Sinkholes in Italy: first results on the inventory and analysis

S. NISIO, G. CARAMANNA & G. CIOTOLI

APAT (Environmental Protection Agency and Technical Services), Via Curtatone, 3-00185 Roma, Italy (e-mail: stefania.nisio@apat.it)

Abstract: The Italian Geological Survey (APAT) carried out field surveys and analysis of collapse phenomena (sinkholes) in Italy. The main goal of the project is to collect geological, geomorphological, geochemical and hydrogeological data about the sinkhole-prone areas in Italy in order to develop a spatial database of the characteristics of each phenomenon. The preliminary results of this study provide information on the distribution, geological setting, and monitoring and remediation actions associated with these natural collapses in Italy. Many Italian regions are affected by these natural disasters. Some of them are caused by karst collapses or anthropic activity. However, some occur in areas characterized by buried carbonate bedrock (up to 190 m), as well as by peculiar geological–structural and geochemical scenarios. In these areas it is not reasonable to ascribe the formation mechanism to karst activity. Instead, these types of cavities quickly develop in terrains with a variable granulometry, often in connection with upwelling fluids. In this work some natural specific cases have been studied in order to define the relationships between the geology (regional tectonic elements, mineral spring waters and strong gas vents) and the genesis of the sinkholes. A first attempt of sinkhole classification is also presented.

Sinkhole definition

Collapse structures occur throughout the world and are particularly common in the USA (California and Florida), where they constitute a significant hazard owing to their unpredictability and the fact that it is difficult to avoid resultant damage (Newton 1984, 1986; Beck & Jenkins 1986; Sinclair & Steward 1985; Snyder *et al.* 1989). These natural processes are generally more important whereas anthropogenic causes are typically secondary, although it should be noted that the number of cases of collapse-structure formation has increased worldwide over the last 20 years, probably owing to urban expansion (Sinclair 1982; Newton 1984, 1986; Tihansky & Galloway 2000).

In the last few years the term *sinkhole* has been used often to indicate collapse phenomena of various natures; however, this has created confusion, particularly in the different usages of the term in the Italian literature v. English literature. Such a term defines a subcircular surface depression or collapse structure formed by the collapse of small subterranean karst cavities (Fairbridge 1968; Monroe 1970). This definition is synonymous of doline, which includes various genetic subtypes such as solution, collapse or subsidence sinkholes or dolines (Sweeting 1972; Jennings 1985; Castiglioni 1986). At present in the United States and Great Britain the term sinkhole is frequently used to define any subcircular cavity regardless of genetic origin (Beck 1984; Beck & Wilson 1987); the term is also used to indicate open cavities caused by anthropogenic activities that are not necessarily subcircular in form.

In Italy the term sinkhole is used to indicate a subcircular cavity that opens suddenly on the surface and is used as a synonym of collapse. A collapse is a rapidly formed depression of variable shape, even if typically subcircular, which occurs primarily in karst terrains, in plains and in areas where subterranean cavities already exist. Sudden collapses are also defined as those events that are not directly linked to karst phenomena, such as subterranean cavities formed by anthropogenic activities in urban areas, above mines, excavations and ancient catacombs.

Of the investigated sinkholes *senso stricto* 38% are filled with water, thereby forming small lakes or ponds. As this water can often be mineralized, it is not surprising that they can occur in correspondence with mineralized springs and are often aligned along tectonic lineaments that are stressed by the presence of water and gas chemical anomalies.

The formation of sinkholes can occur during a single event or with the slow and progressive collapse of the structure. In the first case the subsurface is affected by a single conduit and the cavity maintains a relatively constant dimension over time. In the second case the sinkhole develops with the slow washing away of the sediments from the base to the top of the cavity. It has been shown that the majority of the sinkholes are caused by upward erosion (Littlefield *et al.* 1984; Derbyshire & Mellors 1988; Derbyshire *et al.* 1991; Billiard *et al.* 1992; Faccenna *et al.* 1993; Muxart *et al.* 1994; Nisio 2003). *Deep piping* phenomena are probably originated by this process (Nisio 2003).

From: PARISE, M. & GUNN, J. (eds) *Natural and Anthropogenic Hazards in Karst Areas: Recognition, Analysis and Mitigation*. Geological Society, London, Special Publications, **279**, 23–45. DOI: 10.1144/SP279.4

The deep piping process is a mechanical effect due to the upward flow of groundwater in granular rocks (from clay to gravel-sized particles) that occurs when the deposit is fractured or porous and when the water is under high pressure in a flow path in which high groundwater velocities (turbulence) are maintained. The flow of water results in the erosion of material and the formation of conduits (pipes) (Massari *et al.* 2001; Nisio 2003).

Many Italian regions are affected by these natural collapses, but some of these seem to be karst collapses and some are caused by anthropic activity. However, some sinkholes occur in areas characterized by a deep buried carbonate substratum (up to 170 m), as well as in areas where peculiar geological–structural, hydrogeological and geochemical settings facilitate sinkhole formation. In these areas it is not reasonable to ascribe the formation mechanism of these sinkholes to the mere gravity collapse of a karst cavity, but some other triggering and prone factors should be considered.

The Italian Geological Survey – APAT (National Agency for Environmental Protection and Technical Services) – carried out studies and field surveys on collapse phenomena occurring in sinkhole plains in Italy in the framework of the Sinkhole Project. In this work some natural specific cases were studied in order to define the relationships between the typical geological scenario (regional tectonic elements, mineral springs and strong gas vents) and the genesis of sinkholes. The main goal of the project is to collect geological, geomorphological, geochemical and hydrogeological data about the sinkhole-prone areas to construct a sinkhole hazard map in Italy. A Microsoft Access relational database (RDB) was designed to store, analyse and map the sinkhole-prone areas in Italy. The database (SH-RDB) includes geological, hydrogeological, geochemical and geotechnical data about known sinkhole collapses in Italy. The goal of the sinkhole database project is to provide easy access to sinkhole data via data query and reporting options. A geographical information system (GIS) was used to create thematic maps and to analyse the data.

This paper reports the first results of the Sinkhole Project on the distribution, classification and evolution of sinkholes in Italy. In addition, preliminary results of selected case studies help to reveal the geological setting.

Sinkhole classification

Classification of karst features can be based on genetic mechanisms; our aim is to clarify the genetic mechanism of collapse triggering and to present a general classification of the phenomena. This first attempt of classification considers the genesis of cavities that show similar morphological characteristics but that originate from very dissimilar genetic mechanisms.

Doline is a term derived from the Slav word ‘dol’ that means valley; these were the most common hollows in the landscape of the Dinaric karst. The term refers to natural enclosed depressions found in karst landscapes (Cramer 1941; Sweeting 1972; Castiglioni 1986; Ford & Williams 1989 and many others), principally owing to chemical dissolution of calcareous deposits. Dolines are also sometimes known as sinkholes.

In a strict sense, the term sinkhole in Italy and sometimes in Europe indicates a topographic cavity of various shapes, mainly subcircular, caused by a quick collapse of the soil surface. The origin of a sinkhole, again in the strict sense, is not necessarily related to karst phenomena. Other factors can contribute to the genesis. For this reason the terms doline and sinkhole are not synonymous. Indeed, the international terminology can be very confusing. Hence, in order to avoid the ambiguity that sometimes arises in the general use of these terms, further qualification is required such as ‘solution sinkhole’ or ‘collapse sinkhole’. Table 1 lists the terms used by different authors and the extent to which genetic types are subdivided.

According to the main genetic processes, collapse phenomena can be subdivided into the following groups: (1) anthropogenic sinkhole; (2) karst phenomena; and (3) sinkhole *sensu stricto* or deep piping sinkhole (Nisio 2003; Nisio & Salvati 2004) (Fig. 1). It is widely recognized that enclosed depressions can be formed by four main mechanisms: dissolution, collapse, deep piping and subsidence.

Anthropogenic sinkhole

Anthropogenic sinkholes are caused by the collapse of the roof of an artificial underground cavity (i.e. mining, catacombs, etc.).

Karst phenomena

A genetic subdivision of the karst phenomena is based on the mechanisms that cause cavities in the shallow environment. Such mechanisms consist of: (a) collapse; (b) subsidence; and (c) dissolution mechanisms.

Collapse doline/sinkhole. These depressions formed mainly by mechanical processes. This fact may cause a considerable variation in nomenclature largely owing to the variety of materials and processes involved, and the tendency of some authors to group types and/or to subdivide types (Fig. 1, Table 2). Collapses refer to rapid downward

Table 1. *Sinkhole terminology**

Definition	Main genetic processes	Sedimentological setting	Morphology
Solution sinkhole/doline	Chemical dissolution of karst bedrock	Outcrops of carbonate/evaporitic rocks	Enclosed depression funnel-shaped with a flat bottom. Thin cover of red soil
Subsidence sinkhole, cover-subsidence sinkhole, cover sinkhole	Subsurficial dissolution or collapse of karst voids in the underlying rocks	Karst carbonatic bedrock with non-consolidated cover (i.e. sand, gravel).	Topographic depression with dimension of some tens of metres both in diameter and depth
Collapse/cave-collapse sinkhole, collapse doline	Collapse of the roof of caves	Karst cave overlain by lithoids deposits (i.e. tuff, limestone, travertine)	Deep sinkholes with steep walls and truncated cone vertical shape
Rock-subsidence sinkhole, subsidence doline	Collapse on cohesive, permeable and non-soluble rocks placed over soluble sediments	Karst cave overlain by cohesive deposits (i.e. clay, silt)	Funnel-shaped sinkholes
Piping sinkhole, cover-collapse sinkhole	Upwelling of water and gases with a piping process followed by the collapse of the soil	Sediments of different granulometry and less cohesive	Variable shape from smooth depression to steep sinkholes

*Terms used to describe the sinkholes, the main genetic processes, the sedimentological setting and the morphology (partly taken from Gunn 2004).

movement of the ground, whereas subsidence refers to gradual movement sometimes without even ripping the surface. These processes can occur in karst bedrock (collapse doline or collapse sinkhole: Tharp 1997, 1999; Capelli *et al.* 2001; Salvati *et al.* 2001). They can be subdivided into *cave (or cap-rock)-collapse doline or sinkhole* and, where unconsolidated sediments overlie the bedrock, into *cover-collapse doline or sinkhole*. In all cases, the collapse could be preceded by dissolution of the karst rock to form a void into which material can fall.

A cave-collapse doline or sinkhole is a well-shaped cavity in limestone and karst rocks. The karst cave must be overlain by rock (i.e. tuff, limestone or travertine) and the formation follows the collapse of the cave roof (Cramer 1941; Castiglioni 1986; Ford & Williams 1989). The trigger of the collapse is a progressive thinning of the roof of the cave followed by the failure of the overlying rock. This kind of catastrophic subsidence is often characterized by a large bell-shaped cavity and the absence of premonitory signs. The cover-collapse sinkhole or doline has a thin cover of permeable sediments (20–30 m of sand or gravel). It is promoted by the infiltration of surface water, and the cavity originates by the collapse of the roof of the underlain karst void. Sometimes a collapse extends from a cave below the water-table level; many sinkholes host small ponds.

Subsidence doline/sinkhole. Depressions caused by cover subsidence are called *subsidence dolines*. They can be subdivided into *rock-subsidence dolines/sinkholes* and *cover-subsidence dolines/sinkholes* (Fig. 1).

These landforms originate in unconsolidated deposits such as alluvium, glacial moraine, loess, sands, etc. The sedimentary cover slowly filters downward into the underlying karst voids through corrosionally enlarged fractures and results in gradual subsidence of the surface. The main process involves the gradual winnowing and down-washing (ravelling) of fine sediments by a combination of physical and chemical processes.

Rock-subsidence doline/sinkholes occur in soluble rocks with a thin cover of permeable sediments. The fracturated, soluble rock slowly settles without any surface evidence. The result is a bowl-shaped landform (Castiglioni 1986).

Cover-subsidence dolines/sinkholes are closed depressions in non-cohesive cover sediments (i.e. alluvial deposits), and are caused by the presence of karst voids in the underlying rocks (Castiglioni 1986). The triggering of this process is strictly correlated with the permeability of the materials and the thickness of the cover deposits (Newton 1984, 1986). The evolution of this type of collapse is typically progressive, with final dimensions of some tens of metres in diameter and shallow depth.

Solution doline/sinkhole. Shallow morphologies without collapse structures are called *solution dolines/sinkholes* and are caused by rock dissolution by infiltrating water (Cramer 1941; Castiglioni 1986). The bowl-shaped form of this landform

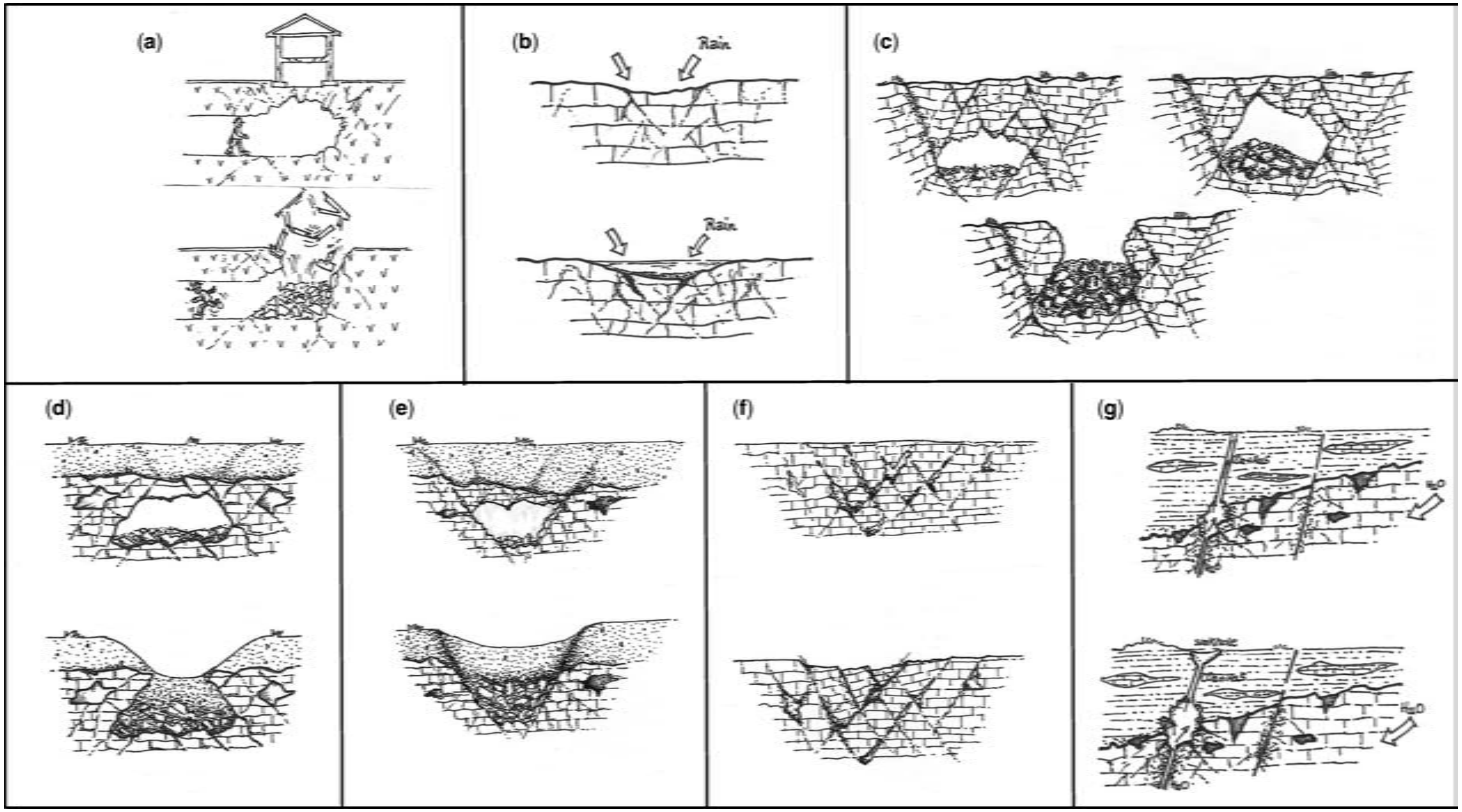


Fig. 1. Sinkhole classification according to literature information and field observations of Italian case studies. (**a**) Anthropogenic sinkhole; (**b**) solution doline/sinkhole; (**c**) cave collapse; (**d**) cover collapse; (**e**) cover subsidence; (**f**) rock subsidence; and (**g**) piping sinkhole.

Table 2. *Sinkhole genetic processes terminology**

Genetic process	Ford & Williams (1989)	White (1988)	Culshaw & Waltham (1987)	Beck & Sinclair (1986)	Jennings (1985)	Bogli (1980)	Sweeting (1972)	Other terms
Dissolution collapse	Solution collapse	Solution collapse	Solution collapse	Solution collapse	Solution collapse	Solution collapse (fast) Subsidence (slow)	Solution collapse	
Cap-rock collapse	Collapse	Collapse	Collapse	Collapse	Subjacent collapse	Collapse (fast) Subsidence (slow)	Collapse	Interstratal collapse
Dropout	Collapse	Cover collapse	Subsidence	Cover collapse	Subsidence	Alluvial	Alluvial	
Suffusion	Suffusion	Cover subsidence	Subsidence	Cover subsidence	Subsidence	Alluvial	Alluvial	Ravelled sinkhole
Burial			Buried					Filled sinkhole Palaeo-sinkhole
Water filling								Drowning

*Sinkhole terms used by various authors related to the genetic process (modified after Waltham & Fookes 2003).

indicates that more material has been removed from its centre than from around its margins. The amount of limestone that can be removed in solution depends upon two variables: the concentration of the solute; and the volume of the solvent (i.e. the amount of water draining through the doline). Variations in either or both of these quantities could be responsible of dissolution near the centre of the depression. The development of this type of doline depends on the ability of water to sink into and flow through karst rocks to outlet springs. The exposure of limestone by erosion provides a boundary for the infiltration of water. These landforms develop slowly without catastrophic subsidence, so they cannot be associated with the sinkhole phenomena.

Sinkhole sensu stricto *or deep piping sinkhole*

The main causes of the *sensu stricto* or deep piping sinkholes are complex and interacting. They can be genetically subdivided into the following categories (Faccenna *et al.* 1993; Nisio 2003).

- Soluble substrate (carbonates, evaporites or sulphate-rich rocks) affected by karst phenomena. The presence of small- or large-scale irregular bedrock morphology with karst macroforms and with karst cavities in the upper substratum (soil–rock interface) results in corrosive and dissolution processes.
- Impermeable or semi-permeable sediments that overlay the bedrock.
- Weak physical–mechanical characteristics of the materials in the upper cover.
- Presence of a network of faults or fractures that allow elevated groundwater circulation and mechanical erosion.
- High groundwater flow and recharge rates.
- The presence of acidic gases, such as CO_2 and H_2S, which dissolve into the groundwater, thereby increasing dissolution rates of the surrounding material.

Recognized triggering mechanisms for surface collapse include loading (such as construction), wetting (intense rainfalls, snowmelt), drying (droughts) and shaking (earthquakes; Snyder *et al.* 1989; Ferreli *et al.* 2004).

The terms sinkhole or deep piping sinkhole should be used with care owing to the great complexity of the phenomenon. Thus, we propose the following nomenclature.

- Deep piping sinkhole: This type of sinkhole occurs in areas characterized by mineralized groundwater with bubbling phenomena caused by the high concentrations of free and dissolved gases. The deep piping process is a mechanical effect caused by the flow of groundwater in fractured or porous granular rocks (from clay to gravel-sized particles) with abundant, high pressurized waters (Fig. 1). In this process a flow path with high groundwater velocities results in the erosion of material and the formation of channels. Furthermore, the presence of fault and fracture systems acts as route for the migration of deep acidic fluids. Mineral springs and/or gas vents enriched in CO_2 and H_2S, which dissolve and/or pass into the groundwater and make it more aggressive, have been recognized inside and/or close to the cavities. This phenomenon is also referred to as *deep suffusion* or *deep piping* (Nisio 2003; Graciotti *et al*. 2004; Nisio *et al.* 2004).

The geological model for a deep piping sinkhole requires the presence of a thick layer of cover deposits (up to 200 m) overlying a karst bedrock. Usually these sediments are alluvial deposits with vertical and horizontal granulometrical variations. The presence of a cover of clay deposits prevents deep deformations and the possibility that a cave collapse in the bedrock could create a sinkhole *sensu stricto* on the surface by ravelling processes. In the presented case studies, no signs of water flow from the surface to the underground occur. Instead, the water head can reach the soil level, and for this reason the presence of a spring in the cavity is possible (some authors define this type of sinkhole as a *spring sinkhole*). The presence of karst materials (i.e. travertine, limestone gravel) inside the cover deposits enhances the deep piping sinkhole formation.

Collapses suspected to be sinkholes *sensu stricto* have been widely reported from central Italy (from Tuscany to the Campania region). The majority of these cases seem to have a common genesis. They occur in groundwater discharge areas near the base of karst ridges in zones with major groundwater circulation. Thick overburden and proximity to a deep gas source and/or thermal upwelling is also present (Ciotoli *et al.* 2001; Annunziatellis *et al.* 2004). The occurrence of such sinkholes within a discharge zone is difficult to reconcile with the traditional conceptual model for two reasons. First, there is no downward moving water that could cause ravelling processes. Second, the upwelling acidic groundwaters have been in contact with limestone for long periods and, generally, these groundwaters are near $CaCO_3$ saturation. This limits the mechanism for creation of voids within the bedrock (Salvati *et al.* 2001; Salvati & Sasowsky 2002). In addition, caves occur within the cover sediments, as additional material is removed to create a substantial void in the cover material. Often the arch in the cover terrain will no longer support the overlying material, and the void propagates upwards until the shear stress becomes greater than the cohesion of the cover material. In these settings, the rising of pressurized and acidic fluids (gases and water) is the main factor of the deep piping sinkhole genesis. The upwelling of groundwaters is controlled by the presence of deep faults, which act as the main pathways for the deep fluids.

- Collapse piping sinkhole: This type of sinkhole differs from deep piping sinkholes for the following reasons: (1) It requires the presence of an unconsolidated cover sediment (i.e. pyroclastic deposits, gravel, sands, etc., with thicknesses of up to 100 m). (2) The carbonatic bedrock hosts a confined aquifer. In high recharge periods the aquifer should be pressurized with a strong increase of the water head that does not, however, reach the soil level. (3) Deep piping mechanisms act on the interface between the bedrock and the cover sediments. A cylindrical-shaped cavity forms along a fracture or fault in the lower sedimentary cover and propagates towards the surface. When the roof reaches a thickness that cannot support acting shear stresses, it collapses quickly. In the major part of the observed cases the cavities are dry. These sinkholes occur diffusely in volcanic areas of the Latium and Campania regions.

From the study of more than 500 natural sinkholes it is possible to suggest a specific classification for the Italian sinkholes. This classification is based on genetic mechanisms and on other factors affecting the sinkhole genesis: the lithology of the sedimentary cover and of the bedrock, the depth to the bedrock, and the geological and morphological setting of the sinkhole-prone areas. The sinkholes *sensu stricto* (or supposed to be sinkholes *sensu stricto*) are clustered into 10 different types. It should be noted that research is ongoing and that these are preliminary results.

Sinkhole evolution

Sinkholes are not ‘static’ features of the landscape. These phenomena are subjected to a sort of evolution with modification of the morphology, increasing or decreasing of the diameter, flooding and displacement. Figure 2 shows the main types of sinkhole evolution recognized in Italy.

Drowning

The drowning process affects sinkholes in areas where the table water is close to the soil surface.

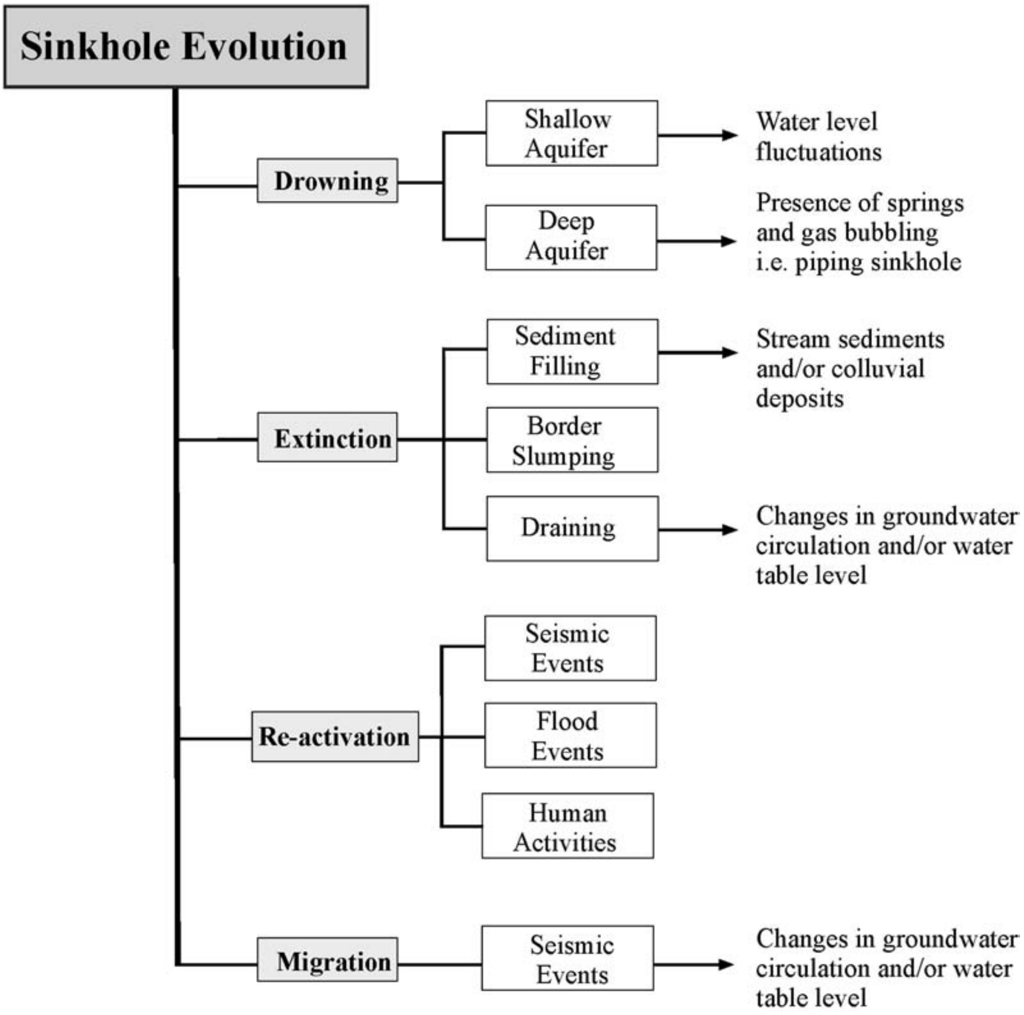


Fig. 2. Flow chart of sinkhole evolution.

In these zones, the formed subcircular depressions often contain small lakes or ponds. This phenomenon generally represents the first stage of sinkhole evolution (Caramanna *et al.* 2004, 2005; Nisio *et al.* 2004). Under such conditions, water levels may be affected by seasonal fluctuations caused by rain and/or by the presence of a water outlet. In some cases, fluctuations of the water surface are not recognized, but gas emissions and stream outflow from the pond may occur; this suggests the presence of a spring on the bottom of the lake fed by the deep aquifer.

These lakes are often characterized by bubbling phenomena caused by deep-origin gases (CO_2, H_2S, H_2, He) that rise along crustal discontinuities. The presence of acidic gases (CO_2 and H_2S), which dissolve into the groundwater, can cause dissolution and weakening of the supporting bedrock, travertine and other carbonate-rich sediments in particular. Carbonate dissolution combined with the siphoning off of fine particles results in a loss of structural integrity and subsequent collapse. The deep origin of the fluids has been verified by chemical analyses of the dissolved gases in the water filling the sinkholes (Ciotoli *et al.* 2001).

Extinction

Several years after formation, a sinkhole cavity could become dry and be filled by sediments until the depression is no longer visible on surface.

Some hypotheses may be advanced regarding the sinkhole extinction:

- filling with stream sediments and/or with colluvial material from range fronts (i.e. Lago Puzzo, Rome or Lago di Caira, Cassino);
- slumping of the sinkhole borders, which increases the diameter and simultaneously causes the filling of the cavity with the collapsed material;
- draining of the sinkhole caused by changes in groundwater circulation and/or water-table level, for example induced by seismic events.

Re-activation

Extinct sinkholes may be re-opened in the same location or undergo a sudden collapse that causes dimensional changes. Sinkhole re-activation may be caused by the conditions that caused the original collapse (seismic events, human activities, flood events, etc.).

The extinct sinkholes can be re-opened in the same position with the same shape or the morphology can change (i.e. variation of diameter and depth). For example, the Lago Puzzo re-opened in 1930 with a wider diameter following some phreatic explosions with gas emissions. The New Lake in the S. Vittorino Plain (Rieti, central Italy) formed in 1891 and underwent several cyclic re-activations from 1902 to 1930. The lake of Pra di Lama (Pieve Fosciana–Lucca, northern Italy) re-opened in 1828 after an earthquake in the same position of a thermal spring used for a health spa. On 15 August 1828 at 11 a.m. several bangs, along with gas and mud emissions, preceded a collapse. The resultant lake was 11 m deep with a diameter of 40 m. In 1842 it was almost totally dry and filled.

Migration

Sometimes extinguished sinkholes could re-open in a shifted position. This is called ‘migration’. The causes of this displacement and of the possible preferential direction are still under study. For example, the collapses formed in the Fosso S. Martino, north of Rome, show a southern trend of migration according to a north–south-oriented tectonic discontinuity. In the Pontina Plain (central Latium) four sinkholes called ‘Sprofondi’ (Collapses) show a northward migration of the collapses along a SE–NW direction. In the S. Vittorino Plain a slow migration of sinkholes, showing southern and western trends from the carbonatic chain of Paterno Mt towards the western section of the plain, has been highlighted. Whether or not these cases indicate a real migration is still not clear (Centamore & Nisio 2002, 2003; Annunziatellis *et al.* 2004; Centamore *et al.* 2004; Nisio *et al.* 2004). Otherwise, the sinkholes’ migration should be explained by the modification of the upwelling paths of fluids caused by seismic events and master fault re-activation (i.e. Fiamignano–Micciani fault in the S. Vittorino Plain) (Annunziatellis *et al.* 2004).

Data presentation

The goal of the Sinkhole Project is to map and study sinkhole *senso stricto* in Italy.

This census considered only collapses located in plain areas characterized by thick sedimentary covers and without bedrock cropping out. Some of investigated cases, of doubtful origins, were shown to be karst-related phenomena or anthropogenic collapses (see Fig. 5b late). Less than 50% of the analysed cases could be considered deep piping sinkholes. The first part of the project focused on the development of a bibliography of national and international literature on Italian sinkholes. In addition, historical data on particular sinkholes were collected to determine their formation date and their geostructural boundary conditions.

Actually more than 550 sinkholes, excluding those of anthropic and/or karst origin, have been investigated in the field in different geological scenarios of Italy (Fig. 3).

Multi-scaling and multi-temporal analysis of aerial photographs of the sinkhole-prone areas allowed the recognition of their morphotectonic features. This analysis integrated field data and facilitated the improvement of geological and geomorphological maps. Geological, structural and geomorphological field surveys were then conducted in order to verify the results obtained from photographic analysis, in particular to identify the thickness of the sedimentary cover above the bedrock, as well as the main tectonic elements that could trigger and affect the evolution of the collapses. Field hydrogeological and hydrogeochemical surveys were carried out to characterize hydrogeological boundary conditions (i.e. depth of water table, spring flow, etc.), as well as physicochemical and hydrochemical parameters of the fresh water and mineral springs, and of the water filling the collapsed areas (see Table 3). The depressions containing small lakes or ponds were investigated using a small inflatable boat equipped with a digital ecosounder in order to map the morphology of the bottom. The data were managed using a geographic information system (GIS). The Relational Database Systems Theory (RDST) provides rules for organizing representing phenomena as collections of attributes stored in tables so that a specific set of procedures can associate, transform and extract information from the

Fig. 3. Sinkhole distribution in Italy using the GIS database. ⊙ Sinkhole.

tables in a reliable way (Fig. 4). 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 stored about that set of entities.

Sinkholes are not isolated phenomena; usually these collapses are clustered or aligned along specific paths. The 555 studied sinkholes are found in 138 sinkhole-prone areas. Some areas are characterized by more than 30 collapses, in other areas only two or three sinkholes occur.

Excluding sinkholes located in northern Italy that are not yet part of this study, sinkholes *sensu stricto* are primarily concentrated along the Tyrrhenian margin near carbonate ridges in complex geological and hydrogeological scenarios.

Other collapses are located in Sicily, in Puglia and in northern Italy, in areas characterized by a widespread presence of evaporitic rocks. However, this census focused only on those cases that, due to the thickness of the cover sediments on the evaporitic bedrock, could be related to an upwards erosion. Collapses clearly related to karst phenomena have not been considered in this inventory.

The presence of regional faults with associated fractures, acting as preferential pathways for deep gas (i.e. CO_2 and H_2S) migration, has been recognized in many cases.

In this paper, the distribution of sinkholes in Italy with respect to the characteristics of the geological scenarios (i.e. fluvial, coastal and intermountain plains) has been evaluated. Cases with similar geological (substratum depth, sedimentary cover, presence of regional fault systems) and geochemical (mineral spring, presence of dissolved and free acidic gases, low pH, etc.) characteristics were identified, and clustered into five main recognized morphological scenarios. Figure 5a–d shows pie charts representing the distribution of the collapses in Italy, the collapse type, the morphological scenarios and the type of the sedimentary cover in which collapses occur. It is worth noting that about 58% of the sinkholes occur in central-southern Italy (Latium, 24.5%; Abruzzo, 13.2%; Campania 12.4%; Tuscany, 7.9%; Fig. 5). A high percentage of cases occurring in the Emilia Romagna and Friuli Venezia Giulia are based on historical information and/or reports. The piping and collapse piping sinkholes are the most frequently occurring types (37.1 and 33.3%, respectively) in alluvial and intermountain (seismically active) plains, at 28.1 and 32.6%, respectively. These plains (about 50% of the total database) are characterized by the presence of alluvial sediments, mainly clay and sandy-clay. These data have been registered in a data sheet subsequently used to construct the GIS database. A brief description of some selected case studies follows.

Sinkholes in fluvial plains

Aterno valley. The Aterno River valley, located in Abruzzo (central Italy), shows a general Apennine trend (NW–SE), with a straight-line path, that in the northern sector changes its direction to a NE–SW trend (Fig. 6). The valley is bordered by mountain slopes characterized by young tectonic activity (i.e. triangular facets) that highlights that this tectonic valley is bordered by a regional master fault with several reactivations up until the Pleistocene.

Five sinkhole-prone areas are located along the Apennine trending section (NW–SE) of the Aterno River within a distance of few tens of kilometres: (1) the northern area is around the village of Pizzoli; (2) the central section of the valley is the area around the S. Gregorio and Civita villages; (3) south of the central section is the third area (Demetrio nei Vestini); (4) south of this area is the Raiano–Prezze villages area; and (5) the fifth area is enclosed in the Sulmona Plain.

A total of 35 sinkholes have been individuated along the Aterno River: three close to Pizzoli; four in the S. Gregorio–Civita area; 11 in the Demetrio nei Vestini area; 10 near Raiano–Prezze; and seven in the Sulmona Plain.

The diameters of the sinkholes range from 30 to 40 m in the first area, with an enlargement trend in the central area of the river valley (up to several hundreds of metres). In the Raiano–Prezze and Sulmona Plain the diameters reach 50–100 m.

All phenomena are many centuries old. The Quaglia lake lies in the Raiano area. The origin of this pond seems to be correlated, from popular legends, with an earthquake in 1456 (in December of this year a strong earthquake affected central and southern Italy). The origin is probably correlated with the earthquake of the Maiella Mountain. In the same year other sinkholes probably also collapsed.

In the first area, on the left-hand side of the river, a NE–SW direct fault (Arischia–S. Pelino fault), SW dipping, occurs. The fault slope with 1.200 m of dip-slip, is highly tectonized. The right-hand side of the valley also shows structural evidence of active tectonics. The carbonatic bedrock, lowered by faults, lies more than 100 m below the cover sediments. These deposits are mainly composed of gravels and sands of various sizes.

The study area is located on the fluvial–alluvial deposits of the Aterno River near the village of San Vittorino (Fig. 6). In this zone two subcircular shaped ponds (Podere Giorgio 1 and Podere Giorgio 2) were recognized. A third irregularly shaped pond occurs close to the main road near the bridge ‘Tre occhi’. The geological and structural setting of the area and the morphology of the ponds

Table 3. *Water chemistry**

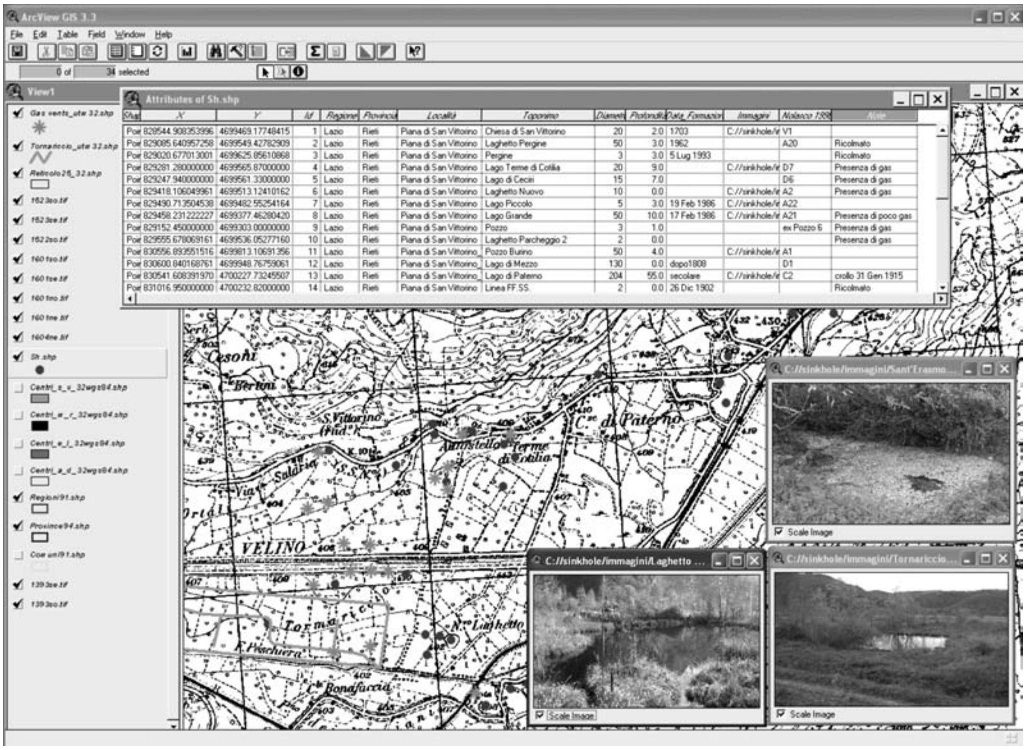
ID	Ca^{2+} (mg l^{-1})	Mg^{2+} (mg l^{-1})	Na^{+} (mg l^{-1})	K^{+} (mg l^{-1})	HCO_3^- (mg l^{-1})	SO_4^{2-} (mg l^{-1})	Cl^- (mg l^{-1})	NO_3^- (mg l^{-1})	DO (mg l^{-1})	TDS (mg l^{-1})	Conductivity (μS cm^{-1})	pH	Eh (mV)	Temp. (°C)	County
1	420	98.8	12.58	10.61	228.2	1303	27	2.74		2112	2130	7.42	309	17	Tuscany
2	439.2	123.4	12.04	2.63	212.3	1378	18.76	2.68		2188	2090	7.57	244	21.5	Tuscany
3	432	113.4	12.65	2.35	196.5	1366	19.02	2.57		2144	2150	7.51	134	21.3	Tuscany
4	431.6	109	12.15	2.02	200.1	1272	18.97	2.49		2049	2160	7.55	241	16.7	Tuscany
5	457	100.8	12.8	2.29	228.4	1384	18.7	2.63		2206	2180	6.98	137	21.3	Tuscany
6	454	114.8	10.47	2.71	255.1	1344	16.05	3		2199	2200	6.75	231	22	Tuscany
7	71.35	8.24	6.41	1.33	298.5	6.12	8.82	6.25		342.2	394	8.17	237	14	Abruzzo
8	28.5	5.5	16.8	10.7	183	5.85	15.2	2.9		232	279	7.49		15.3	Campania
9	17.73	3.97	9.23	9.99	143.6	0.31	10.22	2.08		151	194	6.54	202	17	Campania
10	79.95	7.67	6.17	11.65	452.4	3.74	9.16	8.41		400	465	6.56	270	17.4	Abruzzo
11	82.1	13	3.17	1.5	279.5	30.5	4.79	3.8		418	479	7.1		7.5	Abruzzo
12	145	19	6	4.2	358.8	130	13.9	11.8		688	825	7.29		9.6	Abruzzo
13	111.9	32.3	15	5.7	407.6	43.5	34	0.3		655	757	7.37		9.1	Abruzzo
14	113	5.54	5.99	0.96	430	7.9	8.6	2		429	600	7.16			Abruzzo
15	46.88	7.7	7.61	1.73	234.7	6.15	10.3	3.63		245	316	6.73	213	18.3	Abruzzo
16	97.2	2.3	5.5	0.72	270.9	8.2	19	18.3		171	468	7.94		10.4	Abruzzo
17	21.63	12.47	2.24	0.57	134.2	4.54	3.04	3.05	6.96	299	586	7.46	192	18	Latium
18	25.42	14.64	21	8.56	195.3	5.26	14.94	0	3.48	284	361	8.46	114	28.3	Latium
19	160.8	74	325	15.15	453.6	172.8	546	1.29	3.07	1747	2300	7.91	125	26.2	Latium
20	23.3	12.96	2.06	0.54	122	4.54	2.91	2.8	5.86	171	603	7.14	216	17.8	Latium
21	65.55	1.3	1.75	8.89	211.1	0	5.94	5.1		299	351	7.12	253	17.6	Abruzzo
22	25.04	13.09	2.17	0.55	134.2	5.63	2.95	2.56	4.85	186	584	7.09	210	19.3	Latium
23	83.45	13.05	2.33	0.58	439.3	4.38	3.05	2.5	3.67	548	558	7.09	195	15	Latium
24	107.8	24.51	7.41	2.93	457.6	53.24	10.86	0	3.55	662	761	7.75	139	27.1	Latium
25	134.5	38.1	80.8	5.15	456.3	47.74	136.7	7.87	3.41	695	1162	8.06	128	27.3	Latium
26	38.09	12.51	2.19	0.71	197.8	4.5	3.09	3.06	6.99	210	596	7.08	210	18.4	Latium
27	33.08	9.73	16.63	7.16	804.6	2.26	18.39	51		235	355	5.56	247	22	Campania
28	132.7	37.8	117	11.15	530.9	63.95	207.4	0	3.66	1098	1432	7.69	163	27	Latium
29	87.3	26.9	64.1	4.42	366.1	28.3	117.7	4.6	2.41	697	907	7.32	148	26.2	Latium
30	41.6	15.7	11.58	5	241	1.25	18.51	0	3.68	695	400	8.32	154	28.5	Latium
31	46.28	27.88	22.83	6.24	264.8	11.19	33.14	0		333	498	7.03	218	20	Campania
32	35.79	9.36	15.22	4.9	243.4	4.81	13.3	0.5		332	268	6.82	218	18	Campania
33	19.84	34.78	4.48	0.12	231.9	9.7	6.42	8.67	4.94	269	543	7.06	188	17.5	Latium
34	126.2	21.5	152.3	6.72	122	218.7	230.4	11.6		934.6	1233	6.66	146	4	Tuscany
35	585	127	1230	5.16	281	1899	1824	0		5996	7910	6.66	−30	32.4	Tuscany
36	41.9	11.9	28.5	1.82	171	42.5	22.42	3.64		256	358	7.66	107	8.6	Tuscany

(*Continued*)

Table 3. *Continued*

ID	Ca^{2+} (mg l^{-1})	Mg^{2+} (mg l^{-1})	Na^{+} (mg l^{-1})	K^{+} (mg l^{-1})	HCO_3^- (mg l^{-1})	SO_4^{2-} (mg l^{-1})	Cl^- (mg l^{-1})	NO_3^- (mg l^{-1})	DO (mg l^{-1})	TDS (mg l^{-1})	Conductivity (μS cm^{-1})	pH	Eh (mV)	Temp. (°C)	County
37	112.3	23.5	28.9	5.64	153	227.2	53.11	10.9		522	730	7.2	107	10.4	Tuscany
38	60.1	13.3	54.4	2.7	195	45.3	79.5	15		424.7	594	7.29	121	10.9	Tuscany
39	123.9	256	5.25	2.6	366	6.76	8.7	12.2		407.6	570	6.93	122	11	Abruzzo
40	144.8	103.5	477.1	24.8	301.4	484	727	1.9		2880	3800	9.2		18	Sicily
41	261.5	237	1178	106	368.6	1219	1873			6163	8130	9.2		18	Sicily
42	346.5	43.67	10.85	1.18	1003	83.2	14.98	0.18	5.62	1868	1190	6.3		18	Latium
43	448	70.5	20.4	3.63	2043	240.8	30.19		0.47	2257	2400	6.13	−268	14.4	Latium
44	427	65	17.85	3.36	1537	207.5	25.29	0.07	0.29	2287	2270	6.47	117	14	Latium
45	339.5	50.67	13.73	2.09	1220	140.2	19.15		1.82	1788	1670	6.17	−212	12.9	Latium
46	162.3	24.2	3.65	0.96	634.4	38.36	5.02	1.82	6.36	870.9	936	6.97	262	13.3	Latium
47	353.8	54.5	11.44	2.16	1293	123.8	14.59	0.27	0.43	1857	1867	6.16	−159	13.8	Latium
48	410	59.5	14.69	2.68	1513	156.1	20.7	0.15	0.35	2180	2150	6.08	−1	13.9	Latium
49	551	88.5	26.52	5.26	2062	226	36.53	0.08	0.34	3001	2820	6.23	241	14.3	Latium
50	357.5	48.5	5.11	1.17	1293	102.3	6.29	0.88	0.11	1817	1878	6.31	163	12.9	Latium
51	333.8	37.3	7	2	1220	83	8.17	0.07	0.33	1693	1713	6.08	−385	14	Latium
52	353.8	79	22.8	3.9	1623	233.2	34.05		2.9	2464	2120	6.24	63	13.2	Latium
53	227	30	3.82	1.12	878.4	28.16	4.71		5.9	1174	1208	6.76	293	12.1	Latium
54	238	23.8	3.82	1.68	927.2	18.41	6.05	15.66	4.02	1235	1313	6.69	−50	15.1	Latium
55	272.5	39.2	8.09	1.96	951.6	77.72	9.67	0.24	6.92	1362	1478	6.55	219	14.1	Latium
56	89.2	20.6	4.56	1.27	378.2	33.55	6.01		10.37	533.6	605	7.97	306	12.6	Latium
57	118.5	20.4	6.58	3.59	463.6	36.76	7.41	0.74	13.22	657.3	748	7.75	325	16.1	Latium
58	104.1	17.34	4.9	3.2	402.6	23.96	6.39	0.46	9.35	562.8	656	7.83	324	15.1	Latium
59	179.7	25	5.26	1.12	683.2	66.08	7	1.49	7.07	969.3	1037	6.67	293	11.8	Latium
60					439.2				6.79	438.5	648	7.65	230	20.9	Latium
61	190	9	12	5	29	740	7			534	937	7.2			Latium
62	514	83	97	25	740	1417	102			1830	3210	6.25			Latium
63	517	80	88	26	754	1417	109			1824	3200	6.3			Latium
64	169	57	60	8	201	1389	106			901	1580	7.3			Latium

*Main ion concentration and physicochemical parameters of some studied sinkhole waters.



Shap	X	Y	Id	Regione	Provincia	Località	Toponimo	Diametr	Profondità	Data_Formazion	Immagini	Nolasco 199	Note
Poi	828544.908353996	4699469.17748415	1	Lazio	Rieti	Piana di San Vittorino	Chiesa di San Vittorino	20	2.0	1703	C://sinkhole/i	V1	
Poi	829085.640957258	4699549.42782909	2	Lazio	Rieti	Piana di San Vittorino	Laghetto Pergine	50	3.0	1962		A20	Ricolmato
Poi	829020.677013001	4699625.85610868	3	Lazio	Rieti	Piana di San Vittorino	Pergine	3	3.0	5 Lug 1993			Ricolmato
Poi	829281.280000000	4699565.87000000	4	Lazio	Rieti	Piana di San Vittorino	Lago Terme di Cotilia	20	9.0		C://sinkhole/i	D7	Presenza di gas
Poi	829247.940000000	4699561.33000000	5	Lazio	Rieti	Piana di San Vittorino	Lago di Ceciri	15	7.0			D6	Presenza di gas
Poi	829418.106049961	4699513.12410162	6	Lazio	Rieti	Piana di San Vittorino	Laghetto Nuovo	10	0.0		C://sinkhole/i	A2	Presenza di gas
Poi	829490.713504538	4699482.55254164	7	Lazio	Rieti	Piana di San Vittorino	Lago Piccolo	5	3.0	19 Feb 1986	C://sinkhole/i	A22	
Poi	829458.231222227	4699377.46280420	8	Lazio	Rieti	Piana di San Vittorino	Lago Grande	50	10.0	17 Feb 1986	C://sinkhole/i	A21	Presenza di poco gas
Poi	829152.450000000	4699303.00000000	9	Lazio	Rieti	Piana di San Vittorino	Pozzo	3	1.0			ex Pozzo 6	Presenza di gas
Poi	829555.678069161	4699536.05277160	10	Lazio	Rieti	Piana di San Vittorino	Laghetto Parcheggio 2	2	0.0				Presenza di gas
Poi	830556.893551516	4699813.10691356	11	Lazio	Rieti	Piana di San Vittorino_	Pozzo Burino	50	4.0		C://sinkhole/i	A1	
Poi	830600.840168761	4699948.76759061	12	Lazio	Rieti	Piana di San Vittorino_	Lago di Mezzo	130	0.0	dopo1808		D1	
Poi	830541.608391970	4700227.73245507	13	Lazio	Rieti	Piana di San Vittorino_	Lago di Paterno	204	55.0	secolare	C://sinkhole/i	C2	crollo 31 Gen 1915
Poi	831016.950000000	4700232.82000000	14	Lazio	Rieti	Piana di San Vittorino	Linea FF.SS.	2	0.0	26 Dic 1902			Ricolmato

Fig. 4. Example of the Sinkhole Relational Database constructed in the Microsoft Access environment and used to store information of each case (row) and for each property of the single case (column). The archival Access format of the information regarding the descriptive characteristics, as well as georeferenced and numerical data of the known Italian sinkholes, provides a dynamic and flexible structure in which information can be extracted by using a simple standard database query language (SQL) in order to obtain tables to join with geometric information according to the operator's wishes. The ESRI ArcGis program is used to organize, manage and visualize in thematic 'layers' all collected information.

indicate that these collapses can be considered as deep piping sinkholes. The diameter of the lakes varies from 10 to 40 m, with shallow depths ranging from 1.5 to 3 m. The lakes, Giorgio 1 and Giorgio 2, are surrounded by clay and silt and are joined by an artificial channel. The water table is around 2 m below the soil surface. There are three springs on the bottom of the lake Giorgio 1 (unpredictable flow). The water level of Giorgio 2 is quite a bit higher than in Giorgio 1, so there is a flow towards Giorgio 1. The water is used for agricultural purposes and the surface level in both lakes is quite stable.

The date of the formation is unknown but the lakes, as reported by the landowner, have existed at least since 1960. Giorgio 2 is not reported on the IGM map so it probably formed in the second half of the 1900s. The lake of 'Tre occhi' bridge probably did not form from a sinkhole collapse. It is a depression in the soil fed by a close spring.

Sinkholes in intermountain basins

S. Vittorino Plain (eastern Latium). The S. Vittorino Plain, crossed by the Velino River, is a tectonic valley bordered by direct and transtensive faults (Fig. 7). These displacements affect the morphology of the plain, creating a triangular-shaped plain with the apex facing south (Centamore & Nisio 2003; Centamore *et al.* 2004).

The plain is filled by fluvial and lacustrine deposits of the upper Pleistocene–Holocene; gravel lenses and travertine (mostly sandy) are found locally (Fig. 7). The thickness of the cover increases toward the middle of the plain, and reaches 130–170 m over a faulted and displaced calcareous sequence (Nisio 2003). The S. Vittorino Plain is the drainage basin of the water from the surrounding recharge areas (Boni *et al.* 1995; Capelli *et al.* 2000). Springs are aligned along the northern and southern boundaries of the plain. Some springs, with a flow rate around $0.1–2\,\mathrm{l\,s^{-1}}$, feed some

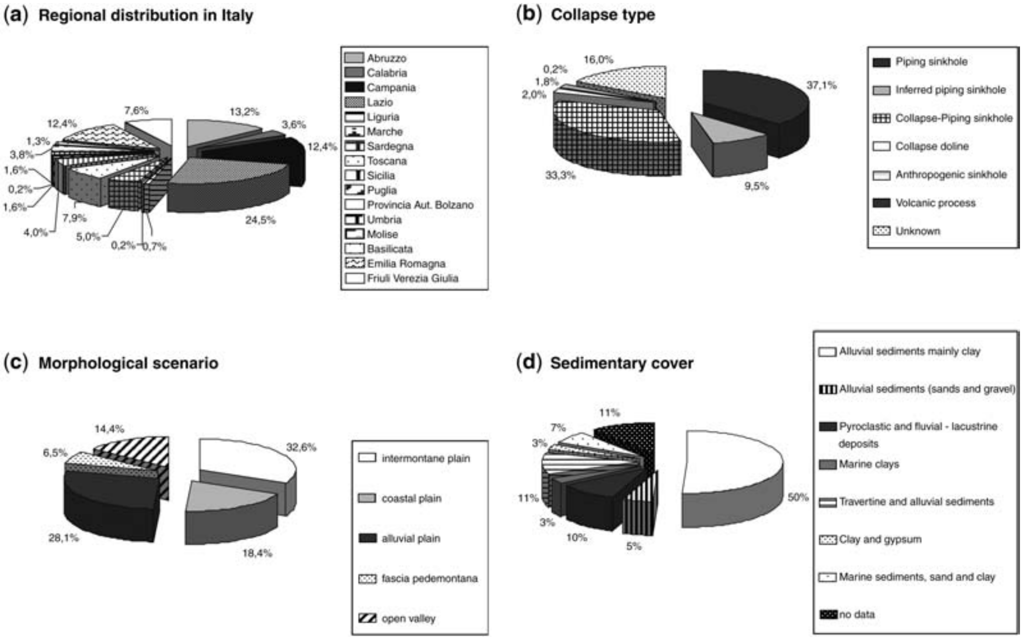


Fig. 5. Pie charts from the data elaboration of more than 500 studied cases: (**a**) regional distribution of the sinkholes; (**b**) genetic mechanism; (**c**) morphology of the area; and (**d**) typology of the sedimentary cover.

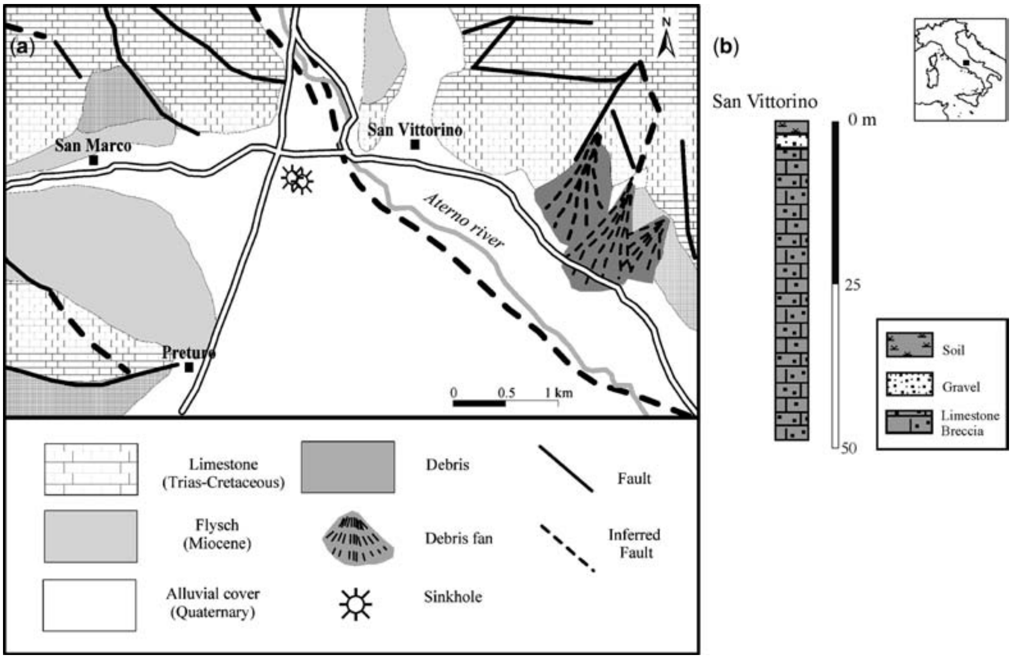


Fig. 6. Simplified geological map of the sinkhole-prone area in the Aterno River Valley (Abruzzo) with a borehole data stratigraphic column.

sinkhole ponds inside the plain. The S. Vittorino Plain is characterized by the presence of collapses (Faccenna *et al.* 1993; Capelli *et al.* 2000; Nisio 2003). Some collapses affect the bordering calcareous structures. We have recognized at least 35 subcircular sinkholes with diameters varying from a few metres to 100 m. Some collapses are naturally or artificially filled. Sinkholes are mainly located in the northern sector of the plain and are aligned along the NE–SE path of the Fiamignano–Micciani fault. Sinkholes host small lakes or spring ponds with mineralized water and gases (free and dissolved). The most recently formed sinkhole lies in the northern sector of the plain close to the Cotilia thermal bath. It is a small circular pond with springs and gas vents. Mineralized springs discharge mainly sulphuric water and ferric water, and are aligned along tectonic displacements (Faccenna *et al.* 1993; Ciotoli *et al.* 2001; Nisio 2003).

Fucino Plain. The Fucino Plain is a rhomboidal intermountain tectonic depression located in the middle of Apennines (central Italy) (Fig. 8). A Cenozoic thrust and fold belt has been undergoing uplift and extension since the Late Pliocene (Blumetti *et al.* 1988, 1993). During the Quaternary, the basin was deprived of a natural outlet and thus hosted a wide lake (artificially drained in the second half of the last century) that collected a thick sequence of Pleistocene and Holocene silty lacustrine deposits interbedded with coarse alluvial fan deposits at its borders. In 1915 the plain was hit by the strong Avezzano earthquake, which testifies to the activity of the faults bordering and crossing the basin (Blumetti *et al.* 1988; Michetti *et al.* 1996). The ENE-trending, SE-dipping Tre Monti (TMF) and Avezzano–Celano (ACF) faults; the NW-trending San Benedetto–Gioia dei Marsi fault (SBGMF) reactivated during the 1915 Avezzano earthquake; and the NW-trending, SW-dipping Ortucchio (OF) and Vallelonga–Trasacco–Avezzano (TF) faults exist in the basin (Blumetti *et al.* 1993). Data from subsurface investigations, as well as geophysical surveys, demonstrate that a network of capable faults affects the very recent deposits of the basin floor and outline two sub-basins that are separated by a near-surface horst located along the NW extension of the Vallelonga–Trasacco ridge. The two sub-basins appear to be half-grabens with the main normal faults (SBGMF and TF) dipping SW without any significant listric component. Faults either bordering or cutting the basin show evidence of Holocene reactivation (Blumetti *et al.* 1988; Michetti *et al.* 1996).

Moreover, palaeoseismic studies performed at several sites along the San Benedetto–Gioia fault (SBGMF) have demonstrated that coseismic

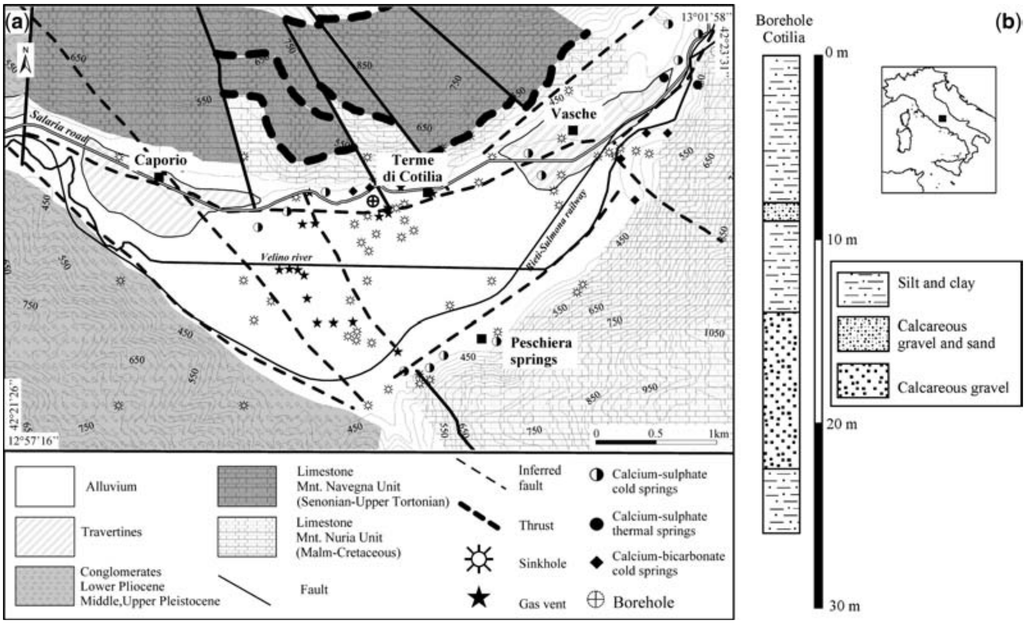


Fig. 7. Simplified geological map of the sinkhole-prone area in the S. Vittorino Valley (Latium) with a borehole data stratigraphic column.

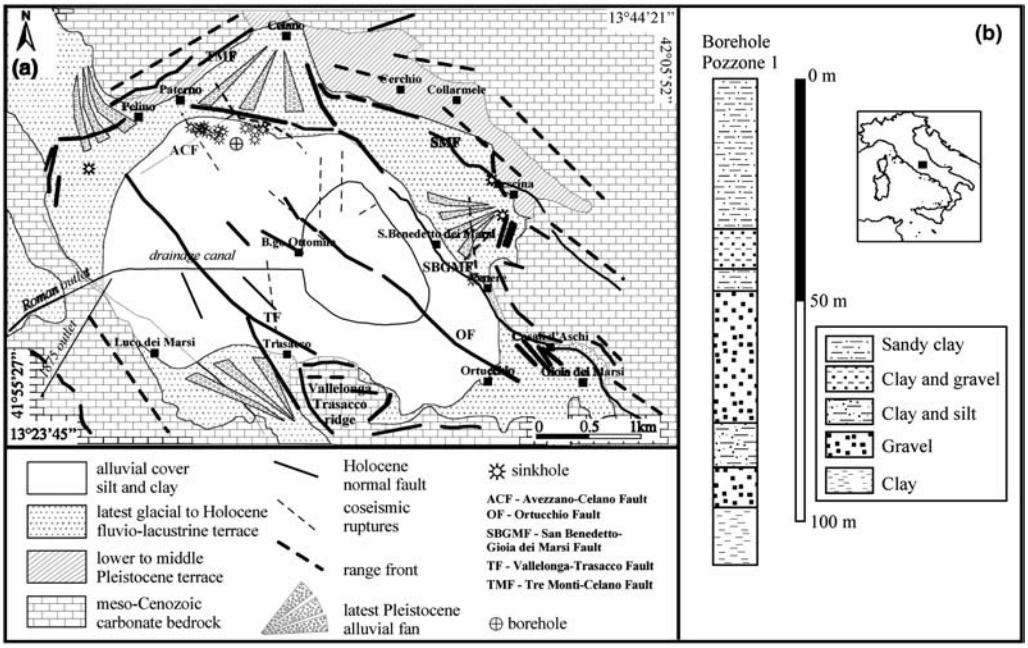


Fig. 8. Simplified geological map of the sinkhole-prone area in the Fucino Plain (Abruzzo) with a borehole data stratigraphic column.

displacement of a magnitude comparable to that of 1915 occurred at least once, and possibly twice, during the Middle Ages (Michetti *et al.* 1996). During the 1915 earthquake, typical seismo-geological effects, such as liquefaction, spring anomalies, and gas and water emissions, were observed at several sites inside the plain (Oddone 1915).

A total of 30 subcircular-shaped cavities (Fig. 8), with diameters ranging from 5 to 30 m and a few metres of depth, have been identified in the plain. The sinkholes occur mainly in the NW sector of the Fucino Plain with an east–west trend similar to the direction of the ACF. In this area, high soil gas concentrations (CO_2, He and Rn) of deep origin have been measured indicating fluid upwelling from a deep reservoir along buried tectonic discontinuities (Ciotoli *et al.* 1998). Some cavities actually host small ponds. Others are buried. Some of these sinkholes are multiple or twin sinkholes. The 1915 earthquake triggered at least three sinkholes. Borehole data show the presence of a thick cover (mainly clay and few gravel levels), of at least 110 m, overlying calcareous bedrock. A pressurized aquifer is hosted in the bedrock; some perched aquifers are in the gravel levels. The collapses have been identified as deep piping sinkholes.

Sinkholes in the coastal plain

Pontina Plain (central Latium). The Pontina Plain is on the border of the carbonatic ridge of the Lepini–Ausoni Mounts (Fig. 9). Since the Pliocene, the area has been subsiding. It has an average altitude ranging from few metres (Sezze and Migliara zone) to 35–50 m above sea level. Quaternary fluvial–lacustrine sediments, lagoon sediments, aeolic deposits and pyroclastic products from the Albani Hills volcano, and from some local emission points, crop out in the area. Travertine is found at various depths under the plain deposits. Furthermore, borehole data and some outcrops also indicate the presence of Pliocene marine sediments. The carbonatic bedrock is characterized by direct faults with a graben structure.

The Lepini–Ausoni Mounts structure, bordered on the western slope by a master regional fault and affected by a widespread karst erosion, hosts an imposing aquifer. Several springs are fed by this aquifer along the contact between the carbonatic ridge and the alluvial cover of the plain. Below the plain there is a confined aquifer that recharges in the Lepini–Ausoni Mounts. Locally, there are some small perched aquifers fed by direct rainfall or from the carbonatic ridge through some faults and fractures. A natural fluvial and artificial

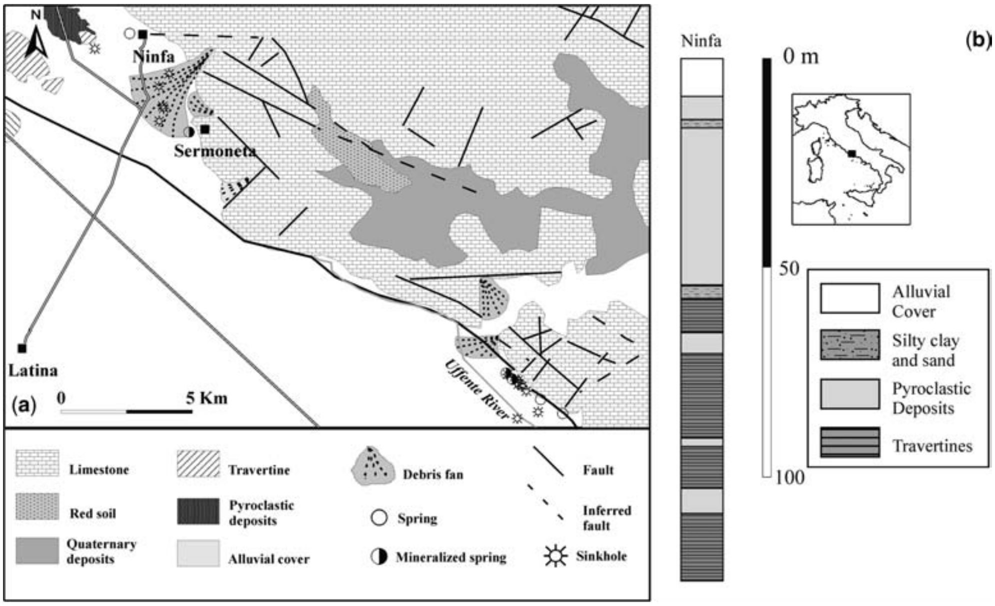


Fig. 9. Simplified geological map of the sinkhole-prone area in the Pontina Plain (Vescovo and Sprofondi lakes sector – Latium) with a borehole data stratigraphic column.

drainage network drains toward the Tyrrhenian shore. Furthermore, a thermal groundwater circulation with two end members (bicarbonatic–calcic and sulphuric waters) occurs (Colombi *et al.* 2001).

The Pontina Plain is considered a sinkhole-prone area with many subcircular ponds. Morphological, geological and hydrochemical studies have been conducted on some of these flooded sinkholes: Vescovo Lakes group, Sprofondi and Doganella di Ninfa sinkhole.

The Vescovo lakes group (from north to south: S. Carlo Lake, Vescovo lakes and Mazzocchio Lake) are aligned along a NW–SE regional fault where some mineralized springs also occur.

The S. Carlo Lake is circular and is located about 200 m from the Lepini–Ausoni carbonatic ridge. The lake is fed by some underwater springs and shows bubbling phenomena that indicate gas rising in the water. The origin of the lake from collapse, according to popular legend, happened some centuries ago. The lake has been plotted on geographical maps since 1777.

The Vescovo lakes are located in the area south of the village of Sezze, close to the carbonatic ridge. There are five ponds (White Lake, Green Lake, Black Lake, Bagno pond and one more without a name) with mineralized and/or opalescent waters showing high levels of dissolved and free CO_2 and H_2S. The Black Lake is the least mineralized of all, with no presence of sulphurs or sulphate, no opalescent water and a pH of greater than 7. On the shores are outcrops of travertine that should be of hydrothermal origin, proving the ancient presence of mineralized warm fluids in the pond. The Green Lake is characterized by acidic ($6.3 < \text{pH} < 6.6$) water with a decreasing pH and increasing electric conductivity from the surface to the bottom. Borehole data show the presence of an alluvial cover (clay and silt) with a thickness of more than 80 m, with some travertine levels at around 50–60 m. The bedrock is at a depth of 170 m.

All the lakes seem to be formed by more than one collapse. In particular, the results obtained by means of a bathymetric survey show that the Black Lake presents an 8-shaped feature characterized by two collapses of 9–10 m depth joined together and separated by a shallow bank occurring at a depth of 2 m.

On the map of 1777 all the lakes were represented with the exception of Bagni pond and the unamed pond. The same map shows the presence of another lake, Manello Lake, that now is buried.

The Mazzocchio Lake is located at about 500 m from the Lepini–Ausoni carbonatic ridge. It is fed by a channel of a pumping station. The outlet is an artificial channel linked to the close Uffente River. This lake has been present for more than three centuries.

The Sprofondi group. These collapses are located in the municipality of Sermoneta (southern Latium). There are five subcircular-shaped aligned sinkholes along the Apennine direction (NW–SE). Two are now buried. One is close to the Sermoneta–Bassiano railway station and the second is a few hundred metres to the SW. The former is mapped on an official IGM map of 1938 as a depression that hosts a small pond of surficial water. Buried after the Second World War, the depression is now not recognizable. Two more depressions with small lakes are on private proprieties. The water surface is about 10 m below the soil level. The regional water table lies 13 m below the soil level. Borehole data show an alluvial cover 50 m thick with pyroclastic deposits. The presence of deep-water supply wells, deeper than 100 m with pressurized water, suggests that the bedrock lies more than 100 m below the alluvial cover.

The last of the Sprofondi, which is known as Sprofondo Lake in the official IGM map, is locally Blue Lake. It is a circular pond. The origin seems to be a catastrophic collapse of the soil on St Jake's day (25 July) of an unknown year, probably 1786. Chemical analyses of the water revealed a bicarbonate–calcic water with $\mathrm{pH} > 7$ that decreases from the surface to the bottom with concomitant increases of conductivity. The water temperature is always less than the average temperature in the area and this should be proof of cold underground water feeding the lake. The lake is used as a fishing facility. The other cavities formed in the 1800s, the authors suggest either 1818 or 1870.

Doganella di Ninfa sinkhole. This sinkhole is close to the small village of Doganella in the NE area of the Pontina Plain (Fig. 9), a few kilometres from the city of Latina. On 22 August 1989, after seismic activity earlier in the month and during a dry period associated with lowering of the aquifer owing to water overpumping, there was a collapse in a field utilized as a kiwi plantation. In just 3 days the diameter of the depression increased from 1 to 3 m; after 3 years it reached 31–32 m. Now this sinkhole hosts a subelliptical lake 30 m deep with a bell-shaped vertical cross-section. The water chemistry is similar to the chemistry of Sprofondo Lake.

The carbonatic bedrock lies at a 124 m depth, as shown from a borehole in the area. Volcanic and volcanoclastics deposits crop out in the area, reaching a thickness of 54 m. Volcanic deposits and travertine are present to a 100 m depth. Below these deposits, travertine and sand beds extend to 124 m. At this depth the borehole ends because of the interception of a confined and pressurized aquifer.

Other authors (Bono 1995; Di Filippo *et al.* 2002) correlate the presence of a travertine bed at around 30–40 m depth with a cave that, after the collapse of the roof, created the sinkhole. Direct investigations of the lake by scuba divers revealed that the sediments are pyroclastic units down to the bottom (35 m from the soil level) with no sign of travertine or underwater springs.

Close to the sinkhole there is the Ninfa Spring with more than $2.000\,\mathrm{l\,s^{-1}}$ flow and a typical bicarbonate–calcic low mineralized water.

From the collected data is possible to hypothesize the genetic mechanism of the Pontina Plain sinkholes. There is a thick alluvial cover (more than 100 m) overlying a deep carbonatic bedrock. The bedrock hosts a confined pressurized aquifer. In some cases (Vescovo lakes) high mineralized springs with a free gas phase (mainly with H_2S and CO_2) lie on the bottom of the flooded sinkholes. The water and gas chemistry indicates a deep origin of the fluids. There is a clear correlation between the sinkhole distribution and the fault systems. In particular, it is possible to identify an alignment of the sinkholes NW–SE for the Vescovo Lake and north–south for the Sprofondi group. Subsurface explorations did not reveal any void that could be correlated with the genesis of the collapses. This geological scenario strongly supports the hypothesis of the presence of conduits in the cover that link the bedrock with the surface. The enlargement of the cylindrical conduits owing to the upward erosion causes the collapse of the soil surface. The collapses should be defined as deep piping sinkholes.

Discussion

In Italy, sinkholes have been recognized since the Roman age. In fact, the presence of catastrophic collapses has been widely reported throughout Italian history. More than 50% of the studied sinkholes are of unknown age. Nevertheless, since 1960 an increase of the phenomena has been noted.

The collapses occur in different geological scenarios and in the same areas with gaps lasting centuries, during which time they could fill through natural or artificial means. Sinkhole extinction, coupled with the long gap between events, causes a lack of attention to this hazard.

In central Italy, sinkholes are mainly located in the Latium, Tuscany and Campania regions along the Tyrrhenian tectonic plains and/or thermal areas. Some collapses have been identified in other regions, but the periadriatic zone, with the exception of a few cases in the Puglia region, does not seem to be affected by sinkhole hazard.

The overall scenario obtained by the analysis of more than 550 cases suggests a specific geological setting that causes a high probability of sinkhole hazard. Field investigations provide a conceptual model for sinkhole genesis. This model could be extended to many other similar cases occurring in other intermountain basins (more than 40% of studied cases) in Tuscany (in the plains of Camaiore and Massa Marittima, and Capalbio towns), in Abruzzo (in the Fucino and Sulmona plains) and in Latium (Pontinia Plain and near Tivoli village).

The case studies demonstrate that sinkholes also occur in alluvial and coastal plains, along pedemountains zones, in small valleys in the immediate vicinity of carbonate ridges, and in complex geological–structural and hydrogeological settings. The observed sinkholes are mainly single collapse features (90%), with diameters ranging from 30 to 100 m, and depths ranging from 5 to 10 m. The following common features have been recognized in these areas.

- A deep carbonate bedrock (5% of cases between 30 and 50 m, 6% between 50 and 100 m, 30% deeper than 100 m and 59% have no data available) overlain by a thick sequence of unconsolidated sediments (predominantly silt and clay). Travertine lenses may be present. In some locations, the geological setting is characterized by the presence of permeable (i.e. sands) or impermeable (i.e. marine clays) covers overlying evaporitic sediments (i.e. gypsum).
- The presence of active faults of local and regional importance. The main direction of the faults are NW–SE and north–south. These faults act as paths for mineralized and/or geothermal fluids enriched in acidic gases (i.e. CO_2 and H_2S) that dissolve and/or pass into the groundwater and cause consumption of the carbonate matrix of shallow sediments and weakening of the supporting geological structure. In this context, the uprising of deep fluids seems to play an important role in the sinkhole formation mechanism. Flooded sinkholes account for 30% of the total; 5% of which are affected by gas emission (38% are dry or buried).
- The presence of confined or unconfined aquifers with high underground water flows and mineralized springs. The small lakes hosted in the sinkholes are usually fed by underwater springs (i.e. S. Vittorino Plain) or represent the outcropping of the water table (i.e. Pontina Plain). In some cases the presence of inlet streams causes a mixing between the low mineralized surficial water and the water inside the sinkholes with a reduction of total dissolved solids concentration.

From a chemical point of view the sinkhole waters may be divided into three main groups (Fig. 10).

- The first group (19% of studied cases) is represented by very shallow aquifers or surficial waters and is distinguished by low values of total dissolved solids (TDS around $300\ \mathrm{mg\ l^{-1}}$) and pH around 7 or less for the influence of acidic soils (i.e. peat layers). Little increments of TDS are due to the presence of mineral-rich sediment covers (i.e. sinkholes hosted in pyroclastic deposits).
- The second group (19% of studied cases) clusters karst waters characterized by a medium TDS ($500\ \mathrm{mg\ l^{-1}}$), and pH values that are neutral or basic. The main ion concentration is HCO_3^{2-} and Ca^{2+} for the dissolution of the calcareous bedrock by the circulating water.
- The third group (28% of studied cases) collects mineralized waters derived from the mixing of karst waters with fluids (CO_2 and H_2S) of deep origin raised through faults and tectonic displacements. The waters could become very acidic owing to the high level of CO_2 as dissolved and free gas enhancing the chemical dissolution of the carbonatic fraction of the sediments and rocks causing a quick sinkhole development and enlargement. In these last cases mineralized springs are usually located close to the sinkholes and are aligned along tectonic displacements. High values of TDS have also been measured in the ponds hosted in evaporitic sediments. These values are not related to deep fluids mixing but only to the evaporitic rocks dissolution (i.e. some gypsum collapses in Sicily).

There are both natural and artificial triggering processes. Seismic activity, flooding or anthropic activities may cause catastrophic collapses. Earthquakes are associated with some collapses (24%); specific investigations concerning the correlation between earthquake and sinkholes have been conducted on 104 cases. The average distance between the collapses and the epicentre varies from 30 to 50 km. The maximum distance is 130 km. The gap between the seismic event and the sinkhole collapse is usually from 1 to 10 days. The maximum registered gap is 23 days.

Strong oscillation in the water-table level is another triggering effect. Human activity, like strong vibrations caused by heavy working machines, could also cause the sinkhole formation. All of the abovementioned triggering factors act like external forces increasing the stress on the structures.

In some cases, results obtained from structural field surveys indicate the presence of minor extensional fault systems causing the formation of a block mosaic characterized by different uplifting rate (e.g. San Vittorino Plain). The extensive movement of these blocks could be responsible for rejuvenating and reactivating older sinkholes and/or forming other new ones.

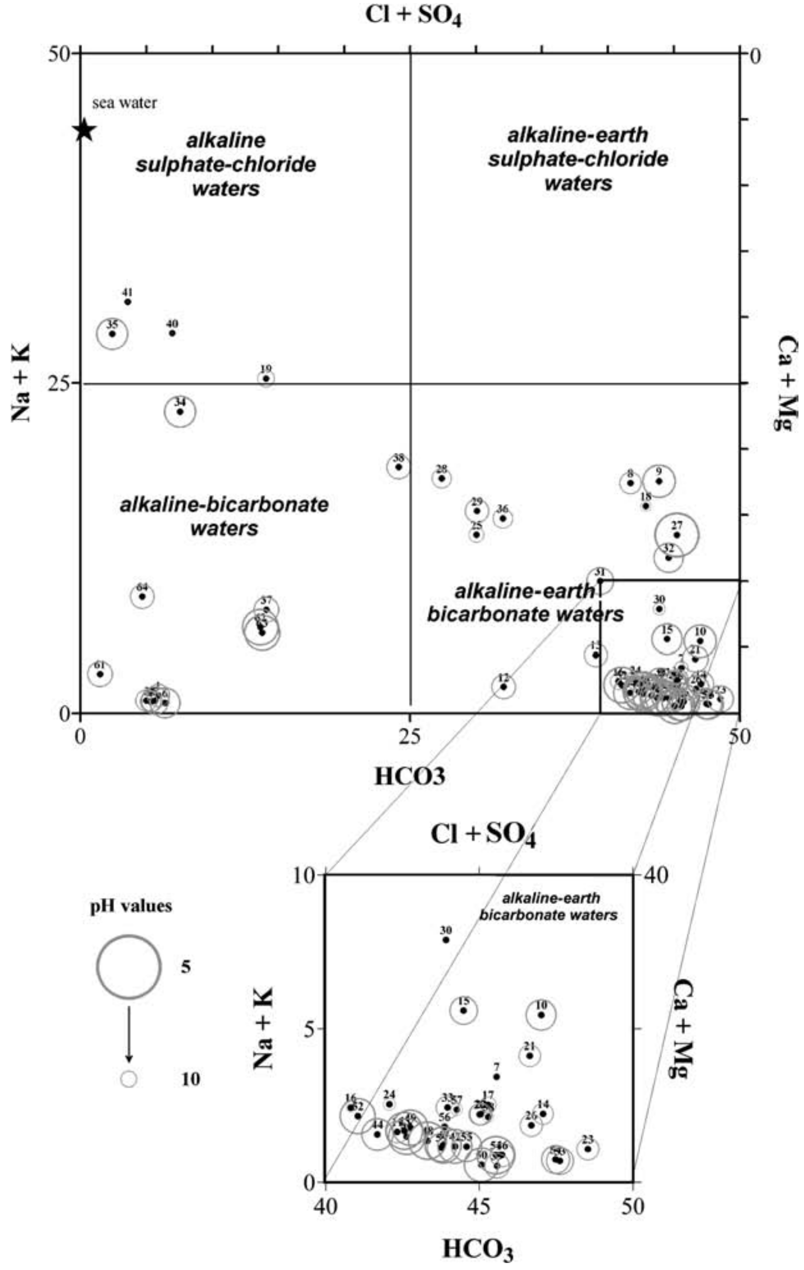


Fig. 10. Most of the sinkholes host alkaline-earth/alkaline bicarbonate waters. The presence of low pH values is related to acidic gas rising in faulted areas. Waters with high salt contents (alkaline-sulphate-chloride waters) are due to the presence of evaporitic bedrock (samples 40–41).

Conclusions

Sinkholes *sensu stricto* in Italy are mainly concentrated in alluvial and intermountain plains, close to carbonate ridges and/or in complex geological–structural and hydrogeological settings. In central-southern Italy, sinkhole-prone areas are characterized by the presence of a deep calcareous bedrock overlain by a thick sequence (100–200 m) of unconsolidated sediments (predominantly silt and clay) with weak physical and/or mechanical characteristics. Pressurized confined aquifers within the bedrock are often recognized.

The widespread occurrence of various faults or fracture systems has been observed in many of the studied areas; faults could act as paths for acidic gases (i.e. CO_2 and H_2S) migration. These gases increase the chemical aggressiveness of the groundwater on the soluble bedrock (i.e. limestone, travertine, gypsum, etc.). Some mineralized water springs with dissolved and free gas are aligned along the main faults close to the sinkholes (i.e. S. Vittorino Plain, Pontina Plain). The water chemistry of the ponds hosted by the sinkholes is not always affected by mineralized fluids. This, in many cases, could be explained by the migration of the springs. Travertine deposits, both as outcrops and in boreholes close to the cavities (i.e. Black Lake in the Pontina Plain), provide clues to the presence of warm mineralized waters.

The morphology of the investigated cavities is usually represented by steep walls and flat bottoms in a bowl or subcylindrical shape. In the flooded sinkholes, echo-sounder surveys show the presence of thick soft silt and clay strata on the bottom; this is also confirmed by direct investigations (i.e. Doganella di Ninfa sinkhole). The cavity is supposed to enlarge by step collapses of the rim. If the debris is not removed by an outlet stream, the depression will fill with sediment and become an ‘extinct’ (buried) sinkhole.

The main factor associated with the collapse seems to be a deep piping effect. The upwelling of groundwater results in the erosion of sediments and the formation of conduits within the unconsolidated sediments cover; the following loss of strength causes the collapse of the overlaying terrain.

Sinkhole formation could be triggered by various natural causes (seismicity, drought, flood, etc.) and human activity (water over pumping, mines, quarries, drilling operations). In several of the studied cases seismic activity was detected days before the collapse. This suggests that earthquakes could be responsible, in part, for sinkhole genesis.

Preliminary statistic data elaborations on some parameters have been conducted on over 500 cases; other data are still being analysed. The census is still ongoing with more than new 200 cases of possible sinkholes.

The construction of an updatable relational database that includes topographical, geological, hydrogeological, geochemical and other environmental data of the studied sinkhole cases in Italy, coupled with the GIS capabilities, allows analysis of the collected data to define genesis of features in sinkhole-prone areas. This may help the national and regional authorities in the assessment of the sinkhole hazard.

References

Annunziatellis, A., Beaubien, S. E., Ciotoli, G., Lombardi, S., Nisio, S. & Nolasco, F. 2004. Studio dei parametri geologici e geochimici per la comprensione dei meccanismi genetici degli sprofondamenti nella piana di S. Vittorino. *In*: *Proceedings of the Workshop ‘State of the art on the Study of Sinkholes, and the Role of National and Local Authorities in the Management of the Territory*’, *Rome*, 20–21 May 2004, 63–82.

Beck, B. F. (ed.) 1984. *Sinkholes: Their Geology, Engineering and Environmental Impact*: *Proceedings of the First Multidisciplinary Conference on Sinkholes*, *Orlando*, FL, A.A. Balkema, Rotterdam, The Netherlands.

Beck, B. F. & Jenkins, D. T. (eds) 1986. *Geotechnical Considerations of Sinkhole Development in Florida. International Symposium of Environmental Geotechnology*, April 21–23, 1986, Allentown, PA.

Beck, B. F. & Wilson, W. L. (eds) 1987. *Karst Hydrogeology: Engineering and Environmental Applications. Proceedings of the Second Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst*, *Orlando*, FL, A.A. Balkema. Rotterdam, The Netherlands.

Billiard, A., Muxart, T., Derbyshire, E., Wang, J. T. & Dijkstra, T. A. 1992. Les glissements de terrain induits par les loess de la province de Gansou, Chine. *Annales de Gèographie*, **566**, 495–515.

Blumetti, A. M., Dramis, F. & Michetti, A. M. 1993. Fault-generated mountain fronts in the Central Apennines (Central Italy): geomorphological features and seismotectonic implications. *Earth Surface Processes and Landforms*, **18**, 203–223.

Blumetti, A. M., Michetti, A. M. & Serva, L. 1988. The ground effects of the Fucino earthquake of Jan. 13th, 1915; an attempt for the understanding of recent geological evolution of some tectonic structures. *In*: Margottini, C. & Serva, L. (eds) *Historical Seismicity of Central-eastern Mediterranean Region*, *Proceedings of the 1987 ENEA–IAEA International Workshop*. Ente per le Nuove Tecnol., l’Energia, e l’Ambiente, Rome, 297–319.

Boni, C., Cappelli, G. & Petitta, M. 1995. *Carta idrogeologica dell’alta e media valle del F. Velino*. System cart, Roma.

Bono, P 1995. The sinkhole of Doganella (Pontina, Plain, Central Italy). *Environmental Geology*, **26**, 48–52.

Capelli, G., Colombi, A. & Salvati, R. 2001. Catastrophic subsidence risk assessment. A conceptual matrix for sinkhole genesis. *In*: Beck, B. F. & Gayle Herring, J. (eds) *Geotechnical and Environmental Applications of Karst Geology and Hydrology*. Balkema, Rotterdam, The Netherlands.

Capelli, G., Petitta, M. & Salvati, R. 2000. Relationships between catastrophic subsidence hazards and groundwater in the Velino Valley (Central Italy). *In*: *Proceedings of the Sixth International Symposium on Land Subsidence SISOLS 2000*, Ravenna, Italy, Volume 1, 123–136.

Caramanna, G., Ciotoli, G. & Nisio, S. 2005. A review of natural sink phenomena in Italian plain areas. *In*: *Sixth International Conference of*

Geomorphology, 7–11 September 2005, Zaragoza, Spain. Zaragoza University.

CARAMANNA, G., NISIO, S. & VITA, L. 2004. Fenomeni di annegamento dei sinkholes: casi di studio su alcuni laghetti di origine incerta. *In*: *Proceedings of the Workshop 'State of the art on the Study of Sinkholes, and the role of National and Local Authorities in the Management of the Territory*', *Rome*, 20–21 May 2004, 229–248. APAT, Rome.

CASTIGLIONI, G. B. 1986. *Geomorfologia*. Opere UTET di geografia e discipline affini.

CENTAMORE, E. & NISIO, S. 2002. Quaternary Morphodynamic between the Velino and Salto Valleys. *Studi Geologici Camerti*, Special Volume. Selca Camerino Macerata, **1999**, 37–44.

CENTAMORE, E. & NISIO, S. 2003. The effects of uplift and tilting in the Central Apennine. *Quaternary International*, **101–102**, 93–101.

CENTAMORE, E., NISIO, S. & ROSSI, D. 2004. Aspetti geologico-strutturali in relazione alla formazione della 'sinkhole plain' di S. Vittorino. *In*: *Proceedings of the Workshop 'State of the art on the Study of sinkholes, and Role of National and Local Authorities in the Management of the Territory*', *Rome*, 20–21 May 2004, 285–298.

CIOTOLI, G., DI FILIPPO, M., NISIO, S. & ROMAGNOLI, C. 2001. La Piana di S. Vittorino: dati preliminari sugli studi geologici, strutturali, geomorfologici, geofisici e geochimici. *Memorie della Società Geologica Italiana*, **56**, 297–308.

CIOTOLI, G., GUERRA, M., LOMBARDI, S. & VITTORI, E. 1998. Soil gas survey for tracing seismogenic faults: a case study in the Fucino Basin, Central Italy. *Journal of Geophysical Research*, **103**, 23,781–23,794.

COLOMBI, A., SALVATI, R. & CAPELLI, G. 2001. Sinkhole in the Latium region (Central Italy). Purposes of the main project. *In*: BECK, B. F. & GAYLE HERRING, J. (eds) *Geotechnical and Environmental Applications of Karst Geology and Hydrology*. Balkema, Rotterdam, The Netherlands.

CRAMER, H. 1941. Die Systematik der karstdolinen. *Neues Jahrbuch für Mineralogie Geologie und Paläontologie*, **85**, 293–382.

DERBYSHIRE, E. & MELLORS, T. W. 1988. Geological and Geotechnical characteristic of some loess and loessic soil from China and Britain: a comparison. *Engineering Geology*, **25**, 135–175.

DERBYSHIRE, E., WANG, J. *ET AL.* 1991. Landslide in the Gansu loess of China. *Catena Supplement*, **20**, 119–145.

DI FILIPPO, M., PALMIERI, M. & TORO, B. 2002. Studio gravimetrico del sinkhole di Doganella di Ninfa (Latina). *In*: *Le voragini catastrofiche, un nuovo problema per la Toscana. Proceedings of the Conference* 31 Marzo 2000, Grosseto R. Regione Toscana, 62–70.

FACCENNA, C., FLORINDO, F., FUNICELLO, R. & LOMBARDI, S. 1993. Tectonic setting and Sinkhole Features: case histories from western Central Italy. *Quaternary Proceedings*, **3**, 47–56.

FAIRBRIDGE, R. W. 1968. *The Encyclopedia of Geomorphology.* Reinhold, New York.

FERRELI, L., GUERRIERI, L., NISIO, S., VITA, L. & VITTORI, E. 2004. Relations among seismogenic structures, earthquakes and sinkhole phenomena: a methodological approach in the Apennines (Italy). *In*: 32nd International Geological Congress, Firenze, 20–28 August 2004, Volume Abstract, Part 1, 669.

FORD, D. & WILLIAMS, P. W. 1989. *Karst Geomorphology and Hydrology*. Unwin Hyman, London.

GRACIOTTI, R., NISIO, S. & VITA, L. 2004. Sinkholes in Italy: inventory of natural phenomena and some study cases. *In*: 32nd International Geological Congress, Firenze, 20–28 August 2004, Volume Abstract, Part 1, 670.

GUNN, J. 2004, *Encyclopedia of Caves and Karst Science*. Fitzroy Dearborn, New York.

JENNINGS, J. N. 1985. *Karst Geomorphology*. Kateprint, Oxford.

LITTLEFIELD, J. R., CULBRETH, M. A., UPCHURCH, S. B. & STEWART, M. T. 1984. Relationship of modern sinkhole development to large scale-pholinear features. *In*: BECK, B. F. (ed.) *Sinkholes: Their Geology, Engineering & Environmental Impact*. Balkema, Rotterdam, The Netherlands.

MASSARI, F., GHIBAUDO, G., D'ALESSANDRO, A. & DAVAUD, E. 2001. Water-upwelling pipes and soft-sedimentary deformation structures in lower Pleistocene calcarenites (Salento, southern Italy). *Geological Society of America Bulletin*, **113**, 545–560.

MICHETTI, A. M., BRUNAMONTE, F., SERVA, L. & VITTORI, E. 1996. Trench investigations of the 1915 Fucino earthquake fault scarps (Abruzzo, Central Italy): Geological evidence of large historical events. *Journal of Geophysical Research*, **101**, 5921–5936.

MONROE, W. H. 1970. *A Glossary of Karst Terminology*. US Geological Survey Water Supply Paper. GV Print, Washington.

MUXART, T., BILLARD, A., DERBYSHIRE, E. & WANG, J. 1994. Variation in runoff on steep unstable loess slopes near lanzhou, China: Initial results using rainfall simulation. *In*: KIRBY, M. J. (ed.) *Process Models and Theoretical Geomorphology*, 337–355. Wiley, Chichester.

NEWTON, J. C. 1984. Review of induced sinkhole development. *In*: BECK, B. F. (ed.) *Sinkholes: Their Geology, Engineering & Environmental Impact*. Balkema, Rotterdam, The Netherlands.

NEWTON, J. G. 1986. *Natural and Induced Sinkhole Development in the Eastern United States*. International Association of Hydrogeological Sciences, Publication, **151**.

NISIO, S. 2003. I fenomeni di sprofondamento: stato delle conoscenze ed alcuni esempi in Italia Centrale. *Il Quaternario*, **16**, 121–132.

NISIO, S. & SALVATI, R. 2004. Fenomeni di sprofondamento catastrofico. Proposta di classificazione applicata alla casistica italiana. *In*: *Proceedings of the Workshop 'State of the art on the Study of Sinkholes, and the Role of National and Local Authorities in the Management of the Territory*', *Rome*, 20–21 May 2004, 573–584. APAT, Rome.

NISIO, S., GRACIOTTI, R. & VITA, L. 2004. I fenomeni di sinkhole in Italia: terminologia, meccanismi genetici e problematiche aperte. *In*: *Proceedings of the Workshop 'State of the art on the Study of Sinkholes, and the Role of National and Local Authorities in the Management of the Territory*', *Rome*, 20–21 May 2004, 557–572. APAT, Rome.

ODDONE, G. 1915. Gli elementi fisici del grande terremoto marsicano-fucense del 13 gennaio 1915. *Bollettino della Società Sismologica Italiana*, **19**, 71–215.

SALVATI, R. & SASOWSKY, I. D. 2002. Development of collapse sinkholes in areas of groundwater discharge. *Journal of Hydrology*, **264**, 1–11.

SALVATI, R., THARP, T. & CAPELLI, G. 2001. Conceptual model for geotechnical evaluation of sinkhole risk in the Latium Region. *In*: BECK, B. F. & GAYLE HERRING, J. (eds) *Geotechnical and Environmental Applications of Karst Geology and Hydrology*. Balkema, Rotterdam, The Netherlands.

SINCLAIR, W. C. 1982. *Sinkhole Development Resulting From Ground-water, Development in the Tampa area, Florida*. US Geological Survey, Water Resources Investigation Report, 81–50.

SINCLAIR, W. C. & STEWART, J. W. 1985. *Sinkhole Type, Development and Distribution in Florida*. US Geological Survey, Map Series 110, Plate 1.

SNYDER, S. W., EVANS, M. W., HINES, A. C. & COMPTON, J. S. 1989. Seismic expression of solution collapse features from the Florida Platform. *In*: *Engineering and Environmental Impacts of Sinkholes and Karst. Proceedings of the Third Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, St Petersburg Beach, Florida*, October 2–4, 1989.

SWEETING, M. M. 1972. *Karst Landform*. Macmillan, London.

THARP, T. M. 1997. Mechanism of formation of cover collapse sinkhole. *In*: *Proceedings of the 6th Multidisciplinary Conference of Sinkhole and the Engineering and Environmental Impact of Karst*. Balkema, Rotterdam, The Netherlands, 29–36.

THARP, T. M. 1999. Mechanism of upward propagation of cover collapse sinkhole. *Engineering Geology*, **52**, 23–33.

TIHANSKY, A. B. & GALLOWAY, D. L. 2000. Land and water-resource development activities increase sinkhole frequency in the mantled karst region of Florida. USA. *In*: *Proceedings of the Sixth International Symposium on Land Subsidence SISOLS* 2000, Ravenna, Italy, Volume 1, 77–90.

WALTHAM, A. C. & FOOKES, P. G. 2003. Engineering classification of karst ground conditions. *Quarterly Journal of Engineering Geology and Hydrogeology*, **36**, 101–118.

WHITE, W. B. 1988. *Geomorphology and Hydrology of Carbonate Terrains*. University Press, Oxford.