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COLLAPSE SINKHOLES DISTRIBUTION IN THE CARBONATE MASSIFS OF CENTRAL AND SOUTHERN APENNINES

RAZPOREDITEV UDORNIC V KARBONATNIH DELIH OSREDNJIH IN JUŽNIH APENINOV

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Abstract UDC 551.435.82(234.41)
Antonio Santo, Alessandra Ascione, Sossio Del Prete, Giuseppe Di Crescenzo & Nicoletta Santangelo: Collapse sinkholes distribution in the carbonate massifs of central and southern Apennines
This study focuses on karst collapse sinkholes of the southern and central Apennines region (Italy), and has the aim of outlining and discussing the factors which contribute to the occurrence of collapse phenomena. By the analysis of the morphometrical/morphological features of the about 600 initially identified sinkholes, about 50% were interpreted as collapse sinkholes related to karst phenomena, which are the object of this study. These were geo-referred and organised in a data base, in which information on the geological-structural and hydrogeological features of areas affected by the collapses was also reported. The collapse sinkhole inventory was paralleled by an analysis of the distribution of the main mineral springs (H_2S- and CO_2- rich waters), of travertine bodies and of extensional faults with late Quaternary activity, which were all considered significant to the study due to the interrelations linking travertines, karst solution processes, CO_2- rich waters and faults. Furthermore, with the aim of investigating the role of seismic shaking in the occurrence of the collapses, the karst collapse sinkhole distribution was compared with the distribution of stronger historical earthquake epicentres. The results of this regional scale synthesis suggests a possible key to the interpretation of karst collapse phenomena. The latter, in fact, appear correlated to the combination of peculiar conditions, which may be envisaged in the presence of active faults and mineral waters. The study, in particular, suggests that karst collapse sinkholes result from enhanced dissolution phenomena related to the rising of fluids of deep origin, for which active

Izvleček UDK 551.435.82(234.41)
Antonio Santo, Alessandra Ascione, Sossio Del Prete, Giuseppe Di Crescenzo & Nicoletta Santangelo: Razporeditev udornic v karbonatnih delih osrednjih in južnih Apeninov
Prispevek je osredotočen na udornice v južnih in osrednjih delih Apeninov (Italija) z namenom ugotoviti in razpravljati o dejavnikih, ki prispevajo k razporeditvi udornih pojavov. S pomočjo analize morfometrično/morfoloških oblik okoli 600 na začetku ugotovljenih vrtač, jih je bilo okoli 50 % interpretiranih kot udornice, povezane s kraškimi pojavi, kar je predmet te študije. Podatki so bili povezani z geo-referencami in urejeni v bazo, iz katere je mogoče dobiti tudi informacije o geološko-strukturnih in hidrogeoloških značilnostih področij, podvrženih udiranju. Vzporedno seznamu udornic so tudi analize o razporeditvi glavnih mineralnih izvirov (H_2S in vode, bogate s CO_2), lehnjakovih teles in večjih prelomnic, aktivnih v poznem kvartarju, za kar vse avtorji sodijo, da je pomembno za to študijo glede na povezave med lehnjakom, procesi zakrasevanja (raztapljanja), s CO_2 bogatimi vodami in prelomi. S pomočjo preučevanja vloge potresnih tresljajev pri pojavljanju udorov, je bila v nadaljevanju primerjana razporeditev udornic z razporeditvijo epicentrov močnejših potresov znanih iz zgodovine. Izsledki teh primerjav v regionalnem merilu nakazujejo možni ključ za razlago udornih pojavov v krasu. V resnici se ti pojavljajo v posebnih okoliščinah, ob prisotnosti aktivnih prelomov in mineralnih vod. Študija posebej nakazuje, da so udori posledica pospešenega raztapljanja, povezanega s pojavljanjem tekočin globinskega izvora, ki jim aktivne prelomnice predstavljajo najugodnejše smeri, kot tudi z relativno plitvo gladino podtalnice. Pri samem udoru imajo lahko pomembno vlogo potresni tresljaji.

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faults represent preferred pathways, and favoured by the presence of a relatively shallow water table. In the collapse events, an important role is possibly played by seismic shaking.
Keywords: karst, collapse sinkhole, seismicity, active tectonics, central and southern Apennines.

Ključne besede: kras, udornica, seizmičnost, aktivna tektonika, osrednji in južni Apenini.

INTRODUCTION

In the scientific literature, the terms "doline" and "sinkhole" are both used in a broad sense to indicate medium-sized, closed depressions, generally not holding water. The term doline is mostly used in the European literature to indicate karst related landforms, and includes several subtypes, e.g., solution, collapse, or subsidence dolines (Jennings 1975; Sauro 2003), while "sinkhole" is mainly used in the North American literature to define any sub-circular cavity regardless of its origin (Beck 1984). Moreover, in engineering geology studies, the term sinkhole indicates a steep-sided, closed depression resulting from a sudden collapse of either hard rocks or soft materials. The same term is also used to indicate open cavities resulting from anthropogenic activities. In the last years, the term sinkhole has been adopted in the Italian literature (Nisio 2008; Caramanna *et al.* 2008 and references therein) for any sub-circular cavity resulting from sudden ground failures not directly related to karst dissolution, but to the presence of subterranean anthropogenic cavities in urban areas, of mines and excavations.

Regarding sinkholes related to karst processes (in the following labelled karst sinkholes), in the last years several genetic classifications have been proposed (Williams 2003; Sauro 2003; Waltham *et al.* 2005). In such classifications, two main categories of karst sinkholes are distinguished, i.e., those resulting from: i) dissolutional lowering of the surface, and ii) internal erosion and deformation processes caused by subsurface karstification. More recently, Gutierrez *et al.* (2008) proposed a further genetic classification applicable to both carbonate and evaporite karst areas. The main sinkhole types were distinguished by two terms that indicate: i) the material affected by downward gravitational movements (bedrock, cover or caprock), and ii) the main type of process involved (collapse, suffusion or sagging).

This study focuses on karst sinkholes of the southern and central Apennines region (Italy), i.e., with reference to Gutierrez et al. (2008), to bedrock collapse sinkholes (or collapse dolines sensu Ford & Williams 1989), and to caprock collapse and cover collapse sinkholes, the latter types respectively referring to alluvial fan conglomerate or slope debris, more or less cemented, overlying carbonate rocks. To date, this issue has been largely neglected. Former studies, in fact, have been mainly devoted to sinkholes resulting from deep piping, evorsion and suffusion phenomena (Caramanna *et al.* 2008, and references therein) which affect the plains of the region, in which thick alluvial or pyroclastic covers overly deeply buried bedrocks.

The main aim of this study is the construction of a robust data set, which represents the starting point for the identification of areas more prone to collapse phenomena. This implies an investigation on the factors which may both predispose and determine the occurrence of collapses. The examination of such factors started from the results of recent studies focused on the study area, which suggest some interrelation between collapse sinkholes and faults (Billi *et al.* 2007; Yilmaz 2007) and, particularly, with active faults, mineral springs (CO_2- and H_2S- rich waters), and intense seismicity (Salvati & Sasowsky 2002; Del Prete *et al.* 2010).

THE GEOLOGICAL FRAME

The Apennines chain is a segment of the circum-Mediterranean Alpine system. The Central-Southern Apennines resulted from shortening occurred from the Miocene to the Middle-Late Pliocene in the central portion of the chain, and lasted until the Early Pleistocene in the southern one (Patacca *et al.* 1990; Patacca & Scandone 2001).

Thrusting, with a general NE sense of transport, involved sedimentary thrust-sheets related to carbonate platform-to-slope domains and their interposed basins (Parotto & Praturlon 1975; Patacca *et al.* 1990). Extensional tectonics has affected the internal portion of the chain since the Late Miocene, with the formation of the

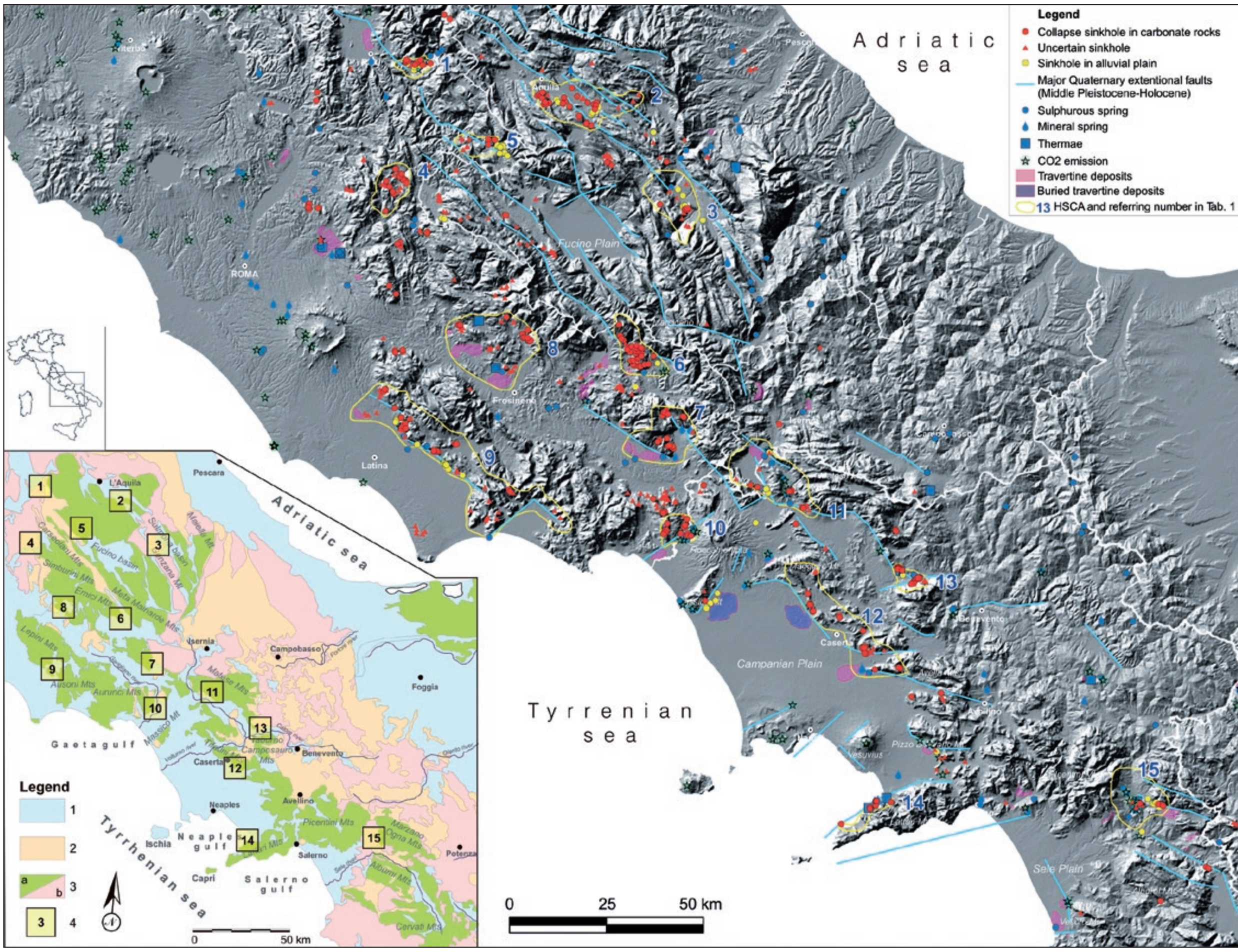


Fig. 1: Collapse sinkholes distribution in Central-Southern Apennines.

Geological sketch: 1) Quaternary deposits; 2) sin-orogenic terrigenous deposits (Miocene – Lower Pleistocene); 3) pre-orogenic deposits (Mesozoic-Tertiary): (A) carbonate platform (B) basinal facies; 4) location of High Sinkhole Concentration Area (HSCA) and referring number (Tab. 1).

Tyrrhenian back-arc basin (Patacca *et al.* 1990; Cavinato & De Celles 1999). Since the Pliocene, the basin extended to the east and the southeast, causing the drowning of the internal sector of the orogenic wedge and the formation of coastal grabens (peri-Tyrrhenian basins) along the SW flank of the chain (Patacca *et al.* 1990). Following the ceasing of the orogenic transport, the chain has been affected by extensional tectonics, which has been responsible for the formation of several intramontane basins (Cinque *et al.* 1993; Hippolyte *et al.* 1994; Cavinato & De Celles 1999; Caiazzo *et al.* 2006).

The extensional tectonics, which is driven by a NE-SW oriented extension direction, is currently active and controls the intense seismicity which affects the axial belt of the chain (e.g., Cello *et al.* 1982; Gasparini *et al.* 1985; Hippolyte *et al.* 1994). Earthquakes in the axial belt are characterised by normal faulting mechanisms, and by focal depths in the upper 15 km of crust (Gasparini *et al.* 1985; Vannucci *et al.* 2004). The major historical shocks (Gruppo di Lavoro CPTI 2004; Vannucci *et al.* 2004) have reached large intensities (I0 > IX MCS, e.g., in 1279, **1349, 1456, 1561, 1654, 1694, 1703,** 1805, 1857) and magnitudes around 7, e.g., the 1980 Irpinia earthquake (M_S 6.9; Bernard & Zollo 1989) and the 1915 Fucino earthquake (M_S 7.0; Gruppo di Lavoro CPTI 2004). Seismic sequences characterised by more aftershocks with high magnitude are also recorded, e.g., the destructive 1703 events (Cello *et al.* 1998b), and the recent 2009 L'Aquila sequence, with a M_w 6.3 main shock followed by seven aftershocks of $M_w \geq 5$ (Pondrelli *et al.* 2009). Coseismic striking ground effects and surface faulting associated with the large earthquakes are documented by both direct observations (e.g. Westaway & Jackson 1984; Pantosti & Valensise 1990; Cello *et al.* 1998a; Vittori *et al.* 2000) and palaeoseismological investigations (e.g., Pantosti *et al.* 1993, 1996; Blumetti

1995; Michetti *et al.* 1996; Esposito *et al.* 2000; Galli *et al.* 2008).

In the study region, the most widespread geomorphologic units are represented by carbonate massifs, coastal alluvial plains and intramontane basins. The *carbonate massif unit* includes the main mountain areas of the Abruzzi, Latium and Campania Apennines (Fig. 1), which are commonly composed of Mesozoic-Tertiary limestones and dolostones pertaining to both carbonate platform and slope environments. The landscape of the massifs is typically characterised by summit plateaux bounded by steep structural hillslopes, which grade to wide piedmonts areas. In this unit, dissolution processes produced a strong karstification in Quaternary times, as shown by the widespread epikarst landforms and cave systems. The *coastal alluvial plain unit*, well represented by the Tiber, Fondi, Campania and Sele plains, includes the large extensional grabens which were formed during the Pliocene-Early Pleistocene in response to the formation of the Tyrrhenian basin (Brancaccio *et al.* 1991; Nisi *et al.* 2003; Barberi *et al.* 1994). Since the Middle Pleistocene, the Tiber plain and the Campania coastal plains have been affected by severe volcanism. The *intramontane basin unit* is represented by large depressions mostly located in the axial portion of the central and southern Apennines. These basins display variable stratigraphical features (lacustrine and/or alluvial facies), drainage conditions (exorheic/endorheic), structural setting (mainly half grabens, or fault dammed), degree of dissection and age of formation/filling up. Formation of the intramontane basins took place since the Late Pliocene (e.g., Fucino basin; Cavinato *et al.* 2002), however most of such basins were formed in Early to Middle Pleistocene times (Santangelo 1991; Miccadei *et al.* 1998; Karner *et al.* 1999; Munno *et al.* 2001; Bosi *et al.* 2003; Galadini & Messina 2004; Aiello *et al.* 2006 and references therein).

METHODOLOGICAL APPROACH

In order to examine what are the factors which possibly both predispose and determine the karst collapse sinkhole (hereinafter, KCS) formation, we used a combined geological-geomorphological and morphometrical approach. Information obtained by this approach was organised in a data base, which allowed quantitative analyses aimed at the identification of areas more prone to the occurrence of collapse phenomena.

The first step of the study was the KCS inventory, which was carried out through the inspection of aerial photographs and topographic maps at various scales (from 1:50.000 to 1:5.000) and allowed the recognition of more than 600 sinkholes. In the preliminary stage, particular attention was devoted to the distinction, based on the morphometrical and morphological features, of collapse sinkholes from dissolution dolines. Taking into account that the former exhibit steep sided to sub-vertical rocky walls and subangular or elliptical perimeters, whereas the latter are generally characterised by gentler slopes and sub-circular shapes (Ford & Williams 1989), the features we considered as diagnostic parameters were the side steepness and the planar shape. The sinkhole location was also considered based on evidence that, generally, the solution dolines are densely distributed on wide plateaux, while frequently the collapse sinkholes are isolated and occur on the hillslopes. The sinkhole evolutionary stage (youthful, mature, degraded, *sensu* Jennings 1975 and Waltham 2005) was also examined. As a result of this analysis, eroded landforms that could not be unequivocally interpreted as degraded KCSs, were taken out of the data set. By the analysis of the morphometrical/morphological features, about 50% of the initially mapped landforms were interpreted as KCSs (Fig. 1). The latter were geo-referred and organised in a data base. In the data base was also reported information on the geological-structural and hydrogeological features of areas affected by the collapses. Such information was obtained by field surveys carried out in some selected sites, and/or by literature data.

The KCS inventory was paralleled by an analysis of the distribution, derived by topographic, geological, and hydrogeological maps (e.g., Istituto Superiore per la Protezione e la Ricerca Ambientale n.d.) of the main mineral springs (Fig. 1), i.e., springs characterised by H_2S- and CO_2- rich waters. This was done based on a recent study regarding the Campania Apennines (Del Prete *et al.* 2010), which suggests that mineral waters rising along major fault zones, where deeply derived fluids mix with meteoric groundwater, strongly affect the KCS formation. In addition, taking into account: i) the well known interactions of normal faults with fluids circulation and migration (Sibson 2000), ii) that intersecting tensional fissures or faults are suggested as responsible for enhancing hydrothermal flow (Hancock *et al.* 1999; Çakir 1999; Brogi *et al.* 2009), and iii) the control exerted by faults on karst dissolution (Billi *et al.* 2007), we examined the possible relation of collapse phenomena with major extensional faults zones. Among the latter, we selected the youngest faults in the region, i.e., faults active in the late Quaternary (the late Middle Pleistocene-Holocene time span), which are mapped in Fig. 1. For most of the mapped faults there is evidence of activity during the Late Pleistocene-Holocene, as shown by numerous stratigraphical, geomorphological and paleoseismological studies carried out in the last decennia. Regional scale syntheses of such studies are provided by Galadini & Galli (2000), Cinque *et al.* (2000), Galadini & Messina (2004), Papanikolaou *et al.* (2005), Caiazzo *et al.* (2006), Galli *et al.* (2008), and related references.

Another information in Fig. 1 is the distribution (derived from literature data and geological maps) of both outcropping and buried travertine bodies. These were considered significant to the study due to the interrelations linking travertines, karst solution processes and CO_2- rich waters, and to those linking travertine deposits, faults and hydrothermal flow. The latter are shown by the preferential location of travertines either above extensional fissures or in the hanging walls of normal faults (e.g., Hancock *et al.* 1999), and by the correlation of some travertine bodies with thermal and cold spring waters (e.g., Minissale *et al.* 2002; Minissale 2004; Uysal *et al.* 2009). Based on such issues, also CO_2 gas vents (derived after Minissale 2004; Chiodini *et al.* 1999, 2000; Istituto Nazionale di Geofisica e Vulcanologia, 2006-2007) were considered and mapped in Fig. 1.

The last step of the study was the identification of events responsible for the collapse occurrence. This was done by consulting historical archives in the search for witnesses of collapse events. Furthermore, taking into account the recently proposed new EEEs INQUA scale (Michetti *et al.* 2004), in which the sinkhole formation is accounted among the secondary ground effects associated with strong earthquakes (and considered as diagnostic of macroseismic intensities larger than VIII degree), the role of seismic shaking in the collapse events was investigated by comparing the KCS distribution with the distribution of stronger historical earthquakes epicentres.

TYPOLOGY AND MORPHOMETRICAL FEATURES OF KARST COLLAPSE SINKHOLES

According to the classification by Gutierrez *et al.* (2008), most of the central-southern Apennines KCSs fall in the bedrock sinkhole typology. In fact, 84% of the KCSs affects carbonate rocks, essentially Cretaceous and Jurassic limestones (Fig. 2A; Tab. 1), and only 4% are cap-rock or cover collapse sinkholes, respectively formed in slope debris and alluvial deposits (2%) overlying the carbonates.

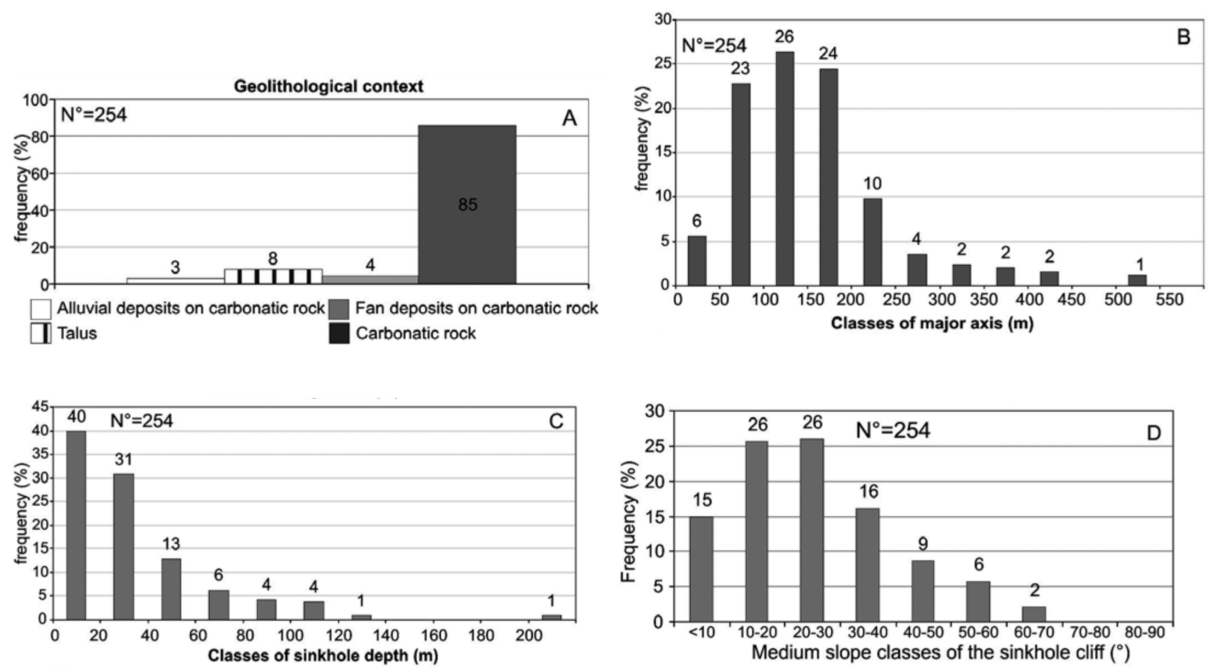
Regarding the KCS morphometrical features, about 75% is characterised by large width, with main axes spanning from 50 to 200 m (Fig. 2B). The depths range from few metres to 140 m, and the more frequent (about 85%) depth values vary from 10 to 50 m (Fig. 2C); the remaining sinkholes are characterised by large depths, with values from 60 to 100 m. For the examined popula-

Tab. 1: Main geographical, lithological and geomorphological features of the HSCAs.

HSCA	***Massif***	***N° of sinkholes***	***lithology***	***Geo-morphological context***	***Villages***
1	Reatini Mts.	13	4: Miocene and Paleogene calcarenites 3: Liassic dolomitic limestones	I B	Paterno S. Vittorino
2	Ocre Mt.	24	9: Cretaceous limestones 9: Quaternary sediments covering limestones	I B	L'Aquila Fossa, Stiffe
3	San Cosimo Mt.	5	3: Quaternary sediments covering limestones 2: Miocene and Paleogene calcarenites	I B	Prezza, Sulmona
4	Lucretili Mts.	11	Miocene and Paleogene calcarenites	CS	Percile, Orvinio
5	Duchessa Mts.	4	4: Jurassic and Cretaceous dolomitic limestones	IB	Castelmenardo Corvaro
6	Tranquillo–S. Nicola Mts.	33	31: Cretaceous limestones 2: Quaternary conglomerates covering limestones	CS, IB	Alvito, Campoli
7	Cassino Mts	17	17: Cretaceous and Paleogene limestones	CS, IB	Cassino, Atina
8	Ernici Mts.	11	11: Cretaceous limestones	CS	Acuto, Collepardo
9	Lepini Mts.	18	18: Cretaceous and Paleogene limestones	B C P	Norma, Sezze, Cori, Priverno

HSCA	*Massif*	*N° of sinkholes*	*lithology*	*Geo-morphological context*	*Villages*
10	Aurunci Mts.	16	16: Cretaceous and Paleogene limestones	CS, BCP	Suio, Santi Cosma e Damiano
11	Venafro Mts.	13	2: Cretaceous limestones 7: Giurassic dolomitic limestones 4: Quaternary conglomerates covering limestone	I B, CS	Venafro, Sesto Campano
12	Caserta and Tifata Mts.	17	17: Cretaceous limestones	B C P	Caserta, Maddaloni
13	Maggiore-Camposauro Mts.	22	12: Cretaceous limestones 10: Quaternary conglomerates covering limestone	I B	Telese, Solopaca
14	Lattari Mts.	8	8: Cretaceous limestones	B C P	Castellammare Vico Equense
15	Marzano Mts.	9	6: Cretaceous and Jurassic limestones 3: Quaternary conglomerates covering limestone	I B	Contursi, Buccino
Total		220			

HSCA= High sinkhole concentration area; I B= border of intramontane basin; B C P= border of coastal plain; carbonate slope= CS



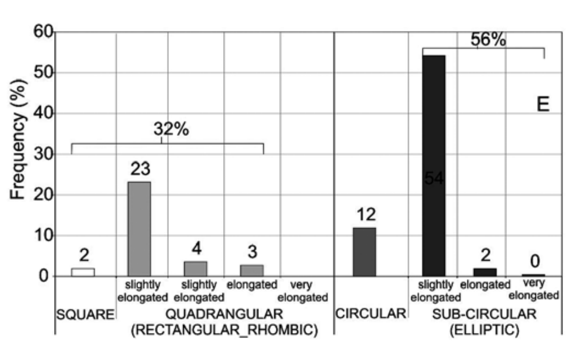


Fig. 2: Main geological and geomorphological features of the examined KCSs.

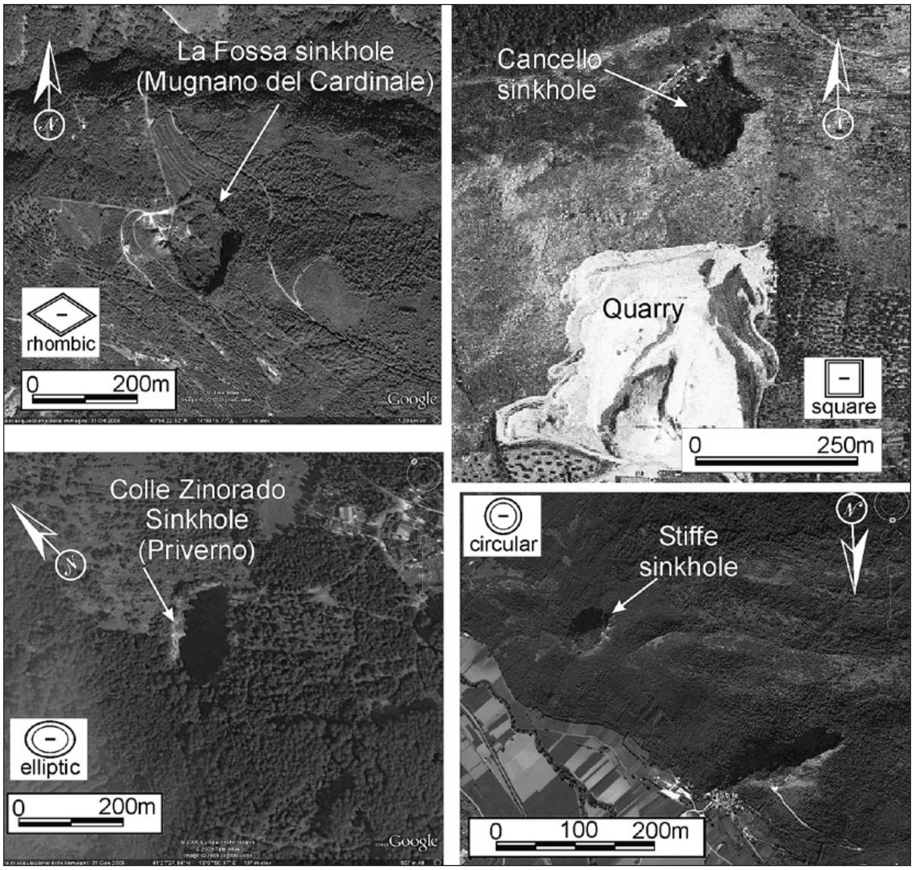


Fig. 3: Examples of sinkholes with different planar shapes.

tion, the volumes range from several thousand to a few millions of cubic metres.

In the evaluation of the sinkhole sides steepness (Fig. 2D), which varies downslope (the upper portion is generally sub-vertical), we calculated the average slope angle by measuring, as height values, the vertical distance separating the maximum elevation along the sinkhole perimeter to the bottom elevation. The obtained values range from 20° to 70° in 70% of the examined KCSs.

The KCS planar shapes vary from squared to rhombic, elliptical and sub-circular (Fig. 3). Only 12% of KCS perimeters is close to a circular shape (Fig. 2E), while 32% displays angular perimeters and about 56% an elliptical shape, with major axis/short axis ratios ranging from 1.4 to 4. Both the angular and the elongated shapes, which characterise most of the KCSs, suggest that the development of such landforms is passively controlled by fractures and fault planes affecting the carbonate rock masses.

KARST COLLAPSE SINKHOLE DISTRIBUTION IN RELATION TO THE GEOLOGICAL AND STRUCTURAL SETTING

The KCS distribution shown in Fig. 1 is probably incomplete. In fact, the inventory (which was based on the inspection of topography) does not account for (i) relatively old, strongly eroded or buried and, therefore, currently unrecognisable sinkholes, and (ii) very small (metre) sized KCSs hypothetically undetected as a result of an inadequate scale adopted in this regional study.

The regional distribution of KCSs appears strikingly uneven: the majority of such landforms is located along the borders of the main coastal plains and intramontane basins (Fig. 1). In relation to the local geomorphological context (Fig. 4A), it results that 22% of the KCSs occurs in piedmont areas, 22% on relief tops, and a much larger amount (57%) along the hillslopes which, in most cases, consist of fault escarpments. Both the large and small scale distributions of KCSs indicate that these landforms post-date not only the major (i.e., distribution of the structural highs and lows) but also the minor (e.g., fault escarpments, piedmonts) features of the present-day landscape. Based on such evidence, formation of the mapped KCS may be framed within the Middle Pleistocene- Present time span.

The inspection of the sinkhole regional distribution suggests a striking relation of these landforms with the main late Quaternary extensional faults (Fig. 1). Several High Sinkhole Concentration Areas (from now on

HSCAs), in fact, show either clustered patterns aligned with, or linear patterns following the trend of such faults. Quantitatively, the spatial relationship between sinkholes and faults was assessed by measuring the distance which separates each sinkhole from the fault bounding the hillslope relatively closer to it, i.e., the horizontal length spanning from each sinkhole outer edge to the toe of the neighbouring fault escarpment. The bar chart in Fig. 4B shows that about 60% of collapse sinkholes fall within a distance of 200 m from the closest main fault, and a large majority (80%) occur at distances lower than 400 m from the fault. Furthermore, on the regional scale a significant coincidence of the more frequent orientation of both the fault zones and sinkhole alignments is observed (Fig. 5), with respectively 48% and 39% showing a NW-SE (N120°-N160°) trend, and 14% and 18% with a NE-SW (N30°- N60°) orientation.

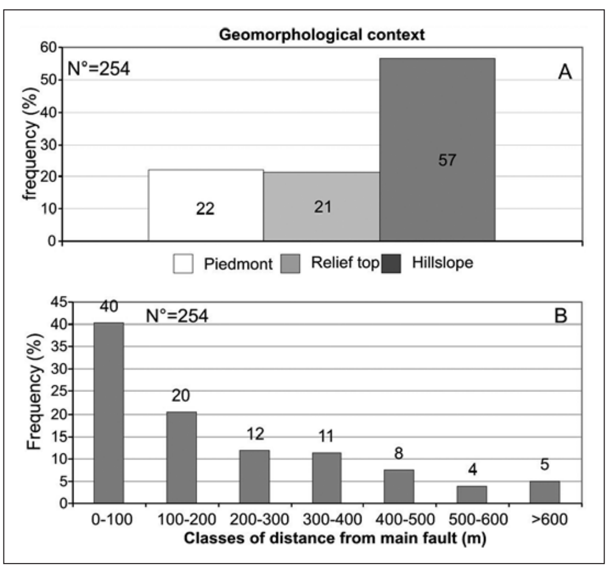


Fig. 4: Frequency diagrams of the distribution of KCSs in relation to the local geomorphological context (A) and to the distance from the closest main fault (B).

A striking alignment of KCSs and faults is present in HSCAs 9, 10, 12, 14, which are located in the horst blocks bounding the Pontina, Fondi and Campania Plain coastal grabens (Fig. 1). Collapse sinkholes, in such HSCAs, show a striking alignment along both the major NW-SE and NE-SW trending (e.g., HSCAs 9 and 14) and the minor WNW-ESE (HSCA 12) normal faults bounding the grabens. These faults have been active since the Late Pliocene (Pontina Plain) or the Early Pleistocene (Campania Plain), and have produced vertical offsets on the order of some thousands of meters. A recent (Late Pleistocene or Holocene) activity of such faults is documented by offset of recent, dated, shore/littoral facies deposits, respectively lying in the subsurface of the grabens and outcropping on the bounding horsts, at elevations different from that of the correlative past sea-levels (Antonioli *et al.* 1988; Nisi *et al.* 2003; Romano *et al.* 1994; Ferranti *et al.* 2006).

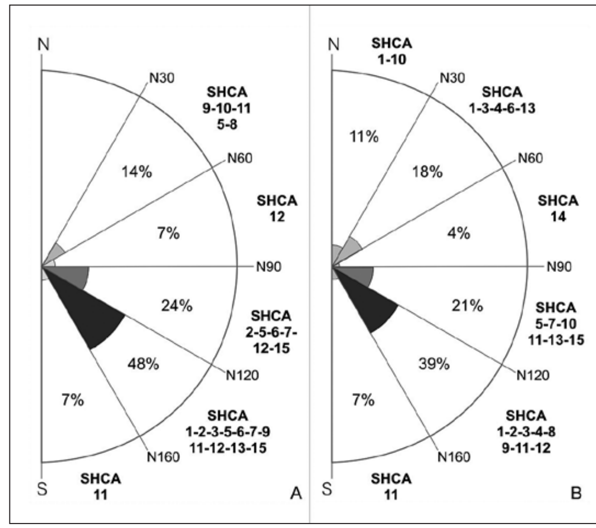


Fig. 5: Fault orientation (A) and sinkhole alignment (B) frequency diagrams.

Further examples of KCS linear patterns which follow faults active in the late Quaternary-Holocene, are those of HSCAs 2 and 15 (Fig. 1). HSCA 15 (Mt. Marzano massif area) follows the NWN-ESE fault zone which bounds to the N the Middle Pleistocene-Holocene Buccino basin (Fig. 1), and shows striking evidences of Late Pleistocene–Holocene activity, i.e., bedrock fault scarps and offset Upper Pleistocene-Holocene alluvial fans and debris slope deposits (Ascione *et al.* 2003; Aiello *et al.* 2006). Worthy to note is also that the basin fill includes buried travertine deposits (Ascione *et al.* 2003). HSCA 15 includes both bedrock sinkholes in the northern mountain front, and cap-rock sinks, which affect a late Middle Pleistocene-Upper Pleistocene alluvial fan in the hangingwall block.

In HSCA 2, the KCSs follow NE-SW trending faults which bound the Pliocene-Quaternary (Bosi *et al.* 2003) L'Aquila intramontane basin to the NE and SW. These faults include the Paganica fault, which defines the NE border of the basin and shows evidence of Late Pleistocene-Holocene activity (Papanikolaou *et al.* 2005). This fault is considered as the surface expression of the fault responsible for the L'Aquila sequence main shock (Pondrelli *et al.* 2009; Atzori *et al.* 2009), which dramatically struck this area in April 2009 and caused coseismic ground deformation (Anzidei *et al.* 2009; Falcucci *et al.* 2009). In the L'Aquila basin area, both bedrock and cover collapse sinkholes are present. The former are located both in the NE and SW mountain fronts. The latter are mostly located in the central portion of the basin (Nisio 2008). Such sinkholes affect alluvial units with ages up to the latest Middle Pleistocene, and follow parallel faults which both bring into contact the Mesozoic carbonates with Quaternary alluvial deposits, and offset Quaternary depositional terraces (Istituto Superiore per la Protezione e la Ricerca Ambientale n.d.).

A relationship with the late Quaternary faults may be envisaged also for the clustered KCSs which surround the Alvito-Campoli and Atina basins, i.e. HSCAs 6 and 7. HSCA 6 is interposed between the southern termination of the Liri fault, which shows evidence of post-18ka activity (bedrock fault scarps; Papanikolaou *et al.* 2005), and the fault bounding the Atina basin to the NE. HSCA 7 is located at the northern termination of a structure with Late Pleistocene-Holocene evidence of activity consisting of bedrock fault scarps and offset debris slope deposits (Bosi 1994; Papanikolaou *et al.* 2005).

SINKHOLES, MINERAL SPRINGS AND RELATIONSHIPS WITH THE WATER TABLE

The census of the mineral springs in the Central-Southern Apennines (Fig. 1) allowed the mapping of 80 springs, among which 57 can be classified as sulphurous. The mineral springs are absent in only three of the HSCAs (2, 4 and 5; Tab. 2).

Most of the mapped springs are important basal springs with significant discharge values (hundreds of l/s). The main springs of Lazio and Abruzzo regions show calcium bicarbonate and calcium sulphate chemical compositions, with a conductivity ranging from 800 μS/cm to 2700 μS/cm (Boni *et al.* 1980, 1986; Minissale 2004 and references there in). In several cases, high values of sulphates and, in some cases, also thermal waters are present (Tab. 3). The main springs of the Campania region (Tab. 4) are characterised by sulphurous and calcium bicarbonate chemical composition (Celico 1983; Allocca *et al.* 2007), with temperatures ranging from 12° to 44°C, CO_2 values of about 2200 mg/l and conductivity from 300 to 2900 μS/cm (e.g., Telese and Contursi springs; Corniello & de Riso 1986; Celico *et al.* 1998).

These data indicate that the majority of the HSCAs is characterised by highly mineralized springs, often sulphurous. According to Klimchouk (2007), the mixing of deeply derived fluids with meteoric waters at the water table level may enhance strong dissolution processes throughout the correlative aquifers. For this reason, in areas for which hydrogeological data are available, the depth of the water table relative to the KCSs was evaluated by estimating the vertical separation between the water table and each sinkhole bottom. The resulting data, which represent maximum

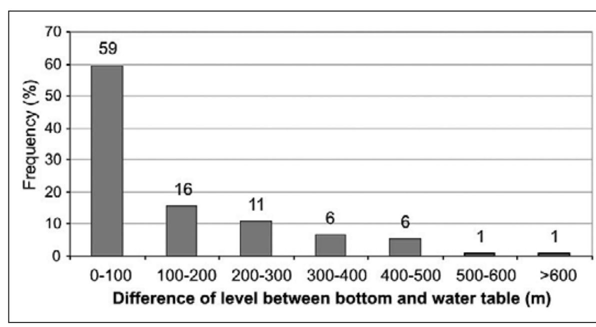


Fig. 6: Relationships between KCS bottom elevation and water table level.

Tab. 2: Distribution of mineral springs and travertine bodies in the Central-Southern Apennines.

HSCA	*N° of sinkholes*	*Sulphurous Springs*	*Mineral springs*	*Travertine deposits*	*CO_2*	*Thermae*
1	13	3	1	1	2	1
2	24	-	-	-	-	-
3	5	2	-	1	-	-
4	19	-	-	-	-	-
5	4	-	-	-	-	-
6	33	1	-	3	3	-
7	17	3	3	3	-	-
8	11	3	2	3	-	2
9	18	10	-	1	2	-
10	16	10	-	1	4	1
11	13	15	3	1	4	-
12	17	2	2	1	1	-
13	22	3	2	1	2	1
14	8	2	3	-	-	2
15	5	3	8	1	6	2

Tab. 3: Chemical features of the main springs of HSCAs in Lazio and Abruzzo regions.

HSCA	Spring name	T (°C)	pH	SO_4	pCO_2
1	Terme di Cotilia	17	6.23	230	0.0
8	Terme di San Pompeo	21	6.00	53	0.0
9	Vescovo Lake	19	6.60	183	- 0.5
10	Terme di Tomassi	58	6.70	384	0.2

values (not accounting for the currently unknown thickness of the sinkhole fillings), indicate that 59% of KCSs falls within 100 m above the water table (Fig. 6). Taking into account i) that strong dissolution may affect a relatively narrow belt overlying the groundwater level, and ii) the water table oscillations related to the climate (humid/arid) fluctuations, by the frequent <100 m height difference it can be hypothesized a correlation between strong dissolution phenomena and past groundwater levels. To the less aggressive circulation in the vadose zone may be related the lesser amount of KCSs developed at larger distances (ranging from 200 to 600 m; Fig. 6) from the water table. Formation of at least some of the relatively higher KCSs, however, might also be related to old, uplifted, water table levels.

Tab. 4: Chemical features of the main springs of HSCAs in Campania and Molise regions.

HSCA	Spring name	Chemical facies	T (°C)	CO_2 (mg/l)	Electrical conductivity (µS/cm)
11	Ielo	Calcium bicarbonate	13	25	480
11	Lete	Calcium bicarbonate	14	1970	1359
11	Prata e Mulinello	Calcium bicarbonate	13	63	776
12	Calabricito	Calcium bicarbonate	16	278	1899
12	Mofito	Calcium bicarbonate	14,5	107,6	1146
12	Triflisco	Calcium bicarbonate	14,5	250-355	1333
12	Fontana Pila	Calcium bicarbonate	14,5	248	1106
13	Grassano	Calcium bicarbonate	12	116	
13	Telese Terme	Sulphureous calcium bicarbonate	16-21	860-1002	1488-2900
13	Fontana Bolla	Sulphureous calcium bicarbonate	--	--	--
14	Scrajo	Sulphureous calcium bicarbonate	17	1232	7520
14	Castellammare	Calcium bicarbonate	12-17,4	164-877	5725-18400
15	Contursi Bagni	Sulphureous calcium bicarbonate	21-29	379,8-1150	2568-6015
15	Contursi Terme	Calcium bicarbonate	14,7-44	240-430	890-4020

Tab. 5: Documented co-seismic karst collapse sinkholes.

Number of events	sinkhole development date	earthquake date	epicentre	distance	I MCS to the epicentre	I MCS to the site	days from the seismic event
8 (minimum) KCSs in Telese area (HSCA13)	1349-9-9	1349-9-9	Cassino	60 km	X-XI	X	0
1 KCS in Castellammare village (Lattari Mts; HSCA 14)	1456-12	1456-12	Central Italy	85 km	X-XI	VII-VIII?	0
1 KCS near Sigillo village (Rieti province) and 1 at Roio Piano near L'Aquila (HSCA 2 & 7)	1703-2-2	1703-2-2	Norcia-L'Aquila	15-30 km	X	IX-X?	0
Jala KCS (Lattari Mts; HSCA 14)	XVII century	1695-1698	Lucania	80 km	V-VII		0?
Enlargement of some KCSs of 1349 earthquake in Telese area (HSCA 13)	1805-07-26	1805-07-26	Molise	30 km	XI	VIII	0
1 KCS in Pianelle loc. (Marzano Mts; HSCA 15)	1981-5	1980-11-23	Irpinia	8 km	X	X	130
1KCS at Mt Nuria, near Pendenza village, Velino valley (HSCA1)	1997-10-11	1997-10-11	Umbria-Marche	70 km	VI-VII		0
Enlargement of 1 pre existing KCS (Sinizzo lake; HSCA 2)	2009-4-6	2009-4-6	L'Aquila	5 km	X-XI	X	0

TRAVERTINE DEPOSITS DISTRIBUTION

Travertine deposits (Fig. 1 and Tab. 2) are present in most of the HSCAs, and are also frequently associated with sulphurous springs and/or CO_2 gas vents.

Travertine deposits and, in some cases, current travertine deposition, characterise several intramontane basins (the largest bodies are located in the intramontane basins of Fiuggi, Frosinone, Cassino, Venafro, i.e., HSCA 6, 7, 8 and 11) and the coastal plains (Cisterna di Latina, Minturno, Cancello, Sarno, respectively HSCA 9, 10, 12). It these areas, subsurface data, when available (e.g., Buccino area, Campania Plain, Venafro plain), testify to the presence of buried travertine deposits in the stratigraphical record. Such superposed travertine deposits, i.e., repeated depositional phases, suggest the persistence in these areas of hydrogeological conditions similar to the present ones.

Buried and outcropping travertine deposits have ages spanning from the Middle Pleistocene to the Holocene (Minissale 2004) and, on a regional scale, are basically coeval to the KCSs.

The co-presence of large volume travertine bodies and clustered KCSs which is often observed, suggests conditions of enhanced dissolution in the surrounding carbonate masses.

SINKHOLES VS. SEISMICITY

In Fig. 7 are reported the epicentres of the main historical earthquakes in the central-southern Apennines. This information compared with the KCS distribution (Fig. 1) indicates that, in several cases (e.g., L'Aquila, Avezzano, Cassino, Sora, Isernia, Benevento, Telese, Solopaca, Contursi), the epicentral zones either fall within or are very close to the HSCAs.

In historical reports on many of the destructive earthquakes, only few collapse events correlated with strong ground-shaking are recorded (Fig. 8 and Tab. 4). The reported events include the large collapses, with gas and fire emissions occurred around Sigillo and Lucoli villages (Central Apennines; HSCA 2) concomitant with the 2 February 1703 earthquake (Cappa 1871; Margottini 1983; Nisio 2008). By comparing the picture by Cappa with present day maps, the co-seismic origin of the Sigillo (Fig. 9) and Roio Piano (Lucoli) sinkholes was recognized. Furthermore, Maffei *et al.* (2005) report the formation, on 11 October 1997, of a collapse sinkhole along the SE slope of the San Vittorino plain (HSCA 1) in connection with one of the Umbria-Marche seismic sequence events (maximum magnitude M=6.0). In addition, the reports on ground secondary effects related to

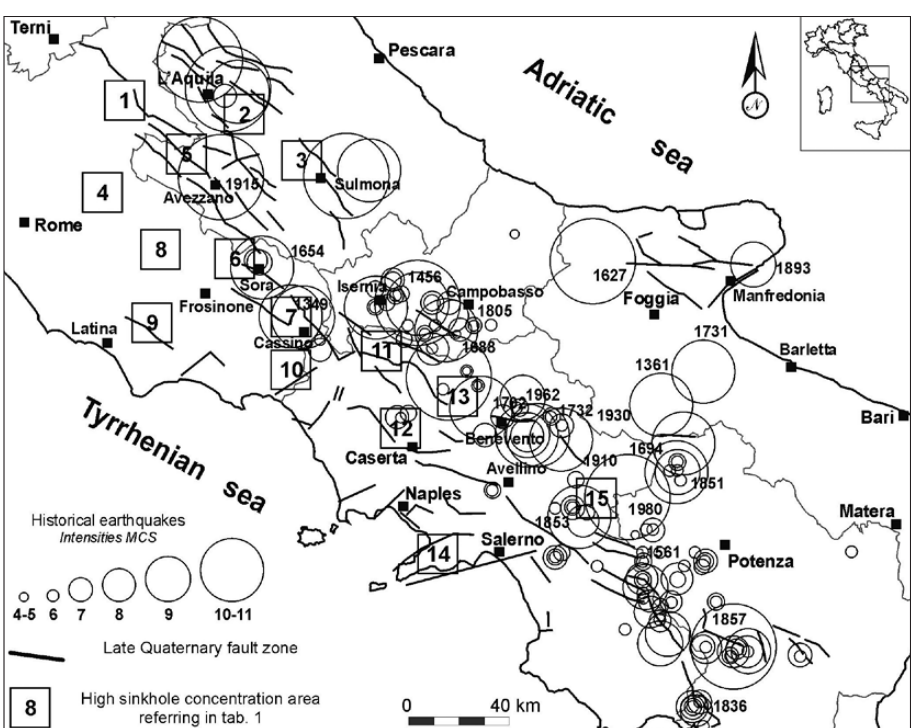


Fig. 7: Epicentral areas of major historical earthquakes of the Central-Southern Apennines region (modified from Porfido et al. 2002 and Gruppo di Lavoro CPTI 2004).

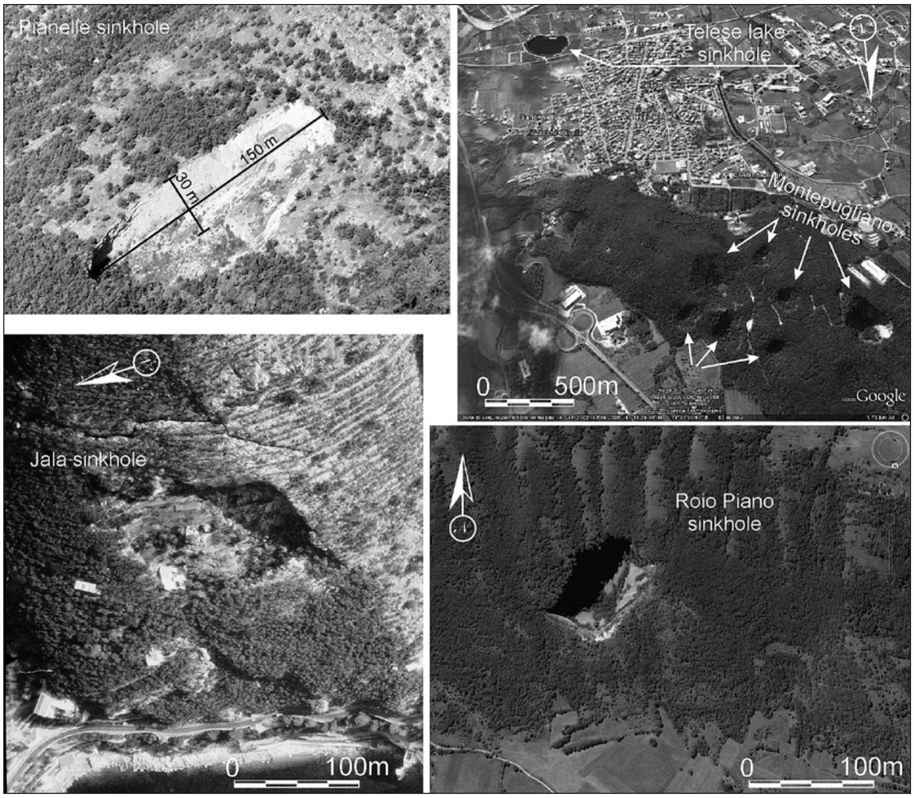


Fig. 8 : Examples of sinkholes originated or enlarged after strong earthquakes.

Fig. 9: Historical picture (from Margottini 1983) and present day view of the Sigillo sinkhole, formed after the 1703 L'Aquila earthquake.

the April 2009 L'Aquila earthquake account for a significant enlargement of the Sinizzo sinkhole (HSCA 2).

Regarding the Southern Apennines, the formation of several sinkholes in the Montepugliano and Telese area (HSCA 13) was correlated by Del Prete *et al.* (2010) with the strong earthquake of 9 September 1349, with epicentre in the Mt. Cassino area (Rossi 1857; Riccardi 1927; Fig. 8). The Montepugliano sinkholes were also enlarged after the M=6.8 seismic events occurred on 26 July 1805 (Porfido *et al.* 2002). In addition, the Pianelle sinkhole, a large ellipsoidal depression (150 m long and 35 m deep) in the Buccino area (HSCA 15; Fig. 8) which was formed in May 1981, six months after the M= 6.9 Irpinia earthquake (Budetta *et al.* 1996), may be considered as a delayed secondary effect of strong ground shaking. A further example is the Jala sinkhole (Sorrento Peninsula; HSCA 14), which is related to a strong earthquake occurred in the Middle Ages (Santo & Tuccimei 1997).

DISCUSSION

The analysis of the KCS distribution throughout the Central-Southern Apennines suggests that collapse phenomena are not the mere response to the concurrence of the climatic and lithological conditions which commonly favour the development of karst processes. The analysis, in fact, has shown that this distribution is strikingly uneven. In addition, the cross correlation among karst collapse sinkholes, H_2S and/or CO_2

mineral springs, travertine deposits and Quaternary extensional faults, has shown the concomitant presence of all such features in HSCAs 1, 6, 7, 9, 10, 11, 12, 13 and 15. Such evidences highlight that karst collapse phenomena are favoured by complex interactions of several factors.

The co-presence of KCS, mineral springs and travertine deposits points to interrelations linking dissolution phenomena, and consequent carbonate deposition, to the rising of aggressive fluids. In particular, it suggests enhanced dissolution, and consequent carbonate deposition, in presence of ascending mineral waters. This supports the hypothesis of Klimchouk (2007) about the interactions of soluble rocks and ascending waters (often thermal and rich in CO_2 and/or H_2S), which may allow strong hypogenic dissolution karst processes at the water table level. Further support to this hypothesis is provided by the relatively short vertical distance which, in the analyzed cases, separates the KCSs from the water table (Fig. 10). However, it is worthy to notice that in the HSCAs important cave systems have not been identified to date. Such lack of knowledge may either result from insufficient speleological surveying, or from absence of significant cave systems. The latter hypothesis rises the question that KCS formation is not uniquely related to the collapse of cave vaults. As an alternative hypothesis, we suggest that the loss of volume which is observed at the sinkholes may originate from diffuse karstification and resulting void enlargement, a process which is more likely to occur in densely fractured rocky masses, as it is suggested by Maffei *et al.* (2005) and Del Prete *et al.* (2010).

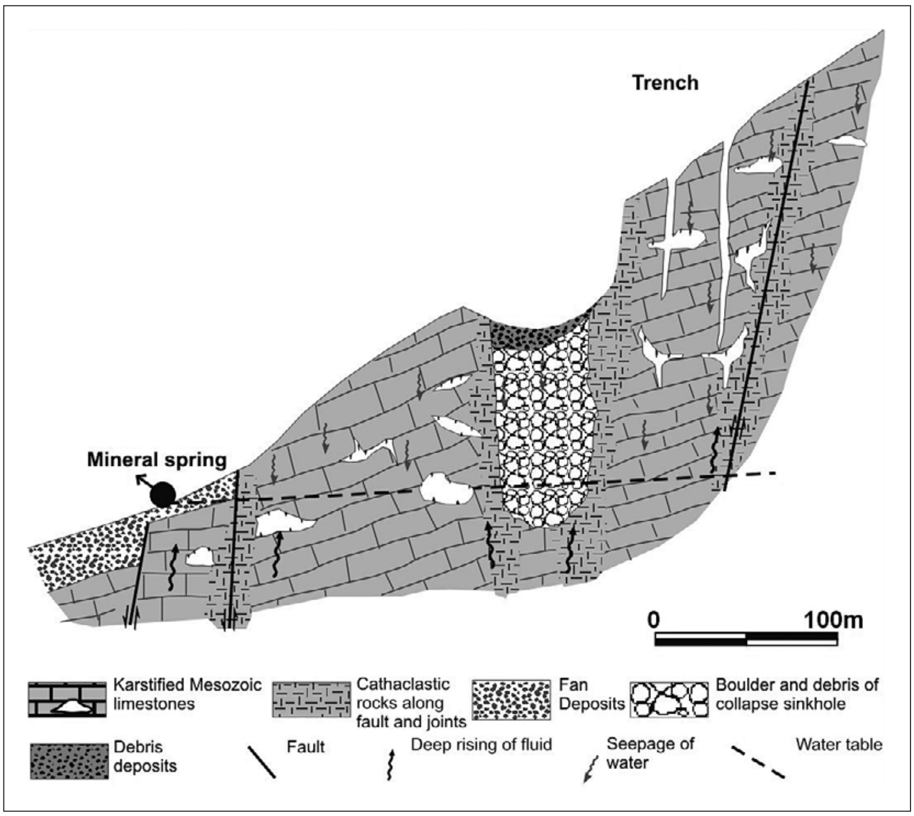


Fig. 10: Schematic cross-section showing the main predisposing factors in the sinkhole formation (from Del Prete et al. 2010, modified).

The collected results point to the control exerted by fault zones in the occurrence of karst collapse phenomena. Such control may be envisaged in the KCS patterns, which are either elongated following the late Quaternary fault zones (e.g., Figg. 1 and 5), or clustered at the fault terminations, and by the short horizontal distance of sinkholes form the closest fault zones (Figg. 1 and 4B). Furthermore, the concomitant presence, at some places, of all features considered in this study (i.e., KCS, mineral springs, travertines and faults), points to an important role played by extensional fault zones in the migration of deeply derived fluids, and supports the results of several former studies (e.g., Kerrich 1986; Aydin 2000; Sibson 2000). In addition, the results suggest that active faults, in particular, represent preferential pathways for fluid rising and mixing with shallow groundwater.

Regarding the basic absence of KCSs in areas with recent tectonics, it may represent the response to either local (i.e., lithology, e.g., Sele coastal plain, in which dolostones and dolomitic limestones prevail), or/and (e.g., Fucino area and area to the N of the Matese massif, in which also mineral springs and travertine deposits are absent) deep seated factors, i.e. the fluid migration is inhibited, or diverted, at depth. The more puzzling non-coincidence of some HSCA with either important tectonic structures (e.g., HSCA 3 and 8) and/or mineral springs/travertine bodies (e.g., HSCA 4) may, on the other hand, result from either insufficient input data (non-detected recent activity of relatively old Quaternary faults, e.g., HSCA 8), or the contribution of other, to date not considered, predisposing factors, urging the development of further studies.

As regard the factors determining the collapse events, the role played by significant ground shaking associated with strong earthquakes may be only hypothesised. Historical evidence collected to date is, in fact, too poor to allow any robust correlation between such phenomena. Nonetheless, the lack of records on collapse events might be related to an older (pre-historical) age of most sinkholes. Therefore, based on observation that HSCA 2, 3, 5, 6, 7, 11, 13 and 15 fall within the epicentral areas of strong historical earthquakes, it can be hypothesized that KCSs pertaining to those HSCAs represent near field effects of past seismic events. In addition, it cannot be excluded that KCSs in the remaining HSCAs represent either far field environmental effects of known seismic events, or near field effects of pre-historical earthquakes.

CONCLUDING REMARKS

This study presents the first karst collapse sinkhole inventory for the Southern and Central Apennines region. In this area, which is representative of a young orogenic system, characterised by recent tectonic activity and high seismicity, the KCS distribution appears to be strongly influenced by structural and hydrogeological conditions.

The results of this regional scale synthesis on the KCSs suggest a possible key to the interpretation of karst collapse phenomena. The latter, in fact, appear correlated to the combination of peculiar conditions, which may be envisaged in the presence of active faults and mineral waters. The study, in particular, suggests that KCSs result from enhanced dissolution phenomena related to the rising of deeply derived fluids, for which active faults represent preferred pathways, and favoured by the presence of a relatively shallow water table. In the collapse events, an important role is possibly played by seismic shaking.

The poor direct observation on karst related collapses indicates that these phenomena occur as sudden ground failures, which may involve rock volumes on the order of 10^5 m^3. It is worth noting that the debutressing associated with collapses may cause instability and further failure upslope. This suggests that karst collapse phenomena may represent a source of hazard which should not be neglected in areas, such as the Apennines, affected by large earthquakes.

Moreover, both the presence of KCSs and the identification of collapse prone areas should be considered in territorial planning (Yilmaz 2007; Galve *et al.* 2008). In fact, the presence of highly fractured and karstified carbonate rocks may seriously affect the construction of infrastructures such as roads or tunnels (e.g., Budetta *et al.* 1996, Maffei *et al.* 2005, Del Prete *et al.* 2010). In this regard, the results of this study may represent a starting point for the identification of collapse susceptible areas which, therefore, should be the foci of detailed studies and the object of monitoring.

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REFERENCES

Aiello, G., Ascione, A., Barra, D., Munno, R., Petrosino, P., Russo Ermolli, E. & F. Villani, 2006: Evolution of the late Quaternary San Gregorio Magno tectono-karstic basin (southern Italy) inferred from geomorphological, tephrostratigraphical and palaeoecological analyses: tectonic implications.- Journal of Quaternary Science, 22, 3, 233–245.

Allocca, V., Celico, F., Celico, P., De Vita, P., Fabbrocino, S., Mattia, C., Monacelli, G., Musilli, I., Piscopo, V., Scalise, A.R., Summa, G. & G. Tranfaglia, 2007: *Note illustrative della Carta Idrogeologica dell'Italia meridionale*.- Istituto Poligrafico e Zecca dello Stato, 1, 211.

Antonioli, F., Dai Pra, G. & P.J. Hearty, 1988: I sedimenti quaternari nella fascia costiera della Piana di Fondi (Lazio meridionale).- Bollettino della Società Geologica Italiana, 107, 491–501.

Anzidei, M., Boschi, E., Cannelli, V., Devoti, R., Esposito, A., Galvani, A., Melini, D., Pietrantonio, G., Riguzzi, F., Sepe, V. & E. Serpelloni, 2009: Coseismic deformation of the destructive April 6, 2009 L'Aquila earthquake (central Italy) from GPS data.- Geophys. Res. Lett., 36, doi:10.1029/2009GL039145.

Ascione, A., Cinque, A., Improta, L. & F. Villani, 2003: Late Quaternary faulting within the Southern Apennines seismic belt: new data from Mt. Marzano area.- Quaternary International, 101-102, 27-41.

Atzori, S., Hunstad, I., Chini, M., Salvi, S., Tolomei, C., Bignami, C., Stramondo, S., Trasatti, E., Antonioli, A. & E. Boschi, 2009: Finite fault inversion of DInSAR coseismic displacement of the 2009 L'Aquila earthquake (central Italy).- Geophys. Res. Lett., 36, L15305, doi:10.1029/2009GL039293

Aydin, A., 2000: Fractures, faults, and hydrocarbon entrapment, migration and flow.- Mar. Pet. Geol., 17, 797–814.

Barberi, F., Buonasorte, G., Cioni, R., Fiordalisi, A., Foresi, L., Iaccarino, S., Laurenzi, M. A., Sbrana, A., Vernia, L. & I.M., Villa, 1994: Plio-Pleistocene geological evolution of the geothermal area of Tuscany and Latium.- Memorie Descrittive della Carta Geologica d'Italia, 49, 77–134.

Beck, B.F. (Ed.), 1984: *Sinkholes, their geology, engineering and environmental impact*.- Balkema, pp. 429, Rotterdam and Boston.

Bernard, P. & A. Zollo, 1989: The Irpinia (Italy) 1980 earthquake: detailed analysis of a complex normal faulting.- Journal of Geophysical Research, 94, B-2, 1631-1647.

Billi, A., Valle, A., Brilli, M., Faccenna, C. & R. Funiciello, 2007: Fracture-controlled fluid circulation and dissolutional weathering in sinkhole-prone carbonate rocks from central Italy.- Journal of Structural Geology, 29, 385-395.

Blumetti, A.M., 1995: Neotectonic investigations and evidence of paleoseismicity in the epicentral area of the January-February 1703, Central Italy, Earthquakes.- In: Serva, L. & D.B. Slemmons, (eds.), Perspectives in Paleoseismology, Bull. of the Association of Engineering Geologists, special issue, 6, 83-100.

Boni, C., Bono, P., Calderoni, G., Lombardi, S. & B. Turi, 1980: Hydrogeological and geochemical analyses on the relationships between karst circulation and hydrotermal circuit in the Pontina Plain (Southern Latium).- Geologia Applicata e Idrogeologia, 15, 203–245.

Boni, C., Bono, P. & G. Capelli, 1986: Schema idrogeologico dell'Italia centrale.- Memorie Società Geologica Italiana, 35, 991–1012.

Bosi, V., 1994: *Evoluzione neotettonica del Lazio Meridionale-Campania Settentrionale, in corrispondenza della terminazione meridionale della linea tettonica "Ortona-Roccamonfina"*.- PhD thesis. Dipartimento di Scienze della Terra, Università "La Sapienza", Roma, pp. 194.

Bosi, C., Galadini, F., Giaccio, B., Messina, P. & A. Sposato, 2003: Plio-Quaternary continental deposits in the Latium-Abruzzi Apennines: the correlation of geological events across different intermontane basins.- Il Quaternario, 16, 55–76.

Brancaccio, L., Cinque, A., Romano, P., Rosskopf, C., Russo, F., Santangelo, N. & A. Santo, 1991: Geomorphology and neotectonic evolution of a sector of the Tyrrhenian flank of the southern Apennines (Region of Naples, Italy).- Zeitschrift für Geomorphologie N.F., Suppl.-Bd, 82, 47–58.

Brogi, A., Capezzuoli, E., Aqué, R., Branca, M. & M. Voltaggio, 2009: Studying travertines for neotectonics investigations: Middle–Late Pleistocene syn-tectonic travertine deposition at Serre di Rapolano (Northern Apennines, Italy).- Int. J. Earth Sci. (Geol. Rundsch.), DOI 10.1007/s00531-009-0456-y.

Budetta, P., Nicotera, P. & A. Santo, 1996: Controlli e monitoraggio di fenomeni deformativi indotti da carsismo in versanti carbonatici dell'Appennino campano.- In: Luino F. (ed.) *La prevenzione delle catastrofi idrogeologiche: il contributo della ricerca scientifica*, 5th-7th November 1996, Alba, C.N.R. – G.N.D.C.I., 383-395.

Caiazzo, C., Ascione, A. & A. Cinque, 2006: Late Tertiary-Quaternary tectonics of the Southern Apennines (Italy): new evidence from the Tyrrhenian slope.- Tectonophysics, 421, 23-51.

Çakir, Z., 1999: Along-strike discontinuity of active normal faults and its influence on quaternary travertine deposition; examples from western Turkey.- Tr. J. of Earth Sciences, 8, 67–80.

Cappa, F. 1871: *Sul terremoto che a '2 di febbraio 1703 rovinò l'Aquila e molti paesi di Abruzzo. Memorie*.- pp. 50, Tipografia Aternina.

Caramanna, G., Ciotoli, G. & S. Nisio, 2008: A review of natural sinkhole phenomena in Italian plain areas.- Natural Hazards, 45, 145–172.

Cavinato, G.P., Carusi, C., Dall'Asta, M., Miccadei, E. & T. Piacentini, 2002: Sedimentary and tectonic evolution of Plio–Pleistocene alluvial and lacustrine deposits of Fucino Basin (central Italy).- Sedimentary Geology, 148, 29–59.

Cavinato, G.P. & P.G. De Celles, 1999: Extensional basins in the tectonically bimodal central Apennines fold-thrust belt, Italy: response to corner flow above a subducting slab in retrograde motion.- Geology, 27, 955–958.

Celico, P., 1983: *Idrogeologia dei massicci carbonatici, delle piane quaternarie e delle aree vulcaniche dell'Italia centro-meridionale (Marche e Lazio meridionali, Abruzzo, Molise e Campania)*.- Quaderni per la Cassa del Mezzogiorno, Progetti Speciali per gli schemi idrici nel Mezzogiorno, pp. 225, Roma.

Celico, P., Piscopo, V. & D. Stanzione, 1998: Sulla genesi di alcune acque minerali effervescenti della Campania (Italia meridionale).- Studi Tridentini di Scienze Naturali, 73, 167-180.

Cello, G., Guerra, I., Tortorici, L., Turco, E. & R. Scarpa, 1982: Geometry of the neotectonic stress field in southern Italy: geological and seismological evidence.- J. Struct. Geol., 4, 385-393.

Cello, G., Deiana, G., Mangano, P., Mazzoli, S., Tondi, E., Ferreli, L., Maschio, L., Michetti, A.M., Serva, L. & E. Vittori, 1998a: Evidence of surface faulting during the September 26, 1997, Colfiorito (Central Italy) earthquakes.- J. Earthqu. Eng., 2, 303–324.

Cello, G., Mazzoli, S. & E. Tondi, 1998b: The crustal structure responsible for the 1703 earthquake sequence of central Italy.- Journal of Geodynamics, 26, 443-460.

Chiodini, G., Frondini, F., Kerrick, D.M., Rogie, J., Parello, F., Peruzzi, L. & A.R. Zanzari, 1999: Quantification of deep CO_2 fluxes from Central Italy: examples of carbon balance for regional aquifers and of soil diffuse degassing.- Chemical Geology, 159, 205-222.

Chiodini, G., Frondini, F., Cardellini, C., Parello, F. & L. Peruzzi, 2000: Rate of diffuse carbon dioxide Earth degassing estimated from carbon balance of regional aquifers: The case of central Apennine, Italy.- J. Geophys. Res., 105, B4, 8423–8434.

Cinque, A., Ascione, A. & C. Caiazzo, 2000: Distribuzione spaziotemporale e caratterizzazione della fagliazione quaternaria in Appennino Meridionale.- In: Galadini, F., Meletti, C. & A. Rebez, (eds.) *Ricerche del GNDT nel campo della pericolosità sismica (1996–1999)*, CNR-GNDT Special Publication, 203–218, Rome.

Cinque, A., Patacca, E., Scandone, P. & M. Tozzi, 1993: Quaternary kinematic evolution of the Southern Apennines. Relationships between surface geological features and deep lithospheric structures.- Annali di Geofisica, 36, 2, 249-259.

Corniello, A. & R. De Riso, 1986: Idrogeologia e idrochimica delle sorgenti dell'Agro Telesino.- Geologia Applicata e Idrogeologia, 21, 53-84.

Del Prete, S., Di Crescenzo, G., Santangelo, N. & A. Santo, 2010: Karst sinkholes in Campania (southern Italy): geo-structural analysis, predisposing factors and genetic hypothesis.- Zeitschrift fur Geomorphologie N.F., 54, 2, 259-284, Berlin Stuttgart.

Esposito, E., Porfido, S., Iaccarino, G. & G. Tranfaglia, 2000: Terremoti e centri storici dell'Irpinia: gli effetti del terremoto del 1930.- Proc. GeoBen 2000, CNR-GNDCI 2133, 477-484.

Falcucci, E., Gori, S., Peronace, E., Fubelli, G., Moro, M., Saroli, M., Giaccio, B., Messina, P., Naso, G., Scardia, G., Sposato, A., Voltaggio, M., Galli, P. & F. Galadini, 2009: The Paganica fault and surface coseismic ruptures caused by the 6 April 2009 earthquake (L'Aquila, Central Italy).- Seismological Research Letters, 80, 6, 940-950.

Ferranti, L., Antonioli, F., Mauz, B., Amorosi, A., Dai Pra, G., Mastronuzzi, G., Monaco, C., Orrù, P., Pappalardo, M., Radtke, U., Renda, P., Romano, P., Sansò, P. & V. Verrubbi, 2006: Markers of the last interglacial sea-level high stand along the coast of Italy: Tectonic implications.- Quaternary International, 145–146, 30–54.

Ford, D.C. & P.W. Williams, 1989: *Karst geomorphology and hydrology*.- Chapman & Hall, p. 601, London.

Galadini, F. & P. Galli, 2000: Active tectonics in the central Apennines (Italy) – Input data for seismic hazard assessment.- Natural Hazards, 22, 225–270.

Galadini, F. & P. Messina, 2004: Early–Middle Pleistocene eastward migration of the Abruzzi Apennine (central Italy) extensional domain.- Journal of Geodynamics, 37, 57–81.

Galli, P., Galadini, F. & D. Pantosti, 2008: Twenty years of paleoseismology in Italy.- Earth-Science Reviews, 88, 89-117.

Galve, J.P., Bonachea, J., Remondo, J., Gutiérrez, F., Guerrero, J., Lucha, P., Cendrero, A., Gutiérrez, M. & J.A. Sánchez, 2008. Development and validation of sinkhole susceptibility models in mantled karst settings. A case study from the Ebro valley evaporite karst (NE Spain).- Engineering Geology, 99, 185-197.

Gasparini, C., Iannaccone, G. & R. Scarpa, 1985: Fault-plane solution and seismicity of the Italian Peninsula.- Tectonophysics, 117, 59-78.

Istituto Nazionale di Geofisica e Vulcanologia, 2004: Catalogo Parametrico dei Terremoti Italiani, versione 2004 (CPTI04).- [Online] Available from: http://emidius.mi.ingv.it/CPTI04 [Accessed 3rd November 2009].

Istituto Nazionale di Geofisica e Vulcanologia, 2006-2007: Results of INGV-DPCV5 project:the catalogue of italian gas emission. - [Online] Available from: http://googas.ov.ingv.it [Accessed November 2009].

Istituto Superiore per la Protezione e la Ricerca Ambientale, n.d.: Cartografia geologica. – [Online] Available from: http://www.isprambiente.gov.it/site/it-IT/Servizi_per_l'Ambiente/Carte_geologiche/ [Accessed November 2009].

Gutiérrez, F., Guerrero, J. & P. Lucha, 2008: A genetic classification of sinkholes illustrated from evaporite paleokarst exposure in Spain.- Environmental Geology, 53, 993–1006.

Hancock, P.L., Chalmers, R.M.L., Altunel, E. & Z. Çakir, 1999: Travitonics: using travertines in active fault studies.- Journal of Structural Geology, 21, 903-916.

Hippolyte, J.C., Angelier, J. & F. Roure, 1994: A major geodynamic change revealed by Quaternary stress patterns in the Southern Apennines (Italy).- Tectonophysics, 230, 199-210.

Jennings, J.N., 1975: Doline morphometry as a morphogenetic tool: New Zealand examples. - New Zealand geographer, 31, 6-28.

Karner, D.B., Juvigné, E., Brancaccio, L., Cinque, A., Russo Ermolli, E., Santangelo, N., Bernasconi, S. & L. Lirer, 1999: A potential early middle Pleistocene tephrostratotype for the Mediterranean basin: the Vallo di Diano, Campania, Italy.- Global and Planetary Change, 21, 1-15.

Kerrich, R., 1986: Fluid infiltration into Fault zones: chemical, isotopic and mechanical effects.- Pure Applied Geophysics, 124, 225–268.

Klimchouk, A.B., 2007: *Hypogene speleogenesis: hydrogeological and morphogenetic perspective*.- National Cave and Karst Research Institute, pp. 106, Carlsbad, USA.

Maffei, A., Martino, S. & A. Prestininzi, 2005: From the geological to the numerical model in the analysis of gravity-induced slope deformations: an example from the central Apennines (Italy).- Eng. Geol., 78, 215-236.

Margottini, C., 1983: Raccolta e classificazione degli effetti naturali collaterali ai maggiori terremoti del Lazio. Un tentativo di interpretazione.- Geologica Romana, 22, 287-295.

Miccadei, E., Barberi, R. & G.P. Cavinato, 1998: La geologia quaternaria della conca di Sulmona, Abruzzo, Italia centrale.- Geologica Romana, 34, 59–86.

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.

Michetti, A.M., Esposito, E., Gürpinar, A., Mohammadioun, B., Mohammadioun, A., Porfido, S., Rogozhin, E., Serva, L., Tatevossian, R., Vittori, E., Audemard, F., Comerci, V., Marco, S., McCalpin, J. & N.A. Mörner, 2004: *The INQUA Scale. An innovative approach for assessing earthquake intensities based on seismically-induced ground effects in natural environment*.- In: Vittori, E. & V. Comerci (eds.), Memorie Descrittive della Carta Geologica d'Italia, 67, pp. 115. Roma.

Minissale, A., Kerrick, D.M., Magro, G., Murrell, M.T., Paladini, M., Rihs, S., Sturchio, N.C., Tassi, F. & O. Vaselli, 2002: Geochemistry of Quaternary travertines in the region north of Rome (Italy): structural, hydrologic and paleoclimatic implications.- Earth and Planetary Science Letters, 203, 709-728.

Minissale, A., 2004: Origin, transport and discharge of CO_2 in central Italy.- Earth Science Reviews, 66, 89–141.

Munno, R., Petrosino, P., Romano, P., Russo Ermolli, E. & E. Juvigné, 2001: A late Middle Pleistocene climatic cycle in southern Italy inferred from pollen analysis and tephrostratigraphy of the Acerno lacustrine succession.- Geographie Physique et Quaternaire, 55, 87-99.

Nisi, M., Antonioli, F., Dai Pra, G., Leoni, G. & S. Silenzi, 2003: Coastal deformation between the Versilia and the Garigliano plains (Italy) since the last interglacial stage.- Journal of Quaternary Science, 18, 8, 709– 721.

Nisio, S. (ed.), 2008: *I fenomeni naturali di sinkhole nelle aree di pianura italiane*.- Memorie Descrittive della Carta Geologica d'Italia, ISPRA, 85, pp. 482, Roma.

Pantosti, D. & G. Valensise, 1990: Faulting mechanism and complexity of the November 23, 1980, Campania–Lucania earthquake, inferred from surface observations.- Journal of Geophysical Research, 95, 15319–15341.

Pantosti, D., Schwartz, D.P. & G. Valensise, 1993: Paleoseismology along the 1980 surface rupture of the Irpinia fault: implications for earthquake recurrence in the Southern Apennines, Italy.- Journal of Geophysical Research, 98, B-4, 6561-6577.

Pantosti, D., D'Addezio, G. & F. Cinti, 1996: Paleoseismicity of the Ovindoli–Pezza fault, central Apennines, Italy: a history including a large, previously unrecorded earthquake in the Middle Ages (860–1300 A.D.).- Journal of Geophysical Research, 101, 5937–5960.

Papanikolaou, I.D., Roberts, G.P. & A.M. Michetti, 2005: Fault scarps and deformation rates in Lazio–Abruzzo, Central Italy: comparison between geological fault slip-rate and GPS data.- Tectonophysics, 408, 147–176.

Parotto, M. & A. Praturlon, 1975: Geological summary of the Central Apennines.- In: Ogniben, L. (ed.) *Structural Model of Italy*, Quaderni della Ricerca Scientifica, 90, 257–311, Rome.

Patacca, E., Scandone, P. & R. Sartori, 1990: Tyrrhenian basin and Apenninic arcs: kinematic relations since Late Tortonian times.- Memorie della Società Geologica Italiana, 45, 425–451.

Patacca, E. & P. Scandone, 2001: Late thrust propagation and sedimentary response in the thrust belt foredeep system in the Southern Apennines (Pliocene–Pleistocene).- In Vai, G.B. & I.P. Martini (eds.) *Anatomy of an Orogen*. Kluwer, 401–440, London.

Pondrelli, S., Salimbeni, S., Morelli, A., Ekström, G., Olivieri, M. & E. Boschi, 2009: Seismic moment tensors of the April 2009, L'Aquila (Central Italy), earthquake sequence.- Geophysical Journal International, 180, 238–242.

Porfido, S., Esposito, E., Vittori, E., Tranfaglia, G., Michetti, A.M., Blumetti, M., Ferreli, L., Guerrieri, L. & L. Serva, 2002: Areal distribution of ground effects induced by strong earthquakes in southern Apennines (Italy).- Survey Geophysics, 23, 529-562.

Riccardi, L., 1927: *Telesia – Ricordi e Speranze*.- Tip. Nazzareno Borrelli, pp. 125, Benevento.

Romano, P., Santo, A. & M. Voltaggio, 1994: L'evoluzione geomorfologia della pianura del fiume Volturno (Campania) durante il tardo Quaternario (Pleistocene medio-superiore–Olocene).- Il Quaternario, 7, 1, 41– 56.

Rossi, D., 1857: Sulle acque minerali di Telese e sullo Stabilimento dei Bagni quivi costruito.- Annali Civili del Regno delle due Sicilie, 61, 121.

Salvati, R. & I.R. Sasowsky, 2002: Development of collapse sinkholes in areas of groundwater discharge.- Journal of Hydrology, 264, 1-11.

Santangelo, N., 1991: *Evoluzione stratigrafica, geomorfologica e neotettonica di alcuni bacini lacustri del confine Campano Lucano (Italia Meridionale)*.- PhD thesis. Università degli Studi di Napoli Federico II - Dip. Scienze della Terra, Napoli, pp. 109.

Santo, A. & P. Tuccimei, 1997: Ricostruzione di eventi deformativi di versante tardo-quaternari ed olocenici attraverso studi geomorfologici e datazioni radiometriche Th/U: l'esempio dell'area di Vico Equense (Campania).- Il Quaternario, 10, 2, 477-484.

Sauro, U., 2003: Dolines and sinkholes: Aspects of evolution and problems of classification.- Acta carsologica, 32, 2, 41-52.

Sibson, R.H., 2000: Fluid involvement in normal faulting.- Geodynamics, 29, 469–499.

Uysal, I.T., Feng, Y., Zhao, J., Isik, V., Nuriel, P. & S.D. Golding, 2009: Hydrothermal CO_2 degassing in seismically active zones during the late Quaternary.- Chemical Geology, 265, 442–454.

Vannucci, G., Pondrelli, S., Argnani, A., Morelli, A., Gasperini, P. & E. Boschi, 2004: An atlas of Mediterranean seismicity.- Annals of Geophysics, 47, 247–306.

Vittori, E., Deiana, G., Esposito, E., Ferreli, L., Marchegiani, L., Mastrolorenzo, G., Michetti, A.M., Porfido, S., Serva, L., Simonelli, A.L. & E. Tondi, 2000: Ground effects and surface faulting in the September–October 1997 Umbria–Marche (Central Italy) seismic sequence.- J. Geod., 29, 535–564.

Waltham, T., Bell, F. & M. Culshaw, 2005: *Sinkholes and subsidence*.- Springer Verlag, pp. 382, Berlin Heidelberg New York.

Westaway, R. & J. Jackson, 1984: Surface faulting in the Southern Italian Campania-Basilicata earthquake of 23 november 1980.- Nature, 312, 436-438.

Williams, P., 2003: Dolines.- In: Gunn, J. (eds.): *Encyclopedia of caves and karst science*.- Taylor and Francis Group, pp. 304–310, New York.

Yilmaz, I., 2007: GIS based susceptibility mapping of karst depression in gypsum: a case study from Sivas basin (Turkey). - Engineering Geology, 90, 1-2, 89-103.