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Sinkhole genesis and evolution in Apulia, and their interrelations with the anthropogenic environment

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Abstract. Sinkhole development occurs in many areas of the world where soluble rocks crop out. Sinkholes are generally the surface expression of the presence of caves and other groundwater flow conduits in carbonate rocks, which are solutionally enlarged secondary permeability features. Their formation may be either natural or caused by man's activities. In both cases, heavy consequences have to be registered on the anthropogenic environment and related infrastructures. Knowledge of the mechanism of formation of this subtle geohazard is therefore necessary to planners and decision makers for performing the most appropriate and suitable programs of land use and development.

The Apulia region of southern Italy is characterized for most of its extension by carbonate rocks, which makes it one of the most remarkable example of karst in the Mediterranean Basin. Based on analysis of literature and in situ surveys, including caving explorations, we have identified in Apulia three main types of possible mechanisms for sinkhole formation: 1) collapse of a chamber in a natural cave or in man-made cavities; 2) slow and gradual enlargement of doline through dissolution; 3) settlement and internal erosion of filling deposits of pre-existing dolines. Since sinkhole formation very often affects directly the human settlements in Apulia, and have recently produced severe damage, some considerations are eventually presented as regards the interrelationships between sinkholes and the anthropogenic environment.

1 Introduction

Sinkholes are a subtle type of hazard, which may produce very serious and unexpected damage to the anthropogenic environment. In many cases, they occur as rapid to very rapid collapses, and their final evolution may be matter of a few hours, if not minutes. This, combined with the difficulty in detecting underground structures and features (natural caves, man-made cavities, inhomogeneities in the stratigraphy), makes them extremely dangerous to the built-up environment. Sinkhole is a quite controversial term, and it has often been used as synonymous of doline. It is beyond the scope of this article to examine in detail the terminological problems and the different uses of the term, for which we invite the interested reader to refer to the recent contribution by Williams (2003).

In the last decade, great attention has been devoted in Italy to sinkholes, pushed by some recent catastrophic events occurred in several regions (Berti et al., 2002; Corazza 2004), even if in some cases the term sinkhole was used to indicate collapses not occurring in karst environment. The present article intends to provide the first results on research about sinkhole distribution and genesis in Apulia, southern Italy, in a setting particularly prone to sinkhole development, where several problems and damage to the anthropogenic environment have been recently registered.

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2 The Apulia region: geological and geomorphological background

The Apulia region of southern Italy is the emerged south-eastern portion of the Adriatic Carbonatic Plate which is formed by Jurassic-Cretaceous limestones and dolostones covered by Tertiary and Quaternary clastic carbonates and subordinate sands and clays (Fig. 1). From the Lower Pleistocene, the region was interested by a general uplifting, until it reached the present configuration (Doglioni et al., 1994). Apulia is fragmented by high dip, NW-SE striking, faults into uplifted and lowered blocks (Ricchetti et al., 1988). Due to the widespread presence of carbonate rocks, surface and underground landforms were extensively involved in karst processes that produced an extensive network of cavities and conduits underground. Today the regional inventory of caves in Apulia, managed by the Apulian Speleological Federation, counts more than 2000 natural caves (Giuliani, 2000).

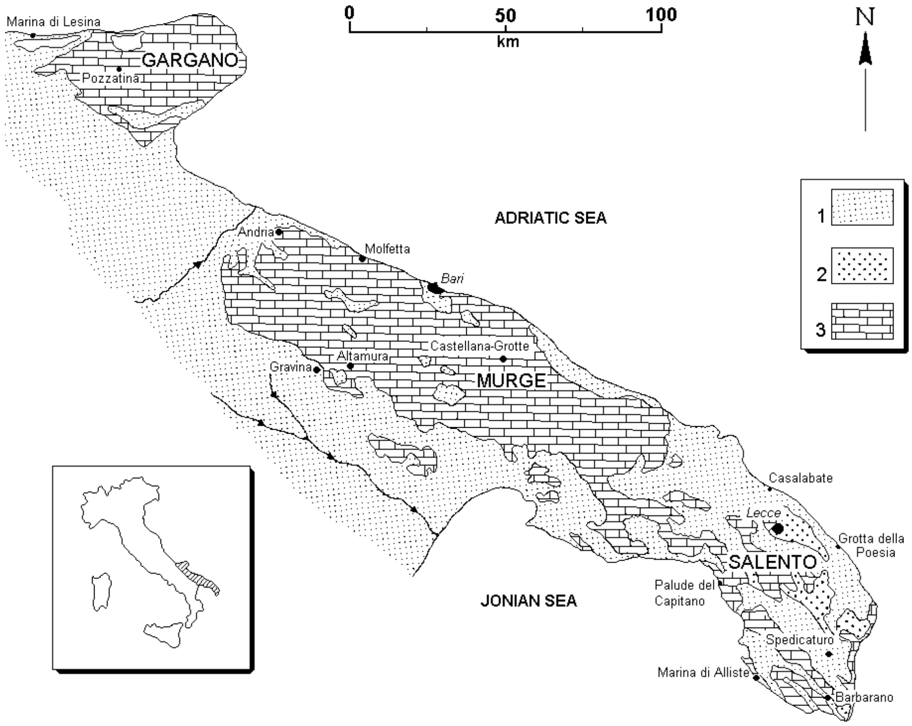

Fig. 1. Geological sketch of Apulia, showing the localities cited in the text. Explanation: 1) alluvial deposits, clays and calcarenites (Pliocene-Pleistocene); 2) bioclastic carbonate rocks (Paleogene) and calcarenites (Miocene); 3) carbonate platform rocks (Cretaceous).

Fig. 2. Dolina Pozzatina, a large sinkhole in the Gargano Promontory.

Even if strongly subordinated to carbonates, Triassic evaporite rocks also crop out in Apulia. These rocks, rised at the surface by diapir and faulting, are interested by sinkhole development (Melidoro and Panaro, 2000), representing a serious geohazard, as also experienced in other countries of the Mediterranean Basin (Cooper and Waltham, 1999; Gutierrez et al., 2002; Cooper, 2002; Parise et al., 2004).

The Apulian landscape is generally flat and characterized essentially by landforms of karst origin, whose best morphological expressions are identifiable on the Murge Plateau of inland Apulia (Neboit, 1974; Sauro, 1991). Over large portions of the region, the natural landscape has been strongly modified by anthropogenic interventions, also thanks to the smoothed morphologies that facilitated land use changes.

Three main karst sub-regions may be identified in Apulia (Fig. 1): from north to south, the Gargano Promontory, the Murge Plateau, and the Salento Peninsula.

The Gargano Promontory is a wide limestone plateau, with a structure gently inclined toward NW, limited by high and steep escarpments. Here the maximum elevations in the carbonate areas of Apulia (about 1000 m a.s.l) are reached. Karst landforms, especially dolines, characterize the landscape: dolines may reach a density greater than 100 per square kilometre in some parts of the promontory (Baboci et al., 1991). Many karst landforms are aligned following the main tectonic directions. Among the dolines, Dolina Pozzatina (Fig. 2) is the largest, with a maximum diameter of some 700 m, and a depth over 130 m.

The Murge Plateau, in central Apulia, represents a planation surface cut on the Cretaceous limestone during Paleogene and Neogene. From its highest elevations (678 m a.s.l. near Mt. Caccia), the plateau slowly degrades toward the Adriatic Sea to the east, through steps of marine terraces. Several sinkholes, also of great size, characterize both the inland plateau (as at Altamura and Gravina) and the area closer to the coast (as at Andria and Molfetta). In this part of Apulia, such landforms are known with the local terms of *pulo* or *gurgo* (Parise et al., 2003).

Salento corresponds to the southernmost portion of the region, and is a NW-SE aligned peninsula, limited by the

Table 1. Sinkhole events in the provinces of Apulia (data after Corazza, 2004).

	Man-made cavities	Natural cavities	total
Bari	24	10	34
Brindisi	1	3	4
Foggia	17	8	25
Lecce	14	11	25
Taranto	2	2	4
total	58	34	92

Adriatic Sea to the north-east and the Jonian Sea to the south-west (Fig. 1). Notwithstanding the overall tabular landscape, it can be considered a wide horst fragmented by high dip NW-SE faults into uplifted and lowered blocks (Doglioni et al., 1994). Due to configuration of the peninsula, Salento has long stretches of coastal areas, where coastal karst processes, and development of hyperkarst (Back et al., 1979; Cigna, 1983) are particularly pronounced. The peninsula took on its present conformation starting from the Lower Pleistocene, when tectonic lifting produced lowering of the sea to its present position. The uplift took place discontinuously, and resulted during the Late Pleistocene in the formation of coastal plains on both the Adriatic and Ionian sides (Dai Pra, 1982; Palmentola, 1987). The coastal plains show elevation at most a few meters above sea level and extend inland for several kilometers, partially covered by swamps.

Actuality of the sinkhole problem in Apulia is well highlighted by the preliminary results of the Project "Sinkholes", started in 2003 by the Civil Protection Department over the whole italian territory (Corazza, 2004): the data so far available indicate Apulia as the fourth region in Italy affected by sinkholes, with 92 events. The highest number of occurrences was registered in Campania (195) and in Latium (161), due to the diffuse presence of man-made cavities in the two most important cities of these regions, respectively, Naples and Rome. If man-made cavities are excluded, and only sinkholes related to natural caves are taken into account, Apulia becomes the first Italian region, with 34 events, followed by Latium (31) and Friuli (29). Table 1 shows the details as regards distribution of man-made and natural cavities in Apulia. It has to be noted that the events reported in Table 1 include both sinkholes and subsidence events, the latter being often related to anthropogenic activities as gas extraction (Calcagnì et al., 1996), groundwater over-exploitation (Melidoro et al., 1996), or underground quarrying (Cherubini and Sgobba, 1997). In particular, the negative effects that excessive groundwater pumpage might have in carbonate aquifers are well-known in the scientific literature (Stringfield and Rapp, 1976; Hall and Metcalfe, 1984; Pewe, 1990; Roje-Bonacci, 1997).

3 A physiographic approach, with hydrogeological implications

To examine sinkhole distribution and evolution in Apulia, we chose a physiographic approach, based on the geomorphology of this peculiar region of southern Italy. Two main settings, which are useful for description of sinkholes, may be easily identified: 1) the coastal environment; and 2) the inland area. The latter can be, in turn, subdivided into inland plateau or highplain and inland karst valleys or drainages. This subdivision derives from topography, but, at the same time, it has important hydrogeological implications. Development of sinkholes in coastal areas is in fact often related to hyperkarst processes: mixing of fresh water and sea water, which occur along the coasts, results in very aggressive waters, which might cause accelerated solution in the carbonate rocks, through enlargement of cavities, eventually leading up to sinkhole formation.

The anthropogenic environment, on the other hand, encompasses with its distribution both the above-delineated settings. Urban areas, lifelines and communication routes are in fact present along the Apulian coasts, as well as inland. This makes still more intriguing the analysis of the interrelations (cause-effect) between man's activities and sinkhole genesis and evolution in Apulia.

Inland, development of sinkholes is generally related to the presence of underground caves, whose stoping towards the ground surface may cause settlement in the anthropogenic structures, where present, eventually leading to collapse. This typology of phenomena, even though numerically diffuse, does not evolve generally to produce coalescent sinkholes, but presents on the other hand a localized character, directly dependent upon distribution and dimensions of subterranean cavities, and the local hydrogeological setting.

A crucial factor which has also to be considered is the local stratigraphy: within the carbonate sequence, in fact, the presence of lithologies with different hydrogeological properties may favour the speleogenesis along specific levels, where karst more easily develops. With time, the evolution of the karst system proceeds, and complex systems of caves are formed. Once these are left by water, moving at greater depths because of the presence of a new base level, the ancient karst caves evolve mostly through detachment of rocks from the roof and the walls of the cave. Upward stoping of the cave roof, combined with surface lowering by erosion, may eventually result in reaching the land surface.

In the last ten years, the coastal plains of Apulia have been repeatedly affected by episodes of land subsidence and sinkholes, some of which have damaged or destroyed roads and buildings (Delle Rose and Federico, 2002). It has to be mentioned here that the Apulian coasts are highly frequented by tourists during the summer season, and are among the most important tourist attractions of the region. Consequently, the understanding of the sinkhole events, including their processes of formation, and the likely evolution in the future, are extremely important in order to evaluate their incidence,

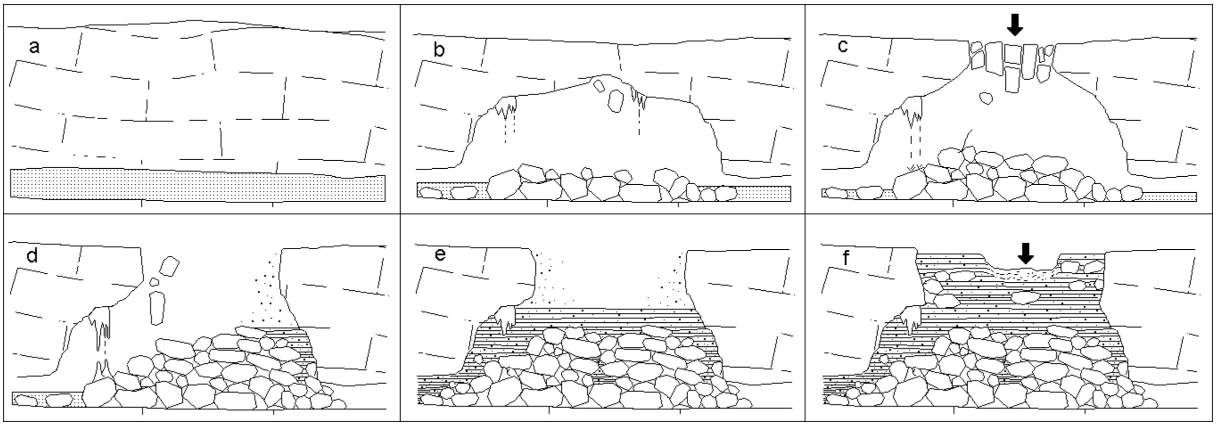

Fig. 3. Karst system evolution and sinkhole development: **(a)** phreatic phase with delineation of the karst cave; **(b)** cave enlargement through rockfalls; **(c)** roof collapse and sinkhole formation; **(d)** sinkhole enlargement through rockfalls at its boundaries; **(e)** filling with terre rosse and continental deposits, and lowering of the cave stream at greater depth; **(f)** new, generally minor-size, sinkholes caused by settlements of the filling deposits.

and to determine the most adequate measures for controlling and mitigating the related environmental hazards.

Sinkhole-like landforms in coastal areas are an interest theme of research also as regards the very rich archaeological remains of Apulia, as evidenced for example along the Adriatic coast, where a new interpretation has been recently proposed for the so-called “Amphitheatre”, an elliptical depression within the ancient town of Gnathia, which was one of the most important harbours during Roman times (Delle Rose et al., 2002).

4 Mechanisms of sinkhole formation

In Apulia, based on analysis of literature and in situ surveys, including caving explorations, three main types of possible mechanisms for sinkhole formation can be identified: 1) collapse of a chamber in a natural cave or in man-made cavities; 2) slow and gradual enlargement of dolines through dissolution; 3) settlement and erosion of filling deposits of buried dolines.

Some of these mechanisms become evident during evolution of underground karst systems, as shown in the sketch of Fig. 3: initially, a karst cavity begins to develop in phreatic environment (Fig. 3a). Once speleogenesis has started, and the proto-cave originated and well developed, its later evolution mostly occurs through mass movements (falls from the vault and walls; Fig. 3b), while, at the same time, the land surface is lowered by surface erosion. These processes go on until the cave reaches a stable configuration, or, alternatively, until partial or total collapse of the vault occurs (Fig. 3c), with formation of a sinkhole at the land surface. The sinkhole walls, in turn, are unstable and may be affected by further falls (Fig. 3d), whilst the cave stream (present on the left side of Fig. 3d) moves at greater depth as a consequence of lowering of the karst base level, and filling of the sinkhole by terre rosse and continental deposits occurs (Fig. 3e). Eventually, new minor episodes of sinkhole formation may happen within the filling deposits, due to differential settlements, subsurface erosion, or piping (Fig. 3f).

Mechanism of sinkhole formation no. 1 appears to be very frequent due to the typical geological configuration of Apulian karst, which consists of stratified limestone with subhorizontal bedding, intensely affected at various depth by paleokarst and active karst processes. This configuration often produces, as result of the underground cave evolution, multiple slab breakdown deposits at the base of the main underground caverns (Davies, 1949). The process of slab breakdown determines with time the tendency toward formation of a dome-shaped surface in the bedrock (“tension dome” or zone of maximum shear stress; White, 1988). The top of the dome extends upward for distances of some 1.5 times the cavity diameter. Any change in loading above the top of the dome is distributed over the cavern walls; once the tension dome extends to the land surface, additional loading would increase the shear along the walls, leading to collapse of the cavity roof (White and White, 1969). As a consequence, a sinkhole is observed at the surface.

Many of the most significant examples of sinkholes in Apulia belong to mechanism no. 1, even though their origin has to be related to underground karst systems more than to a single cavity: this was probably the case of two among the largest sinkholes of Apulia: Pulo di Altamura (Fig. 4) and Pulicchio di Gravina (Castiglioni and Sauro, 2000).

Sinkholes located near the coast, as Pulo di Molfetta and Gurgo di Andria, mostly evolved, on the other hand, through brackish water activity. Their proximity to the coast, together with the presence of sponge-like rock volumes showing widespread sub-horizontal karst conduits and cavities, seem to testify to this origin. The phase of collapse for these large features of the Apulian karst is very difficult to be determined, but has in any case to be considered prehistorical, as attested in some cases by archeological remains.

Mechanism no. 2 is the classical solution process of doline formation in karst environment (Cvijic, 1918; Gunn, 1986; Kastning, 1987; Culshaw and Waltham, 1987; Williams, 2003). In Apulia, there are several areas characterized by high frequency of dolines produced by dissolution through slow and gradual enlargement. They are essentially in bare-karst areas, where Cretaceous limestone directly crop out, with very limited or absent cover. Direct exposure of carbonate rocks facilitates the initiation of karst drainage, and its later evolution through sinkholes at the main points of water infiltration (Ford and Williams, 1989; Waltham and Fookes, 2003). The more intensely corroded zones, even due to weathering processes in the limestone rocks (Fookes and Hawkins, 1988), begin to obtain topographic expression as solution dolines.

The Gargano Promontory (where the above-mentioned Dolina Pozzatina is located) hosts wide sectors characterized by high frequency of sinkholes. The relative vicinity of these features, and the elevated overall density, together with the absence of larger compound sinks, are all elements favouring the origin through slow and progressive development of solution process rather than rapid collapse. In addition to the Gargano, other areas in the Murge Plateau are also characterized by a high number of sinkholes originated by solution. However, some of these have been partly or totally modified in the last years through excavation or infilling, due to heavy land use changes, and namely to the stone clearing practice to gain new lands to agriculture (Parise and Pascali, 2003).

Mechanism no. 3 is at the origin of the problems registered in the lowermost sector of Castellana-Grotte (see Fig. 1 for location), where in three events, from 1968 to 1972, subsidence occurred, producing serious damage in some buildings which had to be evacuated and, later on, abandoned. The complex stratigraphy at the site, reconstructed from borehole examination, showed the presence of a cavity filled with detritus and, in the most surficial part, anthropogenic deposits; likely, erosion within the succession produced differential settlements and the sinkhole development at the land surface (Zezza, 1976). It is interesting to note that the site is located within a larger area, which is the lowest part of a karst valley: there, man strongly changed the original configuration, altering the natural drainage and clogging many ways of underground infiltration for water. This was at the origin of repeated episodes of flooding, until that tragic in November 1896 (Sgobba, 1896). After that event, engineering works to facilitate infiltration of water underground on the occasion of the main rainstorms were realized (Parise, 2003). The Castellana-Grotte example once more puts into evidence the fragility of karst environment, and the difficulty to correctly evaluate the likely consequences that human impact might have in this territory (Williams, 1993; Delle Rose and Parise, 2003; Parise and Pascali, 2003).

Sinkholes related to mechanism no. 3 are probably the most difficult to be detected. Very often, the absence of precursor signs (Szwedzicki, 2001), or the evidence of cracks at the land surface only immediately before the phase of collapse, make them particularly unpredictable.

Fig. 4. Bird's eye view of Pulo di Altamura, one of the most remarkable surface feature of the apulian karst (photo courtesy of M. De Fonzo, property of the Speleological Museum "Franco Anelli" at Castellana-Grotte).

In some cases, where the soluble rocks are covered by other non-soluble and poorly consolidated deposits, the development of a cavity may trigger erosional process even in the cover, until a sinkhole is formed at the land surface (dropout dolines, following Williams, 2003). This was the case for the sequence at Marina di Lesina, in northern Gargano, where gypsum rocks are overlain by poorly cemented sands, and a number of sinkholes formed from 1993 to 2000 (Melidoro and Panaro, 2000). The sinkholes started to develop in the evaporites and then transmitted in the above sands, following the typical modality of the mantled karst (Tharp, 1999; Epstein, 2000; Gutierrez et al., 2002; Cooley, 2002).

5 Interrelations with the anthropogenic environment

Living with hazard has been faced by man since his very first settlements at sites affected by phenomena such as landslides, floods, earthquakes, volcanic activity, etc. If a safer place was not available nearby, and/or economical, social or strategical reasons required to live at the threatened site, man had necessarily to face the problem through knowledge of the hazard, of its spatial distribution (where does it occur?), and, possibly, of its temporal evolution (when is it going to occur again?). Most important, knowledge of the past hazard history, and observation of the repetition of the same type of hazard where it had previously happened, allowed man to learn to avoid the less safe sites, preferring locations not directly involved in the hazard, and its likely consequences as well.

However, growing population, and the increasing demand of new land for living as well as for human activities, combined with loss of memory of past historical hazards, led in the last centuries man to occupy areas affected by some

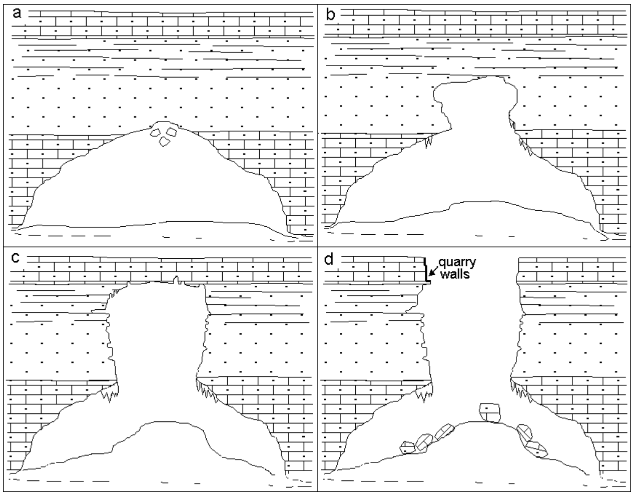

Fig. 5. Sketch of the evolution of Vora Grande at Barbarano (see the text for details).

hazard, neglecting it or underestimating its danger. This was particularly common for subtle hazards, such as sinkholes, for which very few tell-tale signs may be identified, and whose evolution is generally rapid to very rapid. As a consequence, sinkhole formation very often directly affects the human settlements, producing damage and, sometimes, casualties.

The second aspect that has to be considered is, on the other hand, the human activity as a triggering factor for sinkhole development. Several activities, in fact, may produce negative impacts in karst environment, and eventually result in favouring the formation of sinkholes. Among these, underground mining and quarrying (here considered not only during the activity of extraction, but also later on, after such activity ceases, and weathering may act in producing instability phenomena which could progress upward until a sinkhole is formed); over-exploitation of groundwater resources; loading with buildings or other structures areas with presence of karst caves and conduits; etcetera.

With reference to the Eastern United States, Newton (1987) reports that since 1950 there have been more than 6500 sinkholes induced by man. More specifically, Williams and Vineyard (1976) carried out an inventory of sinkholes and subsidence events occurred in Missouri, and concluded that half of the cases were induced by human activities, with alteration of the natural drainage (52% of the cases) as main action, and highway construction (6,5%) and blasting (4,3%) as the less common.

In Apulia, several examples may be drawn to testify the role of human activities in triggering, or at least in accelerating, sinkhole formation. Excavations carried out at the surface can accelerate the sinkhole evolution related to the presence of an underground cavity, and lead to collapse of the roof. The Grotte della Poesia karst system is a complex of three main caverns, and intervening galleries, located on the Adriatic coast of Salento (Fig. 1). The overall system, some 150-m long, presents two collapse sinkholes (maximum diameter between 25 and 50 m) which correspond, respectively, to Grotta della Poesia Piccola and Grotta della Poesia Grande. The former is considered among the most important sites of Apulian archaeology, since it hosts on its walls thousands of inscriptions dating back to the IV-II centuries B.C. (Pagliara, 1987). According to an hypothesis by archaeologists, collapse of the roof of this cave could have been partly related to excavations from the surface, realized sometimes during the first or second millennium a.C.

Again in Salento, the Vora Grande at Barbarano is a 35-m deep, 20-m wide sinkhole. In its case also, a smaller cavity (Vora Piccola) is located nearby. The section of the sinkhole shows vertical walls from the land surface for about 20 m, and below that depth a marked recess is present. Overall, a bell-shape is derived (Fig. 5). This profile is controlled by the presence of well-cemented calcarenites at the upper part of the sinkhole, and at its base as well, whilst the middle part (still with vertical walls) is made of poorly to medium-cemented calcareous sands. Upward evolution of the tension dome (Fig. 5a) intercepted the base of the sandy level, triggering falls in the upper part of the cavity (Fig. 5b), up to the overlying calcarenites (Fig. 5c). The calcarenites are used since many centuries as building materials, and the first meters of the sinkhole clearly shows the presence of ancient quarry walls (Fig. 5d). Since the activity of extraction is not compatible with the sinkhole, it has been hypothesized that the collapse could have been successive to quarrying activity, if not triggered by it (Beccarisi et al., 2003).

Loading areas where underground, and often undetected, cavities are present may result in favouring collapse of the vault, and in sinkhole formation. This had repeatedly occurred at Casalabate, a small village along the Apulian coast, in the last ten years. The loading exerted by buildings in the residential area led to a first crisis in 1993, when two buildings were destroyed due to development of a sinkhole with depth of a few meters, which later on enlarged and affected further buildings. Other events occurred in 1997 and, again, in 2000.

Even the recent (February 2004) case at Marina di Alliste has probably the same origin, being caused by loading of recently built houses (Fig. 6), combined in this case with dynamic loading due to vehicles traffic. The site of the sinkhole is in fact located in correspondence of a crossway.

A similar case was registered on the same side of the Apulian coastline, at Palude del Capitano, in 1992. The site is located along the wide coastal plain of the Jonian Sea, which is carved in Upper Pleistocene calcarenites. The area is characterized by numerous collapse dolines, locally known as spunnulate or spundulate (Parise et al., 2003): they are several meters deep at most, and generally elliptical in shape. The dolines tend to widen and coalesce along tectonic alignments, producing sinkholes extending for some thousands square meters (compound sinks). Falls of rock along the perimeter of the dolines produce significant widening of the depressions, even within the span of human lifetime.

Fig. 6. View of the sinkhole developed at Marina di Alliste on February 2004.

Fig. 7. Sinkhole at Palude del Capitano, in the Ionian coast of the Salento sub-region.

These landforms are mostly aligned according to the average strike of the main tectonic fracture systems. This occurred, for example, for the sinkhole developed in 1992 at Palude del Capitano (maximum axis about 15 m, depth about 2 m), which followed the NW-SE direction (Delle Rose and Federico, 2002). Its sudden collapse caused destruction of a stretch of a provincial road (Fig. 7), but luckily no automobile was passing at the site at the time of failure.

Eventually, underground discharge of water by-man may also work negatively in the subsurface karst systems, increasing erosional and/or piping processes, which in turn might lead to collapse sinkholes. Over large sectors of Apulia, in fact, man has created over time a network of artificial channels to control the flow of meteoric water, and to facilitate its infiltration underground (Delle Rose and Parise, 2002). Once more, the hydrogeological setting is of crucial importance: at Spedicaturo (see Fig. 1 for location), the sub-horizontally bedded stratigraphic sequence is made of Early Pleistocene calcarenites overlying Late Miocene marls, limestones and calcarenites (Beccarisi et al., 1999; Selleri et al., 2003). The difference in permeability between the two formations determines the presence of a shallow aquifer in the calcarenites. Shallow phreatic speleogenesis operates close to the water table level, with formation of karst conduits and proto-caves (sensu Ford, 1988), whose evolution occurs through successive roof collapse, formation of wide caverns and sinkhole development at the surface. This occurred at Spedicaturo in 1996, when collapse of the vault of a karst cavity in the proximity of an important communication route produced the formation of a sinkhole.

6 Conclusions

Sinkholes, a peculiar feature of the karst environment, are very frequent in Apulia, due to wide outcrops of soluble rocks affected by karst processes, and to the complex speleogenetic history of the main karst areas in the region. These features, combined with the human activities, repeatedly acted since 1990 to favour sinkhole development, with heavy consequences for the anthropogenic environment.

Apulia may represent, due to its main physical and social-economical characteristics above outlined, a very stimulating and interesting case of study to examine both the natural processes at the origin of sinkhole development and the interrelationships between man and the karst environment. To this latter regard, a two-fold approach, just outlined in this article, should be developed: firstly, to look at the hazard posed by sinkholes for the built up environment, and, secondly, to analyse the role played by man in favouring sinkhole formation.

Given the high number of sinkhole events which have been registered in Apulia in the last decades, and the resulting damage to the anthropogenic environment, it is very important to deepen the knowledge of the mechanisms of formation of sinkholes in this region, aimed at understanding their likely evolution and at mitigating the related risk. This is further stressed by the need to safeguard the very rich cultural and historical heritage present in this region of southern Italy, which is frequently directly threatened or involved in sinkhole development.

With these aims, co-operation among karst scientists, cavers, professionals and land planners appears to be necessary in order to correctly evaluate this subtle hazard and plan the management of karst territories (Legrand, 1984; Fischer et al., 1987; Lamont-Black et al., 2002; White, 2002).

A good understanding of the mechanisms of formation of sinkholes is therefore mandatory in the process of risk mitigation. For this reason, the present article focused mostly on these aspects, whilst the next steps of the research will consist in the critical review of the data so far collected from several sources, and in analysis of the spatial distribution of sinkholes in the region with relation to the different lithological and hydrogeological conditions.

The preliminary results from this study pointed out to three main types of mechanisms for sinkhole formation in Apulia: 1) collapse of cave roof; 2) enlargement of dolines through dissolution and 3) settlement and erosion of filling deposits of buried dolines. Some cases of dropout dolines have also been identified. With regard to the interrelations with the anthropogenic environment, several examples have been drawn to testify the role of human activities in triggering, or at least in accelerating, the development of sinkholes. These include, but are not limited to, excavations and quarry activities (carried out both at the surface and underground), loading by buildings and infrastructures over areas with presence of caves, dynamic loading due to traffic of vehicles, underground discharge of water.

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