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

ANTONIO SANTO1, ALESSANDRA ASCIONE2, SOSSTIO DEL PRETE3, GIUSEPPE DI CRESCENZO4 & NICOLETTA SANTANGELO2

Abstract

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 database, 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 (H₂S- and CO₂- 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, CO₂-rich waters and faults. Furthermore, with the aim of investigating the role of seismic shaking in the occurrence of the collapse, the karst collapse sinkhole distribution was compared with the distribution of stronger historical earthquake epicenters. 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

Prispevek je osredotočen na udornice v južnih in osrednjih delih Apeninov, ki povezujejo k razporeditvi 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 pojmov. S pomočjo analize morfometrično/morfoloških oblik okoli 600 na začetku ugotovljenih vrtač, jih je bilo okoli 50 % interpretiliranih 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 analizale razporeditev glavnih mineralnih izvirov (H₂S in vode, bogate s CO₂), lehnjakovih teles in večjih prelomnic, aktivnih v pozem kvartarju, za kar vse avtorji sodijo, da je pomembno za to študijo glede na povezave med lehnjakom, procesi zagravavanja (raztapljanja), s CO₂ bogatimi vodami in prelomami. S pomočjo proučevanja vloge potresnih trestljav 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 možno ključ za razlago udornih pojmov 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 trestljaji.

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Received/Prejeto: 9.9.2010
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.

**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$_2$S- 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...
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 (10 > IX MCS, e.g., in 1279, 1349, 1456, 1561, 1654, 1694, 1703, 1805, 1857) and magnitudes around 7, e.g., the 1980 Irpinia earthquake (Mw 6.9; Bernard & Zollo 1989) and the 1915 Fucino earthquake (Mw 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 Mw 6.3 main shock followed by seven aftershocks of Mw ≥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...
ANTONIO SANTO, ALESSANDRA ASCIONE, SOSSIO DEL PRETE, GIUSEPPE DI CRESCENZO & NICOLETTA SANTANGELO

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 KCs, 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 KCs (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 \( CO_3^- \) 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
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.

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 CO₂-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 CO₂ 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-
HSCA = High sinkhole concentration area; IB = border of intramontane basin; BCP = border of coastal plain; carbonate slope = CS

**Table 1: Main geological and geomorphological features of the examined KCSs.**

<table>
<thead>
<tr>
<th>HSCA</th>
<th>Massif</th>
<th>N° of sinkholes</th>
<th>lithology</th>
<th>Geo-morphological context</th>
<th>Villages</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Aurunci Mts.</td>
<td>16</td>
<td>16: Cretaceous and Paleogene limestones</td>
<td>CS, BCP</td>
<td>Suio, Santi Cosma e Damiano</td>
</tr>
<tr>
<td>11</td>
<td>Venafro Mts.</td>
<td>13</td>
<td>2: Cretaceous limestones 7: Jurassic dolomitic limestones 4: Quaternary conglomerates covering limestone</td>
<td>IB, CS</td>
<td>Venafro, Sesto Campano</td>
</tr>
<tr>
<td>12</td>
<td>Caserta and Tifata Mts.</td>
<td>17</td>
<td>17: Cretaceous limestones</td>
<td>BCP</td>
<td>Caserta, Maddaloni</td>
</tr>
<tr>
<td>13</td>
<td>Maggiore-Camposauro Mts.</td>
<td>22</td>
<td>12: Cretaceous limestones 10: Quaternary conglomerates covering limestone</td>
<td>IB</td>
<td>Teleso, Solopaca</td>
</tr>
<tr>
<td>14</td>
<td>Lattari Mts.</td>
<td>8</td>
<td>8: Cretaceous limestones</td>
<td>BCP</td>
<td>Castellammare Vico Equense</td>
</tr>
<tr>
<td>15</td>
<td>Marzano Mts.</td>
<td>9</td>
<td>6: Cretaceous and Jurassic limestones 3: Quaternary conglomerates covering limestone</td>
<td>IB</td>
<td>Contursi, Buccino</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>220</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

A striking alignment of KCSs and faults is present in HSCAs 9, 10, 12, 14, which are located in the horse 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).

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; Minisale 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, CO₂ 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
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 bigger 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.

<table>
<thead>
<tr>
<th>HSCA</th>
<th>Spring name</th>
<th>Chemical facies</th>
<th>T (°C)</th>
<th>CO$_2$ (mg/l)</th>
<th>Electrical conductivity (μS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Ielo</td>
<td>Calcium bicarbonate</td>
<td>13</td>
<td>25</td>
<td>480</td>
</tr>
<tr>
<td>11</td>
<td>Lete</td>
<td>Calcium bicarbonate</td>
<td>14</td>
<td>1970</td>
<td>1359</td>
</tr>
<tr>
<td>11</td>
<td>Prata e Mulinello</td>
<td>Calcium bicarbonate</td>
<td>13</td>
<td>63</td>
<td>776</td>
</tr>
<tr>
<td>12</td>
<td>Calabricito</td>
<td>Calcium bicarbonate</td>
<td>16</td>
<td>278</td>
<td>1899</td>
</tr>
<tr>
<td>12</td>
<td>Moffito</td>
<td>Calcium bicarbonate</td>
<td>14.5</td>
<td>107.6</td>
<td>1146</td>
</tr>
<tr>
<td>12</td>
<td>Triflisco</td>
<td>Calcium bicarbonate</td>
<td>14.5</td>
<td>250-355</td>
<td>1333</td>
</tr>
<tr>
<td>12</td>
<td>Fontana Pila</td>
<td>Calcium bicarbonate</td>
<td>14.5</td>
<td>248</td>
<td>1106</td>
</tr>
<tr>
<td>13</td>
<td>Grassano</td>
<td>Calcium bicarbonate</td>
<td>12</td>
<td>116</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Telese Terme</td>
<td>Sulphureous calcium bicarbonate</td>
<td>16-21</td>
<td>860-1002</td>
<td>1488-2900</td>
</tr>
<tr>
<td>13</td>
<td>Fontana Bolla</td>
<td>Sulphureous calcium bicarbonate</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>14</td>
<td>Scravo</td>
<td>Sulphureous calcium bicarbonate</td>
<td>17</td>
<td>1232</td>
<td>7520</td>
</tr>
<tr>
<td>14</td>
<td>Castellammare</td>
<td>Calcium bicarbonate</td>
<td>12-17.4</td>
<td>164-877</td>
<td>5725-18400</td>
</tr>
<tr>
<td>15</td>
<td>Contursi Bagni</td>
<td>Sulphureous calcium bicarbonate</td>
<td>21-29</td>
<td>379.8-1150</td>
<td>2568-6015</td>
</tr>
<tr>
<td>15</td>
<td>Contursi Terme</td>
<td>Calcium bicarbonate</td>
<td>14.7-44</td>
<td>240-430</td>
<td>890-4020</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Number of events</th>
<th>sinkhole development date</th>
<th>earthquake date</th>
<th>epicentre</th>
<th>distance</th>
<th>I MCS to the epicentre</th>
<th>I MCS to the site</th>
<th>days from the seismic event</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 (minimum) KCSs in Telese area (HSCA13)</td>
<td>1349-9-9</td>
<td>1349-9-9</td>
<td>Cassino</td>
<td>60 km</td>
<td>X-XI</td>
<td>X</td>
<td>0</td>
</tr>
<tr>
<td>T KCS in Castellammare village (Lattari Mts; HSCA 14)</td>
<td>1456-12</td>
<td>1456-12</td>
<td>Central Italy</td>
<td>85 km</td>
<td>X-XI</td>
<td>VII-VIII?</td>
<td>0</td>
</tr>
<tr>
<td>1 KCS near Sigillo village (Rieti province) and 1 at Roio Piano near L’Aquila (HSCA 2 &amp; 7)</td>
<td>1703-2-2</td>
<td>1703-2-2</td>
<td>Norcia-L’Aquila</td>
<td>15-30 km</td>
<td>X</td>
<td>IX-X?</td>
<td>0</td>
</tr>
<tr>
<td>Jala KCS (Lattari Mts; HSCA 14)</td>
<td>XVII century</td>
<td>1695-1698</td>
<td>Lucania</td>
<td>80 km</td>
<td>V-VII</td>
<td>0?</td>
<td></td>
</tr>
<tr>
<td>Enlargement of some KCSs of 1349 earthquake in Telese area (HSCA 13)</td>
<td>1805-07-26</td>
<td>1805-07-26</td>
<td>Molise</td>
<td>30 km</td>
<td>XI</td>
<td>VIII</td>
<td>0</td>
</tr>
<tr>
<td>T KCS in Pianelle loc. (Marzano Mts; HSCA 15)</td>
<td>1981-5</td>
<td>1980-11-23</td>
<td>Irpinia</td>
<td>8 km</td>
<td>X</td>
<td>X</td>
<td>130</td>
</tr>
<tr>
<td>1 KCS at Mt Nuria, near Pendenza village, Velino valley (HSCA1)</td>
<td>1997-10-11</td>
<td>1997-10-11</td>
<td>Umbria-Marche</td>
<td>70 km</td>
<td>VI-VII</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Enlargement of 1 pre-existing KCS (Sinizzo lake; HSCA 2)</td>
<td>2009-4-6</td>
<td>2009-4-6</td>
<td>L’Aquila</td>
<td>5 km</td>
<td>X-XI</td>
<td>X</td>
<td>0</td>
</tr>
</tbody>
</table>
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, Venafrro, i.e., HSCA 6, 7, 8 and 11) and the coastal plains (Cisterna di Latina, Minturno, Cancellò, Sarno, respectively HSCA 9, 10, 12). In these areas, subsurface data, when available (e.g., Buccino area, Campania Plain, Venafrro 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.

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, Sapolaca, 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...
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).

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

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.

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, \( \text{H}_2\text{S} \) and/or \( \text{CO}_2 \)
mineral springs, travertine deposits and Quaternary
extensional faults, has shown the concomitant pres-
ence 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 tra-
vertine deposits points to interrelations linking dissolu-
tion phenomena, and consequent carbonate deposition,
to the rising of aggressive fluids. In particular, it suggests
enhanced dissolution, and consequent carbonate depo-
sition, in presence of ascending mineral waters. This
supports the hypothesis of Klimchouk (2007) about the
interactions of soluble rocks and ascending waters (of-
ten thermal and rich in CO$_2$ and/or H$_2$S), which may al-
low 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).

The collected results
point to the control exerted
by fault zones in the occur-
rence of karst collapse phe-
nomena. 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 clos-
est fault zones (Figg. 1 and
4B). Furthermore, the con-
comitant presence, at some
places, of all features consid-
ered in this study (i.e., KCS,
mineral springs, travertines
and faults), points to an im-
portant role played by ex-
tensional fault zones in the
migration of deeply derived
fluids, and supports the re-
results of several former stud-
ies (e.g., Kerrich 1986; Aydin
2000; Sibson 2000). In addi-
tion, the results suggest that
active faults, in particular,
represent preferential path-
ways for fluid rising and mixing with shallow ground-
water.

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 do-
lostones 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 in-
hibited, or diverted, at depth. The more puzzling non-co-
incidence 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

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

ACKNOWLEDGMENTS

This article benefitted of comments and suggestions from reviewers and editors: the work by İşık Yilmaz, Jo De Waele and an anonimous reviewer is acknowledged.
REFERENCES


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


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


