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# A review of natural sinkhole phenomena in Italian plain areas

**G. Caramanna · G. Ciotoli · S. Nisio**

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**Abstract** Italian sinkholes, which are mainly related to karst phenomena (i.e., solution sinkholes, collapse sinkholes, etc.), are widespread along the Apennine ridge and in pedemontane areas where there are carbonatic bedrock outcrops. However, other collapses, which seem unrelated to karst dissolution, have been identified in plain areas with a thick sedimentary cover over buried bedrock. The main goal of this work is to study the geological, geomorphological, and structural setting of these areas to identify the possible mechanism of the generation and evolution of these collapses. About 750 cases were identified by research based on historical archives, specific geological literature, and information from local administrations. Geological, geomorphological, and hydro-geochemical surveys were conducted in 300 cases, supported by literature, borehole, and seismic data. A few examples were discarded because they could be ascribed to karst dissolution, volcanic origin (i.e., maar), or anthropogenic causes. Field studies regarding the other 450 cases are in progress. These cases occur along the Tyrrhenian margin (Latium, Abruzzo, Campania, Tuscany) in tectonic, coastal, and alluvial plains close to carbonate ridges. These plains are characterized by the presence of pressurized aquifers in the buried bedrock, overlaid by unconsolidated sediments (i.e., clay, sands, pyroclastic deposits, etc.). The majority of these collapses are aligned along regional master and seismogenetic faults. About 50% of the studied cases host small lakes or ponds, often characterized by highly mineralized springs enriched with $CO_2$ and $H_2S$. The Periadriatic margin does not seem to be affected by these phenomena, and only a few cases have been found in Sicily, Sardinia, and Liguria. The obtained scenarios suggests that this type of collapse could be related to upward erosion through vertical conduits (i.e., deep faults) caused by deep piping processes whose erosive strength is increased by the presence of acidic fluids. In order to distinguish these collapses from typical karst dissolution phenomena, they are defined as deep piping sinkholes (DPS).

G. Caramanna · G. Ciotoli · S. Nisio (✉)
Dipartimento Difesa del Suolo, Geological Survey of Italy, APAT,
Via Curtatone, 300185 Rome, Italy
e-mail: stefania.nisio@apat.it

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## 1 Introduction

The term sinkhole has often been used to indicate collapse phenomena of different types and/or origins. The term defines a subcircular surface depression or collapse structure formed by the breakdown of small subterranean karst cavities (Fairbridge 1968; Monroe 1970; Bates and Jackson 1983; Waltham 2002; Waltham et al. 2005; Wilson and Moore 1998; Williams 2004; Neuendorf et al. 2005). This definition is synonymous with a doline, which includes various generating subtypes such as solution, collapse, or subsidence sinkholes or dolines (Jennings 1985; Castiglioni 1986; Sweeting 1972). At present in the United States and Great Britain the term sinkhole is frequently used to define any subcircular cavity regardless of its origin (Beck 1984; Beck and Wilson 1987); the term is also used to indicate open cavities caused by anthropogenic activities that do not necessarily have a subcircular shape (Newton and Hyde 1971). However, this fact has created confusion, particularly between the different terms used in the English versus Italian literature (Nisio 2003; Caramanna et al. 2005; Nisio et al. 2005).

In the Italian literature the term sinkhole is used to indicate a subcircular cavity that opens suddenly on the surface, and is used as a synonym for collapse. The term sudden collapses is also used to refer to phenomena that are not directly linked to karst dissolution, such as subterranean cavities caused by anthropogenic activities in urban areas, above mines, excavations, and ancient catacombs. To avoid any misunderstanding in this work the generic term sinkholes is always combined with a term that indicates the generating mechanism (i.e., solution sinkhole, collapse sinkhole, deep piping sinkhole etc.).

Over the last 20 years several collapse phenomena have been detected in Italian plain areas. Specific observations and field surveys have provided information about the evolution of these events. These studies show that the generating mechanism cannot be typical karst dissolution but could be related to deep piping processes due to the presence of carbonate bedrock buried under a thick sedimentary cover (Ciotoli et al. 2000; Salvati et al. 2000; Nisio 2003; APAT 2004; Nisio et al. 2005, 2007). This sudden collapse is caused by uprising fluids followed by upward erosion. In this paper these sinkhole phenomena are called deep piping sinkholes (DPS) (Nisio 2003).

The aim of this work is to inventory known or inferred DPS located in plain areas in Italy. The first step of this study consisted of the observation of anomalous ancient dry cavities or subcircular hollows, craters, pseudocraters occurring in volcanic areas (described before this census as maar or small volcanic craters), various subcircular forms in other areas, and many subcircular ponds of uncertain origin. Initial results highlighted that the generating mechanisms, the geological and structural setting, and the morphology of several of these cavities was compatible with DPS (Ciotoli et al. 2000; Salvati et al. 2000, 2001; Nisio 2003; APAT 2004; Nisio et al. 2005). However, determining which of these ponds and small cavities are DPS is not easy. Specific investigations (geological surveys, geophysical, geochemical, and hydrogeological studies) were conducted to verify this assumption, but in many cases it was only possible to infer an hypothesis. In particular the correlation of ponds with DPS is made difficult by the presence of water rising in the cavity; in most observed cases the sinkhole fills within tens of days of formation. The water may be of shallow origin (i.e., shallow aquifers) or the pond may host submerged springs fed by a deep regional aquifer. These ponds are usually subcircular, with diameters ranging from a few to one hundred meters with a maximum depth of 50 m.

In this paper only DPS (in Italy defined as "strict sense sinkholes") are considered. About 750 collapse phenomena in plain areas were surveyed to identify ponds and/or small lakes that could have originated due to deep piping phenomenon. Pseudocraters and anthropogenic forms located in the plains, pedemontane, or hill areas were discarded. Historical research (based on ancient maps, reports, etc.) was conducted to identify DPS in Italy, complemented by direct investigation of geological, morphological, and hydrochemical data for the sinkholes and the surrounding areas. All this information was organized using a Microsoft Access relational database (SH-RDB) that was designed and implemented to store, analyze, and map the information regarding sinkhole-prone areas in Italy. The database aims to provide easy access to the data via a variety of data query and reporting options. As there was a strong geographical aspect to the data, a geographical information system (GIS) was used to create thematic maps and further analyses of the information.

## 2 Sinkhole classification according to Italian case histories

In Italy, sinkholes are mainly of natural karst origin. They occur on outcropping carbonatic bedrock or on bedrock with thin sedimentary cover (Macaluso et al. 2002; Delle Rose and Parise 2002; Delle Rose et al. 2004a, b). However, a few sinkholes are related to anthropogenic features (i.e., roof collapse of artificial cavities due to human activity). Another group of collapses in plain areas is characterized by thick alluvial or pyroclastic cover over deep buried bedrock with an upward migration of the phenomenon; these cases represent the DPS described in this paper.

A first attempt at classification of Italian sinkhole phenomena is based on the generating processes as follows:

(1) Anthropogenic sinkhole
(2) Karst phenomena
(3) Evorsion and suffusion phenomena
(4) Deep piping sinkholes (DPS)

Anthropogenic sinkholes originate due to the collapse of the roof of artificial cavities (quarries, mines, catacombs, etc.). Their morphology varies in shape and is not always circular or subcircular.

The karst phenomena classification follows the classical generating classification of dolines (Castiglioni 1986):

- Collapse (quick sinking)
- Subsidence (slow sinking)
- Solution (chemical dissolution of the limestone by acidic rainwater)

Evorsion cavities originate due to erosion processes caused by vertical-axis turbulence. This erosion is typical of large alluvial valleys (Pianura Padana with the Po River system) and is triggered by the rupture of the river bank. In lagoon and river delta areas the erosion is caused by the ingress of an inland sea. The resulting shapes are subcircular ponds, called whirlpools (ital. "gorgo"), with diameters ranging from 30 to 100 m and a maximum depth of 13–15 m. The location of these ponds is usually on the base of the river bank, where there is a strong water flow following the rupture of the bank during flooding. These cavities are usually located on sediments with a high fraction of sand; during floods this sand is liquefied by the high water head, leading to the formation of a sort of spring called a fountain (ital. “fontanazzo”) that can be the triggering factor for collapse (Bondesan 1995). These sinkholes, caused by “eversion” processes are similar to DPS ponds but, in the “eversion” process the main erosion proceeds downward, while the DPS are caused by upward erosion (piping).

Deep piping sinkholes are described in detail in the following paragraphs.

The observed cases have been clustered into six types, including volcanic processes (i.e., maar) and unknown (still undefined) according to their generating mechanisms (Fig. 1).

## 3 DPS morphologies

The origin, triggering factors, and development of DPS are fundamentally different from those that generate karst landforms. The main difference between DPS and karst-related collapses (dolines, solution, sinkholes, etc.) is that a DPS shows a hypogeum upward propagation, instead of the usual downward growth of the karst phenomena (Nisio 2003; Nisio and Salvati 2004).

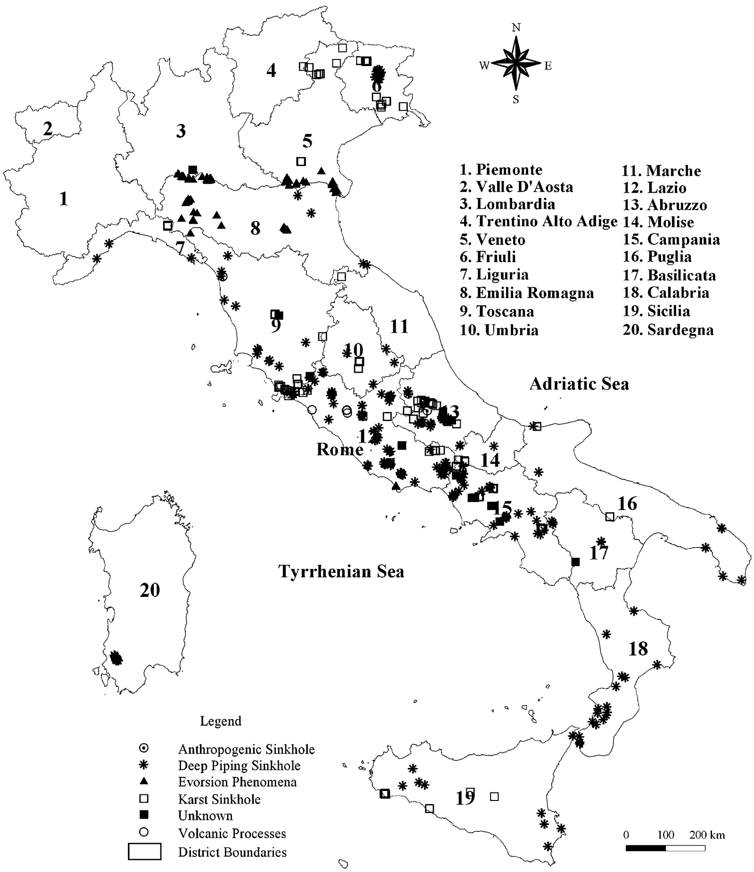


**Fig. 1** Observed sinkholes location and their classification based on the collapse generating mechanism

DPS may have diameters up to some hundreds of meters and, when located on pyroclastic deposits, may be confused with volcanic craters (e.g., maar). Maars are not erosive landforms and there is usually a small deposit at the top of the cavity creating a smooth relief that is not present in the DPS.

The resulting morphologies of dolines, craters, and DPS are very similar and this is the main cause for confusion between these phenomena. The morphology and morfometry of volcanic forms, anthropogenic sinkholes, and dolines have been studied by several authors (Cvijic 1893; Cramer 1941; Monroe 1970; Beck 1984 (cum biblio); Castiglioni 1986; White 1988; White et al. 1995, Sauro 2003; Williams 2004).

DPS are erosive subcircular- and cylindrical-shaped forms that collapse and develop quickly, and are characterized by an endorheic drainage net (White 1988; Canuti 1982; Galloway et al. 1999; Hyatt et al. 2001). This definition fits with the definition of dolines but DPS are located mainly in plain areas characterized by the presence of a very thick sedimentary cover (Canuti 1982; Salvati and Sasowsky 2002; Nisio 2003).

The subcylindrical or pseudoconic shape of deep piping sinkholes has been verified by several authors by means of bathymetric surveys (Ogden et al. 1989; Bono 1995), geophysical scans (Steeples et al. 1984; Chang and Basnett 1995; Kaufmann and Quinif 1999; Argentieri et al. 2002; Di Filippo et al. 2002) or by direct scuba explorations (Caramanna 2001; Gary et al. 2003). Several numerical models highlight this cylindrical shape (Waleed and Gooding 1996; Tharp 1997). This morphology is due to the physical characteristics of the collapse, which can be considered as a collapsed vertical shaft. The geometry of sinkholes is caused by a generating process that starts with the creation of a small cavity close to the carbonatic bedrock with a sort of progressive empting from the bottom to the top of the cover layers. The cave develops upward in steps; the resulting morphology, either a funnel or cylindrical, depends on the leading issue (ravelling or piping or a mixing of both) and on the mechanical response of the soil.

The final collapse, when the deformation reaches the soil surface, is catastrophic and causes the sinkhole to form (Fig. 2). Sometimes the same process can be reactivated several times at the same location (Capelli et al. 2000). In this case sinkholes may be twin or multiple.

## 4 DPS propagation

DPS-prone areas are characterized by the widespread presence of faults affecting the bedrock. DPS are mainly aligned along these tectonic displacements (Brook and Anderson 1985; Veni 1987; Faccenna et al. 1993, 1994; Capelli et al. 2000; Kaufmann and Quinif

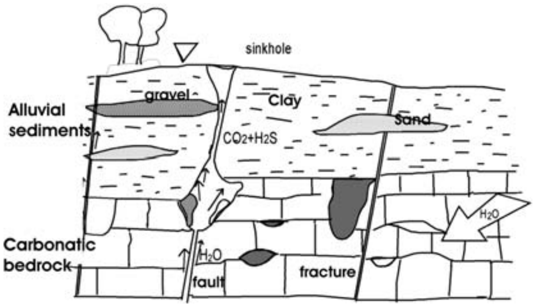


**Fig. 2** Schematic representation of deep piping sinkhole formation and propagation

1999; Salvati et al. 2001; Salvati and Sasowsky 2002). In particular the presence of fault systems of regional importance could be a factor that facilitates and supports the propagation of collapse phenomenon from the triggering point towards the soil surface. The presence of faults coupled with the poor mechanical and rheological characteristics of the covering sediments increases the DPS upward migration, which may be described as a poroelastic deformation of terrains undergoing stress (Tharp 1997, 1999, 2000).

Furthermore, seismic activity linked to some of these tectonic structures could act as a triggering factor for DPS formation and migration. Several other triggering factors may cause sinkhole formation:

1. Sudden and harsh decompression of a confined karst aquifer hosted in the carbonatic bedrock
2. Breaking of the boundary layer bedrock/cover sediments with ravelling phenomena and the formation of microcavities
3. Overpumping of the pressurized karst aquifer with action on the overlying soil layers
4. Deep piping by fast flow and chemically aggressive groundwater, affecting the less-cohesive cover deposits.

The upward propagation of the deformation strictly depends on the mechanical characteristics of the terrains. A noncohesive cover will be like sand in a sandglass with an homogeneous downward flow, creating a cone-shaped form. The presence of cohesive or lithoid layers will cause the collapse to follow a step progression. The resulting shapes are not conic but usually cylindrical. The presence of more-robust materials slows the evolution of the sinkhole, which becomes more dangerous due to the unpredictability of the event. This is the typical situation in the surveyed Italian DPS-prone areas.

Another potential relevant triggering factor is the rising of acidic and aggressive gases ($CO_2$ and $H_2S$) and mineralized fluids through deep faults, which may alter the structure of the covering materials, increasing the dissolution of the carbonate fraction of the sediments cover. This geological scenario is typical of the investigated areas along the Tyrrhenian margin of central Italy where a lot of cold and warm mineralized springs occur (i.e., the San Vittorino, Pontina, Telese, and Tivoli plains).

However, anthropogenic factors can also affect DPS migration, for example the overpumping (i.e., for the groundwater supply) of deep aquifers, which can alter the equilibrium of the overlying strata once the boundary layer between the deep aquifers and the cover sediments has been broken. In this case the pressurized aquifer affects the sediments with direct mechanical erosion, plus chemical dissolution where acidic waters occur. The eroded sediments will be flushed away by the underground water flow (Pontina plain).

## 5 DPS features

According to field observations and collected data, it is possible to define two kind of DPS typologies.

(1) DPS—These cavities are usually water filled (mineralized waters and gas emissions, mainly $CO_2$ and $H_2S$) and occur in areas characterized by more than 100 m of thin-grained impermeable or semipermeable sediment covers (silty clay or silt) that prevent downward water filtration (Nisio 2003; Nisio and Salvati 2004). The water head is often artesian with the formation of springs inside the cavities. For this reason in Italy these sinkholes are also defined as spring sinkholes (Capelli and Salvati 2002). Artesian water head and gas

uprising both contribute to the formation of the sinkholes through upward mechanical erosion (Nisio and Salvati 2004).

In other words the water filling these sinkholes represents the outcrop of the deep aquifer hosted in the buried carbonatic bedrock (Nisio 2003; Nisio and Salvati 2004); deformation starts from the roof of the bedrock and is not related to the depth of the bedrock itself. Pressurized water migrates through faults in the bedrock, facilitated by the presence of gases acting as carriers (Faccenna et al. 1993).

The combined chemical action due to the presence of aggressive acidic waters, as well as the mechanical motion due to the turbulence (water and debris) inside the enlarging fractures in the bedrock, increases the erosion, even causing DPS formation in very thick covers (up to 100 m).

(2) Collapse-DPS—The geological conceptual model of a collapse-DPS suggests the presence of thick permeable or semipermeable cover sediments overlying the bedrock. These sediments are more coarse and cohesive than in the DPS scenario (Galloway et al. 1999).

This is a complex erosive situation: in general, the piping processes affect only the deepest layers of the cover. The cavity propagates upward by step collapse. Ravelling phenomena are possible in the shallow layers. The whole process is halfway between a DPS and a cover-collapse doline. The triggering factor is the formation of a cavity inside the cover material and the subsequent migration of the void from the roof of the bedrock towards the soil surface (Sasowsky et al. 1995; Tharp 1999, 2000). When the residual cover thickness is not strong enough to support the overlying layers there is a final collapse. Usually the aquifer is not pressurized, and the water head is never above the soil level. Observations suggest that the main triggering cause is watertable oscillation due to periods of heavy rain or severe drought after strong rainfalls.

The distinctive characteristics of these sinkholes is the absence of water in the cavity or the presence of a small stagnant pond. This pond is fed by shallow water and is affected by seasonal oscillations. This kind of sinkhole mainly occurs in intermountain valleys or along pedemontanes belts on pyroclastic deposits. Their diameter and depth may reach some tens of meters, and the sinkholes are cylindrically shaped with steep walls. Subsequent erosive processes smooth the morphology of these cavities.

Many of the studied cases are characterized by the presence of water filling the cavities to create ponds or small lakes. This water may originate from deep aquifers hosted in the carbonatic bedrock or may derive from shallow or perched aquifers or from surface streams. Ponds fed by regional aquifer underwater springs are permanent; however, sinkholes flooded by superficial water show seasonal fluctuation of water level and in some cases are dry during the summer.

Usually these ponds do not have large streams as inlets or outlets; in several cases the water only flows through inner voids in the sediments where the sinkhole is located.

According to the geological, geomorphological, and lithological data collected in this study, the DPS have been assessed according to 10 features, as reported in Table 1.

## 6 Data presentation

In Italy karst areas with thousands of sinkhole phenomena (solution, collapse, cover collapse, etc.) are widespread. In other areas such as alluvial or coastal plains, sinkhole phenomena (mainly DPS) that do not show clear shallow karst erosion are also observed.

**Table 1** Prevalence of the main features that characterize DPS and surrounding areas

| DPS and surrounding area features | Presence (%) |
|---|---|
| *Feature 1*: Intermontane valleys. Alluvial sediments, clay layers, travertine lenses, mainly impermeable. Deeply buried bedrock (>160 m). Usually filled with mineralized water with gas bubbles, watertable at soil level | 15 |
| *Feature 2*: Valleys and pedemontane areas. Alluvial fans, mixed-grade alluvial deposits, gravel and sand. Deep buried bedrock (60–100 m). Shallow aquifer feeding, no mineralized water, watertable below soil level | 12 |
| *Feature 3*: Alluvial plains, pedemontane belt. Unconsolidated pyroclastic deposits, alluvial deposits with silt and sand layers, lacustrine and travertine deposits. Bedrock depth 100–150 m. Watertable below the soil level | 5 |
| *Feature 4*: Volcanic areas, pedemontane belt, valleys. Unconsolidated or semi-lithoid pyroclastic deposits. Bedrock depth from 80 to more than 100 m. Usually dry cavities | 9 |
| *Feature 5*: Alluvial plains, hill valleys. Outcropping travertine overlying clay strata. Watertable at soil level. Cavities fed by regional aquifer | 5 |
| *Feature 6*: Alluvial or coastal plains. Marine sediments mainly impermeable, travertine. Buried bedrock (50 m). Watertable at soil level | 5 |
| *Feature 7*: Intermontane and inner valleys. Clay and metamorphic deposits, limestone. Medium–deep bedrock. Watertable at soil level. Fresh and mineralized water | 2 |
| *Feature 8*: Coastal plains. Marine clay, fine-grained lacustrine sediments. Very deep bedrock (190 m). Watertable at or below the soil level. Freshwater | 2 |
| *Feature 9*: Inner areas, coastal plains with evaporitic deposition with clay and gypsum. Mineralized water | 3 |
| *Feature 10*: River and open valleys. Mixed grained deposits, alluvial deposits. Medium–deep bedrock. Usually dry cavities | 6 |
| No data available | 37 |

These phenomena may be caused by the collapse of deep buried carbonatic carsified bedrock. Our research has focused on this latter type of collapses, in particular those occurring in areas characterized by very thick sedimentary cover.

This work has been conducted by the Italian Geological Survey in the framework of the "Sinkhole Project" since 2000.

The cases described were identified by collecting information from the geological and historical literature (i.e., official geological maps of Italy, ancient reports, and maps) available, for example, from the Hystorical Geographic Society of Italy, Italian Geological Survey (old database), and local municipalities. For ancient phenomena the research mainly focused on analysis of historical maps and reports. For the recent collapses technical reports available from local municipalities and professionals were acquired and studied (Tables 2, 3, and 4).

The information acquired was: formation date, morphology, geometry, geological scenario (cover sediments litology, depth of the bedrock, structural setting), hydrogeology, and seismicity of the area. These information allowed the identification of 750 cases of natural collapses in plain areas excluding those phenomena clearly related to karst erosion (Fig. 3).

**Table 2** Example of the sinkhole database

| Longitude UTM32 | Latitude UTM32 | Region | District | Formation date | Diameter (m) | Depth (m) | Altitude (m a.s.l.) | Lithology | Bedrock depth | pH | Eh | Cond (μs/cm) | T (°C) | Faults orientation | Geological scenario | Activity | Morfometric evolution |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 899355.18 | 4672651.65 | Abruzzo | L'Aquila | Dec 1456? and 1706? | 124 | 9 | 351 | AS | >50 | 6.91 | 213 | 318 | 18.3 | N–S | AP | F | S |
| 872863.31 | 4664921.99 | Abruzzo | L'Aquila | After 1875 | 250 | 5 | 659 | AS | >100 | 7.1 | | 480 | 7.5 | NW–SE, E–W | IV | F | S |
| 854498.04 | 4702713.28 | Abruzzo | L'Aquila | Before 1950 | 41 | 1.5 | | AS | >100 | 7.16 | | 600 | 9.8 | N–S | AP | F | S |
| 877406.28 | 4692413.86 | Abruzzo | L'Aquila | 13 Sep 1903 | 90 | | 670 | AS | >100 | 7.24 | 85 | 366 | 15.7 | NW–SE | AP | F | S |
| 902033.61 | 4669312.15 | Abruzzo | L'Aquila | Before 1950 | 80 | | | AS | >50 | | | | | | IV | D | S |
| 901430.73 | 4668568.60 | Abruzzo | L'Aquila | Before 1951 | 91 | | | AS | >50 | 6.75 | 270 | 456 | 23.2 | ENE–WSW | AP | F | S |
| 872182.46 | 4664837.93 | Abruzzo | L'Aquila | 1875–1950 | 61 | 4 | 659 | AS | >100 | 7.29 | | 777 | 9.6 | NW–SE, E–W | IV | F | S |
| 872529.89 | 4664739.87 | Abruzzo | L'Aquila | 1875–1951 | 25 | | 659 | AS | >100 | 7.37 | | 778 | 9.1 | NW–SE, E–W | IV | F | S |
| 854532.50 | 4702676.20 | Abruzzo | L'Aquila | After 1950 | 10 | 1.5 | | AS | 60 | 7.16 | | 600 | 9.8 | N–S | AP | F | S |
| 884494.97 | 4663658.73 | Abruzzo | L'Aquila | 13 Jan 1915 | | | 705 | AS | >101 | | | | | NW–SE, E–W | IV | B | S |
| 853604.82 | 4707123.50 | Abruzzo | L'Aquila | 2 Feb 1703 | | | 715 | AS | >100 | | | | | NW–SE | AP | B | EX |
| 866407.46 | 4693645.94 | Abruzzo | L'Aquila | 1352 | 135 | | 640 | AS | >100 | 8.09 | 64 | 484 | 10.9 | NW–SE | AP | F | S |
| 866407.46 | 4693645.94 | Abruzzo | L'Aquila | Before 1950 | 30 | 2 | | AS | >100 | 7.94 | | 478 | 10.4 | NW–SE, E–W | IV | F | S |
| 921630.71 | 4572979.86 | Campania | Caserta | 276 BC | 230 | 6.8 | 12 | PD | >60 | 7.49 | | 270 | 15.3 | N–S | PB | F | S |
| 964154.47 | 4577284.34 | Campania | Benevento | 9 Sep 1349 | 300 | 17 | 50 | AST | >65 | 8.39 | 153 | 492 | 20.0 | NW–SE | AP | F | S |
| 1030457.14 | 4515417.79 | Campania | Salerno | Between 1871 and 1923 | 120 | | 111 | AST | | 6.91 | 107 | | 17.7 | NW–SE | AP | F | S |
| 984035.41 | 4538262.39 | Campania | Avellino | 12 June 2005 | 20 | 20 | 408 | PD | 83 | | | | | NW–SE | IV | A | E |
| 985455.02 | 4537633.19 | Campania | Avellino | 1960–1970 | 50 | 7 | 401 | PD | 83 | | | | | NW–SE | IV | D | S |
| 984680.33 | 4538061.83 | Campania | Avellino | 1 Mar 2005 | 8 | 4 | 411 | PD | 83 | | | | | NW–SE | IV | D | S |

**Table 2** continued

| Longitude UTM32 | Latitude UTM32 | Region | District | Formation date | Diameter (m) | Depth (m) | Altitude (m a.s.l.) | Lithology | Bedrock depth | pH | Eh | Cond (µs/cm) | T (°C) | Faults orientation | Geological scenario | Activity | Morfometric evolution |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 927212.85 | 4591514.42 | Campania | Caserta | Before 1800 | 40 | 2.5 | | AS | >40 | 6.88 | 218 | 268 | 18.0 | N–S | AP | F | S |
| 828544.91 | 4699469.18 | Latium | Rieti | Jan 1703 | 20 | 2 | 404 | AS | 190 | 6.65 | 293 | 1,037 | 11.0 | NW–SE, E–W | IV | R | E |
| 829555.68 | 4699536.05 | Latium | Rieti | 1986? | 5 | 2 | 406 | AS | 190 | 6.17 | −212 | 1,670 | 12.9 | NW–SE, E–W | IV | F | S |
| 829490.71 | 4699482.55 | Latium | Rieti | 19 Feb 1986 | 5 | 3 | 405 | AS | 190 | 6.57 | −50 | 1,313 | 19.7 | NW–SE, E–W | IV | F | S |
| 829458.23 | 4699377.46 | Latium | Rieti | 17 Feb 1986 | 50 | 10 | 404 | AS | 190 | 6.55 | 219 | 1,478 | 20.5 | NW–SE, E–W | IV | F | S |
| 830556.89 | 4699813.11 | Latium | Rieti | Before 1808 | 50 | 4 | 412 | AS | 190 | 7.1 | 324 | 637 | 21.0 | NW–SE, E–W | IV | F | S |
| 830541.61 | 4700227.73 | Latium | Rieti | Roman age, new collapse 31 Jan 1915 | 204 | 55 | 429 | AS | 190 | 7.97 | 306 | 787 | 20.0 | NW–SE, E–W | IV | R | S |
| 829934.00 | 4698855.84 | Latium | Rieti | Jan–Feb 1915 | 10 | 4 | 407 | AS | 190 | 7.53 | 324 | 656 | 26.0 | NW–SE, E–W | IV | F | S |
| 828937.41 | 4698831.41 | Latium | Rieti | 6 Mar 1991 | 32 | 8.5 | 404 | AS | 190 | 6.52 | 293 | 1,126 | 20.0 | NW–SE, E–W | IV | F | S |
| 829180.77 | 4698487.33 | Latium | Rieti | 27 Jul 1876 | 120 | 10 | 404 | AS | 190 | 6.42 | | 1,040 | 25.4 | NW–SE, E–W | IV | F | S |
| 829348.61 | 4698155.68 | Latium | Rieti | 22 Sep 1891 | 50 | 10 | 405 | AS | 190 | 6.42 | 163 | 1,878 | 15.1 | NW–SE, E–W | IV | F | S |
| 829281.28 | 4699565.87 | Latium | Rieti | 1 Sep 2003 | 4 | 0.5 | 404 | AS | 190 | 6.38 | 79 | 4,500 | 14.0 | NW–SE, E–W | IV | F | E |
| 829020.68 | 4699625.86 | Latium | Rieti | 1962 | 20 | 3 | 405 | AS | 190 | 6.39 | | 882 | 12.2 | NW–SE, E–W | IV | F | S |
| 828360.03 | 4610393.20 | Latium | Rieti | 5 Jul 1933 | 3 | 3 | 408 | AS | 190 | 6.53 | | 887 | 12.3 | NW–SE, E–W | IV | F | S |

**Table 2** continued

| Longitude UTM32 | Latitude UTM32 | Region | District | Formation date | Diameter (m) | Depth (m) | Altitude (m a.s.l.) | Lithology | Bedrock depth | pH | Eh | Cond (μs/cm) | T (°C) | Faults orientation | Geological scenario | Activity | Morfometric evolution |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 830801.20 | 4608964.47 | Latium | Rieti | 1915 | 50 | 9 | 406 | AS | 190 | 6.06 | 256 | 2,820 | 17.1 | NW–SE, E–W | IV | A | S |
| 830949.56 | 4608207.10 | Latium | Rieti | 19 Feb 1986 | 5 | 3 | 405 | AS | 190 | 6.57 | −50 | 1,313 | 19.7 | NW–SE, E–W | IV | F | S |
| 830982.57 | 4608125.46 | Latium | Rieti | 17 Feb 1986 | 50 | 10 | 404 | AS | 190 | 6.55 | 219 | 1,478 | 20.5 | NW–SE, E–W | IV | F | S |
| 830810.60 | 4607640.38 | Latium | Rieti | Jan–Feb 1915 | 10 | 4 | 407 | AS | 190 | 7.53 | 324 | 656 | 26 | NW–SE, E–W | IV | F | S |
| 844472.18 | 4597781.24 | Latium | Rieti | After 1990 | 5 | Unknown | 403 | AS | 190 | 6.07 | 63 | 2,200 | | NW–SE, E–W | IV | F | E |
| 844357.98 | 4597769.01 | Latium | Latina | Before 1777 | 161 | 11 | 3 | ASTCB | >100 | 7.91 | 114 | 2,300 | 28.0 | NW–SE | CP | F | S |
| 844468.42 | 4597622.56 | Latium | Latina | Before 1777 | 120 | 8 | 3 | ASTCB | >100 | 6.6 | | 5,500 | 19.0 | NW–SE | CP | F | S |
| 844781.46 | 4597363.33 | Latium | Latina | After 1777 | 15 | 3 | 3 | ASTCB | >100 | 7.06 | | 4,050 | 21.4 | NW–SE | CP | F | S |
| 844068.11 | 4597998.56 | Latium | Latina | Before 1777 | 30 | | 2 | ASTCB | >100 | 8.06 | 128 | 1,162 | 27.3 | NW–SE | CP | F | S |
| 793608.25 | 4673057.17 | Latium | Roma | 28 Oct 1856 | 70 | 0.5 | 96 | ASTPD | 55 | 9.3 | | 412 | 27.0 | N–S | AP | R | S |
| 814958.53 | 4657867.31 | Latium | Roma | 24 Jan 2001 | 35 | 15 | 230 | ASPD | 170 | | | | | N–S | IV | A | E |
| 826202.75 | 4629088.16 | Latium | Roma | Before 1884 | 160 | 20 | 250 | ASPD | >74 | 7.5 | 90 | 256 | 14.9 | E–W | IV | | S |
| 814165.99 | 4644704.94 | Latium | Roma | Before 1800 | 60 | 16 | 180 | PD | >100 | | | | | | PB | B | S |
| 813863.46 | 4645129.33 | Latium | Roma | Before 1800 | 95 | 10 | 165 | PD | >100 | | | | | | PB | | S |
| | | Latium | Roma | 10 Aug 1824 | 40 | 5 | 110 | PD | 50–100 | | | | | | PB | B | EX |
| 902205.57 | 4608723.16 | Latium | Frosinone | 18–19 Feb 1724 | 280 | 23 | 65 | AS | 100 | | | | | N–S | AP | B | EX |
| 890704.01 | 4626681.20 | Latium | Frosinone | Unknown | 5 | 0.5 | 288 | AS | | 7.46 | 192 | 586 | 18 | NW–SE | IV | A | E |
| 697107.76 | 4705213.46 | Latium | Frosinone | Unknown | 3 | 0.5 | 288 | AS | | 7.14 | 216 | 603 | 17.8 | NW–SE | IV | A | E |
| 668500.00 | 4746500.00 | Latium | Frosinone | 23 July 1654 | 210 | | 271 | AS | 40 | | | | | NW–SE | AP | B | E |
| 654500.00 | 4761500.00 | Latium | Frosinone | 1650 | 380 | | 63 | AS | 100 | | | | | N–S | IV | F | S |

**Table 2** continued

| Longitude UTM32 | Latitude UTM32 | Region | District | Formation date | Diameter (m) | Depth (m) | Altitude (m a.s.l.) | Lithology | Bedrock depth | pH | Eh | Cond (μs/cm) | T (°C) | Faults orientation | Geological scenario | Activity | Morfometric evolution |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 676200.00 | 4808400.00 | Latium | Frosinone | Before 1715 | | | 67 | AS | 100 | | | | | N–S | IV | B | E |
| 675900.00 | 4808400.00 | Latium | Frosinone | 1700–1800 | 47 | | 29 | AS | >135 | | | | | N–S | AP | A | E |
| 676600.00 | 4809500.00 | Latium | Frosinone | 7 Jul 2004 | 15 | | 102 | AS | >100 | | | 445 | 13.05 | N–S | IV | F | S |
| 904620.38 | 4611134.42 | Latium | Frosinone | Before 1650 | 5 | 8 | 84 | AS | >100 | 6.63 | 164 | 935 | 13.05 | N–S | IV | F | S |
| 464483.46 | 4347252.77 | Sardinia | Iglesias | 1999 | 18 | 15 | 130 | AS | 60 | | | | | E–W | AP | F | E |
| 464569.91 | 4347311.56 | Sardinia | Iglesias | 1999 | 18 | 15 | 130 | AS | 60 | | | | | E–W | AP | F | E |
| 464528.41 | 4347280.44 | Sardinia | Iglesias | 1999 | 18 | 15 | 130 | AS | 60 | | | | | E–W | AP | F | E |
| 824464.35 | 4168414.38 | Sicily | Trapani | Centuries old | 30 | 10 | | MS | 20 | 8.7 | | 4,210 | 18 | NW–SE | CP | F | S |
| 822053.41 | 4169262.80 | Sicily | Trapani | Centuries old | 30 | 10 | | MS | 20 | 9.2 | | 3,800 | 18 | NW–SE | CP | F | S |
| 822967.00 | 4169872.85 | Sicily | Trapani | Centuries old | 30 | 10 | | MS | 20 | 9.2 | | 8,130 | 18 | NW–SE | CP | F | S |
| 1026103.18 | 4659153.21 | Trentino | Bolzano | Autumn 2000 | 10 | 15 | | AS | 50 | | | | | | IV | B | EX |
| 604850.00 | 4866500.00 | Tuscany | Lucca | 15 Oct 1995 | 30 | 11 | | AS | 170 | | | | | NW–SE, E–W, N–S | IV | B | EX |
| 694390.68 | 4700076.17 | Tuscany | Grosseto | Before 1832 | 195 | 5 | | MS | 100 | 7.29 | 121 | 594 | 10.9 | NW–SE | CP | F | S |
| 927661.54 | 4596875.18 | Tuscany | Grosseto | 1970 | 80 | 1.5 | 398 | C | 100 | | | 175.4 | 6 | NW–SE | IV | F | S |
| 925335.31 | 4588169.52 | Tuscany | Siena | 1334 | 10 | 1.5 | | MS | >100 | 2.73 | 485 | 11,000 | | NW–SE | IV | F | S |

*Lithology*: alluvial sediments (AS); pyroclastic deposits (PD); alluvial sediments with travertine lens (AST); alluvial sediments with travertine overlying carbonatic bedrock (ASTCB); alluvial sediments with travertine and pyroclastic deposits (ASTPD); alluvial sediments and pyroclastic deposits (ASPD); marine sediments (MS); clays (C). *Geological scenario*: alluvial plain (AP); intermontane valley (IV); pyroclastic basin (PB); coastal plain (CP). *Activity*: flooded (F); dry (D); buried (B); active (A); reactivated (R). *Morphometric evolution*: stable (S); extinct (EX); enlarging (E)

**Table 3** Main ion concentrations in the studied DPS water (153 samples)

| Statistic | Ca (mg/l) | Mg (mg/l) | Na (mg/l) | K (mg/l) | $HCO_3$ (mg/l) | $SO_4$ (mg/l) | Cl (mg/l) |
|---|---|---|---|---|---|---|---|
| Minimum | 17.73 | 1.3 | 1.75 | 0.12 | 29 | 0 | 2.91 |
| Maximum | 585 | 256 | 1,230 | 106 | 2,062 | 1,899 | 1,873 |
| Mean | 201.07 | 47.057 | 70.728 | 6.5949 | 532.99 | 313.3 | 107.95 |
| Median | 132.7 | 26.9 | 12 | 2.93 | 366.05 | 47.74 | 15.2 |
| First quartile | 67 | 13.012 | 5.32 | 1.545 | 211.7 | 7.045 | 7.1025 |
| Third quartile | 351.98 | 69.125 | 22.823 | 6.105 | 711.6 | 226.9 | 33.785 |
| Standard deviation | 166.58 | 50.544 | 219.9 | 13.912 | 476.42 | 522.21 | 338.7 |

**Table 4** Main physicochemical parameters in the studied DPS water (153 samples)

| Statistic | Conductivity (μs/cm) | TDS (mg/l) | pH | Eh | T (°C) |
|---|---|---|---|---|---|
| Minimum | 194 | 151 | 5.56 | −385 | 4 |
| Maximum | 8,130 | 6,163 | 9.2 | 51 | 32.4 |
| Mean | 1420.5 | 1204.3 | 7.124 | 325 | 16.92 |
| Median | 921.5 | 695 | 7.095 | 150.4 | 16.7 |
| First quartile | 564 | 371.1 | 6.61 | 192 | 13.23 |
| Third quartile | 2,105 | 1843.5 | 7.56 | 121.3 | 19.82 |
| Standard deviation | 1465.9 | 1191.8 | 0.74 | 240 | 5.79 |

Total dissolved solids (TDS)

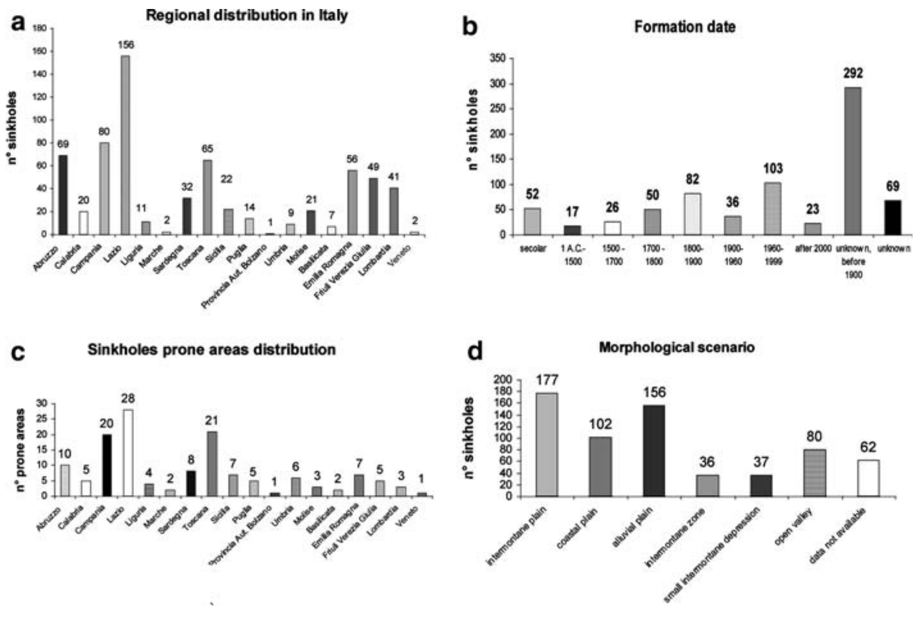


**Fig. 3** Statistical graphs regarding the studied sinkholes: regional distribution (**a**); date of formation (**b**); distribution of sinkhole-prone areas (**c**); morphological scenarios (**d**)

Field verification was conducted in 300 cases, mainly located in Central Italy. In these areas the following specific studies were carried out (Table 2):

- Geology (sediment cover type, bedrock type, and depth)
- Geomorphology (morphology and morphotectonic of the sinkholes and surrounding areas)
- Hydrogeology (aquifer type and geometry, surficial hydrology)
- Structural survey (presence, geometry, and activity of faults)
- Earthquake epicentre locations
- Hydrochemical study (T, pH, total dissolved solids, Eh and, in a few cases, the main ion concentration by chromatographic techniques)
- Aerial photos interpretation (to highlight the morphotectonic elements, extinct subcircular forms, and eventually karst features)
- Bathymetric surveys of the flooded sinkholes conducted with the use of an ecosounder carried on an inflatable boat (Fig. 4)
- Scuba dives aimed at collecting stratigraphic, morphologic, and lithological data in some of the deeper lakes hosted by the collapses

Some of these studies have been published in Italy and the related cartographic material is owned by the Italian Geological Survey (Ciotoli et al. 2000; Nisio 2003; Centamore et al. 2004; Nisio et al. 2004; Annunziatellis et al. 2004; Caramanna et al. 2004; Campobasso et al. 2004; Nisio et al. 2005; Nisio and Scapola 2005, Nisio et al. 2007).

In the remaining 450 cases direct surveys are in progress, although it will be not possible to extend the research for about 60 collapses because they are buried and no shallow evidence remains. These buried collapses have usually been triggered by seismic activity following soil liquefaction or gas bursts and have been filled as a precaution after collapse.

All these data have been used to construct a relational database in the framework of a GIS architecture. The studied sinkhole-prone areas are shown in Fig. 5.

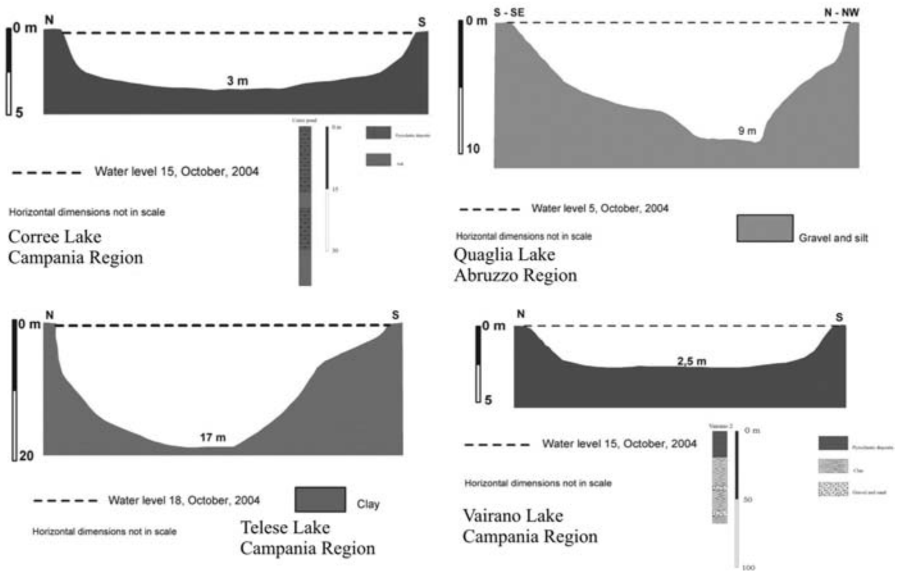


**Fig. 4** Examples of sketch maps of the ecosound bathymetric surveys

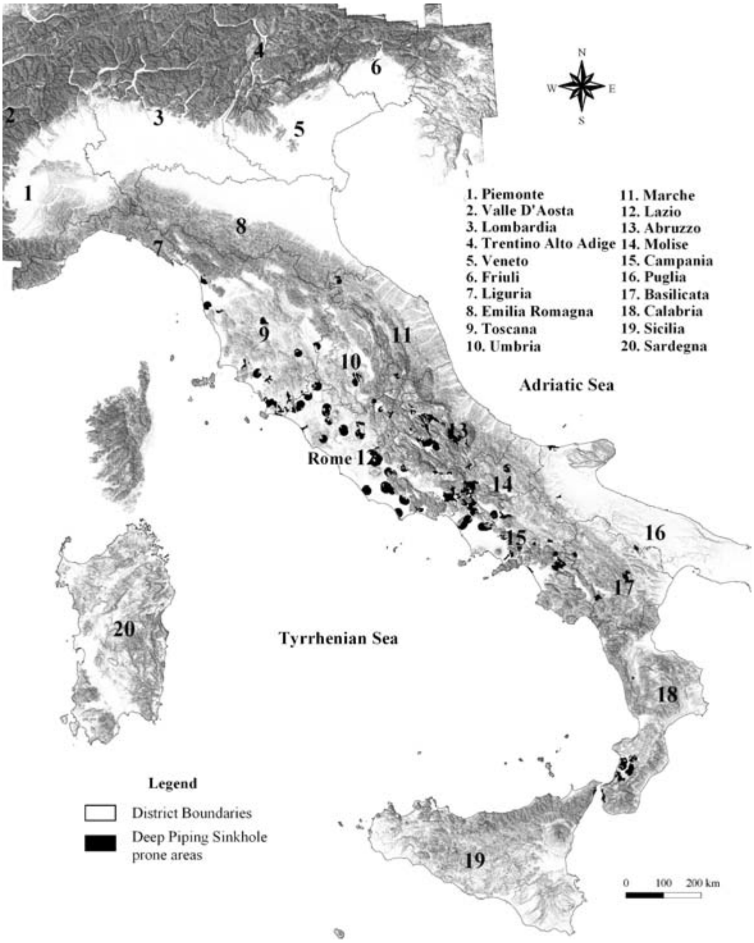


**Fig. 5** Studied sinkhole-prone areas in Italy related to the 750 cases included in the entire database

The results of the study highlight that 379 collapses are DPS (of which 115 are probably DPS but require further investigation), 126 are related to karst erosion, 105 are evorsion phenomena, 12 seem to be linked to anthropogenic collapses, volcanic-related cavities etc. The remaining cases are of unknown origin because of the lack of data (Fig. 1).

The cases studied indicate that DPS are mainly located along the Tyrrhenian margin in the Latium, Tuscany, Abruzzo, and Campania regions. In particular they mainly occur in intermontane, alluvial, and coastal plains, as well as in pedemontane belts and in small hill valleys. The Adriatic foredeep and the Alps chain seem to be unaffected by DPS (Fig. 5).

DPS mainly occur in the 0–100 and 200–400 m altimetric belts. This could be related to the fact that in these areas the bedrock is more deeply buried than in the areas close to the Apennine chain, excluding the intermontane plains.

The investigated areas show a clear tectonic origin with structural primary evidence of Apennine trending faults and, secondary N–S faults. In general DPS are not single phenomena but occur as diffuse collapses affecting the same area. DPS- and sinkhole-prone areas exhibit clustering along regional tectonic lines several tens of kilometres long. Some such master faults include the Aterno River fault (Abruzzo region), the Pontina fault along the Lepini Mounts (Latium region), the Fiamignano-Micciani fault (San Vittorino plain, Central Italy) and its extension to the Fucino plain (Latium-Abruzzo regions), and the Ancona-Anzio tectonic discontinuity (Central Italy) (Fig. 6). The area with the highest DPS density (35 collapses) is the Latium region.

This fact suggests a possible correlation between DPS and active faults, which provide rising channels for deep-seated fluids. In this regard a good correlation between earthquakes and DPS was highlighted in 136 cases; in a few of these cases the collapses happened within 24 h of the seismic event, many DPS originated a few days after the event, while in some cases it occurred more than one month later (Figs. 7a–d, 8).

The water type in flooded sinkholes (230) can be divided into three main groups (Tables 3 and 4):

(a) The first group is represented by shallow aquifers or surficial waters, including rainfall. This water is characterized by low total dissolved solids (TDS) and a pH of about 7. Sometimes the pH drops below 7 due to organic acids released by peat layers. Increases of TDS are due to water infiltration through mineral-rich sediments in zones characterized by pyroclastic deposits.

(b) The second group includes karst waters hosted in deep-seated carbonatic bedrocks. These waters are characterized by a medium TDS, and neutral or basic pH values. The main ions present are $HCO_3^{2-}$ and $Ca^{2+}$ due to the dissolution of the calcareous rocks by the circulating water.

(c) The third group includes mineralized waters, usually derived from the mixing of karst waters with deep-origin fluids (enriched in $CO_2$ and $H_2S$) migrating through active

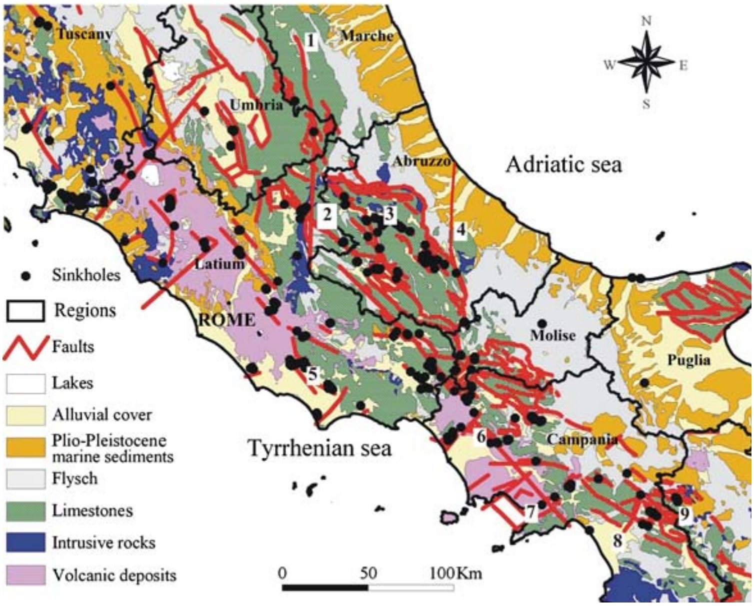


**Fig. 6** Main regional faults in central-southern Italy and sinkholes distribution. 1—Ancona-Anzio fault, 2—Fiamignano-Micciani fault, 3—Aterno fault, 4—Pescara-Volturno fault, 5—Lepini fault, 6—Salerno-Liri fault, 7—Manfredonia-Sorrento fault, 8—Trinitapoli-Paestum fault, 9—Fortore-Vulture fault

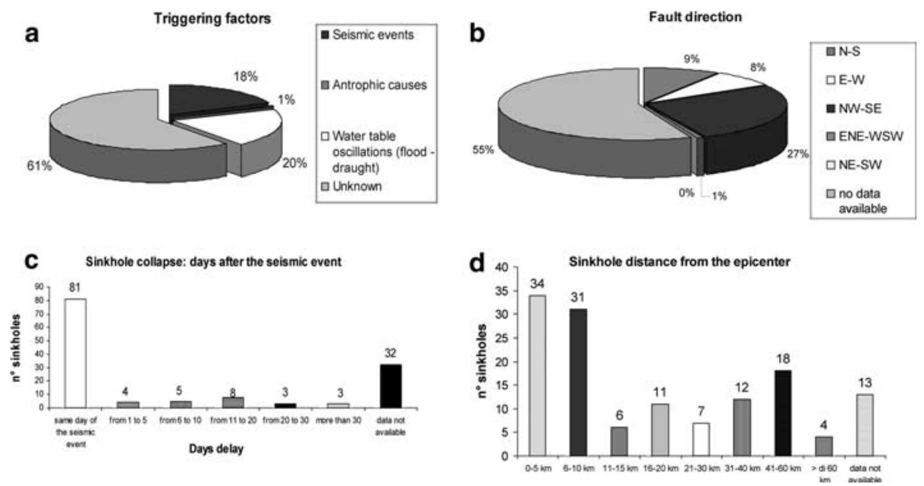


**Fig. 7** Statistical graphs reporting the main triggering factors (**a**); the main fault directions (**b**); number of collapses occurred after the seismic event (**c**); collapse distance from the earthquake epicentres (**d**)

faults and regional tectonic displacements. The highly mineralized waters can be very acidic (pH value less than 3) with high concentrations of dissolved and free $CO_2$ and $H_2S$. These acidic fluids increase the aggressiveness of the waters, enhancing their chemical dissolution of the carbonatic fraction of the sediments and rocks. In these cases DPS may develop quickly and can reach imposing dimensions.

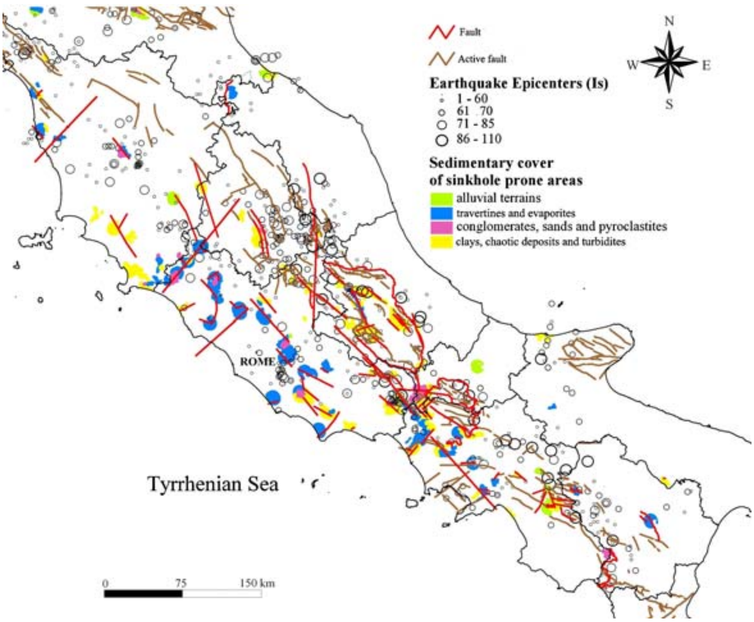


**Fig. 8** Sedimentary cover types of the sinkhole-prone areas, location of the main earthquakes epicentres and distribution of the main tectonic structures

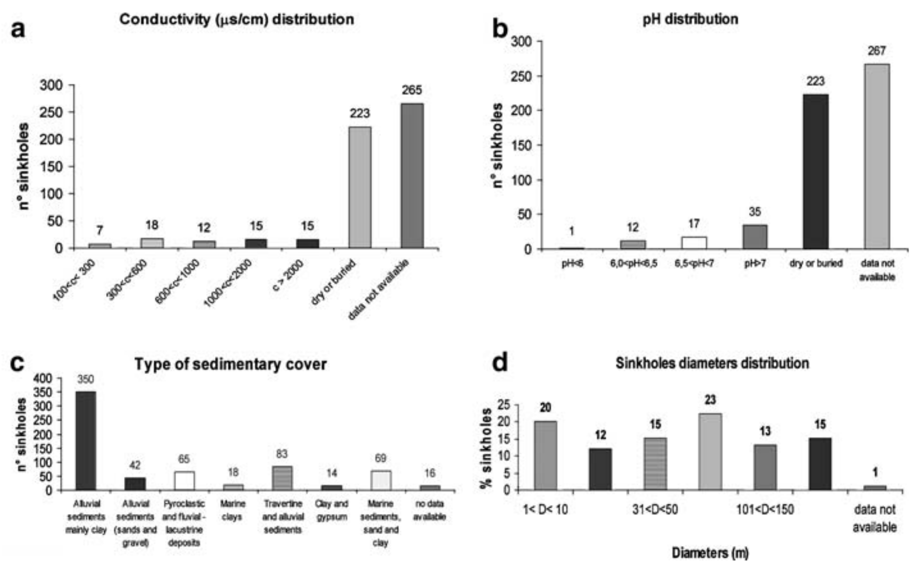


**Fig. 9** Statistical graphs showing results obtained from collected data: electric conductivity of sinkhole pond waters (**a**); pH of the sinkholes ponds waters (**b**); type of sedimentary cover in the sinkhole prone areas (**c**); diameter distribution of the studied sinkholes (**d**)

Of the studied cases 19% show TDS of less than 300 mg/l typical of shallow waters, 19% have TDS about 500 mg/l and are filled by waters circulating in the calcareous bedrock, 28% show highly mineralized waters due to the presence of rising deep fluids. In these latter cases mineralized springs were clearly aligned along tectonic displacements and usually located close to the collapse. The remaining 34% do not show a particular TDS concentration (Fig. 9).

## 7 Sinkhole distribution in Italian regions

### 7.1 Latium sinkholes

Deep piping sinkholes in Latium are well-known natural phenomena that have been studied since the 1980s. They occur mainly in the alluvial and coastal plains and in intermontane valleys. In these areas the carbonatic bedrock is lowered by regional faults that allow the circulation of deep highly mineralized fluids. These fluids are seldom acidic or geothermic, increasing the chemical erosion of the karst bedrock.

In the Latium region 34 DPS-prone areas were detected with 163 active, filled or buried sinkholes. Some of these areas are located in seismic zones, and some are believed to have been triggered by high-magnitude earthquakes.

Sinkhole-prone areas mainly occur in: intermontane valleys (Faccenna et al. 1993; Ciotoli et al. 2000; Nisio and Scapola 2005, Argentieri et al. 2002); fluvial valleys (Nisio et al. 2004); and close to boundary faults between the carbonatic ridge of the central Apennines and the coastal plains (Colombi et al. 2001; Capelli and Salvati 2002; Nisio 2003; APAT 2004; Nisio et al. 2004).

### 7.2 Tuscany sinkholes

In 1995 a DPS formed inside the Camaiore village, causing serious damages to several buildings (Buchignani and Chines 2002). In 1999 another sinkhole with a diameter of about 170 m opened in a farm area close to the city of Grosseto. These collapses highlighted the dramatic importance of sinkhole genesis in Tuscany. Since these events several studies have been conducted by the local administration (Tuscany Region Administration 2000).

144 sinkholes, clustered in 18 areas, have been identified In the region (Caramanna et al. 2004).

Sinkholes in Tuscany seem to be related to a high karst bedrock that lies 30–170 m below the soil level. This bedrock is a limestone formation known as Calcare Cavernoso" (cave limestone) that is characterized by the presence of voids inside the structure. This limestone is seldom affected by strong circulation of geothermal and mineralized fluids that could increase the dissolution of the calcareous fraction.

### 7.3 Abruzzo sinkholes

Collapse phenomena in the Abruzzo region are still relatively poorly known and studied. The DPS are located in intermontane valleys bordered by direct or strike-slip faults of regional importance (i.e., the Sulmona and Fucino plains). Other sinkholes are located in Apennine river valleys of structural origin. For example, along the Aterno River fault several sinkhole-prone areas are aligned for more than 60 km. The Periadriatic foredeep in not affected by DPS.

In general, sources of information about these sinkholes relate collapses to previous high-magnitude earthquakes. Ancient chronicles of a strong seismic event (Aquila earthquake in 1703, seismic intensity 95–100) report a sudden collapse in which a tall sulphurous water geyser emerged "to the height of a poplar" from this cavity and lasted for 17 days (Nisio et al. 2005). Other collapse phenomena were formed in the Fucino plain during the Avezzano earthquake of 1915, $M = 7.0$). These chronicles are compatible with DPS phenomena; in the Abruzzo plains several subcircular ponds are presumed to be evidence of these ancient collapses.

### 7.4 Campania sinkholes

In the Campania region natural sinking phenomena are recognized in volcanic areas, mainly close to the border with the Latium region on pyroclastic deposits (Del Prete et al. 2004). These phenomena were presumed to be volcanic craters (maar), but data collected in this work demonstrate that these are catastrophic collapses related to DPS. In general, these sinkholes are represented by a cylindrically shaped cavity on pyroclastic deposits. The triggering factor is believed to be watertable oscillation due to drought periods followed by heavy rains.

Other cases have been studied in the alluvial plains, where a thick cover of alluvial and pyroclastic sediments overlies the deep buried carbonatic bedrock of the Campania carbonatic platform. In these areas mineralized and/or geothermal springs occur along some regional fault systems.

## 7.5 Other collapse phenomena in Italy

The inventory of collapses in Italy also includes cases located in other regions. Data were obtained from the literature, technical reports of local administration, and field investigations (Sicily), and data collection continues.

### *7.5.1 Northern Italy*

The Alps ridge and most of the northern regions of Italy cannot be considered as DPS-prone areas. Collapses in the Piemonte, Veneto, and Friuli Venezia Giulia regions are karst phenomena. Soil liquefaction phenomena were detected in the Friuli region after the Gemona earthquake in 1976. Some ponds in the Po river valley (Emilia Romagna and Veneto regions) were originated by water filling small collapses in the alluvial cover due to suffusion processes on the river banks (i.e., evorsion phenomena). Piping and suffusion phenomena are also involved in the genesis of these ponds.

### *7.5.2 Southern Italy (Molise, Basilicata, and Calabria regions)*

The geological setting of southern Italy, which is characterized by a thick cover of marine clays, flysch, and metamorphic or igneous sequences, is not prone to DPS genesis. Consequently the reported cases are isolated sinkholes in coastal or small valleys and collapses due to soil liquefaction during high-magnitude earthquakes.

### *7.5.3 Puglia and Sicily sinkholes*

Collapses in Sicily and Puglia are mainly of karst origin due to the characteristic geological-structural scenario (outcropping carbonatic bedrock) and various triggering and propagation mechanisms. The lithological setting of the investigated areas is mainly represented by alluvial cover (i.e., sands, clays) of reduced-thickness overlying evaporitic sediments (i.e., gypsum) (Melidoro and Panaro 2000; Macaluso et al. 2002; Delle Rose and Parise 2002; Delle Rose et al. 2004a, b). Dissolution of evaporitic sediments creates upward erosion of the cover sediments.

Sicilian sinkholes are located in the interior of the island in closed basins in the Miocenic foredeep. The main collapse process is dissolution of Messinian gypsum. In Sicily sequences of clay, sandstone, and gypsum are often recognizable. Where the gypsum is overlaid by unconsolidated sediments its dissolution may trigger collapses. These sinkholes are caused by upward erosion by ravelling or suffusion.

Collapses in Puglia are located in the shore areas; the collapses affect silty-sandy marine sediments of reduced thickness that overlie carbonatic and evaporitic sequences.

## 7.6 Sardinia sinkhole

Collapses in Sardinia have been identified as sinkholes only recently, in 1999 (Balia et al. 2001; Caredda et al. 2004). Several collapses have been observed in the southwestern mining district aligned with an E–W trending master fault. The lithology is represented by carbonate and metamorphic bedrock overlaid by alluvial deposits (sand and gravel). Only a few of these cases are related to mining operations (i.e., the collapse of inactive mines).

### 7.7 Susceptibility map of piping sinkhole-prone areas in Italy

A Microsoft Access relational database (RDB) was designed and implemented to store and analyze the information collected in the areas prone to sinkhole hazards in Italy. The sinkhole relational database (SH-RDB) includes general details, geological, hydrogeological, geochemical, and geotechnical data of known and investigated DPS in Italy. The database aims to provide easy access to the data via a variety data query and reporting options. The relational database systems theory (RDST) provides rules for organizing and representing items and phenomena as collections of attributes stored in tables so that a specific set of procedures can associate, transform, and extract information from the tables in a reliable way (Fig. 10). The storage of information in the SH-RDB is organized into rows and columns in a table, with a separate row for each entity and a column for each property.

As there was a strong geographical aspect to the data, a geographical information system (GIS) was used to manage the data and create thematic maps for further spatial analysis. The ArcGIS structure is organized with elementary units called layers. According to whether vector or raster format is used for the geographical elements, layers or themes are stored as “shapefile” or “grid” data models. Vector layers have a geometrical base (points, lines, and polygons) with descriptive variables, e.g., types of outcropping formations, type of fault geometry, hydrogeological complexes. The shapefile format (shp) is used to represent and store thematic maps (i.e., geology, hydrographic network, socio-economical data), while the grid format (grd) is better to represent and store spatial distributions of points (i.e., DTM, isopleth maps, etc.), and to integrate and overlay the different themes to construct synthetic maps (Fig. 4, GIS).

Geometric information for the location and shape of each DPS relates to the following data types:

- Aerial photos.
- Base maps (many at the national level): raster topographic maps from the Istituto Geograpico Militare (IGM) (1:25,000 scale) georeferenced in the ED50 system UTM 32. A digital elevation model (DEM) was obtained from these maps by interpolating point elevation values.
- Thematic maps: vector data (points, lines, and polygons) combined with the descriptive attributes reported in the database tables.
- Data from field surveys and laboratory analyses.
- Socioeconomic data: populated areas, population census, administrative boundaries, etc., and their descriptive attributes.

These layers are organized in an ArcGIS view called “Sinkhole Project”. ArcGIS functions allow the creation of new views in order to add all source data (themes) stored in the access database. Vector layers were graphically completed with class descriptions (legend files). The integration of the different layers in a layout produces real-time thematic maps at different scales.

As previously reported numerous parameters (i.e., the depth of the substratum, the geotechnical characteristics of the sedimentary cover, seismicity, and the presence of active faults, etc.) combine to define a sinkhole-prone area (Fig. 5). All the collected data

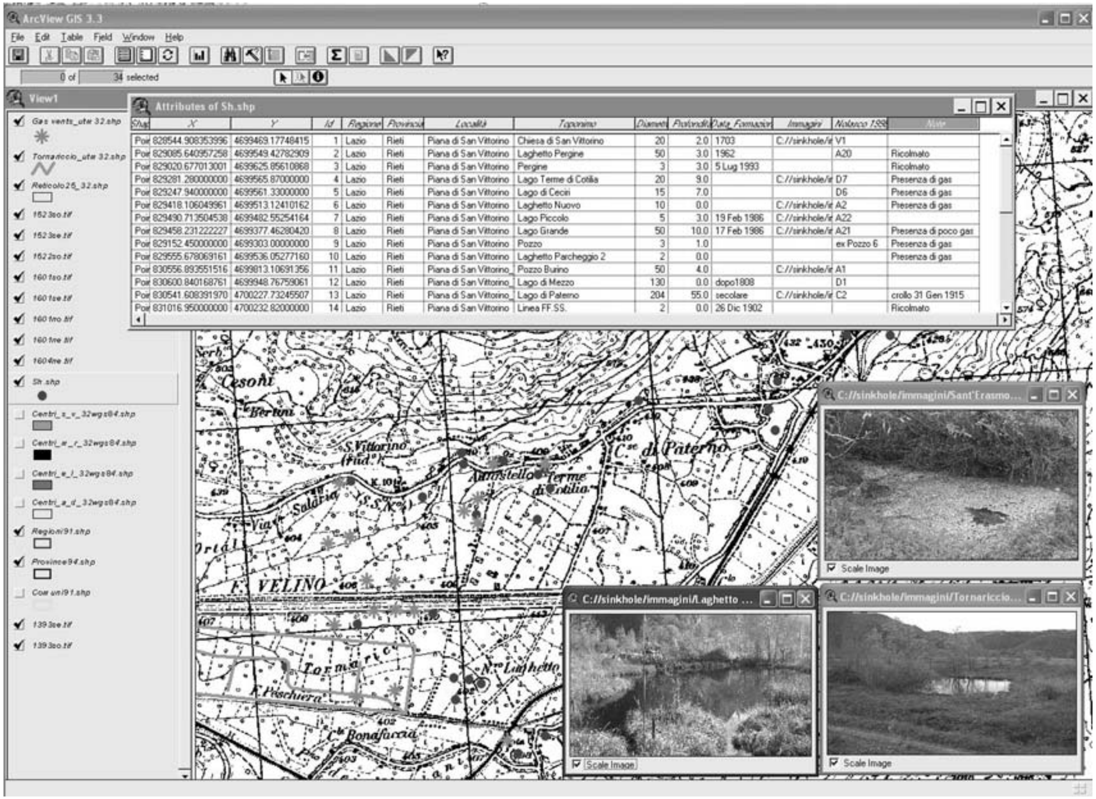


**Fig. 10** Example of the sinkhole relational database constructed in the Microsoft Access environment and used to storage information of each case (row) and for each property (column). This format for the descriptive characteristics and georeferenced numerical data for Italian sinkholes provides a dynamic and flexible structure from which information can be extracted using a simple standard database query language (SQL) to obtain tables that can be combined with geometric information according to the operator's requirements. The ESRI ArcGis program was used to organize, manage, and visualize the collected information in thematic layers

have now been used to calculate a preliminary risk map of sinkhole occurrence. This map was elaborated using the following vector geo-themes: a geo-lithological map of Italy (1:500,000) (Geological Survey of Italy), characteristics of the sedimentary cover (thickness and geotechnical characteristics), the presence of faults (capable and normal), the presence of strong earthquake (Is > 6) epicentres and mineralized springs in neighboring areas.

Three buffer distances were created around each of the sinkhole cases; this new geo-theme was combined by using the intersect function of ArcView GIS (© ESRI, Inc. 1992–2002) with the geo-lithological map of Italy to obtain a map of the main lithology of sinkhole areas. After this preliminary elaboration all the geo-themes were classified by assigning a subjective score according to the potential risk as follows:

- Sedimentary cover was classified into four classes with different geotechnical characteristics (score 1–4);
- Thickness of the sedimentary cover was considered as a Boolean value (1 and 0) for more or less than 100 m;
- Discrete distance buffers (every 1,000 m) were created around faults up to a distance of 3,000 m (score 3 to 1), the score was doubled for a capable fault;
- Discrete distance buffers (every 10,000 m) were created around earthquake epicentres (Is > 6) up to a distance of 30,000 m (score 3 to 1);
- A score was assigned to indicate the presence of different types of mineralized springs (thermo-mineral = 3; mineral = 2, and freshwater = 1) in neighboring zones.

The classified vector geo-themes were transformed into grid geo-themes and summed by using a topological overlay in ArcView GIS. The resulting grid represent sa map of the sinkhole susceptibility of central Italy in which each grid cell assumes a single score obtained by the sum of the scores of each grid geo-theme (Fig. 11). In the near future the main objective will be to consider more geo-themes and use geostatistical analysis (i.e., variography and cokriging) to elaborate the data and obtain a more-objective risk map of the sinkhole-prone areas.

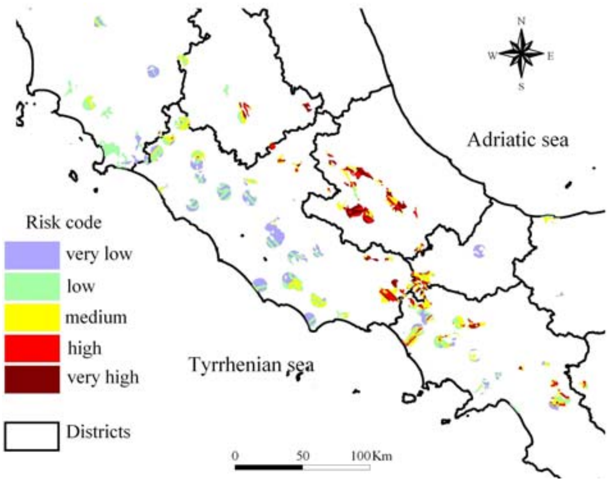


**Fig. 11** Map of the susceptibility of DPS-prone areas in central Italy. In the map each grid cell assumes a single score obtained by the sum of the scores of the considered grid geo-themes

## 8 Conclusions

Since the Roman age collapses have been reported in specific areas with gaps of tens or hundreds years between events. Obviously these phenomena have not been identified as sinkholes because of the lack of knowledge and the fact that they were confused with volcanic morphology.

In recent times several natural collapse phenomena, not related to karst dissolution, have been recognized in Italian plain areas. These areas are characterized by the presence of thick sedimentary, impermeable or semipermeable, covers (up to 100 m), overlying deep buried bedrock. This type of collapse is more widespread in Italy than was supposed before these studies.

Data obtained from specific field surveys provided useful information regarding the triggering factors and evolution of these collapses. Due to the thickness of the cover, it is not possible to correlate these phenomena to karst erosion, but a deep process produced mainly by aggressive fluids could be hypothesized. The literature and historical data coupled with field studies for some specific cases in Central Italy suggest that these cases could be related to a deep piping event with upward erosion; for this reason these collapses are called deep piping sinkhole (DPS) (Nisio 2003). The generating process of DPS is strictly related to gas-rich groundwater upwelling and watertable oscillations capable of producing upward mechanical erosion of unconsolidated or less-cohesive strata overlying the bedrock. Fractures and faults in the bedrock, crossing the quaternary cover, constitute weak points and paths for this upward erosion.

Initial results obtained from the collection of geological, structural, and hydrogeochemical data for more than 750 cases (300 with direct investigations) mainly located in plain areas allowed the identification of the geological-structural and hydrogeological setting of the DPS-prone areas in Italy.

All the investigated cases show the following characteristics:

(a) Very deep carbonatic bedrock (over 100 m).
(b) Thick cover of continental sediments of variable granularity, usually umpermeable or with very low permeability (clay, silt). From the lithological point of view these sediments are of alluvial origin with lenses of travertine; in some areas the cover is represented by unconsolidated pyroclastic deposits.
(c) Poor physicomechanic characteristics of the overlying sediments.
(d) The presence of a ressurized aquifer and high-flow springs with mineralized waters in the surrounding areas.
(e) Tectonic origin of the sinkhole-prone areas, with more than 40% of the phenomena located in intermountain valleys, other cases occuring in river valleys, coastal plains, pedemontanes belts, or small hill valleys.
(f) The presence of regional and local faults and fractures in the bedrock; most of these faults (61%) show a NW–SE orientation (Apennine trend), while other faults (20%) show a N–S trend. The rest do not show any particular trend.
(g) Fractures and diaclasis network allowing hydraulic connection between the permeable and impermeable strata.
(h) Presence of acidic ($CO_2$, $H_2S$) and fault (Rn) gases inside the cavities, and underwater springs in the flooded sinkholes.

In some cases earthquakes, floods, and human activities (i.e., drilling) have been observed to be the triggering factors for DPS. In general these collapses happen within 24 h of an earthquake but some cases were delayed by up to 30 days after the seismic event. However, strong earthquakes may trigger a collapse up to several tens of kilometres from the epicenter, instrumental magnitude events may anyway trigger collapses in restricted areas.

Not enough data is available to verify the real correlation between sinkholes and floods.

In the investigated areas of Central Italy the DPS are mainly located along the Tyrrenian margin and in some intermontane valleys of the Apennine ridge. Some cases have also been detected in the islands of Sicily and Sardinia and in the northern Apennine. In Northern Italy and in some areas of the Calabria region the geological scenario does not seem to be prone to DPS formation due to the thickness of the impermeable sediments and the presence of igneous and metamorphic bedrock.

In Sicily, Puglia, and in some areas of the Trentino, Veneto, and Friuli regions we investigated only sedimentary cover collapses, disregarding the clear karst-related collapses (dolines) that are widespread in these areas (Delle Rose and Parise 2002; Delle Rose et al. 2004). The litology affected by these collapses is mainly represented by permeable layers no more than 30 m thick, overhanging evaporitic sequences. In the same way, if there is no outcropping bedrock it is possible that these sinkholes are not related to deep piping but are merely classic karst erosion features.

The geological-structural setting of the Periadriatic belt (several hundred meters of clay and sandstones) is absolutely not prone to DPS. To date there are no reports of collapses in these areas.

In the Padana Plain along the Po river valley some subcircular ponds lie on a very thick alluvial deposit. The study of these phenomena highlights that they originate from water filling small collapses in the alluvial cover due to suffusion processes on the river banks by the water head during flooding events. In the delta area these ponds are associated with marine ingressions during high tides and storm events. This mechanism is totally different from deep piping erosion.

Field measurements and data obtained from the literature highlight a wide range of sinkholes diameters (from a few meters up to 200 m) and depths (a few meters up to 50 m); the average diameters vary from 50 to 100 m and the depths are usually shallow. The morphological ratio (diameter/depth) is between 3 and 5. Sinkholes are usually single but there are also some twin and multiple examples with either a mature or developing evolutionary state.

More than 50% of the investigated cavities are water-filled, creating small lakes or ponds. In some cases the water body is fed by underwater springs that allow the pond to be permanent. Other sinkhole ponds are recharged by shallow aquifers or streams with seasonal oscillation of the watertable. In some cases the water is mineralized (enriched in $CO_2$ and $H_2S$ as free and dissolved gases) and show high mineralization due to the presence of rising deep fluids. In other cases the collapses have been totally dry since their formation.

The results of this research suggest a first classification of six types of generating mechanisms for DPHS and a detailed description of the 10 types of DPS and the characteristic features of the surrounding areas.

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