). Some dolines are clearly aligned along a NE-SW direction (Fig. 5). This is an indication that their formation was controlled by structural or stratigraphic factors, as has often been documented inland (e.g., Nisio, 2008). We counted eleven major circular depressions ranging from 155 to 50 meters in diameter and from about 0.5 to 20 meters in depth (Figs. 2, 4, 5; Table 3). Only one doline is as much as 20 meters deep (Figs. 4, 5). This most prominent doline is named Oyster Pit, as its flanks and bottom are intensely colonized by *Neopycnodonte cochlear* oyster reefs and clumps (Taviani et al., 2009). Because Oyster Pit is by far the deepest and best-developed doline in the study area, most of the following discussion is focused on it.

Oyster Pit

This doline is characterized by an almost circular shape with a diameter of 120 m, relatively steep flanks (about 25° dip), and a rather flat bottom. Its top is at about 49 m depth and its bottom is about 73 m deep (Figs. 4, 5).

The ROV visual inspection of the entire doline provided no obvious information on the nature of the karstified bedrock because no bare rock is exposed anywhere. ROV images reveal that the bottom is carpeted by intensely bioturbated sandy sediments (Fig. 6) peppered by recent and pre-modern shells and pebbles that often serve as host to living epifauna (Figs. 6, 7B). The upper part of the doline between 55 and 60 m depth is characterized by similar deposits, at places clearly visible when entrapped by modern oyster rims (Fig. 6C). The pre-modern shelly component (Fig. 7B) is mostly composed of brackish/lagoonal (*Loripes lucinalis, Cerastoderma glaucum, Gastrana fragilis, Abra segmentum, Gibbula albida, Hydrobia* cf. *acuta, Bittium reticulatum*) and shallow marine (e.g., cf. *Chamelea gallina, Donax trunculus, Ensis* sp., *Solen marginatus*, *Gibbula albida*, *Nassarius mutabilis, Cyclope neritea*) mollusks. Calibrated ^{14}C-AMS dating (Table 2) of these pre-modern shells (Fig. 7) indicates that these were of late Pleistocene age, with *Cerastoderma* (Station [st.] ARCO72, −73.4 m; Fig. 7B) and *Solen marginatus* (st. ARCO71, −73.8/−52.8 m) having calibrated ages of 45,521 ± 2,189 yrs and 44,257 ± 1,451 yrs, respectively, while *Hydrobia acuta* (st. ARCO71) had a calibrated age of 12,190 ± 212 years and *Gibbula albida* (st. ARCO71) provided a calibrated age of 12,636 ± 112 yrs. Pebbles from the doline bottom and flanks are well rounded and often spherical, with dimensions ranging from 2 to 65 mm,

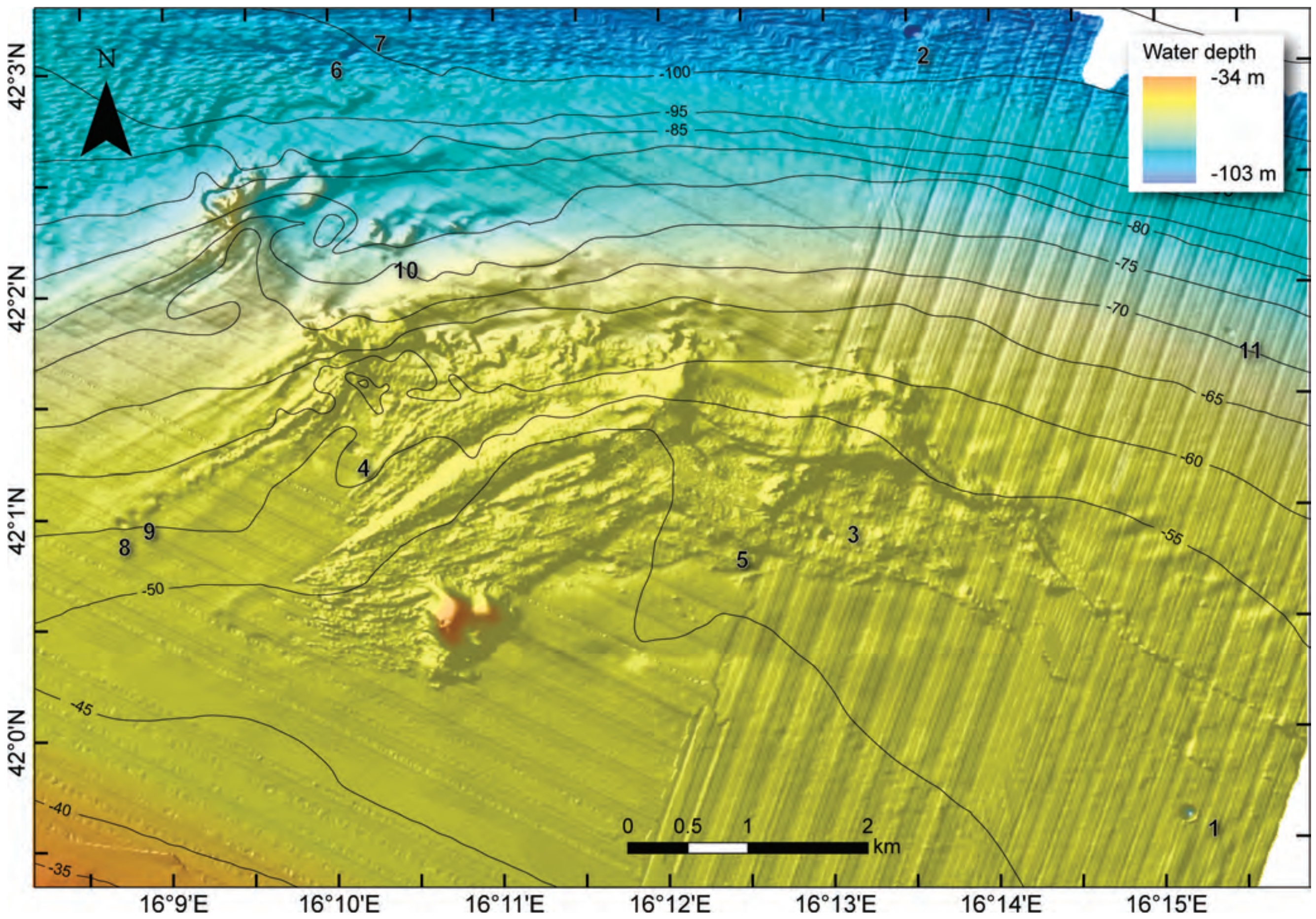

Figure 2. Multibeam-sonar map of the study area showing the complex, rough topography punctuated by many circular depressions interpreted as dolines. Major dolines are numbered and their characteristics are reported in Table 3; 1 is Oyster Pit, the major doline in the area (see text); and 10 is a double doline formed by two partly coalesced depressions. Note NE-SW alignment of circular depressions, including dolines 8 and 9. Isobath spacing is 5 m.

occurring loose or as conglomerates, lithologies, dominantly limestone, and chert (Fig. 7A).

Chirp-sonar profiles provide a view of the subsurface geological setting, documenting a relatively thin sedimentary infilling. Profile AR-246 (Fig. 8) highlighted the stratigraphy of the Oyster Pit area. Post-glacial transgressive sediments characterize the seafloor outside the doline, indicating sediment undersupply during the late Holocene. The doline's bottom is characterized by a chaotic seismic signature. Two gravity cores obtained from the bottom of Oyster Pit at 73 m depth shed light on the nature of this sequence. Core ARCO 69 was collected at 41°59.62′ N 16°15.15′ E (recovery 134 cm; Fig. 9A), while core ARCADIA A105 was collected at 41°59.62′ N–16°15.13′ E (recovery 259 cm; Fig. 9B). Both cores contained a rather similar sequence. The main motif of the most recent infilling of Oyster Pit is a repetition of sandy to gravelly deposits containing Pleistocene brackish/lagoonal and shallow marine mollusks (*Loripes lucinalis, Cerastoderma glaucum, Hydrobia* cf. *acuta, Bittium reticulatum* etc.). These deposits alternate with fine-grained sediments. Two *Cerastoderma* shells from core ARCO-69 (Fig. 9A) have been dated at 44,422 ± 1,461 yrs cal BP (core depth 22–23 cm) and 45,882 ± 3,391 yrs cal BP (core depth 95–96 cm), respectively. Pebbles associated with the infilling units likely originate from Mesozoic (limestone with calcispheres and chert: Maiolica Fm; floatstone and rudstone: Montesacro Fm or Ripe Rosse Fm) and Neogene (Pietra Leccese or Calcareniti di Apricena Fm) units cropping out on the adjacent Gargano Promontory. Most probably Pleistocene brackish/lagoonal deposits were episodically remobilized from the upper flanks and external rim of the doline (Fig. 6C). This phenomenon is active currently, because modern *Neopycnodonte cochlear* oyster shells contribute to these sediments (Fig. 9). In short, Oyster Pit seems to be at present a moderately quiet environment subject to occasional redeposition of material from its flanks.

Interestingly, the shelly assemblages recovered from the bottom of Oyster Pit contain terrestrial (*Truncatellina* sp., *Chondrula tridens, Xerotricha* sp.) and freshwater (*Lymnaea stagnalis, Planorbis* sp., *Gyraulus crista, Acroloxus lacustris,*

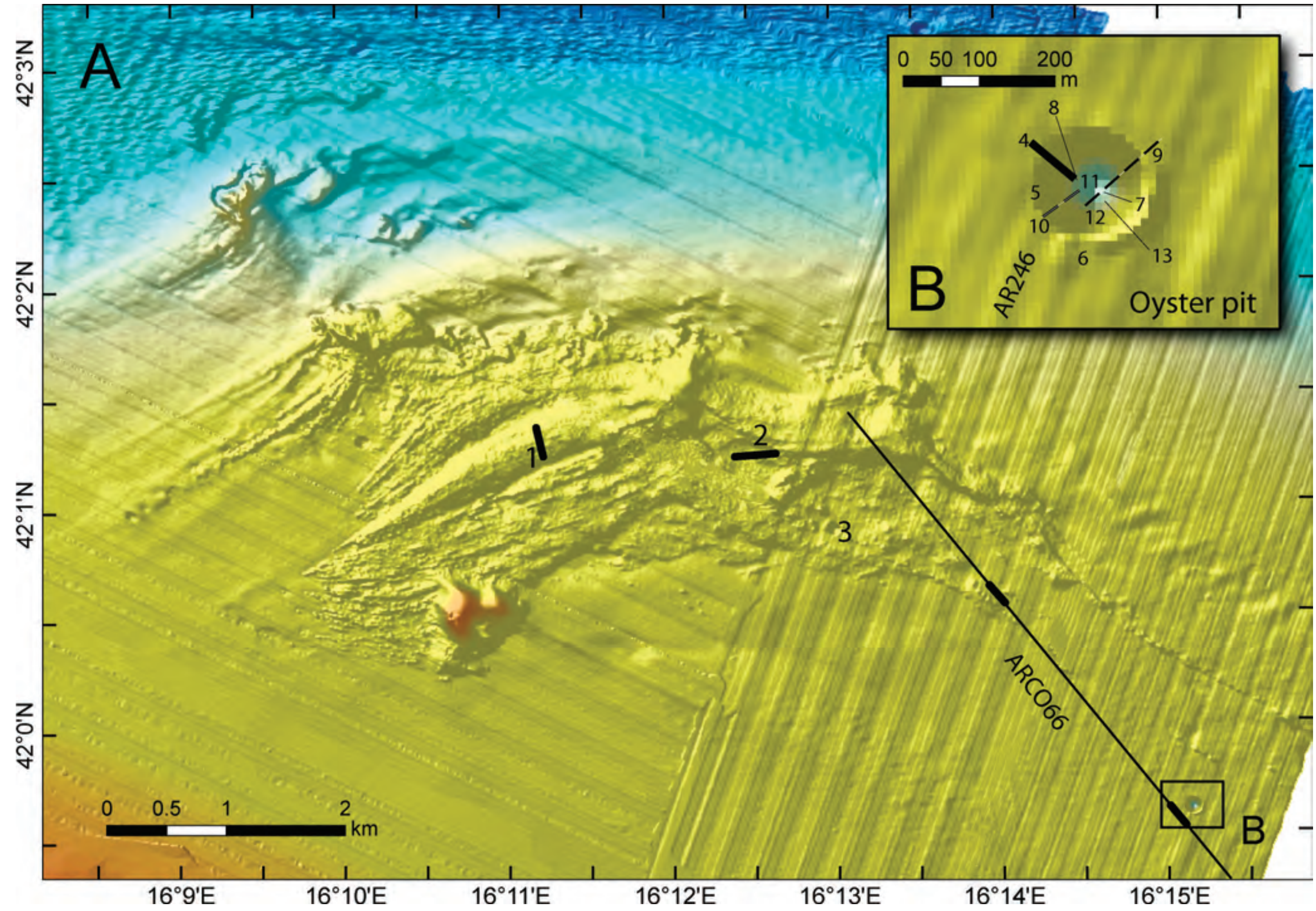

Figure 3. A: Multibeam-sonar map of the study area showing location of bottom samples, CTD (Conductivity/Temperature/Depth) casts, ROV, Chirp (AR246), and sidescan sonar (ARCO66) profiles discussed in the text (see Table 1); st. 73 and st. 78 provided the Pleistocene calcarenites (see Fig. 10 and text) that are thought to form the superficial bedrock of the submerged karst area. Inset B is the magnification of the Oyster Pit doline (marked by a rectangle) where most of the sampling took place. Stations are: 1 = ARCO73 (heavy dredge); 2 = ARCO75 (epibenthic trawl, lost); 3 = ARCO74 (grab); 4 = ARCO77 (grab); 5 = ARCO71 (epibenthic trawl); 6 = ARCADIA106 (grab), 107 (grab); 7 = ARCADIA110 (grab); 8 = ARCO67 (grab); 9 = ARCO68 (grab), 69 (gravity core), 72 (grab), ARCADIA105 (gravity core); 10 = ARCADIA109 (ROV); 11 = ARCO70 (ROV); 12 = ARCO76 (CTD), ARCADIA104 (grab), 108 (CTD); 13 = ARCADIA111 (grab), 112 (grab).

Theodoxus sp., etc.) gastropods (Fig. 7D), as well as *Candona* ostracods and oogones of Characeae. One shell of *Lymnaea stagnalis* provided a calibrated age of 12,771 ± 147 yrs BP (st. ARCO71). This fossil assemblage indicates that immediately before its postglacial flooding, the doline may have hosted a shallow lake or pond surrounded by xerophilic vegetation.

Calcarenites and sandstones were found in samples from the floor of Oyster Pit, often fouled with modern epifauna such as oysters and corals (Fig. 10). The poorly lithified sandstones, together with co-occurring dark, muddy sands, entrap articulated or loose brackish/lagoonal shells (*Loripes* and *Cerastoderma*: Fig. 7E, F) and are possibly coeval with the older brackish/lagoonal faunas described above. Calcarenites are weakly cemented medium- to coarse-grained carbonate (at times arkosic) sandstones embedding highly decalcified sub-littoral marine mollusks of likely Pleistocene age (e.g., *Acanthocardia* sp.: st. ARCADIA111; *Turritella* sp.: st. ARCO72, Fig. 10C, D).

DISCUSSION

GEOLOGIC SETTING

The study area offshore the Gargano coast is part of the southern Apennine foreland. The Gargano Promontory is built mainly of carbonate rocks belonging to a large paleogeographical domain known as Apulia Carbonate Platform that was part of the southern margin of the Tethys Ocean during the Mesozoic (Eberli et al., 1993). The backbone of the Gargano Promontory consists of various stratigraphic units, Late Jurassic to Eocene in age, deposited in inner-platform and basin settings (Bosellini et al., 1999), and of scattered outcrops of Oligo-Miocene and Plio-Pleistocene sediments (Casolari et al., 2000).

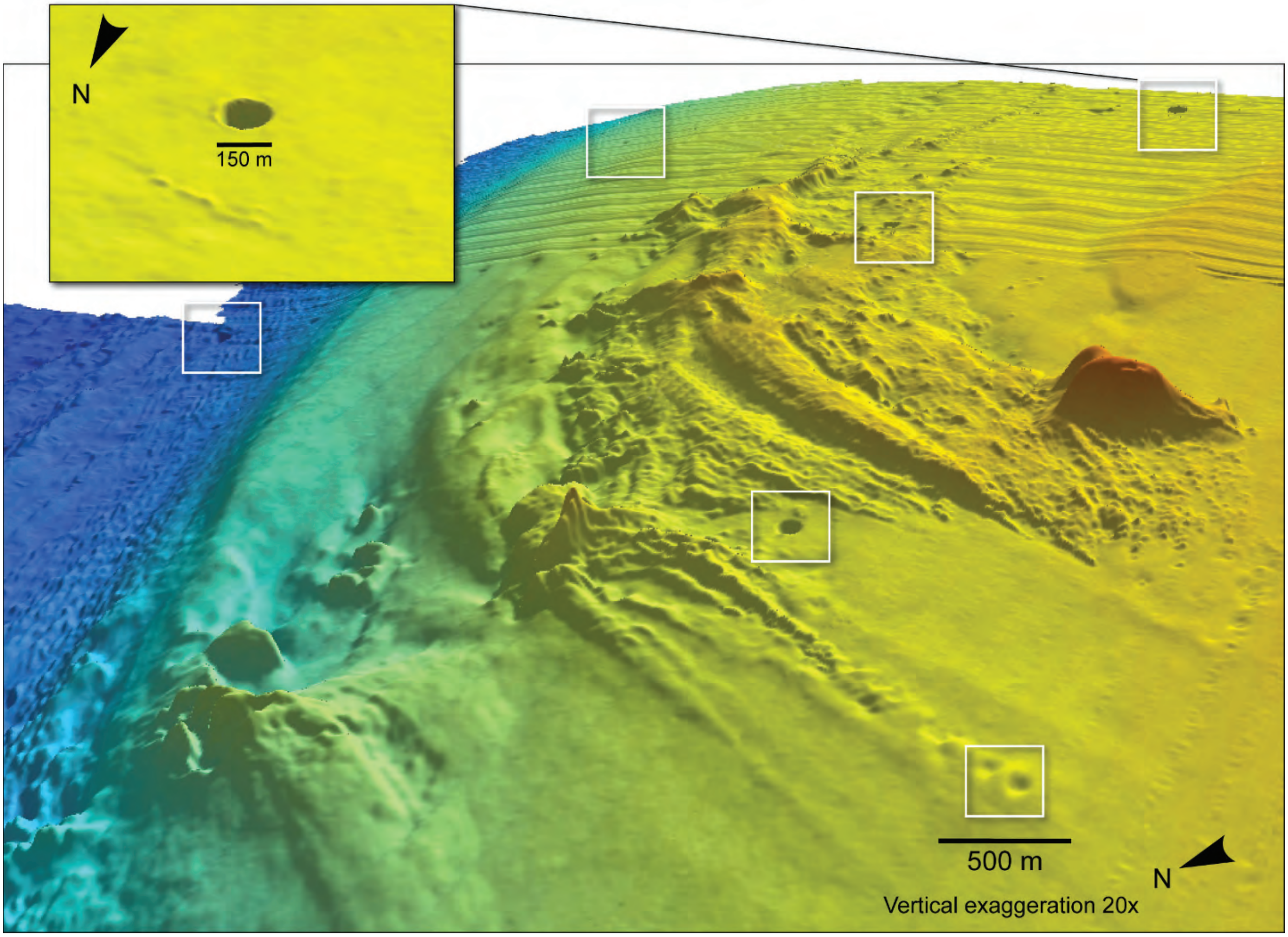

Figure 4. Reconstruction of the study area as seen as a 3-D view from the west showing the aligned dolines 8 and 9 in the foreground and other main dolines, including the almost solitary Oyster Pit in the background (inset).

Table 3. Location and main characteristics of major dolines identified in the drowned karst area offshore Gargano Promontory. Oyster Pit is number 1. See Figure 2 and text.

	Location					
StationNo.	Lat., °N	Long., °E	Top, mbsl	Bottom, mbsl	Depth, m	Diameter, m
1	41°59′36.5″	16°15′08.9″	54.4	73.8	19.3	155.0
2	42°03′08.6″	16°13′33.1″	102.2	106.5	4.3	150.0
3	42°00′53.5″	16°12′58.9″	51.7	55.0	3.3	125.0
4	42°01′18.4″	16°10′07.7″	55.7	58.5	2.8	120.0
5	42°00′52.9″	16°12′22.9″	49.6	51.3	1.8	109.0
6	42°03′04.6″	16°10′06.9″	98.4	100.6	2.2	100.0
7	42°03′06.7″	16°10′11.4″	99.0	100.0	1.0	100.0
8	42°00′58.9″	16°08′43.6″	52.8	53.9	1.1	90.0
9	42°01′01.1″	16°08′48.6″	53.3	54.0	0.7	70.0
10	42°02′09.3″	16°10′20.9″	72.4	72.8	0.4	60.0
11	42°01′46.4″	16°15′26.6″	70.7	71.7	1.0	50.0

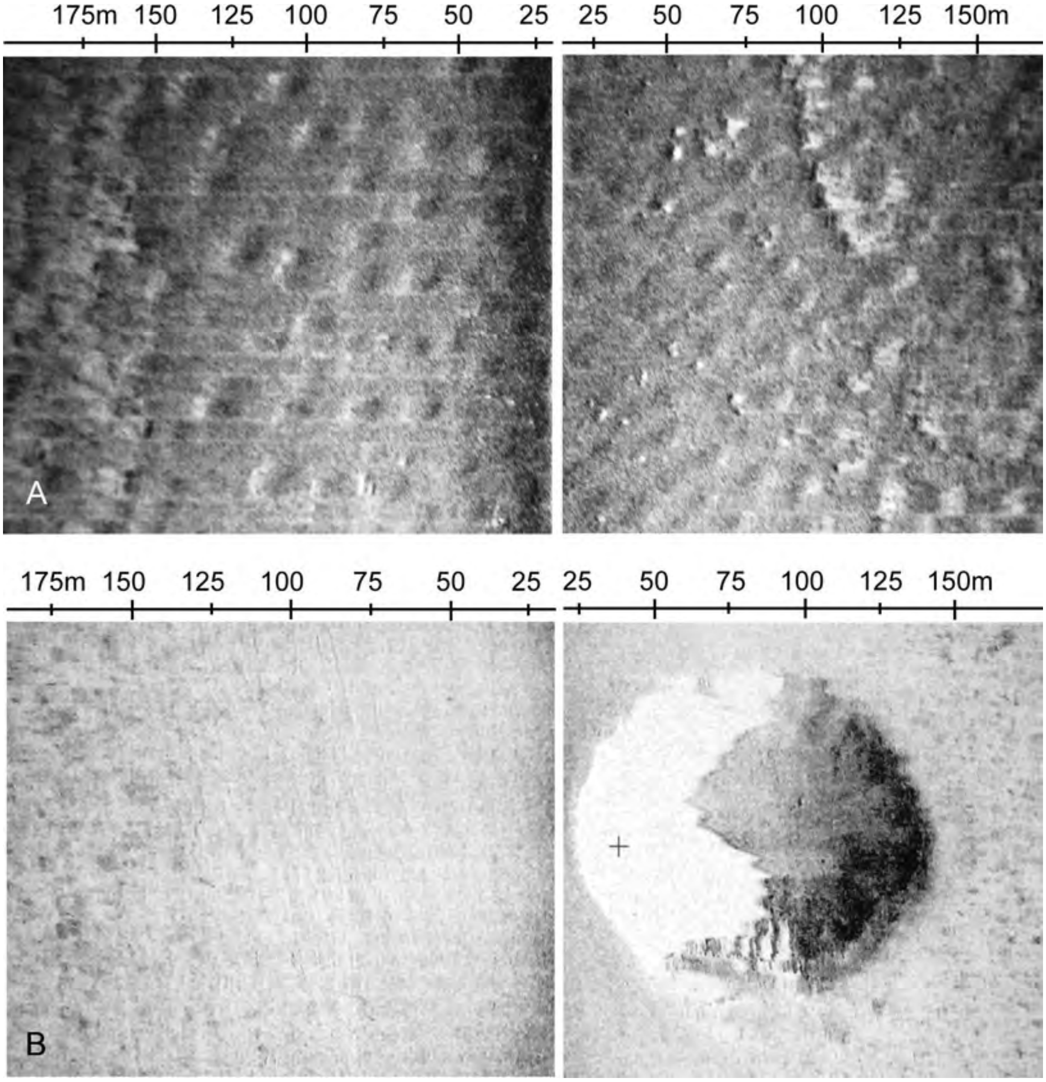

Figure 5. Details of sidescan-sonar images of the offshore drowned karst area made during the ARCO66 traverse shown in Figure 3, where the locations are indicated by the thickened portions of the traverse line. (A) A field of small circular depressions up to about 20 m in diameter, resulting in a distinct pitted seascape. (B) The Oyster Pit doline.

The geologic setting of the region containing the submerged karst features can be reasonably constrained by combining information provided by exploratory commercial wells, reflection-seismic data, and on-shore outcrops (see Argnani et al., 2009, for a review of the Adriatic offshore stratigraphy). The wells closest to the study area are Gargano Est Marine 1 (about 43 km NE), Cigno Mare 1 (about 47 km ESE), and Gondola 1bis (about 52 km SE). The stratigraphic record intercepted by these wells documents various units deposited in a basin setting from the Lower Jurassic at least (De Dominicis and Mazzoldi, 1987; De Alteriis and Aiello, 1993; Argnani et al., 2009). Evidence of shallow water is limited to times in the middle Pliocene (Cigno Mare 1) and early Pleistocene (Gargano Est Marine 1), marked by the deposition of few tens of meters of skeletal limestone (Calcarenite di Gravina Fm). In particular, this sector of the Adriatic Sea is formed by an uppermost sequence (130 to 200 m) of Plio-Pleistocene clastics (Argille Azzurre Fm), followed by more than 50 m of Plio-Pleistocene skeletal limestone (Calcarenite di Gravina Fm), Tortonian green marls and limestones (Bisciaro Fm), upper Oligocene marls (Scaglia Cinerea Fm, not always present). These Tertiary units unconformably cap over Upper Cretaceous (Cenomanian to Coniacian) chert-bearing chalky limestone (Scaglia Fm), Lower Cretaceous marls and marly limestone (Marne a Fucoidi Fm), chert-bearing micritic limestone (Maiolica Fm), and older Mesozoic carbonates.

The stratigraphic succession cropping out in the eastern corner of the Gargano Promontory between Vieste and Peschici (Bosellini and Morsilli, 2001) exposes only four main litostratigraphic units, i.e., the Maiolica Fm, the

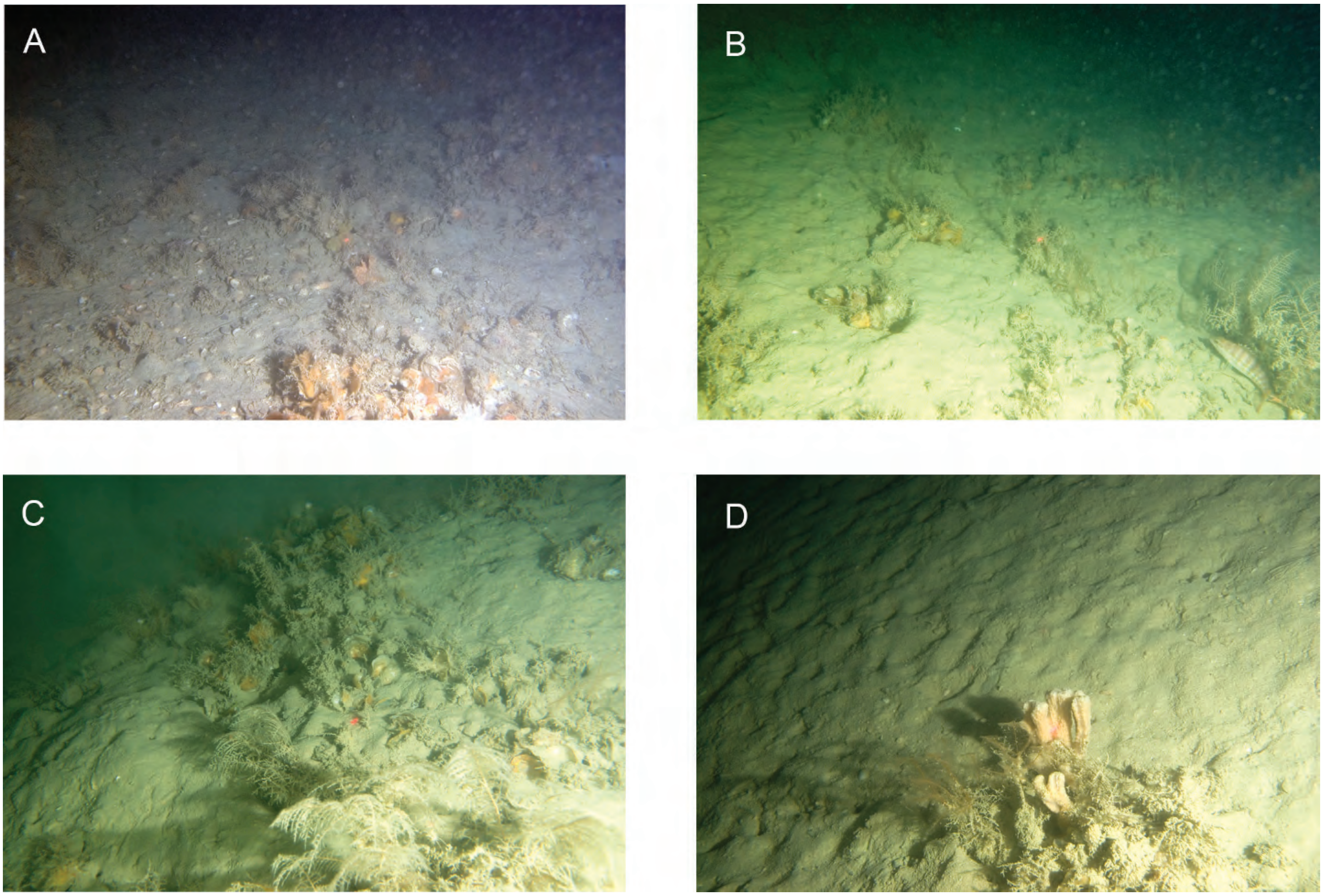

Figure 6. Views of the Oyster Pit doline. (A) Sandy bottom, depth about 70 m, with sparse living epifauna, pebbles (p), and valves of older lagoonal shells (c). (B) Sandy bottom with sparse epifauna (b). (C) Flank of the doline, about 55 m. Note fringe of living oysters and other epifauna damming older lagoonal shells (c). (D) Bioturbated sandy bottom with clusters of oysters, sponges, and hydroids; note parallel small bedforms. All photographs taken by S. Canese and L. Rossi during cruise ARCADIA using the ISPRA ROV *Pollux*.

Marne a Fucoidi Fm, the Scaglia Fm, and the Peschici Fm (thin- to thick-bedded lime mudstone, with calcarenite and breccia intervals). That last, middle Eocene unit crops out extensively inland and is also found in the Tremiti and Pianosa Islands, some tens of kilometers toward the NNW, but was not recorded in the offshore wells. The areal distribution of the unit (De Dominicis and Mazzoldi, 1987) suggests a possible extension of this formation to the study area offshore.

Apulian Karst

The dominantly carbonate Apulian landscape is profoundly imprinted by karst features (Parise, 2008a). Most of the Gargano Promontory shows surface and subsurface karst landforms related to dissolution processes of variable intensity. These are dominantly dolines, locally accompanied by poljes, and by a remarkable number of underground karst systems, with more than 700 caves charted so far (Fusilli, 2007). Dolines range from solution dolines to collapse features, representing almost the whole spectrum of types described by Waltham et al. (2005). This is the case, for instance, in the so-called Chiancate area, where the density of dolines reaches its maximum, over 100 per km^2 (Baboci et al., 1991). Most dolines developed in the Jurassic and Cretaceous limestones are solutional in origin and create circular depressions with slightly inclined margins, have a flat bottom a few tens of meters wide, and are up to 20 meters deep. Collapse dolines are also present, showing features significantly sharper, usually represented by steeply inclined to subvertical walls; the best example in Gargano is the Dolina Pozzatina, 600 m wide and 130 m deep (Castiglioni and Sauro, 2000; Parise, 2008b).

Analogous features can be observed farther south, in the Murge plateau (Fig. 11), and represent the most renowned examples of the Apulian karst landscape (Parise, 2008b, 2011). All such landforms affect the Mesozoic

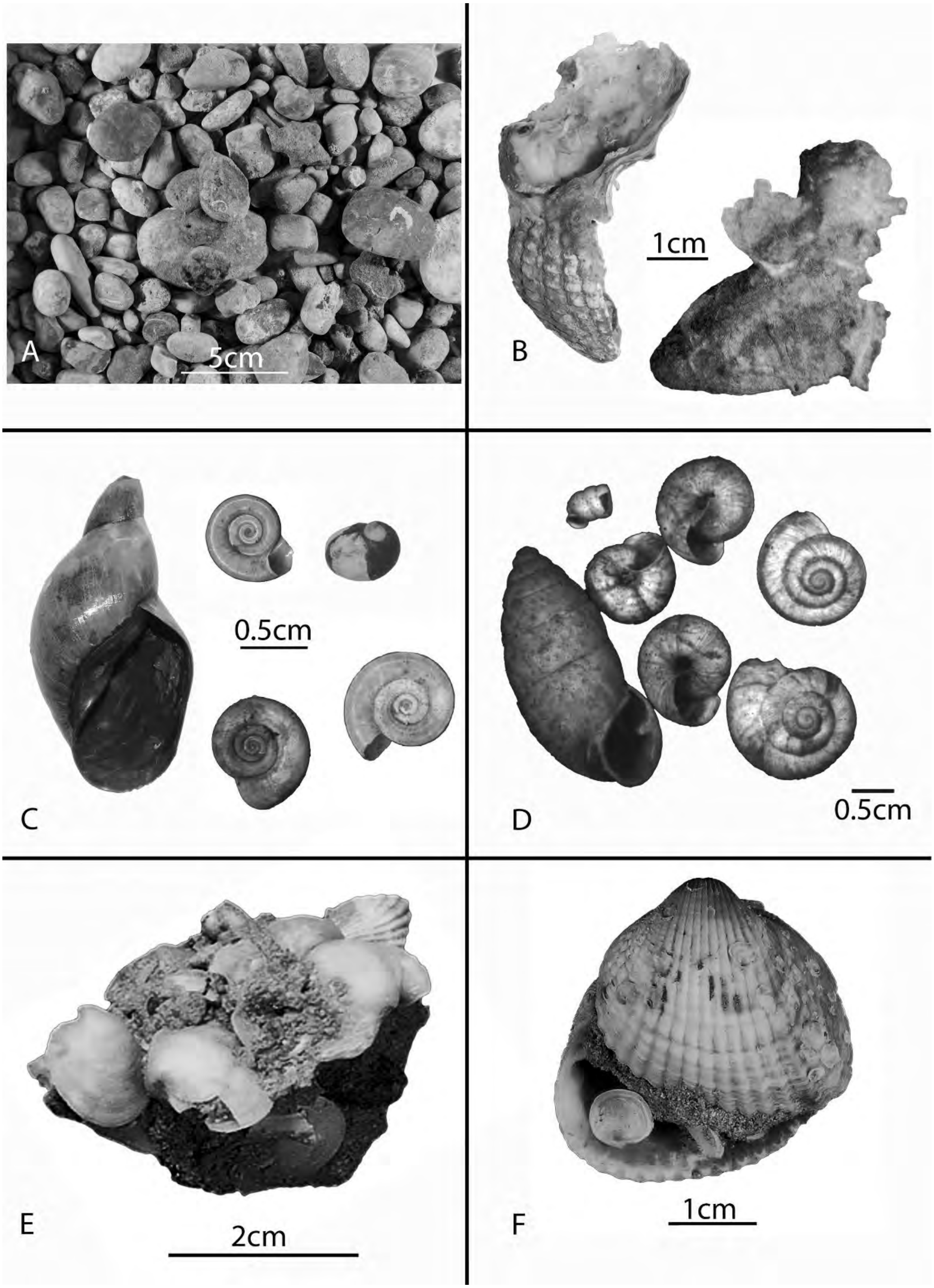

Figure 7. Examples of rocks and fossil fauna recovered from the bottom of Oyster Pit. (A) Pebble assemblage after washing of sandy matrix and removal of bioclastic particles. Notice the high roundness and sphericity and low diversity of the pebbles composed of Mesozoic chert and limestones (ARCADIA104). (B) Old brackish/lagoonal shells (left, *Cerastoderma*, ARCO72, dated at about 45.5 ky BP, see text) and pebbles (right, ARCO68) serve as substrate for living *Neopycnodonte* oysters. (C)

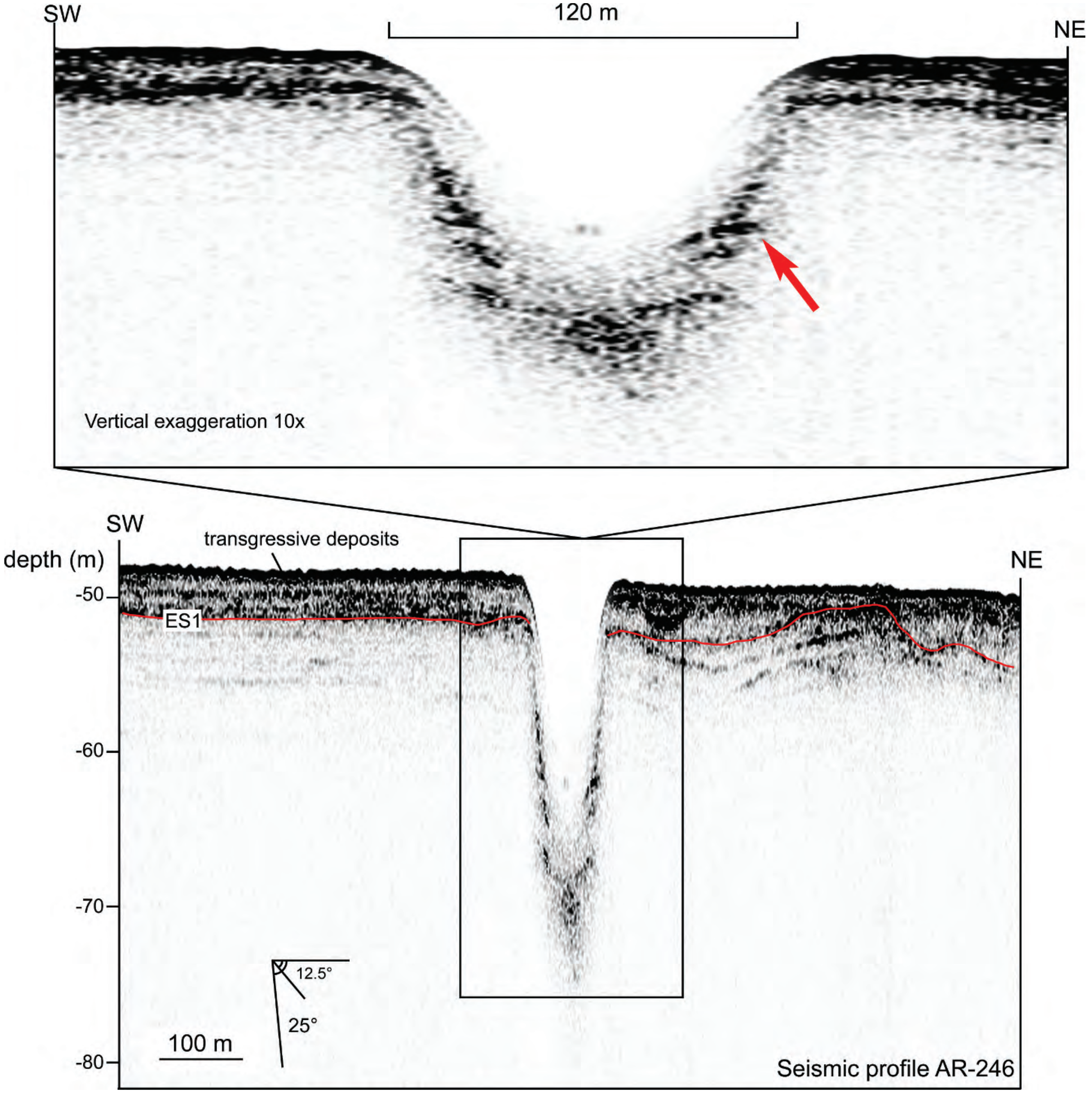

Figure 8. High-resolution chirp-sonar profile AR-246 (cruise ARCADIA; see Fig. 3 for its location) highlighting the stratigraphy of the Oyster Pit doline. Outside the doline, the area is characterized by about 3 meters of transgressive deposits, covering the ES1 erosional surface connected to the last sea-level lowstand (Ridente and Trincardi, 2005). The seismic profile shows that the doline is filled by a few meters of chaotic deposits at least, and, possibly, blocks (arrow) connected to mass gravity processes.

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Fresh-water gastropod shells. Large shell on left, *Lymnaea*, (ARCO71, dated at about 12.5 ky BP, see text); *Theodoxus* and Planorbidae (ARCO67). (D) Shells of terrestrial pulmonate gastropods (*Chondrula*, large shell on the left, *Truncatellina*, upper left, and *Xerotricha*) ARCO67. (E) Concretioned sandstone embedding paired and disarticulated shells of the brackish/lagoonal bivalves *Loripes* and *Cerastoderma* (upper right), from ARCO72. (F) Large articulated shell of the brackish/lagoonal bivalve *Cerastoderma* infilled with *Loripes*-bearing sandstone (ARCADIA104).

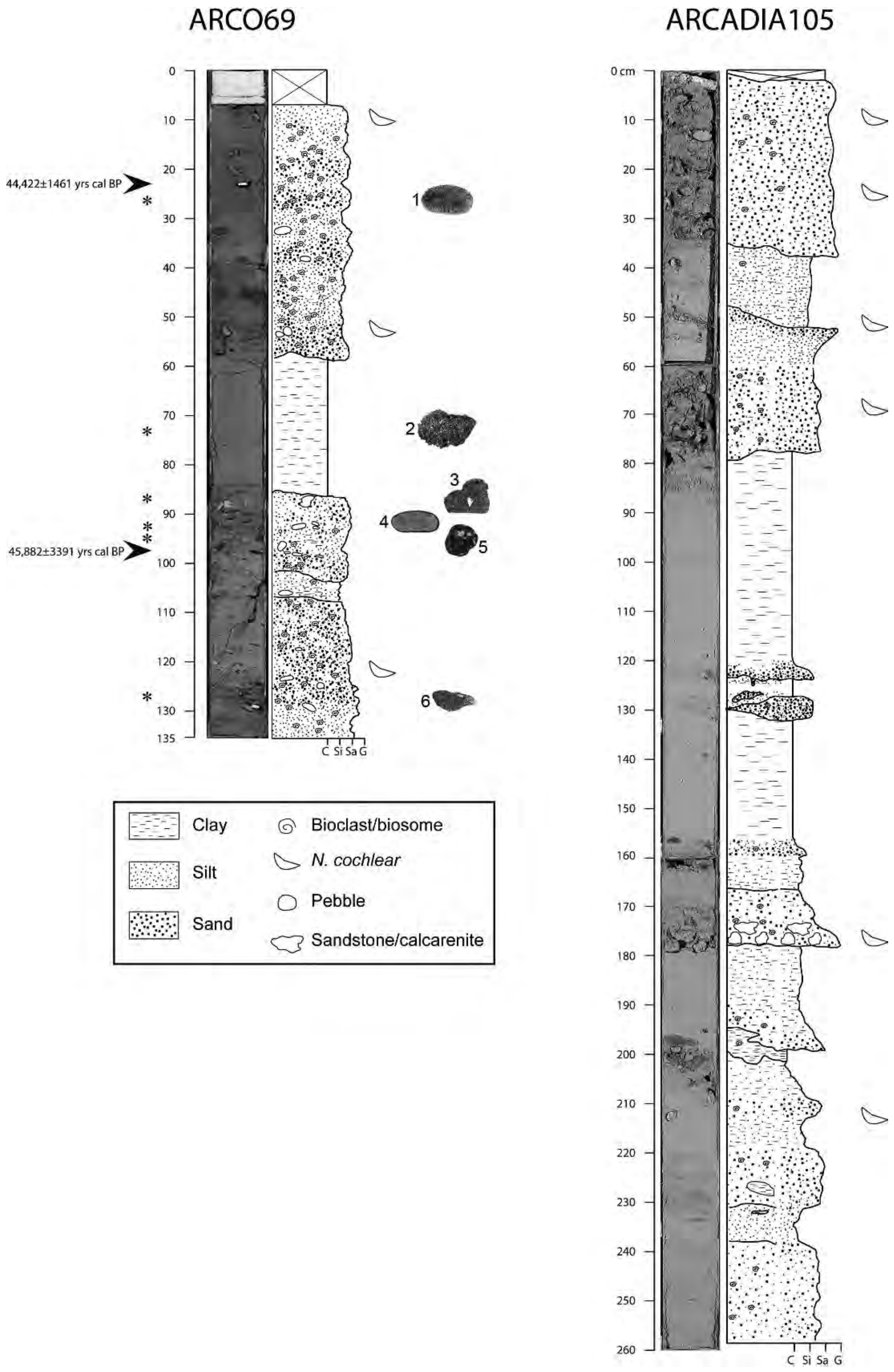

Figure 9. Photographic (left) and interpreted (right) logs of cores from Oyster Pit. Multiple mass gravity deposits are evident, involving old (pebbles, brackish/lagoonal loose shells and sandstones) and modern (e.g., *Neopycnodonte cochlear*) components. (A) core ARCO69, recovered from the bottom of Oyster Pit at 73.6 m depth. Sectioned pebbles within the core are shown and their source formation based on thin section reported. Key: 1. Limestone with calcisphere and rare planktonic forams (Maiolica

limestones, while farther south, in the Salento Peninsula, different types of dolines, both inland and along the coastline, are developed in younger rocks (Delle Rose and Parise, 2002; Bruno et al., 2008; Del Prete et al., 2010). In particular, the Plio-Pleistocene Calcareniti di Gravina Fm is mostly affected by dolines related to the solution, suffusion, and dropout types (Waltham et al., 2005), showing subtle morphology and reduced sizes, on average up to 10 m wide and 4 m deep. Nevertheless, the same rocks may be locally involved in collapses related to the presence of underground caves, whose evolution may result in upward stoping of the cave ceilings until it reaches the ground surface and produces the final collapse. Some dolines display morphological features similar to Oyster Pit, such as a well-defined circular shape, steep walls (often subjected to further minor failures due to tensional release), and breakdown material at the bottom. The bottom may be partially or totally covered by debris or alluvial sediments, so that nowadays the doline's bottom appears flat or smooth. The size of these collapse dolines is between 5 and 30 meters in width and 3 and 15 meters in depth (Parise, 2008a, b).

Drowned Offshore Karst

In the investigated area, Mesozoic rocks only occur as highly rounded pebbles in coastal deposits. On the contrary, Pleistocene calcarenites were found in onshore and offshore wells. Moreover, sampling inside the dolines (Fig. 10) and on the topographically rough area on the erosional surface (Fig. 10) provided marine calcarenites that could be correlated to the Calcareniti di Gravina Fm. Therefore, at the present state of knowledge, we hypothesize that the karst landscape identified offshore of the Gargano Promontory formed on or at least likely involved this unit at a time of lowered sea level during the late Pleistocene. This hypothesis is supported by the well-developed karst features observed on Plio-Pleistocene calcarenites in different coastal settings of the Mediterranean Basin (De Waele et al., 2011). Although lipoclastic, and therefore not as pure as a typical Mesozoic limestone, these Plio-Pleistocene deposits have been intensely affected by karst processes, as pointed out by the widespread occurrence of dolines, often related to underground caves and other macro- and micro-karst landforms dotting their outcropping areas. Thus, the landscape described in this paper seems to resemble the analogous features that were observed in different locations of Apulia.

On the other hand, we cannot exclude the possibility that other units, such as the Peschici or Maiolica Fms, were karstified in this offshore portion of the margin, but available data do not provide any robust supporting evidence.

We hypothesize that any active karstification in the area had to stop due to the postglacial inundation approximately 12 ky BP that brought on the shelf brackish/lagoonal and then fully marine conditions when sea level reached −50 m in Marine Isotope Stage 1 (Siddall et al., 2003). However, the presence of older brackish/lagoonal marine fauna (*Cerastoderma*) at Oyster Pit older than 40 ky may well indicate that a depression existed already at that time, thus perhaps moving back the time of karstification to MIS4. The area would have been inundated during the relative high-stand MIS3 (Simms et al., 2009), re-exposed during the MIS2 sea-level drop, and definitely submerged again at 12 ky BP.

At present, there are no signs indicating any on-going karst activity, such as karst springs like those seen in similar contexts in other parts of the Mediterranean Sea (e.g., Cossu et al., 2007; Mijatović, 2007; De Waele, 2009). Hydrologic data acquired from inside the best developed doline, Oyster Pit, support this presumption since there is no anomaly with respect to the surrounding marine water mass (Fig. 12). In our view, therefore, the submerged karst topography is a drowned relic.

CONCLUSIONS

The scenario proposed here to account for the submerged topography recognized off the shore of the Gargano Promontory calls for a subaerially formed karst landscape submerged by the sea. Our main lines of reasoning are:

I. The morphology of some key features, namely the almost perfectly circular shape and vertical profile of depressions punctuating the seafloor reminiscent of dolines on shore.

II. The carbonate nature of the superficial bedrock of this terrigenous-starved sector of the Apulian Adriatic, identified tentatively as Plio-Pleistocene calcarenites, likely the Calcarenite di Gravina Fm, prone to karstification and well documented in outcrop and offshore wells in this region; however, the possible involvement of other carbonate units (Peschici or Maiolica Fms) is not fully discarded, but at present

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Fm). 2. Chert with intraclasts (cf. Maiolica Fm). 3. Bioclastic rudstone (Ripe Rosse Fm). 4, 5. Packstone with planktonic forams and bioclasts (cf. Pietra leccese Fm or Calcareniti di Apricena Fm). 6. Polymictic arkosic sandstone. The ^{14}C-AMS ages relate to brackish-lagoonal mollusks (*Cerastoderma*) remobilized together with pebbles from the upper part of the doline. (B) Core ARCADIA105, recovered from the bottom of Oyster Pit at 73.4 depth.

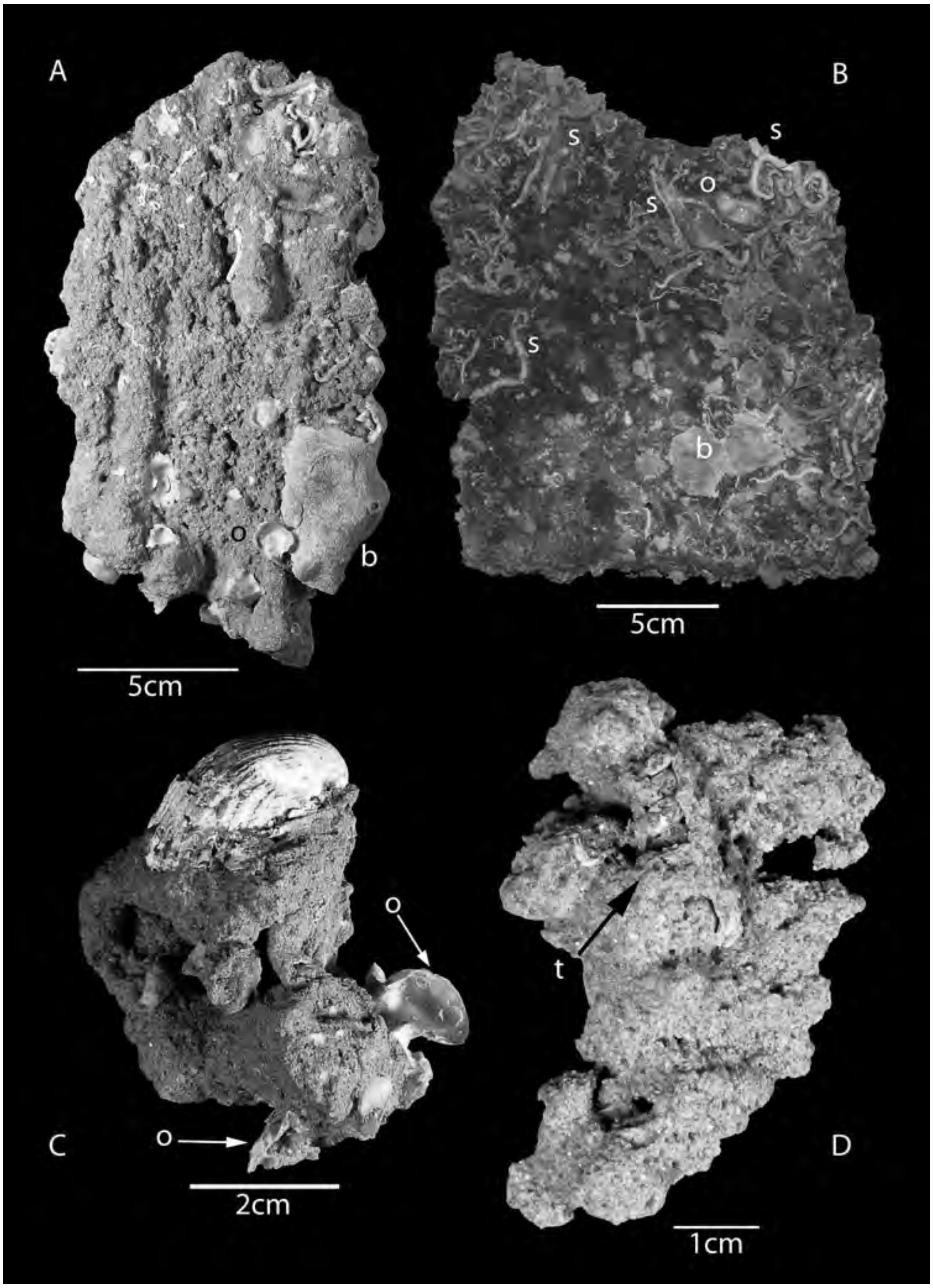

Figure 10. Examples of calcarenites recovered from the drowned karst area and tentatively attributed to the Calcarenite di Gravina Fm. (A) Slab of coarse-grained, porous calcarenite dredged from the bedrock in the rough-topography zone at 42°01.23′ N and 16°11.23′ E, 48 m water depth (ARCO73). Notice parallel grooves, possibly karren (dissolution micro-karst features), and the surface fouled by modern oysters (*Neopycnodonte cochlear*) (o), serpulids (s), and bryozoans (b). (B) Flat slab of well-lithified (hardground) calcarenite from the rough-topography zone at 42°00.88′ N and 16°13.03′ E, 52 m water depth (ARCO77). Observe that the surface is fouled by modern oysters (o), serpulids (s), and bryozoans (b) and stained by oxides, an indication of prolonged exposure on the seabottom. (C) Piece of fossiliferous calcarenite from inside Oyster Pit (ARCADIA111, 71 m) embedding a decalcified marine bivalve (*Acanthocardia* sp.) and exploited as an attachment base by modern oysters (*N. cochlear*, arrows). (D) Piece of fossiliferous calcarenite from inside Oyster Pit (ARCO72, 73 m). Notice the mold (arrow) of a marine gastropod (*Turritella* sp.).

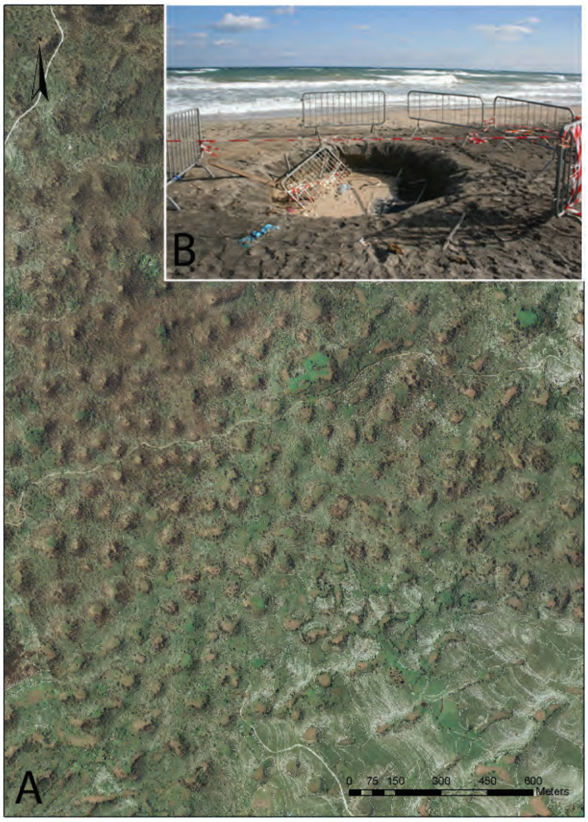

Figure 11. Example of karst landscape on Apulia resembling the submerged features off of the Gargano Promontory. (A) Karst landscape from inland Gargano Promontory near San Giovanni Rotondo (photo downloaded from Google, 2010). (B) Small doline (sinkhole) on the coastline near Lecce at Casalabate, March 2010).

we lack seismic data suitable to image the deeper structure of the dolines to explore this option further.

III. The late Pleistocene sea-level history of the margin, which was repeatedly subaerially exposed during the last glacial cycle, including the major drop at the Last Glacial Maximum, Marine Isotope Stage 2, thus permitting the action of karstification on its carbonate rocks.

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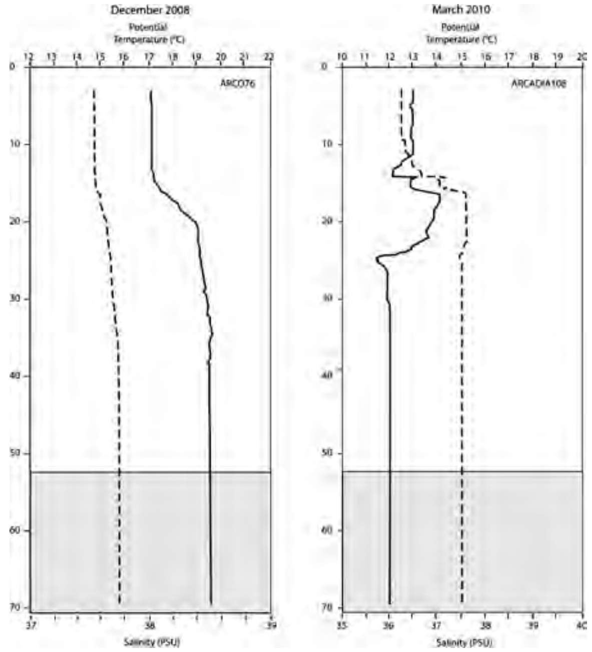

Figure 12. CTD cast hydrologic profiles showing temperature and salinity measured during ARCO (ARCO76, number 12 in Fig. 3, December 2008) and ARCADIA (ARCADIA108, number 12 in Fig. 3, March 2010) missions. No anomalies due to freshwater from springs are detectable, showing instead that seawater within the main doline (gray) is indistinguishable from the overlying Adriatic water at this location.

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FIVE BLUES LAKE NATIONAL PARK, BELIZE: A CAUTIONARY MANAGEMENT TALE

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Abstract: Karst is inherently dynamic, and this may be manifest in unexpected ways, which may have major implications for management of protected areas, where changes may have major impacts on visitor numbers and revenue streams. In Five Blues Lake National Park, Belize, the principal visitor focus is Five Blues Lake itself. An anomalous feature with characteristics of a karst window or cenote but in the setting of a polje or ponor lake, Five Blues has both surface and underground drainage components. Establishment of the national park proceeded under the impression that the lake was a permanent feature, but over July 20 to 25, 2006, the lake drained rapidly underground. Without the lake, visitor numbers and park revenues declined, and the park was all but abandoned. The lake refilled in 2007, but visitor numbers continue to lag. Management and promotion of hydrologic features within protected areas needs to take such possibilities into account, emphasizing variability and change and avoiding a focus on conditions that may not prevail at any given time.

INTRODUCTION

Designation as protected areas is an important component in the conservation and management of karst landscapes at local, national, regional, and global scales (Day, 1996, 2011; Kueny and Day, 1998, 2002; Watson et al., 1997). Such designation necessitates, however, consideration of impacts on local communities and requires implementation of usage policies that usually must reconcile conservation goals with visitor expectations and economic development priorities (Bundschuh et al., 2007; Day, 2011).

Visitor expectations in protected karst areas often focus on landscape vistas and on specific impressive features, such as caves, valleys, waterfalls, and springs (Bundschuh et al., 2007). These are not, however, fixed and immutable, changing in response to floods, storms, hydrologic variations, and human disturbance. For example, many protected karst areas in Belize were ravaged by Hurricane Richard in 2010, with parks such as St. Herman's Blue Hole and Guanacaste being closed to visitors for several months (Belize Audubon Society, 2010a).

Hydrologic changes, either natural or human-induced, may alter the fundamental character of karst sites, particularly those centered around surface rivers, waterfalls, lakes, stream sinks, underground conduits, and springs. Such features epitomize karst landscapes, and although they represent an interface between the realities of karst science and public perceptions, it is important to recognize and acknowledge their temporal variability in ways that all audiences can appreciate. One particularly dramatic example of this is provided by Five Blues Lake, a protected karst site in Belize whose susceptibility to hydrologic change was essentially unrecognized at the time of its establishment and whose recent history provides a salient lesson for management of similar areas.

PROTECTED KARST IN BELIZE

Reflecting its colonial history, its low population density, and its post-independence commitment to the conservation of nature and to ecotourism, Belize probably has a higher percentage of its karst under protection than any other country in the world (Day, 1996). Although there is considerable fluidity in precise numbers, currently about 3400 km^2, or 68%, of Belize's terrestrial karst, excluding the islands (cayes) of the barrier reef, is designated as some form of protected area, with an additional 900 km^2 (18%) being incorporated within Special Development Areas, where human activities are supposed to recognize the inherent environmental fragility of the landscape. Karst is present within more than twenty separate terrestrial protected areas and five Special Development Areas (Day, 1996; Escott and Day, 2005). Most of this protection stems not from an explicit recognition of the inherent scientific uniqueness or environmental fragility of the karst, but rather from the intricate association between the karst and other conservation priorities: intact forests with important flora and fauna, hydrologic catchment areas, and significant pre-Hispanic Maya archaeological sites (Day, 1996, 2003a,b). Accordingly, the karst is protected under various categories, including national parks, forest reserves, and archaeological reserves (Day, 1996; Belize Audubon Society, 2010b).

Conservation aside, these protected karst areas also represent significant resources for ecotourism and economic development. Approximately one third of Belize's tourism activity is focused on the karst, with over 50,000

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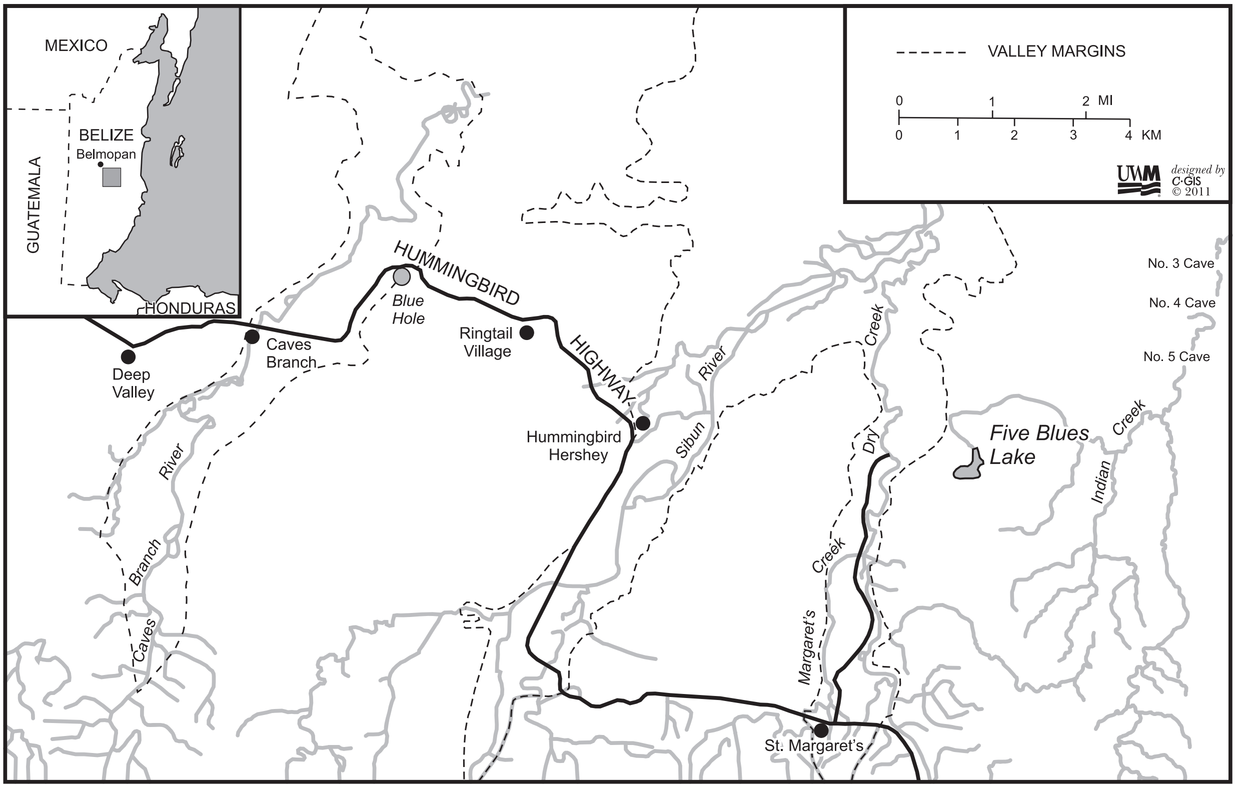

Figure 1. Location of Five Blues Lake.

visitors and an economic income of some US$15 million annually (Bundschuh et al., 2007).

Five Blues Lake

Five Blues Lake National Park is located within the Indian Creek valley in the Stann Creek District, bordering the Cayo District of west-central Belize (Fig. 1). It is a component of what has been termed the Hummingbird Karst (Day, 1986, 1987a,b, 1991, 1993; Day and Rosen, 1989), which flanks the Hummingbird Highway and is itself part of the broader Northern Boundary Fault Karst of central Belize (Miller, 1996). The karst consists of a slightly arcuate east-west belt some 60 km in length and 5 to 10 km wide and is formed in brecciated Cretaceous-age limestones and dissected into blocks by allogenic rivers draining northward from the adjacent non-karst Maya Mountains (Day, 1986; Miller, 1996). The karst blocks have only intermittent surface drainage and have a rugged topography characterized by dry valleys and karst depressions (Day, 1987c). In contrast, the intervening valleys, some of which are clearly poljes, have alluviated floors and considerable seasonal allogenic surface flow. Surface flow in the Sibun and Caves Branch valleys, with respective upstream catchment areas of some 250 km^2 and 90 km^2, is perennial, but that in St. Margaret's Creek (20 km^2), Dry Creek (40 km^2), and Indian Creek (30 km^2) is essentially limited to the June–December wet season, and even then, it may be sporadic (Day, 1987b).

Five Blues Lake National park was established in 1991 and enlarged in 1994 to comprise approximately 1640 hectares (4000 acres). Uniquely among Belize's national parks, it is managed by a local NGO, the Association of Friends of Five Blues Lake, with the income being used for park upkeep and management and for local community development (Community Conservation Consultants, 1999; Horwich and Lyon, 1999; Young and Horwich, 2011; Fig. 2). The Belize Forest Department, within the Ministry of Natural Resources and the Environment, has oversight because the park is located within the Sibun Forest Reserve, but does not participate in park management. Access is via an unpaved road leading northward from Mile 32 on the Hummingbird Highway at Santa Martha/St. Margaret's village, the nearest local community, which was established in the mid-1980s and is a center for the local lime-burning industry (Day, 1987b, 2005; White, 1994; Warner, 1996).

Although there are many karst attractions within the park, notably caves, dry valleys, conical hills, and serrated ridges, the principal visitor focus is the 4 ha (10 ac) Five Blues Lake itself. The spectrum of blue shades, reflecting the dry-season water clarity and variable depths, is visually attractive, the lake is important ecologically, and visitors use it for swimming and boating (Fig. 3). Visitor numbers

Figure 2. Park sign.

Figure 3. Five Blues Lake before draining.

to the park, although never large, increased gradually between 1991 and 2006, from a handful to well over one hundred annually (Community Conservation Consultants, 1999; L. Wengrzyn, personal communication, 1994; M. Perez, personal communication, 2011). Official counts underestimate actual numbers, but the trend of visitor numbers was encouraging, and the contribution to local revenues, although only about Bze$500 to 600 (US$250 to 300) annually, was welcome.

Although there have been no detailed studies of Five Blues Lake, it is clearly an anomalous feature, although in some ways it is analogous to the nearby Blue Hole, a karst window in the St. Herman's Blue Hole National Park adjacent to the Caves Branch valley or polje (Miller, 1977, 1981, 1983, 2006; Day, 1992; Day et al., 1987). Drainage through the Blue Hole involves a trunk conduit running alongside the valley, with cave tributaries beneath both the valley-side ridges and the alluviated polje itself (Miller, 2006). The Caves Branch Cave System includes multiple components, including higher-level breakdown passages, phreatic loops, and collapse-truncated conduits (Miller, 1983, 2006), and "hydraulically restricted cave channels pirate allogenic river water from the polje into the conduit" (Miller, 2006, p. 91). At the same time, surface drainage via the Caves Branch River is maintained by allogenic drainage from the adjacent non-karst Maya Mountains. The surface and subsurface systems are interconnected, with drainage pathways at any particular time reflecting variations in drainage inputs, local system capacities, and hydrologic outputs, and flow eventually into the Sibun River system. Discharge through the 20 m deep Blue Hole is perennial, but baseflow during the dry season is about 1 m^3 s^{-1}, with wet-season discharges increasing to over 15 m^3 s^{-1} (Day, 1992).

Despite similarities, the Blue Hole and Five Blues Lake differ in several respects. First, Five Blues Lake occupies a landscape position differing from that of the Blue Hole. While the latter is set within the polje border hills, at an elevation of about 60 m above sea level, the former is located within, although close to the edge of the valley, at an elevation of about 40 m. Second, flow into the Blue Hole is known to be largely from the upstream Petroglyph Cave segment of the Caves Branch system via St. Herman's Cave (Miller, 1983, 2006; Day et al., 1987), but the source of water in Five Blues Lake has not been established, although it is likely from one or more conduits flanking and underlying Indian Creek valley and perhaps the adjacent St. Margaret's/Dry Creek valley. Meerman (2001, 2007) reports shallow subsurface-stream inputs and there appears to be very little surface-stream input. Third, flow out of the Blue Hole is entirely underground via a downstream phreatic loop in the Caves Branch cave system, whereas drainage from Five Blues Lake is usually at least partially via a surface stream (Fig. 4), that flows north, then eastward into Indian Creek, which itself eventually joins the Sibun River some 5 km south of Churchyard, east of Belmopan. The presence of this surface outlet is perhaps critical to understanding the behavior of Five Blues Lake. Dry season, base-level discharge for the outlet stream was estimated at less than 1 m^3 s^{-1} in March 1986, with wet season discharge in August 1986 estimated at 3 m^3 s^{-1} (Day, unpublished). Despite the futility of attempting to correlate surface and underground drainage catchments in karst (Ford and Williams, 2007), it is notable that the apparent surface catchment area upstream from the Blue Hole is about 90 km^2, whereas that for Five Blues Lake is less than 10 km^2.

Its geomorphological and hydrological characteristics suggest that Five Blues Lake is perhaps best characterized as a compound feature, having many characteristics of a karst window, yet being located within a border polje (Bonacci, 2004a; Ford and Williams, 2007), where it in some respects resembles a polje or ponor lake. Clearly, its

Figure 4. Northeastern part of Five Blues Lake. Surface outlet at right and outlet cave location below water level in right-center.

hydrology involves both surface and underground components, with its level reflecting multiple local inputs and outputs, particularly via sub-alluvial channels and a reversible ponor (sink), or estavelle, (Bonacci, 2004b; Ford and Williams, 2007) that may function as an input or drain, depending on specific hydrological conditions. Drawing an analogy with the Caves Branch polje, Five Blues may exist as a result of the blocking of subsurface drainage from the valley into an adjacent conduit system.

Five Blues Lake is not the only valley or polje lake within the Hummingbird karst; several others within the Caves Branch and Sibun watersheds are depicted on the 1:50,000 topographic sheet (Directorate of Overseas Surveys, 1973), although these have not been studied in detail. These lakes within the karst, including Five Blues and the Blue Hole, are sometimes referred to as cenotes, but this terminology is not really appropriate, because in some ways they are unlike cenotes both morphologically and hydrologically (Beddows, 2004; Day, 2004).

RAPID LAKE DRAINAGE IN JULY 2006

Between 1986 and 2006 water levels in Five Blues Lake appear to have remained relatively stable (Meerman, 2001), although no regular monitoring was conducted and major seasonal fluctuations may have escaped local attention. Minor seasonal fluctuations in lake-surface elevation of less than 1 m were noted (Day, unpublished), reflecting the seasonal discharge fluctuations estimated above, but these appeared unremarkable. It thus came as a great surprise to all concerned when, over the days July 20 to 25, 2006, the lake essentially disappeared, much of the water draining rapidly underground via what was described as a whirlpool (Meerman, 2001). Fish were stranded, submerged tree trunks were exposed, downstream surface drainage ceased, and the alluviated lake bed was revealed (Fig. 5). Although no detailed measurements were made and water persisted in the deepest parts of the lake's basin, it appeared that the lake surface area decreased by about 75 to 85%, with initial rapid drawdown followed by slower drainage over a three-week period (M. Perez, personal communication, 2011).

Figure 5. Five Blues Lake after draining.

Drainage of the lake revealed that the former depth of much of the lake had been less than 5 m, although with at least five deeper areas (Meerman, 2007; M. Perez, personal communication, 2011). Of these deeper areas, or pits, two were characterized as small, two as larger, and one, adjacent to the surface outlet on the eastern edge of the basin and referred to as the cenote, was apparently up to 45 m in width and had shear bedrock walls in excess of 70 m in depth beneath the rim (M. Perez, personal communication, 2011). While these reported dimensions may be questionable (elevation of the Indian Creek valley is only about 40 m above sea level), clearly the lake developed around at least one deep bedrock pit that had contributed to the deepest blue coloration. Also, significantly, a large cave opening was exposed in the lake bed just north of the cenote, close to the then-abandoned surface stream outlet (Fig. 4). Approximate calculation suggests that the lake volume prior to drainage may have been in excess of 10×10^6 m^3.

POSSIBLE CAUSAL MECHANISMS

Heavy rainfall may have played a role in the lake's drainage, in that both June and July 2006 experienced rainfall well above average, which resulted in surface flooding and may have dislodged sediment fills or organic debris in the cave systems. Average monthly rainfall at Belmopan is about 300 mm in June and 280 mm in July (Belize National Meteorological Service, 2011a), but rainfall at Hummingbird Hershey, within the Sibun River valley, totalled 432 mm in June and 672 mm in July 2006, with 881 mm of rainfall recorded between June 21 and July 21 (Belize National Meteorological Service, 2011b).

Although the precise cause of the lake's rapid drainage remains uncertain, two immediate possibilities arise. First, the drainage may have resulted from a dramatic, near-instantaneous failure of a plug in the lake-bed cenote that facilitated near-vertical discharge into an underlying cave conduit. Such a process would be unusual; rapid drainage of cenotes has not been reported previously, nor has rapid drainage of polje lakes via collapsing estavelles or ponors been reported previously (A. Kranjc, personal communication, 2010), although such lakes may fill rapidly, and their hydrology is locally complex (Petric and Kogovsek, 2005; Kovacic and Ravbar, 2010). The heavy rainfall of July 2006 may have increased the pressure head in the lake itself, but there is no evidence of a lake-bottom plug either prior to drainage or as a result of sediment erosion before refilling, and the reported depth of the cenote, which puts it well below sea level, suggests that vertical drainage there is unlikely.

Second, the lake may have drained in response to an unblocking event farther downstream within the underlying, perhaps water-filled cave-conduit system downstream of the cave entrance that was exposed at the northern end of the lake, perhaps, again, due to the failure of a conduit obstruction or plug (Meerman, 2007). This latter explanation appears the more probable, given the retention of water within the cenote and exposure of the downstream cave entrance, and it accords generally with the situation in Caves Branch, which includes multiple underground components, including higher-level breakdown passages, phreatic loops, and collapse-truncated conduits (Miller, 1983, 2006).

Thus, Five Blues Lake may indeed be a karst window, analogous to the Blue Hole, although one whose underground outlet is at least partially blocked under normal conditions, leading to water occupying a basin considerably larger than the karst window proper, and with surface overflow via the stream outlet. Thus the local hydrology is complex, involving multiple inlets and outlets, and with considerable vertical differentiation.

Interestingly, Meerman (2001) reported that local residents had previously noted increasingly abrupt fluctuations in the lake and that turbidity appeared to have become less seasonally predictable, perhaps presaging later developments. Also, local residents reported that a new, smaller lake appeared in another part of the park when Five Blues Lake drained, suggesting an underground hydrologic connection. Perhaps most significantly, there were contemporaneous reports in 2006 of unusually high discharges in caves within the Sibun Forest Reserve adjacent to Five Blues Lake (Meerman, 2007), perhaps supporting the unblocking hypothesis outlined above.

Post-Drainage Developments

With the lake drained, the primary attraction of the national park was gone. Five Blues Lake was never an easy destination to reach without a four-wheel drive vehicle, and word of its fate soon spread via the Internet (Meerman, 2007). Initially, curious visitors, particularly from within Belize itself, visited the site to view the desiccation for themselves, with 250 visitors recorded in 2006 and numerous others undocumented. This rather ironic influx soon dwindled, however, and in subsequent years recorded visitor numbers declined to pre-2000 levels, totalling 70 in 2007, 40 in 2008, and 45 in 2009 (M. Perez, personal communication, 2011). Tourism revenues declined precipitously, from about US$250 annually, which had been significant for park upkeep, given the essentially subsistence nature of much of the local economy, to less than half that amount, and the park and its access road were neglected until after Hurricane Richard in 2010 (M. Perez, personal communication).

Little was heard from Five Blues Lake in late 2006 and early 2007, but in late June 2007 visitors reported that the lake had refilled. The refilling was a result of groundwater replenishment rather than surface flow, and it occurred very rapidly, like the earlier drainage. After 344 days, during which standing water was more-or-less restricted to the cenote, Five Blues Lake refilled within a single 24 hour period on June 27, 2007 (M. Perez, personal communication, 2011). During the same time the new, smaller lake apparently disappeared, suggesting a subterranean hydrologic connection between the two, where rapid passage constriction, presumably through collapse, had interrupted flow to the smaller lake and caused a rapid backup into the Five Blues Lake basin.

Since 2007, road access has again been improved and facilities have been redeveloped. Visitor numbers, however, continue to lag well behind those pre-drainage (M. Perez, personal communication, 2011), and the park's managers remain understandably concerned both about the cause of the sudden drainage and the future viability of a park centered on an iconic feature which may or may not be present at any given time.

Management Implications and Conclusion

Although sinkhole collapse, sometimes engulfing small lakes, ponds, sewage lagoons, or swimming pools, is a widely recognized hazard in karst terrain (Waltham et al., 2005), sudden underground drainage of large natural karst lakes appears to be a relatively rare phenomenon, and thus, there are few international parallels to the dramatic disappearance and refilling of Five Blues Lake. Human activities often have profound impacts on karst hydrology (Drew and Hotzl, 1999), but rapid natural fluctuations in tropical karst-lake levels typically involve rain-fed flooding rather than accelerated subterranean draining (e.g., Day, 2007). Relatively rapid historical drainage of karst lakes has been reported in Florida (Kindinger et al., 1999), but polje or ponor lakes typically fill relatively rapidly and drain more slowly, often on a seasonal basis (Bonacci, 2004a,b), and groundwater fluctuations have impacts on karst lakes such as turloughs (Naughton et al., 2010) and meres (Day and Goudie, 1978).

The establishment and operation of Five Blues Lake National Park proceeded under the impression that the lake was a permanent feature, and the potential for rapid drainage was not appreciated. This may have been a reasonable assumption, although seasonal and other hydrologic variations had perhaps been underestimated. More significantly, anecdotal information suggests that the drainage in 2006 was not the first occasion on which such an event had occurred. In 1981, a since-deceased long-term resident of the Sibun valley, J. Roberts, who had been involved in forestry throughout the Hummingbird karst told the senior author that Five Blues Lake had not existed in the 1950s, but had appeared after Hurricane Hattie in 1961. Additionally, he claimed that the lake had varied in size throughout its history, had shrunk considerably in the early 1970s, and had assumed its full extent only by around 1980.

These claims were initially given little credence, and they cannot be tested. Cartographic evidence appears to refute them, in that the lake appears, apparently unchanged, on 1:50,000 topographic maps dated 1945, 1955, and 1962 (Directorate of Overseas Surveys, 1945, 1955, 1962). Similarly, the lake appears on various air photographs taken in 1939, 1962, and 1969. Nonetheless, the intervals between these dates are such that cycles of filling and draining may not have been captured, so that it remains possible that dramatic fluctuations are not unusual and that there have been several episodes of filling and draining in historic times. The exposure of tree trunks in the lake bed by the rapid drainage is also suggestive of former variations in lake depths, as these trees must have become established when lake levels were lower.

Regardless of the recent history of Five Blues Lake, the lesson of the 2006 episode is that karst landscapes, and particularly hydrologic features such as lakes, rivers, waterfalls, swallets, and springs, are inherently dynamic over even very short periods of time. Their management and promotion within protected areas needs to take this into account, emphasizing variability and change, and avoiding a focus on conditions that may not prevail at any given time. Appropriate management strategies, then, should acknowledge the temporal variability of the hydrologic regime and prepare visitors for an experience falling within a wide spectrum of hydrologic conditions. This has the advantages of presenting a realistic scientific assessment of karst phenomena, buffering against potential visitor disappointment and, at the same time, adding to the karst mystique.

This approach has broad parallels at other karst sites where distinct temporal variations, although at differing scales, are in effect, such as in breathing caves or those exhibiting seasonal airflow reversals. Littoral karst that is subject to tidal inundation presents a further analogy, as does the timing of geysers such as Old Faithful in Yellowstone National Park (Azzalini and Bowman, 1990). More generally, all temporal changes relevant to a given protected karst area, such as climate changes, sea-level fluctuations, geomorphic development, or human vegetation modification, might usefully be incorporated into interpretive literature or websites during the establishment and development of the site.

In the case of Five Blues Lake, the story of the lake's dramatic drainage and refilling provides a considerable incentive for potential future visitors, who will now come to the park with realistic expectations and a sounder appreciation of the lake's hydrology. Visitor numbers may never be substantial, but they may now be expected to return to pre-drainage levels and even increase as a result of the lake's new-found notoriety, representing a significant contribution to park upkeep and the restricted local economy. A similar approach might be useful at the nearby Blue Hole, which is a far more popular tourism venue and where some visitors are disappointed during flood stages when the water is turbid and not the expected color. Management there might also prepare for the possibility of rapid drainage or even hydrologic abandonment of the Blue Hole, which is less deep and at a higher elevation than Five Blues Lake, so that such an event would not necessarily have an immediate adverse impact on tourism revenues.

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A SUSTAINABILITY INDEX FOR KARST ENVIRONMENTS

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Abstract: With growing populations and ever increasing pressure on resources, the need to live sustainably with our environment has increased in significance. When considering such anthropogenic pressures, karst landscapes are as vulnerable, if not more so, than any other environment. Such vulnerability arises from the rapid transit times of percolating water, the poor filtering ability of carbonate bedrock, and the highly specialized biota of subterranean karst. The Karst Sustainability Index (KSI) was created as a standardized metric of sustainable development practices in karst settings. The KSI uses predetermined targets to ascertain the overall sustainability of a karst region. Indicators are designed to incorporate common measures of sustainability for the three domains of social, environmental, and economic resource use. Benchmarking the current state of karst environments allows the comparison of sustainability practices temporally and spatially to highlight areas where remedial policies or actions are needed. This is the first index to incorporate the emerging field of environmental sustainability with karst landscape assessment. To test the applicability of the KSI, a study was undertaken in the Tampa Bay Metropolitan Area, which encompasses four counties that are entirely karst. The TBMA was found to be progressing towards the sustainable management of karst resources, and the KSI provided a robust measure of sustainability.

INTRODUCTION

Karst environments are settings of predominantly carbonate rocks that have been subject to dissolution over time, resulting in a unique physical landscape characterized by sinkholes, disappearing streams, dry valleys, and caves (Ford and Williams, 2007). Rapid flow of water from the surface into the carbonate rocks and the aquifers they contain is a typical feature of karst, but also one that is problematic for resource managers (Fleury, 2009). Subterranean cavities are renowned for their fragile ecosystems, and many are sites of endangered species, with some species endemic to single caves (Culver and Pipan, 2009).

These unique characteristics of karst environments make them highly vulnerable to human disturbance. Activities such as agriculture, urban development, waste disposal, deforestation, and resource extraction constitute environmental pressures leading to polluted aquifers, destroyed caves, declining biodiversity, and denuded landscapes (Table 1). Aquifers can become contaminated because surface spills percolate quickly through the epikarst and plumes can expand kilometers in a single day, characteristics that make mitigation difficult. Caves are destroyed either through quarrying, construction, vandalism, or sediment influxes from deforestation. Slow degradation of these conduits can occur from misguided tourist operations. Agriculturally contaminated water, excessive water withdrawals, human visitation, and quarrying can cause cave biota to become stressed or even disappear altogether. Table 1 provides a more detailed overview of how human practices can alter karst systems. The Karst Disturbance Index created by van Beynen and Townsend (2005) uses environmental indicators to measure qualitative and quantitative human impacts on karst landscapes. It has been successfully applied in different countries by various researchers (Calò and Parise, 2006; van Beynen et al., 2007; De Waele, 2009; North et al., 2009; Day et al., 2011).

Due to increased awareness of the effects of human disturbance across many different landscapes with growing human populations, efforts have been made to reduce negative impacts and promote sustainable development. The modern sustainability movement in the West emerged from the transcendental thinkers of the nineteenth century. However, the publication Leopold's *Sand County Almanac* (1949) and Carson's *Silent Spring* (1962) brought together the philosophical value of nature with the need to change human practices to preserve the planet. With the advent of the UN's Brandt and Bruntland reports in the 1970–80s, sustainability has become a cornerstone of a more ecocentric worldview of environmental management (Dalby et al., 2009). The Brundtland report presented one of the first definitions of sustainability, characterizing it as ''development that meets the needs of the present without compromising the ability of future generations to meet their own needs'' (World Commission on Environment and Development, 1987). At the 1992 Rio de Janeiro UNCED Conference, discussions led to the development of environmental indices that address sustainable development. A decade later, the 2002 UN World Summit on Sustainable Development in Johannesburg further cemented the world's resolve that steps had to be taken to

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Table 1. Examples of human uses of karst environments and issues arising from human use.

Uses	Components: Subcomponents	Issue
Quarries	Opencast: Aggregate/ore extraction	Destruction of caves, epikarst, forests; Alteration of hydrology; Groundwater pollution from tailings
Mining	Underground: Ore extraction	Hydrology alteration; Water pollution; Surface subsidence
Agriculture	Extensive: Grazing	Pesticide/herbicide use; Deforestation; Fertilizers; Soil compaction; Erosion from over grazing
	Intensive: Feed lots Horticulture	Soil compaction; Effluent runoff; Fertilizers; Pesticides/herbicides/antibiotics; Erosion; Alteration of hydrology
Forestry	Parkland: N.A. Logging: N.A.	Clearcutting; Alteration in hydrology; Fertilizers; Increased erosion from roads and clearing; Poor management of caves on land
Tourism	Springs: Private/Public	Pollution; Overuse; Infrastructure; Clogging
	Caves: Private/Public	Overuse (too many visitors); Destruction (vandalism, desiccation); Infrastructure (buildings, lights, paths, roads)
	Surface Features: N.A.	Removal; Infrastructure; Destruction;
Urban Landuse	Low Density: N.A. High Density: N.A. Commercial: N.A. Industrial: N.A.	Increased impervious surfaces; Water pollution; Decreased forests; Changes in hydrology; Infilling of sinkholes
Water Use	Withdrawals: N.A.	Over extraction
	Dumping/Disposal: N.A.	Pollution

change human-environment interaction, steps that mutually recognize that development is inevitable, but must occur within a sustainable framework that ensures future access to our natural resources. At the 2005 World Summit in New York City, sustainable development was defined as incorporating three components, economic development, social development, and environmental protection (United Nations General Assembly, 2005). The exact framework for achieving sustainability has yet to be agreed upon, reflecting the conflicts between ecological conservation and resource exploitation and a lack of political will. There is a clear need to develop quantitative measures and plans that help facilitate a sustainable society (Brinkmann and Garren, 2011). Following these international efforts, a variety of environmental indices have been created to determine how nations or states incorporate sustainability measures into their societies (Table 2). Examples of these indices include State of the Environment (Briggs, 1998), Wellbeing of Nations (Prescott-Allen, 2001), the Millennium Ecosystem Assessment (Hassan et al., 2005), the Report on the Environment (US EPA, 2008), and the Heinz State of the Ecosystem report (H. John Heinz III Center for Science, 2008). Other indices that attempt to measure the impact humans have on their environment are the ecological footprint (Wackernagel and Rees, 1996), the human development index (United Nations Development Program, 2003), the water poverty index (Sullivan et al., 2003), and the water footprints of nations (Chapagain and Hoekstra, 2004). This list is by no means comprehensive, but provides some evidence of the efforts taken to promote the concept of sustainability. Sustainable development requires factoring social, environmental, and economic-resource use considerations into decision-making pertaining to environment management (Kelly, 1998). All of the above approaches incorporate these factors in different ways.

To date, little work has been done on creating sustainability indices for specific environments. The Environmental Sustainability Index (World Economic Forum, 2002) is a large, comprehensive index that is applied regardless of the intricacies of environment type. Environmental sustainability indices that are landscape-specific are the Working Wetland Potential (McCartney and Houghton-Carr, 2009), Coastal Index (Shi et al., 2004), and several for agricultural and urban settings (van Dijk and Zhang, 2005; Rao and Rogers, 2006). Additionally, it has been suggested that environmental indicators can only address the concept of sustainability if they take into account the temporal scale and have a target in mind (Meadows, 1998).

While many sustainability indices rely heavily on economic indicators, recognition of the need for a stronger environmental component led to a new approach, the Pressure State Response model. This model was developed to highlight pressure on the environment, and it measures alterations to the environment and the resulting policies or programs (OECD, 1993). While the PSR model works well for environmental factors, it is less useful for describing the social and economic pillars of sustainability. In response,

Table 2. General sustainability measures.

Sector	Sustainability Measure
Government engaged in sustainability	Several measures of government sustainability such as incentives for green redevelopment
Agriculture	Green practices, availability of organic food, humane animal husbandry, access to affordable food
Building and development	Presence of benchmarking, access to green building technology, sustainable approaches to development and redevelopment, preserving historic buildings, access to affordable housing
Economic Development	Green industry, green energy development, green job availability, green real estate
Tourism	Ecotourism, green hotels
Energy	Use of green energy, conservation availability, education on green energy and conservation
Natural Resource Management	Preserve lands for future generations, provide access to out of doors, provide outdoor exercise opportunities, protect habitat of endangered species
Transportation	Provide green public transportation, develop green fuels and vehicles, build for walking and biking
Waste	Reduce waste generation, promote reuse and recycling, eliminate hazardous wastes
Education	Teach about sustainability in public schools, higher education options, informal education efforts
Water	Conserve water, fresh water access to public, storm water management, appropriate sewage management
Greenhouse Gas Management	Plan in place for greenhouse gas management, inventory complete

the DPSIR model was created, whereby the driving forces (D) arise through society's use of natural resources to stimulate the economy, thereby exerting pressure (P) on these resources. The state (S) of the environment describes the results of this pressure, and impact (I) includes the health and biological effects due to the state of the environment. Both the state and the impact lead to a response (R) in society that can include environmental policies, taxes, and regulations (Lundin, 1999). This latter model provides a comprehensive treatment of sustainable development. Similar approaches to those described above have been taken by the US Environmental Protection Agency in their Report on the Environment (US EPA 2008), the Heinz State of the Ecosystem report (H. John Heinz III Center for Science, 2008), and the Millennium Ecosystem Assessment (Hassan et al., 2005).

While many of these sustainability indices strive to describe all facets of sustainability, an unintended outcome is unwieldy indices that hinder effective translation of the local state of the environment into concrete regional or national courses of action (Ronchi et al., 2002). One method of portraying the results of the application of a certain index is to use the dashboard approach, a simple visual display that clearly delineates to the public and policy makers the current state of sustainability for the location (Ronchi et al., 2002).

In this study, we take a modified approach in the creation of a sustainability index specifically created for karst environments by integrating relevant environmental, economic-resource use, and social indicators. The Karst Sustainability Index (KSI) attempts to address a specific landscape type, an approach that cannot be used in larger national indices. Our index incorporates both qualitative and quantitative variables, similar to that undertaken by the Karst Disturbance Index. The KSI uses a set of core indicators that capture the specificity of karst environments, and it sets targets that can be actionable goals for municipalities to measure their success at living with karst in a sustainable manner. We believe that the results of this effort make a strong case for the development of regional sustainability indicators that make sense within particular environments.

CRITERIA FOR ASSESSING SUSTAINABILITY

The U.S. Environmental Protection Agency states that the criteria for selecting indicators for environmental indices are that they be measurable, sensitive, reproducible, representative, have reference values, cost effective, easily detected, widely accepted, and understandable (US EPA, 2008). The PICABUE method of Mitchell et al. (1995) as described by Sunkar (2008) includes seven criteria to be considered when developing sustainability indicators: 1) Indicators must specify the sustainability principles to the applied. 2) Indicators should identify issues that are both locally and globally important. 3) Indicators should be constructed according to stated program objectives. 4) Indicators should address principles of equity, futurity, and environment to communicate progress towards sustainability. 5) Indicators should include local attributes that relate to administrative boundaries. 6) Indicators must consider uncertainty that arises from limited knowledge, poor datasets, and unpredictable behavior of the system. 7) Indicators should be assessed whether they are relevant to issues of concern, sensitive to change across space and social groups, temporally sensitive, supported by data, understandable, measurable, expressed in way that makes sense, and able to identify targets and trends to show progress, or lack thereof, towards sustainability.

As stated above, sustainability indices attempt to include most measures of sustainable development while environmental indices take the approach of measuring individual components of the entire environment. Hence the Karst Sustainability Index is somewhat of a hybrid, dealing directly with sustainable practices that are undertaken in karst settings. Overall selection criteria for indicators were:

1) Incorporate environmental, economic, and social components of sustainability.
2) Within these components, characteristics of karst are recognized.
3) Comprehensive treatment of all human activities related to environmental management.
4) Variables are meaningful for any karst landscape.
5) Variables can be easily and inexpensively measured.

The KSI is divided into the three domains, social, environmental, and economic-resource use. The rationale for taking this approach is to fulfill the criteria identified by Mitchell et al. (1995) that are outlined above. Accordingly:

1) The KSI is similar to more traditionally accepted measures of sustainability indices, but still captures karst-specific indicators.
2) The indicators are quantifiable, with little subjectivity, although there may be some debate about the targets for certain indicators.
3) Users can easily determine how far they are from these targets.
4) It is possible to visually display the results of our index to non-specialists using the dashboard approach.
5) This approach can be applied equally to all karst environments, in both rural and urban areas.
6) The KSI can show temporal change in these indicators over a defined period, measuring progress towards the targets.

Table 3 lists some of the many different practices and measures that pertain to karst and sustainability. All the variables outlined in the KSI can be applied to any karst region in the world, whether it is within a developed or developing nation. Finally, all the variables are easily measured and do not require field measurements, making the KSI very cost-effective. All that is needed is expertise in karst environments and knowledge of the management practices utilized in that region. The latter may involve some research and interviewing of local officials, but such an endeavor is not prohibitive in time or cost.

The Karst Sustainability Index

The three principal domains, social, environmental, and economic, each possesses a subset of indicators and target levels that determine progress towards sustainability (Table 4). The time frame over which these targets are achieved depends on the ability of the entity with jurisdiction over the karst region. This ability may be affected by the current state of the environment under the controlling body's jurisdiction. If the environment is already well managed, then little time and effort would be required to move the KSI indicators below the targets outlined below. However, if the opposite situation applies, with a heavily disturbed environment or with little political or economic will, the time to achieve the KSI goals may be greater. In light of this issue, it is up to the managing entity to determine what time frame is reasonable. Each domain contains several indicators. Their inclusion is justified below.

Social Domain. The social domain is complex and includes a variety of indicators, including issues of equity and environmental justice, indigenous peoples' rights, and the ability of local residents to obtain work and take part in governance. These are covered in the first five indicators. As this index is applied to karst environments, these indicators have karst-related themes, with local ownership of caves, local employment in karst jobs, and equitable access to karst resources for native people.

Education is an essential component of any sustainability index, regardless of scale or environment, and our index is no exception. However, once again, the education indicators concentrate on karst and how schools, tourist facilities, and local governments take advantage of their local karst setting to inform the public about the issues and fragility of their environment.

Environmental Domain. The environmental-domain indicators are concerned with the sustainable environmental management of karst landscapes. A variety of indicators, from surface practices to water quality to environmental monitoring, are included. Caves and surface karst have extremely fragile and rare biota and flora that can be easily disturbed. Consequently, their preservation is imperative to the biodiversity of the planet. If these species are to be protected, areas around the caves should be forested or protected from development. The prevention of widespread deforestation, especially in native forests, can prevent accelerated soil erosion, thereby reducing cave sedimentation and negative impacts on cave biota. In addition,

Table 3. Sustainable practices to reduce human impact on karst environments.

Uses/Components	Sustainable Practices
Quarries	
Opencast	Reclamation after use/avoid caves/placement to reduce alteration of hydrology/containment of waste
Mining	
Underground	Minimize hydrology alteration/protection of groundwater from contamination/reduction of possible subsidence/ fewest mines possible
Agriculture	
Extensive	Prevention of overgrazing/minimal fertilizer and pesticide use/erosion reduction measures/setbacks around sinkholes, springs and caves
Intensive	Contain effluent runoff/reduced chemical use/prevent alteration of hydrology/monitor water quality
Forestry	
Logging	No clearcutting/minimize hydrological alteration/erosion control measures/ creation of setback zones around caves and springs/ no use of chemicals/active management and monitoring of caves/ monitor water quality
Tourism	
Springs	Pollution reduction measures within spring catchments/control of water extractions/control of development in spring catchment/erosion control in catchment to prevent clogging/public education
Caves	Effective management plan and installation of plan/monitoring of cave and surface connections/ protection of cave surface catchment/public education
Surface features	Prevention of removal of features/management and monitoring plan/effective enforcement/public education
Urban Landuse	
All categories	Effective laws and regulations to prevent pollution of aquifers (long list of possibilities here)/ reduction in impervious surfaces/increase urban forests
Water Use	
Withdrawals	Effective management and monitoring of aquifer/regulations, laws and enforcement of these are fundamental
Dumping/disposal	Effective laws and enforcement to make sure contaminant levels at safe levels regardless of seasonal changes in hydrology/public education/monitoring

riparian zones around hydrologic inputs to the karst can reduce sedimentation and also remove some contaminants harmful to the karst groundwater.

Measures of the quality of the water, common in all environments, can be biological in origin, such as biological oxygen demand or chlorophyll B. Elevated nitrate levels are also seen as problematic and are commonly measured. To maintain water quality at acceptable levels, monitoring is necessary, though it is unrealistic to expect every small stream to be monitored. Another consideration in assuring the sustainability of karst-water resources is reducing the likelihood of their contamination from landfills and waste water-disposal. Industrial and residential wastes can easily contaminate groundwater, and their collection and treatment are vital to prevent pollution. Karst aquifers and their associated outflows (springs) are especially vulnerable to groundwater contamination due to rapid infiltration through the epikarst and quick flow-through times of groundwater via natural conduits. In non-karst lands, bacterial degradation and filtering is common, but in karstified bedrock, it is uncommon. Indicators En7–9 provide viable targets for municipalities to achieve sustainable use of this resource. Modern design of landfills is a safeguard for groundwater, and residential wastewater must be collected and treated properly.

As part of management plans, the condition of caves, especially those that have regular visitation or are commercial, should also be monitored to ensure this karst resource is not being degraded. Regulations can help with these measures, and their enforcement is imperative.

Economic Resource Use Domain. Finally, the economic domain focuses on economic activities and local resource

Table 4. The three principal domains, social, environmental, and economic of The Karst Sustainability Index.

Indicator	Target, %
Social Domain	
S1. Local ownership, private or public, of caves and springs	>80
S2. Locals employed in karst-related jobs	>80
S3. Equitable access for population to karst water resources	100
S4. Percentage of population displaced by development of karst landscape	<5
S5. Indigenous peoples' access to karst resources	100
S6. Percentage of schools offering karst education in curriculum	100
S7. Percentage of karst-related tourist facilities offering informal education	100
S8. Local governments offering karst-related information on websites or through publications	100
Environmental Domain	
En1. Increase in amount of karst area forested or in native vegetation	↑ 20
En2. Increase in amount of karst area designated protected	↑ 20
En3. Biodiversity of species in karst environment	Stable
En4. Riparian zones around sinking-streams and sinkhole sources	>75
En5. Decrease in number of impaired springs as measured by biological or water quality indicators	↓ 20
En6. Percentage of water-supply springs and wells that are monitored	100
En7. Current landfills preventing groundwater contamination	100
En8. Collection of sewage from all homes in urban areas	100
En9. Tertiary treatment of urban wastewater	100
En10. Monitoring of the condition of heavily used caves	100
En11. Enforcement of local regulations	100
Economic Domain (Resource Use)	
Ec1. Abandoned commercial quarries or mines that have been reclaimed	100
Ec2. Water extraction from aquifer and springs	Stable
Ec3. Increase in agricultural water efficiency ($ value/consumption)	↑ 20
Ec4. Area of urbanization and roads	Stable
Ec5. Forestry on the karst landscape that is sustainable	100
Ec6. Increase in number of ecotourism ventures related to karst landscape	↑ 20

use. The indicators measure whether particular practices within the karst landscape can be considered sustainable.

Quarrying and mining are destructive activities, but can also be important sources of income. The sustainable practice of quarrying and mining should focus on ensuring long-term plans for reclamation. The sustainable use of karst water resources such as aquifers and springs is essential, and consumption from these per capita should decrease with time. Greater efficiency and conservation practices that make such a goal attainable are currently available. The agricultural sector is an important source of income for most karst regions, but in some locations it extracts more water from aquifers than any other user. To determine the water sustainability of this sector, one approach would be to divide the value of agricultural output by its water use; for an improvement in sustainability, this ratio should increase over time.

The development of urban areas is often seen as economic progress. However, such development also requires more resources and adds stress to the karst landscape via deforestation and increased stormwater runoff. The karst hydrology of an area is often altered during this process through soil compaction, grouting of subterranean voids, and the interception of precipitation before it enters the epikarst. Restricting the growth of urban areas maintains agricultural areas and forests. Their preservation allows for natural infiltration rates into the epikarst, resulting in less groundwater pollution. Higher population density of urban areas is a likely consequence, but indirectly achieves one of the aims of sustainability, the reduction of our carbon footprint. Commercial forestry needs to be sustainable if it is to survive. Widespread removal of native forests simply depletes this finite resource. Selective logging of the larger native trees allows the smaller ones to replace them for future harvesting. However, if native forests have already been felled, replanting is essential.

Ecotourism is a growing trend in many countries where the natural environment is impressive enough to draw visitors from around the world. Many karst areas have the necessary physical features such as caves, tower karst, or large springs to draw the tourists. Best practices of ecotourism attempt to reduce the human impact on these features by limiting numbers and reducing the building of infrastructure at these sites.

RATIONALE OF TARGETS FOR INDICATORS OF KSI

SOCIAL DOMAIN

The World Commission on Environment and Development (1987) argues that greater equity will lead to more sustainable development. "Poverty itself pollutes the environment… Those who are poor and hungry will often destroy their own immediate environment in order to survive." Local ownership and local employment levels are set at greater than 80% to ensure that the local community has significant control and involvement in the local economy. External entities often take control of local resources with little concern for improving the quality of life and incomes of people in the surrounding area. Where this is true, sustainable practices should include local stakeholders into the decision-making process rather than relying on external paternalistic control of the economic resources. Urich et al. (2001) provide an excellent example of including local vested interest groups in this process. Local participation and oversight of resource extraction focused on the long term needs of the people and the karst environment is crucial for sustainable practices. Related to these indicators are those pertaining to equity and social justice. All of the population should have access to the water supplies of the area, in accordance with the 2010 UN declaration that water and sanitation are basic human rights (Banerjee, 2010). Additionally, displacement of local populations can result from the development of important economic resources. Two examples of this displacement of local population due to the exploitation of natural resources in karst environments are the development of the Three Gorges Dam in China, which required the relocation of more than a million people (Heming et al., 2001) and the expansion of mining operations in Jharkhand, India, which led to subsequent environmental degradation that caused the displacement of the local indigenous peoples (Areeparampil, 1996). This is unfortunate, and it should be kept to a minimum; hence we set the target for the displacement of the local population at 5%. Where population densities are high, even a small percentage can be a large number of people, and the target can be set lower in such cases (Ronchi et al., 2002).

Indigenous peoples should have access to their karst resources, especially if they used these for many years. Indigenous needs may seem unusual to our Western culture, but this should not affect access. Two examples are access to caves that are traditional burial sites and preservation of sites of religious or cultural significance.

Ideally, the most effective approach to promote sustainable use of karst landscapes is education. Schools in a karst region should offer some type of karst-related education. Tourist caves offer a rare opportunity to educate the general public. During most cave tours, a small amount of scientific information is given to tourists, so there could be subtle inclusion of how we can improve our interactions with the surface and subterranean karst environment. There is no reason why 100% of tourist caves cannot achieve this target. Finally, to encourage public interest in their effects on their karst environment, 100% of local governmental agencies should have information on their websites or written information available to the public at their offices.

ENVIRONMENTAL DOMAIN

Sedimentation of streams and rivers is a real threat to vulnerable karst ecosystems. The area of forest and protected karst should be increased by a target of 20% over a designated period of time. Karst is known to have species that are endemic to small areas such as caves. In fact, certain species have been identified that can only be found in one cave. These can include certain types of isopods, aquatic species, and plants (Christman et al., 2005). It is essential that all species are kept stable and that no species go extinct. One approach to protecting species is to remove eroded sediment or contaminants before they reach streams by replanting and preserving riparian zones along waterways. Most waterways should possess riparian barriers, and 75% is a realistic target for a significant difference in water quality to be achieved.

It is also important to reduce the number of impaired water bodies if a sustainable water resource is to be maintained for future generations. Reducing the number of water bodies that are impaired by 20% is not an excessive or unattainable goal given certain best management practices and small changes in consumer behavior. Agricultural practices are a significant cause of water degradation, and best management should be adopted in this sector. These practices include sustainable logging instead of clear-cutting, keeping pesticide use to below 7.5 kg/ha (Ronchi et al., 2002), and ensuring there is a reduction of soil erosion and overgrazing of 50% over the target period. Monitoring the water quality of all municipal springs and wells is essential for not only safeguarding drinking water supplies but also allowing the rapid identification of sources of pollution that may negatively impact this vital resource for some time. In addition to these measures, leachates from landfills and untreated sewage must not be allowed to become pollutants. To attain such a target, all landfills must have liners to prevent leachates escaping. All sewage must be directed to treatment plants in urban areas, and rural areas can have large receptacles that can be emptied when necessary. Such companies already exist to remove human effluent from point sources such as homes.

Monitoring the condition of caves will determine if any surface activities are having a detrimental effect. Heavily used caves, especially those that are commercial entities, should undertake monitoring that includes counting cave species, measuring CO_2 concentrations, watching for lampenflora, and observing the condition of speleothems. Finally, enforcement of environmental regulations related to the above indicators would help government agencies meet their targets and reduce environmental degradation. While the target of 100% enforcement of environmental regulations is ambitious, it is an important goal for municipalities, due to the particular fragility of their karst environment.

ECONOMIC DOMAIN

Due to the extreme destructiveness of quarries, it is important to reduce the impact of this sector of the economy. Best management practices for this sector include the rehabilitation and reclamation of those sites where commercial operations have ceased. One way to quantify this approach is to simply require a decrease in the amount of bedrock or minerals extracted from area. A realistic target that would not destroy a local economy reliant on this sector would be a reduction of 20% of extracted material.

In most developed nations water consumption far exceeds what could be needed given more conservative practices. Excess consumption leads to falling water tables and decreases in water quality. Reduced water levels impact karst by affecting percolation rates to caves and by allowing rapid saltwater intrusion in coastal areas. A 20% reduction in water consumption over the designated time period is possible, as evidenced by experiences during droughts that required conservation measures. A reduction in water use by the agricultural sector is an important goal for the sustainable use of the karst aquifer. Here the KSI requires an increase of 20%. Roadways and development of urban areas are essential components of economic development. However, such development can be contained within existing areas or brownfields through the intensification of land use, so as not require additional roadways and to make mass-transit systems more viable.

The forestry sector, especially one that destroys native forests, is not usually sustainable, and even exotic forests can struggle in karst areas where thin soils predominate. A target that calls for 100% of the forestry sector to practice sustainable harvesting techniques is reasonable, and it would allow for long-term employment in this industry. Finally, ecotourism is seen as the future of the sustainable exploitation of the natural beauty of an area. By increasing these types of ventures by 20%, the end product would be less impact on the karst landscape and a better-educated tourist.

APPLICATION TO THE TAMPA BAY METROPOLITAN AREA

West-central Florida's Tampa Bay Metropolitan Area consists of four counties, Hernando, Hillsborough, Pasco, and Pinellas (Fig.1). While they may differ somewhat in their land use, they all fall within the same karst area characterized by flat terrain, a high density of sinkholes, a highly utilized aquifer, and important springs. The population of 2.5 million has led to karst degradation and karst-related environmental problems (Tihansky and Knochenmus, 2001). The Ocala and Suwannee Limestones constitute the bedrock that lies below meters of poorly drained clay to sandy-clay sediments interspersed with calcareous rock (the Hawthorn Group) (Stankey, 1982). The TBMA covers 6,637 km^2, with Pinellas and Hillsborough Counties holding most of the population in the region and Pasco County in transition from being predominantly rural to hosting low-density residential communities. Hernando County is rural, with only 106 people per km^2, and it also contains all the vadose caves in the TBMA. Conduits in the rest of the region are all phreatic in nature.

DATA SOURCES

Data for equity and environmental justice measures in the social domain such as ownership, employment, access, displacement, and indigenous rights for the areas of interest can only be gathered by local data collection, policy assessment, and interviews. Information on karst education in school curricula, education centers, and tourist locations can be gathered from school officials, education centers, and cave managers. For the Tampa Bay Metropolitan Area study, all of the necessary information we already knew from our work in the area or was found on county, state, and federal government websites. Consequently, data collection was fairly straightforward.

The environmental domain has a number of data sources. Local or regional councils or governmental agencies can be a wealth of information on forests, protected areas, riparian zones, and the monitoring of various water-quality indicators. They may also be responsible for enforcing local and national environmental regulations. Departments of environmental protection or conservation, if they exist, often measure the state of the environment for areas under their control. In addition, all these agencies may have GIS map files and spatial data that can be invaluable in illustrating changes that have occurred in their regions. Cavers and cave organizations possess a wealth of information that should not be ignored, particularly regarding cave management plans and eco-tourist activities. The TBMA study confirmed these sources of data were essential and often readily available from individuals and organizations like the South West Florida Water Management District. Relevant regulations were found in county management plans. Florida state agencies, such as the Department of Environmental Protection, also collected useful data. In addition, research by universities is another important source of environmental data for assessing the state of certain aspects of the karst environment.

Finally, information for economic or resource use indicators generally comes from local, regional, or national governmental entities. Data about water consumption and waste collection and treatment are typically collected by local municipalities or waste and water management organizations. Regulations that influence landuse and urbanization can be assessed at the local, regional, and national levels. For the TBMA, these data had been created by the SWFWMD and groups at local universities such as the Institute of Food and Agricultural Sciences.

Scale

There are various scales at which a Karst Sustainability Index can be applied. These include large areas such as states or counties that encompass an entire area of karst, as well as small karst watersheds. Applications at both scales have their advantages and disadvantages. In large areas, all of the karst can be included, and any small local differences between areas can be smoothed. Data collection at this scale is facilitated by national and regional data networks. The obvious disadvantage to this approach is that major problems can occur when individual watersheds are ignored. In addition, while this approach may be more efficient, interagency cooperation is not always guaranteed. In the same vein, larger organizations often have different groups working on the same area without any communication, collaboration, or coordination.

The major advantage of working at the watershed level is being able to collect very detailed local data and information; this produces more accuracy in the assessment of sustainability. Another advantage is that it is possible to keep building the study area outwards from a single watershed to allow for comparative analysis.

During our application of the KSI, the issue of scale did not appear to be a problem. Although the study area contains several large watersheds, they are fairly homogeneous in their geology, and, given that the area is entirely karst, this greatly simplified the process. If the KSI had been applied to the entire state of Florida, then issues associated with scale would have been more apparent. Much of our data came from the SWFWMD, but Florida is divided into five water management districts, and there would be no guarantee that all the required data would be available or directly comparable.

The results of the Karst Sustainability Index can be seen in Table 5. Progress towards the KSI targets for the TBMA was measured between the years 1997 to 2010 or less, depending on the period for which data were available. While a ten-year period was the most common time over which progress was measured, only a shorter span of data could be collected for certain indicators; our shortest period of data was five years. The social domain (Table 5) was the component that demonstrated the region's most effective efforts towards sustainability. All major springs are under the authority of the South West Florida Water Management District. Of the caves in the TBMA, they are, with the exception of one, all within Florida State Forest holdings or are privately owned by local residents. Karst-related employment, whether at the water management authorities or spring attractions, is locally derived. With the TBMA being in a developed country, everyone has access to the water pumped from the karst aquifer. However, permits are required from the SWFWMD if significant amount of water is extracted by commercial entities.

While displacement of a segment of a population may be common in developing countries and indigenous peoples access to the karst resources may be restricted, these two indicators are not applicable for the TBMA. Although the entire school population of the region resides on karst, most schools in the area do not receive any education on the karst landscape, but several schools with an environmental focus in the Tampa area have been visited by graduates of the University of South Florida for talks on karst-related matters. Among the state environmental teacher-training programs uncovered, only one fieldtrip to a sinkhole has been incorporated into the science section, and no specific teaching module on karst exists. While formal education is somewhat lacking in teaching the children of TBMA about their environment, the springs that are tourist attractions, such as Homosassa and Weeki Wachee Springs, provide karst-specific information via display boards describing the formation of springs and the importance of the karst aquifer to the populace. Local government and water-authority agencies produce brochures and have information on their websites pertaining to the sustainable utilization of the local karst resources.

For many karst regions, the environmental domain poses the greatest challenge to achieving sustainability. Table 5 shows that the TBMA has a somewhat mixed record when it comes to sustainability. Over a ten-year period from 1996 to 2006, there has been a decrease in the region's forests by 10% (Hernandez et al., 2010). However, the need to protect the aquifer that is the main source of the region's drinking water has resulted in land acquisition by local government agencies. For example, in 1997 SWFWMD was authorized to acquire 600,000 acres, and by 2001 360,000 acres had been bought. By 2010 that total had risen to 444,000 acres. The target of 600,000 acres was not achieved due to the severe economic downturn in Florida (SWFWMD 2001, 2011b), but the area of karst that is protected has increased as a result of this process. The indicator pertaining to riparian zones is directly related to this increase in the lands that have been acquired. In addition, regulations and management plans (e.g., the 2011 plan in Hernando County) for all the counties call for either setbacks around sinkholes or the exclusion of these features for stormwater drainage (Florida Administrative Code Rule 62-28.700).

The decline in the TBMA forests but an increase in protected land creates a difficulty in determining how biodiversity has been affected. The clearing of forests occurred decades prior to SWFWMD's land acquisition (Janicki et al., 2001). In addition, many wetlands were drained, and deforestation continues. The overall reduction of the TBMA forests and wetlands implies a decline in biodiversity. Countless studies from around the world that have measured the effects on biodiversity of such environmental changes would confirm this assumption (Lawton et al., 1998; Brook et al., 2003). However, local

Table 5. Scores for the three principal domains, social, environmental, and economic of The Karst Sustainability Index.

Indicator	Progress Towards Target
Social Domain	
S1. Private or public local ownership of caves and springs	Achieved
S2. Locals employed in karst-related jobs	Achieved
S3. Equitable access for population to karst water resources	Achieved
S4. Percentage of population displaced by urbanization of karst landscape	N/A
S5. Indigenous peoples access to karst resources	N/A
S6. Percentage of schools offering karst education in curriculum	<10%
S7. Percentage of karst related tourist facilities offering informal education	Achieved
S8. Local governments offering karst related information on websites or through publications	Achieved
Environmental Domain	
En1. Amount of karst area forested or in native vegetation	Declining
En2. Amount of karst area designated protected	Increasing
En3. Biodiversity of species in karst environment	Declining
En4. Riparian zones around hydrological input sources to karst groundwater	Increasing
En5. Number of impaired springs as measured by biological or water quality indicators	Declining
En6. Number of monitored municipal springs and wells that are used for water supply	Achieved
En7. Current landfills preventing groundwater contamination	Achieved
En8. Collection of sewage from all homes in urban areas	Achieved
En9. Tertiary treatment of urban waste water	Achieved
En10. Monitoring of the condition of heavily used caves	Increasing
En11. Enforcement of local regulations	Increasing
Economic Domain (Resource Use)	
Ec1. Non-operational commercial quarries or mines that have been reclaimed	Increasing
Ec2. Water extraction from aquifer and springs	Increasing
Ec3. Agricultural sales ($ per year)/water use (mgd)	Achieved
Ec4. Area of urbanization and roads	Decreasing
Ec5. Sustainable forestry on the karst landscape	Increasing
Ec6. Number of eco-tourism ventures related to karst landscape	Stable

caves are relatively undisturbed due to lack of public access or knowledge, and those that do receive frequent visitors have cave management plans either by karst conservation associations or the Withlacoochee State Park.

Unfortunately, water quality in the TBMA has declined as measured by nitrate levels in streams that emerge from springs or drain into the aquifer. Elevated nitrate levels increase algae in the water, reducing dissolved oxygen, which negatively impacts aquatic biota. Of the 191 water bodies measured, 116 of these have been classified as impaired based not only on nitrate levels but also on other biological assessments. Additionally, there has been a 31% increase in the region's springs that are deemed degraded by the water-management district (SWFWMD, 2011b).

Monitoring allows the region's resource managers to identify areas of special concern that require mitigation efforts. All the major first and second order springs that are used for municipal drinking-water supplies are monitored, as are the wells that extract water from the aquifer for the same purpose. No cave monitoring in the TMBA exists.

Finally, the enforcement of the regulations that protect the karst landscape and its waters from negative human impact are measured by fines and consent orders, which are agreements between the Florida Department of Environmental Protection and the offending party. Fines that have been levied have increased by 35%, and the average number of consent orders for the four counties from 1995 to 2005 has increased by 55%. It should be noted that this figure is elevated by Hernando County, which had an increase over this period of 91% (North et al., 2009).

Limestone and phosphate quarries are the two main factors in the economic domain for the TBMA. Phosphate mining is concentrated in eastern Hillsborough County, while limestone quarrying only occurs in Hernando County. The Florida phosphate industry has been required to reclaim their open-cast mines under the Mandatory Phosphate Program (MANPHO) since 1975. The program administers the rules of the legislation on Environmental and Wetland Resource Permits for phosphate-mined lands. (Chapters 378, Part II, and 373, Part IV, Florida Statutes; Chapters 62C-16, 62-312, 62-4, 62-343, 62-341, and 40X-4, Florida Administrative Code). The law created a voluntary trust fund that helps fund the reclamation of lands disturbed prior to this legislation (http://www.dep.state.fl.us/water/mines/manpho.htm). Although the reclaimed land does not possess all the biodiversity and character of the natural landscape, this approach is better than the alternative of no reclamation at all, as was the case prior to 1975. Hernando County has a history of reclamation of limestone quarries. In 1992 and 2002 two quarries were transformed into golf courses and residential developments after gaining approval from the Hernando County Commission (http://quarrypreserve.info/pdf/qp_quality_development.pdf). A preferable alternative would have been to return these sites to their original natural state instead of approving two land uses that do not fit the ideal of sustainable development. Consequently, while TMBA has seen some progress towards reclamation, some reclamation efforts are questionable. There are many non-operational phosphate mines and limestone quarries that still require rehabilitation.

Water extracted from the aquifer and springs decreased in TBMA from 123 to 101 gallons/day/capita on average for the period 2001 to 2009 (SWFWMD, 2004a, 2011b). This decrease has been achieved through incentives such as community education and rebates for more efficient irrigation systems and other water-saving technology. For improved agricultural usage of groundwater, west-central Florida improved its efficiency by 21% from 1997 to 2007 (US Department of Agriculture, 1999, 2009; SWFWMD 2003, 2004a, 2004b, 2009, 2011a). Pinellas County is not included in the calculation as it contributes very little to the agricultural production of the area.

The changing area of urbanization is often an indicator of economic growth, and the TBMA is an excellent example of this. For sustainable use of the karst landscape, this area should not increase, but the TBMA has seen a 21% increase from 1996 to 2006 (Hernandez et al., 2010). However, this rate of growth has slowed dramatically with the economic downturn in the state. Logging is another economic activity that can be important to a local economy. While this sector is not a significant component of employment in the TBMA, there has been a shift towards a more sustainable use of this resource through the replanting of cleared forests with native species, particularly slash pine. However, a failure in this measure is that the area of forest in the region has declined over this period due to the increase in the urban footprint. Finally, tourism is an important source of income to the TBMA, but the karst landscape contributes little to this sector. The karst-related tourist attractions are the springs of the area, particularly Homassassa and Weeki Wachee. These constitute sustainable eco-tourist entities, but the number of such ventures has not increased in recent years.

Every indicator for each domain is displayed (Fig. 2) using the dashboard approach similar to that used by Ronchi et al. (2002). It is readily apparent that the TBMA has achieved nearly all of its sustainability targets set by the KSI for the social domain. The region is also making progress in the environmental domain, with only three indicators showing no improvement or worsening conditions over the measured timeframe. In the economic domain much progress is still required, as none of the KSI targets have been achieved. Consequently, the overall rating of the KSI for the TBMA is that the region is progressing toward the target of sustainable development.

Discussion

We have provided a framework for measuring the sustainability of karst landscapes using an index that sets targets for government entities, taking into consideration issues of equity, environment, and economic development. As with any index, it is not possible to incorporate every aspect of sustainability. One measure we have struggled with is enforcement. It is recognized that while the simple creation of regulations protecting karst is laudable, their enforcement is just as important. However, there is no single method of enforcement to measure. Fines, imprisonment, loss of access, and requirement of restoration are all possible techniques. In addition, assessing enforcement within a sustainability index is difficult. In an attempt to measure this Karst Sustainability Index indicator in the Tampa Bay Metropolitan Area, we used consent orders, which are agreements between the regulators and offenders that the guilty party pays fines or the violations are to be rectified. As these consent orders increased over time, it was deemed that enforcement was improving. No region will be able to enforce regulations on every violator, but if these efforts are increasing, then this indicator can be included in the KSI.

Many sustainability indices applied at a national scale have economic indicators such as gross national project, per capita income, and employment rates. These types of measure do not have much bearing on a sustainability index developed for a specific environment at a local level. We initially considered as indicators the contributions of various karst-related industries to the local economy. However, collecting this data at municipal and county levels proved problematic. For example, when attempting to collect information on the quarrying and mining sector, we could only find data at the state level or for the entire company's operations that extended beyond the Tampa Bay area. It was impossible to find what we needed for the specific karst region we were investigating. The same issue arose with the commercial water-bottling industry.

Another approach to try to quantify certain industries was to collect employment data. For industries that are particularly unsustainable, such as mining, the desire is to see it decrease in significance in the region. However, an indicator that calls for a decline in employment seems inappropriate in a sustainability index that aims to balance the needs for human and economic development with

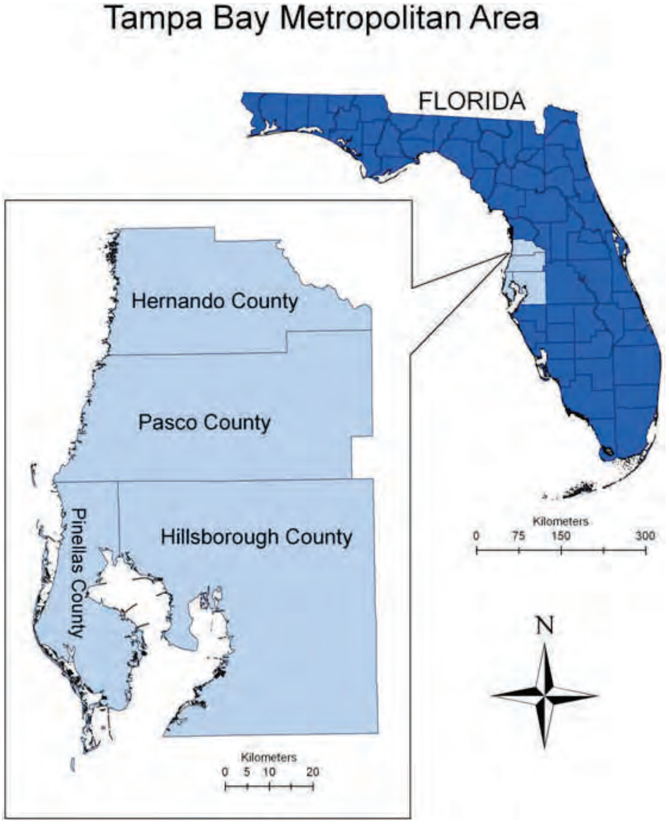

Figure 1. The Tampa Bay Metropolitan Area, Florida, USA.

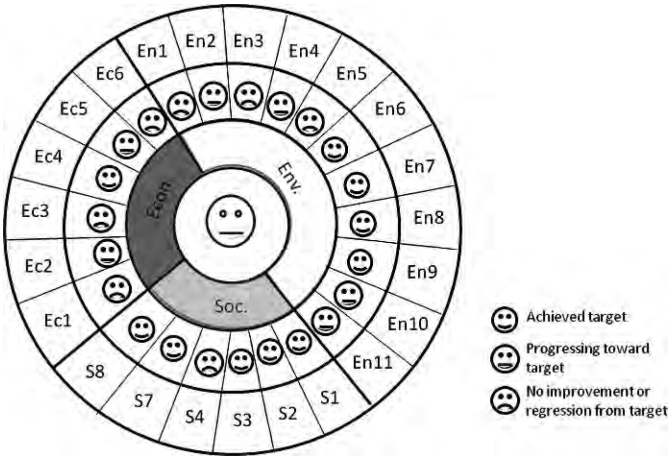

Figure 2. Dashboard display of progress toward sustainability in the Tampa Bay Metropolitan Area.

preserving the quality of the environment. Finally, sales or financial data for major companies operating in the region were extremely difficult to come by or too general to be of any use. These issues lead us to concentrate on some very simple indicators where the data would be readily available.

Truth in reporting and uniform application is another possible limitation of any index. Company and government officials may feel it is more important to give the impression of sustainable operations and environmental stewardship. As such, third party evaluation and verification may be appropriate.

In developing countries where there are globally significant areas of karst (for example South East Asia or the Caribbean), shortages of both data and experts may be an obstacle to the implementation of the KSI. In some areas of the developed world, access to and use of natural resources are tightly controlled, but in many developing countries illegal logging, unsanctioned quarries, and unregulated water use are common, and in some cases government officials are unaware of or unwilling to address these problems. In addition, few individuals with specialized knowledge on the karst environments may be available. Consequently, the application of the KSI may be limited until the necessary data and experts are created. During information gathering in the TBMA to apply the index, none of these issues arose. The data needed to score the indicators were available, with the exception of changes in biodiversity for the region. Even so, the values of related environmental indicators allowed a justifiable assumption to be reached of the state of biodiversity in the study area. Well-funded government agencies and a number of local university studies produced all of the data in reports that are readily available to the public. All that was needed was finding these reports and the collation of the data. We recognize that the aforementioned issues are still valid for many karst areas in developing countries.

Conclusions

In summary, a Karst Sustainability Index was developed that takes into consideration the three pillars of environmental sustainability to evaluate karst landscapes: social equity, environmental values, and economic development. The index differs from other karst management approaches in that it seeks to address issues of environmental sustainability, as defined by the Brundtland Report and the UN Millennium Goals (Dalby et al., 2009; United National Development Program, 2003). Several specific variables are measured within each of the three domains that can be mapped and assessed with a GIS. The KSI is a useful tool for assessing overall environmental sustainability to manage karst landscapes, as demonstrated by the application to the Tampa Bay Metropolitan Area. Our society, local governments, businesses, and other organizations are seeking ways to measure and benchmark sustainability within their communities, and the KSI provides a framework for assessment within karst lands. While the index has limitations, the KSI is the first to attempt to address broad sustainability issues within this unique landscape. However, in TBMA study these limitations were found to be minimal.

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