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ORIGINAL ARTICLE

A present risk from past activities: sinkhole occurrence above underground quarries

Mario Parise

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Abstract Sinkholes are extremely common in Apulia, a low-relief carbonate region of southern Italy that is highly predisposed to this hazard due to the widespread presence of soluble rocks. In addition to the natural setting favoring their development, sinkholes may also be induced by anthropogenic activities and in particular by extensive systems of underground quarries. Many types of rocks have been historically quarried in Apulia, from the Cretaceous limestones to the Quaternary calcarenites, and used in different epochs as building and ornamental materials. In several areas, the rocks with the best petrographic characters are located at depths ranging from a few to some tens of meters. This, combined with the need to save pieces of land for agriculture, caused opening of many quarries underground and development of complex networks of subterranean galleries, especially at the turn between the nineteenth and twentieth centuries. Later on, many quarries were progressively abandoned, partly because of appearance of the first signs of instability, both underground and at the ground surface. With time, memory of the existence and precise location of the quarries was progressively lost, with severe repercussions for safe land use above the excavated areas. Lack of knowledge of the subterranean pattern of galleries, combined with the expansion of built-up areas at the surface, resulted in increasing the vulnerability of the exposed elements at risk. As a matter of fact, a strong increase in the frequency of events had to be recorded in Apulia during the last 5 years, as pointed out by the accounts reported in this paper.

M. Parise (✉)
National Research Council of Italy,
Institute of Research for the Hydrogeological Protection,
Via Amendola 122-I, 70126 Bari, Italy
e-mail: m.parise@ba.irpi.cnr.it

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Introduction

Karst environments are extremely fragile and vulnerable to a number of hazards, which result from the intrinsic features of karst (White 1988; Ford and Williams 2007; Parise and Gunn 2007; Gutierrez 2010; Parise 2010a; De Waele et al. 2011). Among the main types of karst hazards, sinkholes are certainly the most peculiar of this environment (Waltham and Lu 2007; Parise 2008; Zhou and Beck 2011). Sinkholes occur as natural events, deriving from karst processes in soluble rocks, either cropping out at the surface or covered by other materials (Waltham et al. 2005); they can also be related to presence of underground cavities realized by man in different epochs and for different purposes. The use of the underground space has characterized several time periods in Italian history, and in southern Italy it has also represented the main setting established for living and to be protected from the attack of enemies.

Apulia, the heel of the Italian boot (Fig. 1), is a low-relief carbonate region where karst represents the main geomorphological agent modeling the landscape, both at the surface and underground. Regarding the presence and development of sinkholes, these are distributed throughout the region as a surface expression of paleokarstic underground processes (D'Argenio et al. 1986) and of recent karst evolution as well (Delle Rose et al. 2004; Bruno et al. 2008; Del Prete et al. 2010).

Since the beginning of the last century, sinkholes in Apulia were frequently caused by anthropogenic activity, and particularly by quarrying, which, among human activities, is certainly one of those producing the worst impacts on

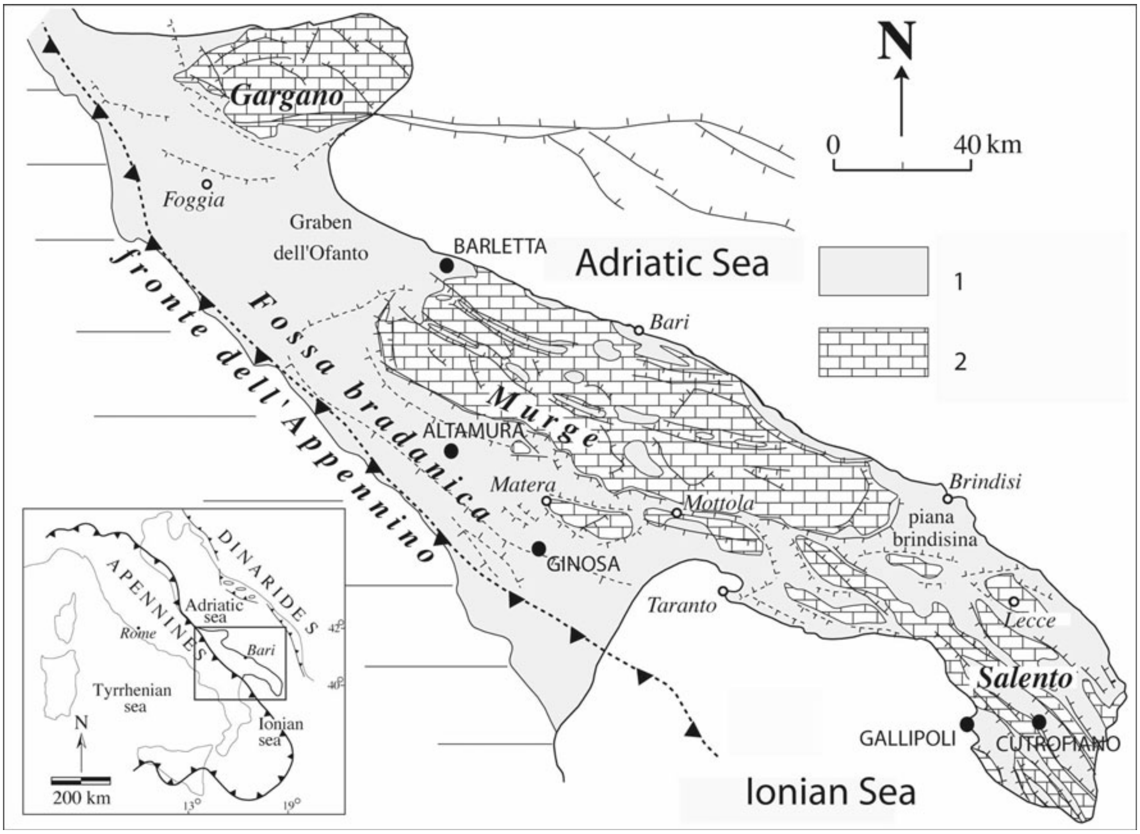

Fig. 1 Locations cited in the text, and sketch geology of Apulia (modified after Pieri et al. 1997): *1* Bradanic Trough sediments and terraced deposits (Pliocene–Pleistocene); *2* carbonate units of the Apulian Foreland (Mesozoic–Cenozoic). The three main karst areas of the region (Gargano, Murge and Salento) are shown

the natural Apulian landscape (Parise and Pascali 2003; Calò and Parise 2006; North et al. 2009; Formicola et al. 2010). Development of quarries causes immediate, and sometimes irreversible, changes to the original environment such as loss of surface karst features, destruction of the epikarst and diversion of the surface hydrography (Gunn 1993). If quarries are realized underground, besides producing likely changes to the hydrogeological setting, they become potential dangers which, once abandoned, are affected by instability processes in which upward stoping may eventually lead to sinkhole development at the surface. In an attempt to highlight this issue, this paper analyzes the case histories in Apulia where sinkholes developed as a consequence of the presence of underground quarries, and contributes to a thorough knowledge of the sites affected by sinkholes, while at the same time providing useful hints for protection of the public from sinkhole hazards.

What are the reasons to quarry underground?

Apulia has been interested in quarrying activity for centuries, focused on the extraction of the most widespread rocks in the region, which include Cretaceous limestone, Miocene marly calcarenites and Plio-Pleistocene calcarenites (Fig. 1). These rocks, and particularly the Plio-Pleistocene calcarenites, described in the geotechnical literature as a "soft rock" (Lagioia and Nova 1995; Lagioia et al. 1998; Andriani and Walsh 2002, 2003), were quarried not only at the surface, but also through development of extensive systems of subterranean excavations (Parise 2010b).

Underground quarrying historically developed throughout the region due to a number of reasons, the main ones being: (1) the presence of the rocks with the best characteristics at a certain depth, not exposed at the surface; and, (2) the need to preserve surface land to be used for agriculture. The latter point is particularly important for the local economy, which is based on agricultural production, including some products of remarkable quality such as olive oil and wines. Thus, subterranean works were carried out to reach the rock levels to be cultivated for extraction. This goal was achieved by digging vertical shafts from the surface, or by approaching the level to be excavated by lateral tunnels from the flanks of slight valleys or topographic scarps. Even though generally the most productive levels were present at shallow depth, in some cases it was necessary to dig shafts over 30- to 40-m deep. Such works, started in the nineteenth century undoubtedly represented a good piece of engineering capability of that time, and to date at those sites the tunnels are sound and safe, thus constituting interesting examples of industrial archeology. With time, the expansion of the urban areas that occurred during the twentieth century often resulted in construction of buildings and communication routes just above the underground galleries. This was due to loss of memory of the presence of the underground cavities, once these had been abandoned. A further problem is that, with time, weathering processes due to water circulation and/or to illegal discharge of liquid and solid wastes underground caused a decrease in the strength properties of the materials, a factor which undoubtedly favored degradation of the underground quarries and development of failures.

Brief history of the events

Aimed at collecting data on sinkhole occurrence, with particular reference to spatial distribution and temporal chronology of the events, scrutiny of different types of sources, including newspaper reports (from national and local daily newspapers), scientific articles, caving reports, books and texts of local history, etc., was started. Further, interviews with professionals and technicians were conducted, in an attempt to collect additional information. This part of the work was very frustrating, since it required a long time and resulted in very few and fragmentary data, often not supported by documents. Even though the occurrence of sinkholes was generally acknowledged, the collection of certain and reliable data (i.e., in terms of size, morphometry, date of occurrence of the sinkhole) was extremely difficult and successful only in a limited number of cases. This outcome was not surprising, the same having already been faced in previous investigations and research on other types of natural hazards (i.e., landslides, floods) in Italy (Calcaterra and Parise 2001; Carrara et al. 2003; Calcaterra et al. 2003).

The cases of occurrence of sinkholes related to underground quarries for which a date was found are reported in Table 1. Overall, 24 cases of sinkholes due to underground quarries were found, while in 9 other cases the occurrence of sinkholes attributed to subterranean quarries was likely, but not sure. With regard to the more ancient documented events, two towns deserve particular attention: Canosa di Puglia, where in the first decade of the twentieth century a series of sinkholes occurred, which were at the origin later on of a crisis during the 1990s with subsequent reclamation works in the town (Società Italiana per Condotte d'Acqua 1989); and Andria, where at least nine events were recorded, showing lower impact than at Canosa di Puglia with regard to the damage produced, but nevertheless producing great alarm in the town.

Apart from these two sites, the chronology reported in Table 1 points out to a very high frequency of sinkhole events related to underground quarries in the last few years. Since 2006, as a matter of fact, several towns in Apulia have been affected by collapse events that in many cases repeatedly threatened or directly involved urban areas.

The total number of sinkhole events listed in Table 1 (33) is certainly a strong underestimation of the real number of occurred sinkholes. This is because many events are unreported, or the related documentation has been lost with time. Nevertheless, Table 1 highlights well the existence of the problem in Apulia, a danger which has been for a long time ignored by the local authorities (Barnaba et al. 2010) and only recently gained due attention, in the aftermath of the impressive sequence of events that occurred in the last 5 years.

In the following section, some of the most significant case histories of sinkholes related to underground quarries will be described, subdividing the account according to different settings of Apulia, from urban areas, to periphery of towns, to rural areas.

Recent history of sinkhole occurrence in different settings

Urban areas

Sinkhole occurrence in urban areas causes the greatest concern in terms of civil protection issues and safeguard of public safety, due to likely direct involvement of buildings and people. Ideally, any expansion of built-up areas should be preceded by geological engineering surveys, also addressed to recognize the possibility of the presence of underground voids in the area. In practice, however, it has to be said that in many historical sectors of the Apulian towns, memory of the excavations realized in the past centuries has been lost, or, when location of underground cavities is known, a detailed map is lacking, as well as any information about degradation of the excavated material and occurrence of failures.

This was dramatically highlighted and put under the eyes of the mass media and public opinion on 29 March 2007, when at Gallipoli, one of the most important towns of the Ionian coastline of Apulia, a sinkhole opened, due to collapse of the vault of a calcarenite quarry. Gallipoli is one of the main coastal towns of Apulia, heavily frequented by tourists during the summer season. Urban expansion of the town in the last century brought buildings located above many areas that had previously been the object of underground quarrying, due to the wide use of the local calcarenite rocks for building purposes. In the recent past, several warnings about the stability conditions of the

Table 1 Chronology of sinkhole events related to underground quarries in Apulia

No.	Date	Location	Setting	Notes
1	1925	Canosa di Puglia	A	
2	1947	Altamura	C	
3	08 March 1955	Canosa di Puglia	A	
4	July 1956	Cutrofiano	B	
5	08 April 1957	Canosa di Puglia	A	
6	May–June 1957	Cutrofiano	C	
7	27 November 1959	Andria	A	?
8	03 February 1972	Andria	A	
9	13–14 October 1972	Andria	A	
10	11 December 1972	Andria	A	?
11	03 January 1973	Andria	A	?
12	21 July 1973	Andria	A	?
13	05 May 1974	Andria	A	?
14	05 (?) February 1979	Andria	A	?
15	20 February 1980	Andria	A	?
16	Before April 1985	Cutrofiano	C	
17	1986	Canosa di Puglia	A	
18	04 May 1990	Canosa di Puglia	A	
19	February 1996	Cutrofiano	B	
20	05 September 1999	Canosa di Puglia	A	
21	March 2006	Altamura	A	
22	29 March 2007	Gallipoli	A	
23	05 May 2007	Gallipoli	A	?
24	07 May 2007	Altamura	A	
25	12 February 2008	Lequile	C	?
26	15 July 2008	Cutrofiano	B	
27	03 December 2008	Altamura	A	
28	February 2009	Ginosa in Puglia	B	
29	March 2010	Cutrofiano	B	
30	03 May 2010	Barletta	C	
31	May 2010	Cutrofiano	B	
32	October 2010	Cutrofiano	B	
33	November 2010	Gallipoli	A	

Key to setting column: *A* urban areas, *B* periphery of towns, *C* rural areas. Question marks in the last column indicate the cases of uncertain attribution to underground quarries

subterranean quarries at Gallipoli have been presented by cavers (Fiorito and Onorato 2004), but these were not taken into consideration seriously.

On the evening of 29 March 2007, following some days of intermittent, locally prolonged rainfall, part of Via Firenze (Firenze street) at the crossing with Via Galatina collapsed, and a sinkhole 12 × 18-m across and up to 10-m deep formed, engulfing three cars (Fig. 2b). According to the testimonies, the collapse was abrupt, without any premonitory sign, and was accompanied by a strong roar. The sinkhole margins were not far from the two buildings that were soon evacuated. During the following days, the sinkhole enlarged twice, also due to improper decision by the local authorities to fill it. Eventually, on 1 April, the final areal extent of the sinkhole was three times the original area. It soon appeared clear that the final enlargement was due to the weight of the machines that were working to fill the sinkhole and to the vibrations induced by such operations.

Apart from the wrong decision to fill the sinkhole, it has to be noted that such action was carried out without a full knowledge of the extension of the quarry.

The 2007 sinkhole at Gallipoli is a good example for highlighting the lack of adequate preparation by technicians and local authorities that, during an emergency phase, had to take important decisions. When dealing with underground voids, the first step to be carried out is surveying the cave(s), producing a topography of the underground spaces and comparing the areal extension of the cavities to the built-up areas above, in order to identify the buildings and infrastructures potentially at risk. Without such a survey, any decision on remediation works has a

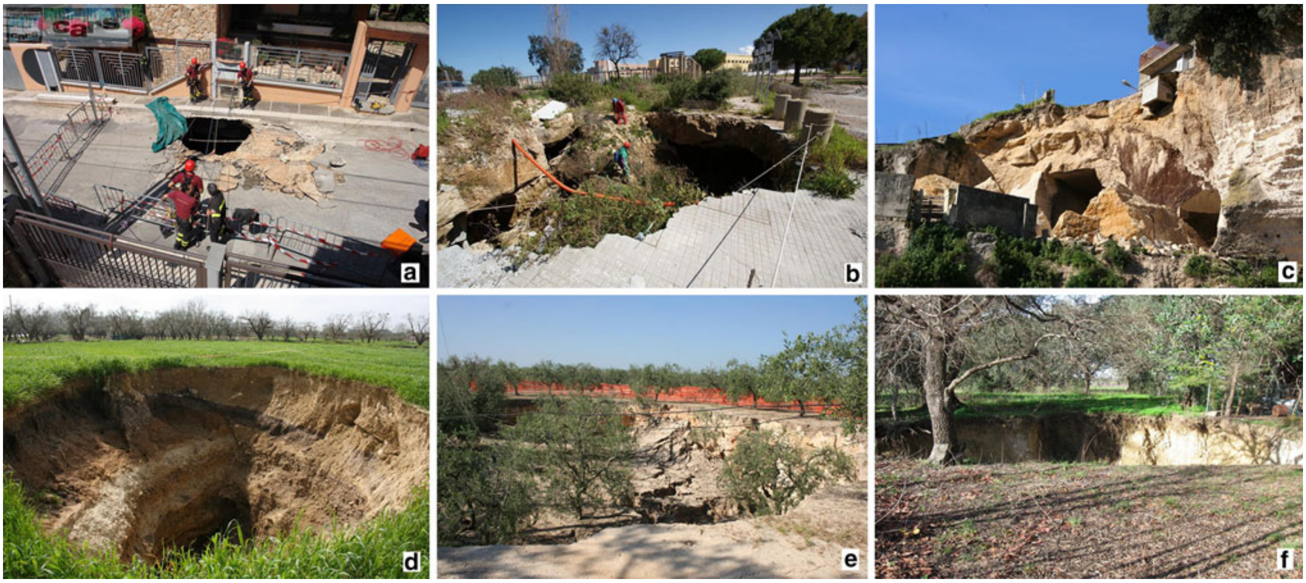

Fig. 2 Some examples of recent sinkholes in Apulia, due to the presence of underground quarries. **a** Altamura, case no. 21 in Table 1 (photo courtesy of CARS); **b** Gallipoli, case no. 22 in Table 1; **c** Ginosa in Puglia, case no. 28 in Table 1; **d** Cutrofiano, case no. 29 in Table 1; **e** Barletta, case no. 30 in Table 1; **f** Cutrofiano, case no. 32 in Table 1

high probability to be ineffective or, in some cases (as at Gallipoli), to create greater damage and problems.

Gallipoli is not the only case in Apulia. The town of Altamura, in the central part of the region, is presently expanding the urban area in a sector located north-east of the historical part of town. There, several houses were built since the 1990s, but it was only on March 2006 (case no. 21 in Table 1) when a sinkhole opened in Via Barcellona (Fig. 2a) that the presence of a wide network of underground quarries below the area came to light. This was the first event that made the presence of a wide system of underground quarries in the calcarenite, below the clays cropping out at the surface, clear. The quarries soon appeared to be very irregular, with regard both to height and development of the areas of extraction. This made it even more complex to gain a detailed knowledge of the subterranean environment below the newly built area and required the direct involvement of cavers who carried out long and difficult explorations, coming out with topographic surveys of a network consisting of several kilometers of underground passages. These surveys have become the first step on which to build a GIS to collect and manage all the data about the underground environment at Altamura. Based upon this newly acquired knowledge, the underground quarries are being filled by grouting in order to allow new construction in the area. However, it has to be noted that in many cases, the presence of the quarry had to be known (even not "officially") by geologists and engineers, as demonstrated by the foundation piles of several buildings observed within the quarry (Fig. 3).

Periphery of towns

Sinkholes threatening directly inhabited areas pose, of course, major concerns, given the elements at risk (buildings, people, infrastructures, etc.) that are present. However, even outside of the towns, and in particular at their outskirts, the problem has to be taken into serious consideration. The underground quarries were originally located not directly below the built-up areas, but at a certain distance from this, and not too far, to avoid long transport of the building materials. Over time, urban areas expanded, and the buildings located at the borders of the towns increasingly closer to those sectors where the underground quarries had been excavated.

The area of Cutrofiano (Fig. 1) represents one of the main quarrying districts in Apulia, with a long history of activity, both at the surface and underground. The local geology presents the Pleistocene calcarenites, widely used for construction purposes, covered by a succession of sands and clays. While the latter are quarried at the surface, and used for the local pottery industry and artisanal crafts, the calcarenites have been the object for several decades of underground quarrying. This occurred through manual excavation of a number of 2.5–3 m-wide wells through the stratigraphic succession to reach the best level within the calcarenite formation. Once this level was reached, the excavation proceeded horizontally, with a network of galleries, generally 5-m wide, and 6.5 to 7-m high, in a regular room-and-pillar pattern. Because the overall stratigraphy was slightly dipping toward the southwest, this resulted in

Fig. 3 Infrastructure at risk because of the occurrence of sinkholes related to underground quarries: **a** and **b** foundation piles within underground quarry at Altamura (photo courtesy of CARS) and Cutrofiano; **c** solid wastes in underground quarry at Cutrofiano; **d** buildings threatened by the sinkhole at Gallipoli (case no. 27 in Table 1); **e** cavers entering the sinkhole near buildings of recent construction at Altamura (photo courtesy of CARS)

underground quarries 7- to 10-m deep at the outskirts of the town, and up to 45-m deep farther south. The network of underground galleries thus realized has overall length of several tens of kilometers. The quarries represented for many years the main work of most of the Cutrofiano inhabitants, but, starting from the 1970s, these activities slowly decreased and were progressively abandoned. Apart from a temporary use of some for mushroom cultivation, the quarries soon became sites where solid and liquid wastes were illegally discharged, until a project of reclamation of the area started in the last 5 years.

After abandonment of the quarries, several sinkholes occurred in the area, which caused heavy changes in the local topography, with lakes appearing at the surface due to the outcropping of the perched water table sustained by the clay layers. The first events for which documentation has been found occurred during the 1950s and produced a number of depressions that now characterize the area south of the town (De Pascalis et al. 2010). Initially, the link between the underground quarry and sinkhole events was not fully investigated, due to difficulties in entering the subterranean systems. Starting from 2004, within the framework of the project aimed at reclaiming the sites from the wastes, caving surveys in the quarries have been carried out. Besides the very high amount of solid wastes discharged underground, these surveys have shown that at many sites the quarries were affected by serious instability phenomena (Fig. 4). In addition to those already occurred, as detachment from the vault or slab failures coming out of the walls, also several incipient signs of instability have been identified: bulging in the walls, wedge failures, deformations and opening of cracks. These are generally premonitory signs of instability, as observed in many sites worldwide, and can be used to understand the mechanical behavior of the rock mass and the degradation processes occurring within the caves (Szwedzicki 2001; Parise and Lollino 2011).

At Cutrofiano, the last sinkhole events were registered on 15 July 2008 and in March, May and October 2010 (cases no. 26, 29, 31 and 32 in Table 1). Their size ranged from a few meters up to 25 m in diameter (Fig. 2d, f).

Even though they are mostly located at the outskirts of town, therefore only marginally involving the inhabited area, the underground quarries (and the related sinkholes) pose a serious threat to several communication routes linking Cutrofiano to the south, and to the safety of vehicles running along them. Some of the sinkholes are only a few meters apart from the roads, which have been inhibited to heavy traffic, thus causing severe economical damage to the local activities, consisting essentially of working in the surface quarries of clays, used for the pottery industry and arts and crafts.

In the last few years, research has been carried out in the underground quarries at Cutrofiano, aimed at two main

Fig. 4 Failures in underground quarries, potentially leading to upward stoping of instability and development of a sinkhole at the ground surface. **a** Open cracks in the pillars and falls from the vault (Cutrofiano); **b** wall deformations and failures (Cutrofiano); **c** diffuse failures from the walls (Cutrofiano); **d** large failures affecting the entire wall (Gallipoli)

goals: (1) to improve the knowledge of the extension and distribution of the underground passages; and (2) to ascertain their stability conditions, and the likely danger to man-made structures above ground. More than 30 km of underground galleries have been mapped, and the main evidence of instability (both collapsed and incipient) has been identified and documented (Fig. 5). This work is fundamental to identify the sites most prone to likely failures, and should therefore represent the first step in the process of sinkhole risk mitigation. However, so far this has not been followed by any further action regarding the identified unstable sites.

Rural areas

Sinkhole events in rural areas are generally not reported, since they do not affect directly elements at risk, and in many cases no trace is left in any documents. For this reason, the number of reported events is strongly underestimated. In the chronology shown in Table 1, only five events are attributed to this category.

The most recent occurred during the night between 2 and 3 May 2010 (case no. 30 in Table 1), when a sinkhole 32-m wide and 6–9-m deep opened in the territory between Barletta and Andria, at a site occupied by a field of olive trees (Fig. 2e) and crossed by a municipal road with heavy traffic, due to the nearby presence of active open quarries. The sinkhole cut a 10 m-long stretch of this road on its northeastern side.

At the lowest part of the sinkhole, at least two entrances to underground quarries were visible. The presence of underground quarries was not known to the locals, at the sinkhole site and in the surrounding areas. Caving explorations carried out at the site identified a complex system of underground quarries (De Giovanni et al. 2011), developed at about 10 m of depth, showing also several exits to the ground at a distance of about 100 m that had been closed with solid wastes. The quarry was excavated in the Lower–Middle Pleistocene calcarenite underlying Pleistocene-terraced marine deposits (poorly cemented coarse calcarenites and calcareous sands), with a mean thickness of 6 m. The calcarenite shows a clear clino-stratification, dipping about 30° to the NNW, well visible in many places within the underground quarry.

The sinkhole was caused by collapse of the pillars in what was probably one of the largest rooms of the quarry, and was likely triggered by the vibrations induced by heavy traffic. Even in the rest of the subterranean spaces, up to a distance of several tens of meters from the sinkhole edges, the stability conditions were very poor. Survey of the stability conditions, carried out through analysis of the fracturing systems, and the failures that occurred as well,

Fig. 5 Survey map of an underground quarry at Cutrofiano, showing the main signs of instability identified. The *colors* mark areas with different susceptibility to failures, increasing from *white* (not susceptible) to *yellow* (low-medium susceptibility), *orange* (high susceptibility) and *red* (very high susceptibility)

allowed discriminating the instability into falls from the vault and from the walls; further, the pillars were carefully analyzed, to evaluate their stability (Fig. 6). The structural survey resulted in showing the high degree of hazard present in the whole underground quarry, pointing out to the likely possibility of further collapses in the area.

Conclusions

The high number of sinkholes related to underground quarries that have been registered in the last few years in Apulia highlights the need to face a hazard that until recent times was greatly underestimated. Direct involvement of inhabited areas and important communication routes and infrastructures make clear that numerous elements at risk can be threatened by these phenomena, which therefore should deserve greater attention and be the object of thorough studies. The latter should ideally deal with:

- historical research, aimed at identifying the interested sites by the presence of man-made caves;
- recognition of the mechanisms of failures occurring within the quarries;
- evaluation of the decrease in the mechanical properties, related to degradation of the rock mass;
- analysis of premonitory signs of the catastrophic phase of collapse, to understand whether or not the collapse was preceded by signs that could be used for forecasting purposes.

Fig. 6 Examples of pillars with open cracks and deformations in underground quarries of Apulia: **a**, **b** detachment (**a**) and open cracks (**b**) in pillars at Gallipoli; **c**, **d** open and crossed cracks in pillars at Barletta

Recent experiences, with particular regard to the event at Gallipoli in 2007, have shown how far Apulia is from a correct management of sinkholes in built-up areas and, in particular, of the emergency phase related to sinkholes. Only by chance, the evolution of the situation following the 29 March 2007 sinkhole did not result in casualties, but even this had no effect on the approach followed by the local authorities. No effort was made to carefully map the underground quarries, and to carry out works devoted to a complete reclamation of the site. Still today, the buildings above the quarry are in a dangerous situation.

In regions like Apulia, where tens of towns are faced with more or less developed systems of underground quarries beneath the urban areas (in addition to a great variety of other typologies of anthropogenic cavities; see, for instance, Parise et al. 2009), the issue should be properly and carefully addressed, starting from a detailed inventory of the quarries, and of their stability conditions as well. As aforementioned, historical research should play a very important role in the process of recovering old information about location of abandoned quarries, and the existing catalogs of natural and man-made caves should be taken into account.

The actual number of events is certainly underestimated, due to difficulty in finding informative accounts, and, when these were found, in their frequent fragmentation and/or inconsistency. As observed in many cases dealing with different types of natural and anthropogenic hazards, availability of historical information is not an easy issue, and must take into account the need to critically evaluate all the different sources analyzed, in order to establish a degree of reliability for each source (Wieczorek and Jager 1996; Calcaterra and Parise 2001; Glade et al. 2001). Historical information is therefore extremely useful for getting a better understanding of the vulnerable areas, and, when properly considered and used by local land planners and managers, may significantly contribute to reduce the possible negative effects of future events.

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