

The San Vittorino Sinkhole Plain: relationships between bedrock structure, sinking processes, seismic events and hydrothermal springs

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ABSTRACT

The San Vittorino Plain is located along the Velino River Valley within an intermontane depression, filled with continental deposits. This plain is characterized by the presence of numerous sinkholes, often filled with mineralized spring waters. From a structural point of view, the study area is characterized by four tectonic units with different paleogeographical evolution and deformation styles. From the innermost unit they are: the *Reatini Unit*, the *Navegna Unit*, the *Salto Unit*, and the *Nuria Unit*. The main tectonic lineaments are represented by the *Anzio-Ancona line*, the *Olevano-Micciani line*, the *Fiamignano-Micciani Fault* and the *Cerquara-Piedimozza Fault*. The development of sinkholes in the study area is mainly due to deep suffusion and deep piping processes, linked to fluid upwelling along fracture-fault systems and to dissolution (by H₂S and CO₂) in the continental deposits. The sinkhole distribution suggests that they are mainly formed in a collapsed sector of the Mt. Paterno block whose structural setting, characterized by several splays, with marly-clayey and siliciclastic deposits at the footwalls, favoured the development of confined aquifers. The rise of groundwater to the surface along the network of faults and fractures crossing the carbonate bedrock is likely controlled by hydrostatic pore pressures, which may be strongly increased by earthquake shaking. The surface distribution of sinkholes in the San Vittorino Plain, showing differences within the study area, is strictly linked to the bedrock structure and the related hydrogeological setting, as demonstrated by the detailed survey carried out in the area.

KEY WORDS: *Sinkholes, Structural Geology, Hydrogeology, Central Italy.*

RIASSUNTO

La Piana dei Sinkhole a San Vittorino: relazioni tra geologia del substrato, fenomeni di sprofondamento, eventi sismici e sorgenti termo-minerali.

Nella Piana di San Vittorino, che rappresenta una depressione tettonica colmata da depositi continentali tardo quaternari, sono localizzate numerose cavità subcircolari, che spesso racchiudono piccoli laghi, talora con acque mineralizzate identificati come *sinkholes s.s.*. I recenti rilevamenti hanno permesso di ricostruire in dettaglio il quadro geologico-strutturale, geomorfologico e idrogeologico della Piana di San Vittorino e di formulare nuove ipotesi sulla formazione dei *sinkholes*. La Piana di San Vittorino, ricade nella zona di convergenza di quattro unità tettoniche, caratterizzate da una differente evoluzione paleogeografica, da un diverso stile deformativo e separate tra loro da elementi strutturali di importanza regionale. Dalla più interna e strutturalmente più rilevata alla più esterna esse sono: l'*Unità dei M.ti Reatini*; l'*Unità M.te Navegna*;

l'*Unità Salto e l'Unità M.te Nuria*. Nell'area in esame, dove predominano largamente le formazioni carbonatiche, sono molto sviluppati i processi carsici, che costituiscono uno degli agenti morfogenetici più importanti nell'evoluzione morfodinamica dell'area. La maggior parte delle forme carsiche presenti nella zona studiata si sono sviluppate sulla paleosuperficie più bassa e più recente (*paleosuperficie di Fontanelle, o paleosuperficie del 2° ordine*) e la loro evoluzione risulta fortemente condizionata dall'assetto strutturale dei singoli settori. Tra i fattori predisponenti l'innescio e la propagazione dei *sinkholes* della Piana ha sicuramente giocato un ruolo predominante la presenza di sistemi di faglie che si intersecano, nonché il reticolo di fratture, presenti all'interno della copertura quaternaria, che hanno determinato comunicazione tra substrato carbonatico e i sedimenti alluvionali-lacustri. Dalla distribuzione dei *sinkholes*, delle acque mineralizzate, e dall'andamento delle anomalie dei gas i *sinkholes* si sono sviluppati in un'area localizzata sul settore sprofondato del blocco di M.te Paterno. Le complesse caratteristiche geologico-strutturali e idrogeologiche di questo blocco, sembrerebbero favorire la formazione e la localizzazione dei collassi catastrofici. Le cause principali degli sprofondamenti vanno ricercate principalmente nei processi di *suffosione profonda o deep piping*, che si sviluppano per la risalita delle acque attraverso le faglie e le fratture che dislocano il substrato carbonatico, provocando la mobilitazione e l'erosione dal basso (*deep piping*) dei depositi continentali sovrastanti, cui si aggiungono gli effetti dei processi di dissoluzione legati alla risalita di H₂S e CO₂ attraverso le stesse dislocazioni. Il settore sud-orientale della piana non presenta fenomeni di sprofondamento recenti come anche nel settore localizzato a SW dell'allineamento Micciani-San Vittorino (prolungamento della *faglia Fiamignano-Micciani*). Le cause vanno ricercate nel contesto geologico-strutturale e idrogeologico di questi due settori, molto diverso da quello desunto per il blocco di M.te Paterno.

TERMINI CHIAVE: *Sinkhole, Geologia Strutturale, Idrogeologia, Italia Centrale.*

1. INTRODUCTION

In the Italian lowlands sub-circular catastrophic ground collapses, called sinkholes, are widespread. Such phenomena represent a source of risks for human environment and public infrastructures. Sinkholes form in different geological contexts, through complex genetic mechanisms which favour the upward enlargement of an underground cavity (NEWTON, 1984; THARP, 1999; CAPELLI *et alii*, 2000; SALVATI & SASOWSKI, 2002; NISIO, 2003, 2004; NISIO & SALVATI, 2004; NISIO *et alii*, 2004). The structural pattern plays a remarkable role in the development of the sinkholes. In this frame, the presence of an intersecting network of faults and/or fractures, that favours the connection between the carbonate bedrock and the overlying superficial cover, is a necessary condition. Among the priming factors for sinkholes a wide specialist literature emphasizes a tight connection with seis-

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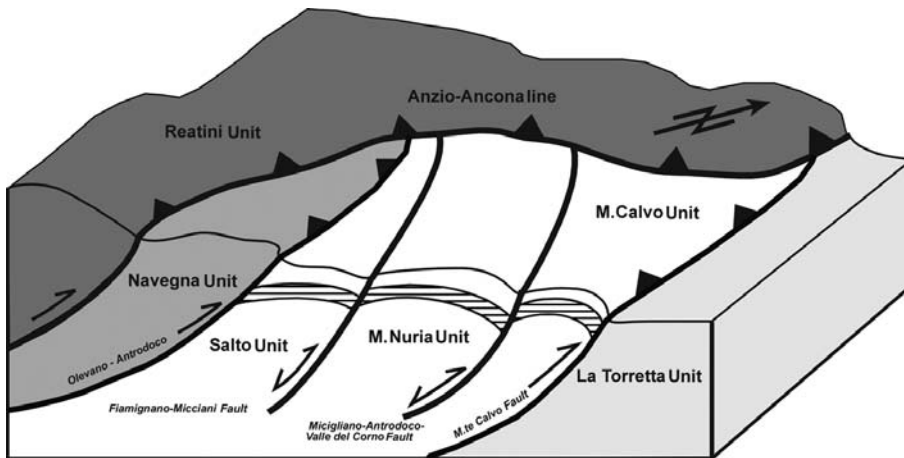


Fig. 1 - Scheme of the relationships among the main structural units recognized in the study area.

- Schema delle relazioni esistenti tra le principali unità strutturali riconosciute nell'area di studio.

mic events (FERRELI *et alii*, 2004; CARAMANNA *et alii*, 2006 and reference therein).

In the San Vittorino Plain, a tectonic depression containing Middle-Upper Pleistocene and Holocene continental deposits, numerous sinkholes are present, often filled by fresh water and/or mineralized water. For this reason the San Vittorino Plain has been and is still the object of numerous studies (MORI, 1895; CREMA, 1924; RICCARDI, 1951; MORI, 1983; NOLASCO, 1996; FACCENNA *et alii*, 1993; BIGI *et alii*, 2000; COLOMBI *et alii*, 1999; BERSANI *et alii*, 2000; CAPELLI *et alii*, 2000; CIOTOLI *et alii*, 2001; BERSANI & CASTELLANO, 2002; CENTAMORE & NISIO, 2002a,b; BEAUBIEN *et alii*, 2003; NISIO, 2003; NISIO *et alii*, 2007; CARAMANNA *et alii*, 2006a,b, 2008); it represents a classic sinkhole prone area and a type example for study of the sinkhole forming processes. In order to understand the sinkhole genesis, a detailed field survey, integrated with stratigraphic, structural, geomorphological and hydrogeological analyses, have been carried out on the San Vittorino area. The results of these studies allow us to formulate a new hypothesis on the control exerted by the fault/fracture network on the sinkhole development.

2. GEOLOGICAL SETTING

The San Vittorino Plain is located in the convergence zone among four main tectonic units, characterized by different paleogeographic evolutions and by different structural styles. Such units are separated by several main tectonic elements. From the uppermost unit to the lowermost one, they are: the *Reatini Unit*, the *Navegna Unit*, the *Salto Unit* and the *Nuria Unit* (fig. 1).

The *Reatini Unit*, cropping-out in the north-western sector of the study area, belongs to the pelagic Umbrian-Marchean-Sabine domain. This unit overlies the *Navegna* and *Nuria Units* through the *Reatini Thrust*, characterized by a low angle NNW dipping surface. This structural element constitutes a segment of the *Anzio-Ancona line*, a major structural element interpreted by several Authors as an important thrust (DALLAN NARDI *et alii*, 1971; KOOPMANN, 1983; CALAMITA *et alii*, 1987; BALLY *et alii*, 1988; CALAMITA & DEIANA, 1988), by others as a strike slip fault, or as a dextral transpressive ramp separating the Umbrian-Marchean-Sabine pelagic domain from the

Latium-Abruzzi neritic domain (OGNIBEN, 1969; COLI, 1981; BARCHI *et alii*, 1988; CENTAMORE & NISIO, 2002a, 2003), or as a polyphase fault (CASTELLARIN *et alii*, 1978).

The *Reatini Unit* is subdivided into minor tectonic subunits by several splays, sub-parallel to the main *Reatini Thrust*. In the study area two of such splays are distinguished (fig. 2). The upper subunit, consisting of a Jurassic-Cretaceous sequence (Calcere Massiccio, Corniola, Marne del Serrone and Maiolica), is arranged in a gentle syncline with N30° hinge; the lower subunit, at the hangingwall of the main thrust, is characterized by an overturned Scaglia Rossa-Scaglia Cinerea sequence. The splays are arranged into leading imbricate fan geometry, with dextral transpressive kinematics (fig. 3). Tectonic elements, characterized by a compressive N30°-40° trending dip-slip movement, were locally observed (fig. 3). The numerous, often disharmonic meso-folds within the Cretaceous-Paleogene units confirm the main direction of tectonic transport (fig. 4). Sets of folds with N-S and N10° hinge direction have been locally observed. This trend is referred to drag processes, resulting from the strike-slip movements along the *Ancona-Anzio line* after the formation of the Apennine trending folds. Within the *Reatini Unit*, meso-structures, such as fabric S/C foliations (fig. 5), pressure solution cleavage, meso-folds with overturned eastern limbs, are frequently observed. These structures are compatible with the trend of the main regional tectonic transport.

The *Reatini Unit* overthrusts the *Navegna Unit* near the Calcariola Ridge and the *Nuria Unit* along the right-hand side of the Velino River Valley (fig. 2). The *Navegna Unit* locally outcrops near Micciani and at the Calcariola Ridge; it is formed by a Meso-Cenozoic carbonate ramp succession followed by Lower Messinian syn-orogenic, siliciclastic turbidites. The above mentioned unit is bounded by the *Olevano-Antrodoco Line Auct.*, renamed *Olevano-Micciani Line* by CENTAMORE & NISIO (2002a). This thrust, SW dipping, is dislocated by a set of dextral tear faults, with a NE-SW trend (CENTAMORE & NISIO, 2002a).

The *Salto* and *Nuria Units* belong to the *Gran Sasso-Marsica Unit*, a wider regional tectonic unit of the Latium-Abruzzi domain (CENTAMORE & NISIO, 2002b). The *Salto Unit* is bounded in the hangingwall by the *Olevano-Micciani Line*, and in the footwall, by the *Fiamignano-Mic-*

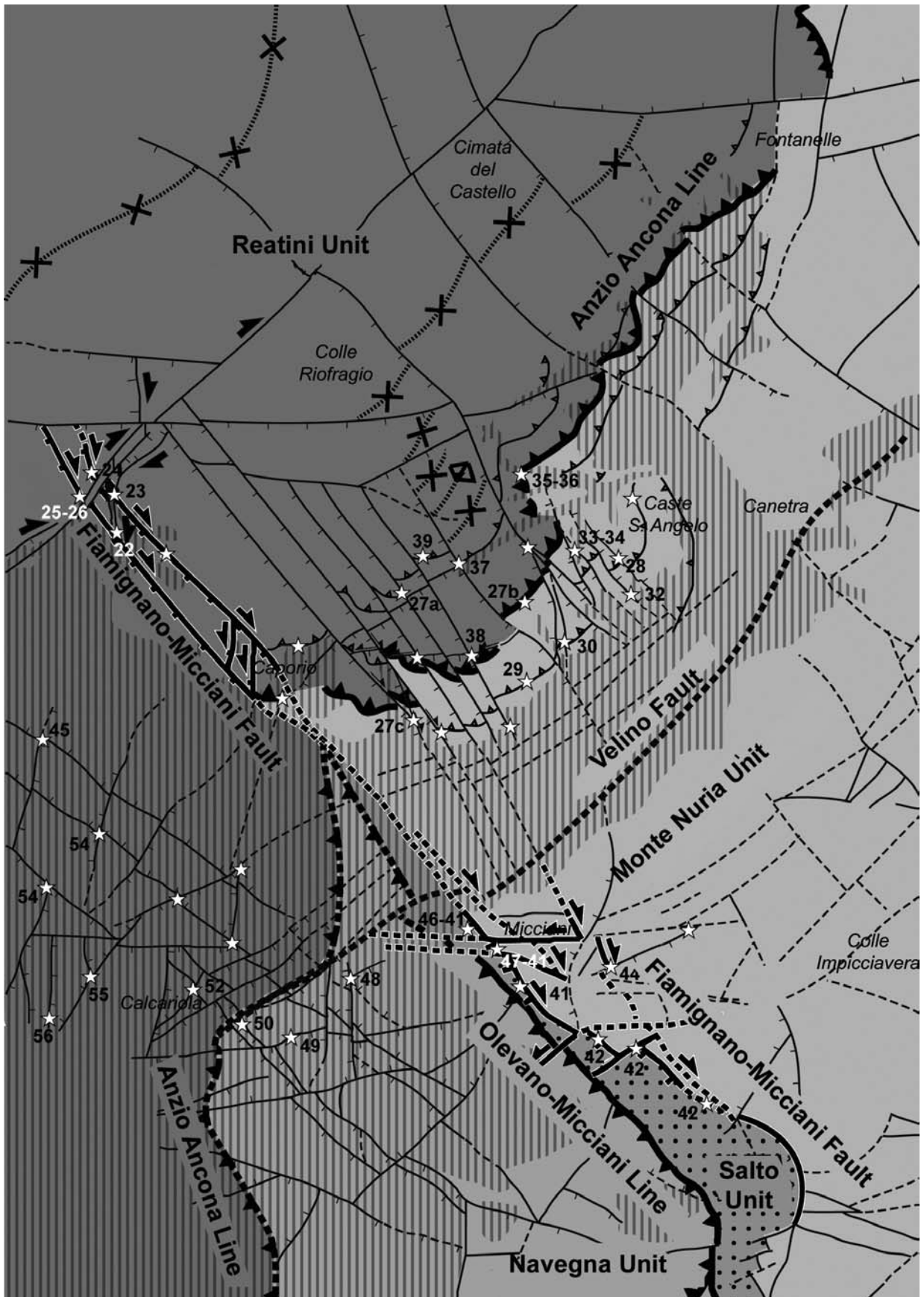


Fig. 2 - Tectonic sketch map of the study area; the dashed vertical lines represent the Plio-Pleistocene cover, the stars represent the structural analyses carried out.

- Schema strutturale dell'area studiata, il tratteggio verticale si riferisce alle coperture Plio-Pleistoceniche. Con le stellette sono indicate le stazioni di misura strutturale.

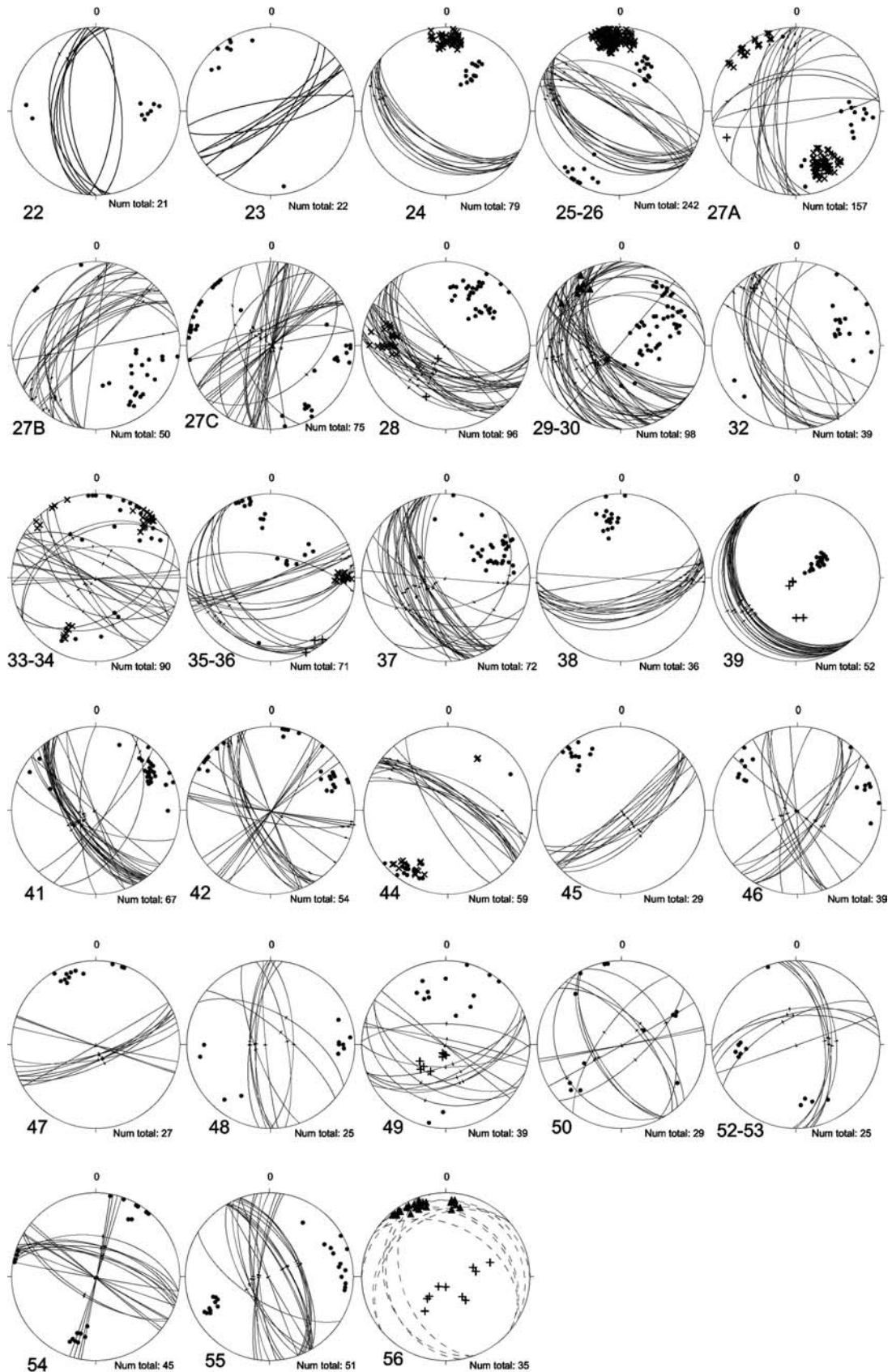


Fig. 3 - Stereograms, lower hemisphere, of the structural data acquired in the study area. The distribution of the data collected is represented in fig. 2. The dots represent the pole of the fault planes; the «x» represent the pole of the fracture planes (S1); the «+» represent the pole of bedding (S0); the triangle represents the hinge of the meso-folds; the little arrows represent the fault kinematic indicators.

– Rappresentazione stereografica, emisfero inferiore, delle stazioni strutturali riportate in fig. 2. Con i pallini sono rappresentati i poli dei piani di faglia, le «x» rappresentano i poli dei piani di fratturazione (S1); le «+» rappresentano i poli dei piani di strato (S0); i triangoli rappresentano le linee di cerniera delle meso-pieghe; le freccette rappresentano gli indicatori cinematici riferiti alle faglie campionate.

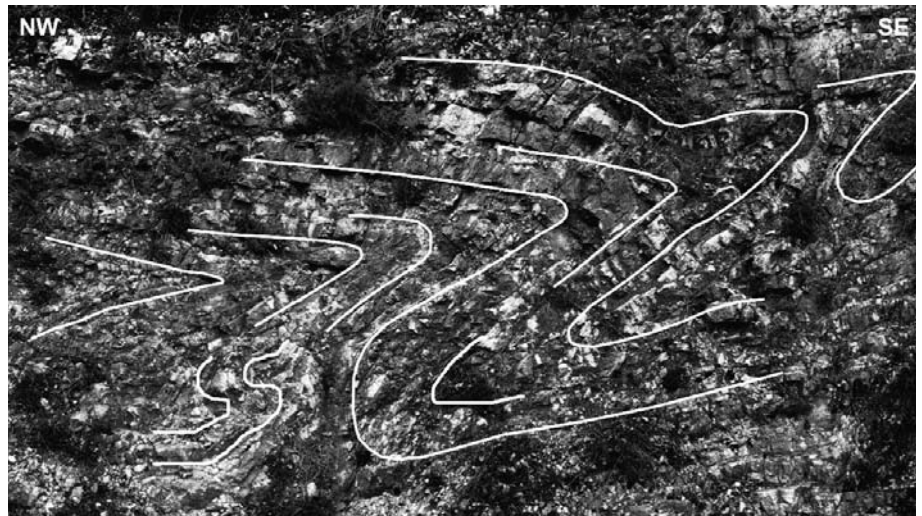


Fig. 4 - Disharmonic mesoscopic folds developed in a carbonate layers.
 – *Pieghe mesoscopiche disarmoniche all'interno di depositi calcarei.*

ciiani Fault. This last is a very complex structural element, characterized by a polyphase activity, developed in different times with several tectonic inversion processes (CENTAMORE & NISIO, 2002b, and reference therein). In the study area only a limited strip of the *Salto Unit* (formed by the Lower Messinian syn-orogenic, siliciclastic turbidites) outcrops. These deposits outcrop widely, with a considerable thickness, in the River Salto depression and are also present in the south-western sector of San Vittorino Plain, under the Villafranchian deposits and those of the *Navegna* and *Reatini Units* (fig. 2). The *Nuria Unit* represents the outer and structurally lower unit of the study area. It is bounded to the SW by the *Fiamignano-Micciani Fault*, to the NW by the *Reatini Thrust*, and to the NE by the *Micigliano-AnTRODoco-Valle del Corno Fault* (fig. 1). This unit mainly consists of inner carbonate platform Mesozoic deposits; Paleogene-Lower Miocene, carbonate ramp deposits crop out only in the right-hand side of the River Velino, followed by the argiloso-marnosa unit and by Lower Messinian siliciclastic turbidites.

On the south-eastern side of the Velino River Valley, the *Nuria Unit* is arranged in a wide anticline cut by a set of minor NW-SE trending thrusts. In the Mt. Paterno-Canetra area, this unit is dislocated by a series of splays, characterized by low-angle, NW-dipping surfaces (Pl. 1). The hangingwalls of these splays is located in the carbonate succession while, at the footwalls, the argiloso-marnosa unit or the siliciclastic turbidites outcrop (CENTAMORE & NISIO, 2002b).

After the Late Miocene-Early Pliocene compressional phase, the study area has been affected by extensional and/or transpressive tectonics, and regional uplift, particularly intense in Lower-Middle Pleistocene (DRAMIS, 1993; CENTAMORE & NISIO, 2003) which gave rise to a block pattern with differential vertical movements.

In such context normal faults developed, often reactivating by inversion former structural elements.

The tectonic extensional network is represented by four main fault systems (Pl. 1; fig. 2); N150°, N45°, N90° and N-S. The most important element recognized in the study area is the *Fiamignano-Micciani Fault*. This fault, trending NNW-SSE and dipping SW, is characterized by an intense polyphase activity: extensional in the post-rift



Fig. 5 - Mesoscopic S/C foliation in the scaglia rossa formation.
 – *Strutture mesoscopiche di foliazione S/C nella scaglia rossa.*

stage; compressive, with positive inversion tectonic processes, during the chain building phase; extensional with new negative tectonic inversion, with a Middle Pleistocene transpressive sinistral kinematics, during the Plio-Pleistocene stage (CENTAMORE & NISIO, 2002b). The fault trace within the S. Vittorino Plain is not easily recognizable in the field, because of drastic anthropic reworking, that modified the former landscape; it seems to coincide with the *Micciani-S. Vittorino* alignment (CENTAMORE & NISIO, 2002a) (Pl. 1).

The same system includes: The stepwise fault system dislocating the NE slope of the *Calcariola Ridge*; the dense fault network of the *Reatini Mts.* and the *Colle Impicciavera-Pendenza* sectors, the most important of which are the *Fiamignano-Micciani* and the *Piedimozza-Querquara faults*.

The NE-SW system is well represented in both the north-western and south-eastern sectors which are gradually lowered towards the San Vittorino Plain. The most

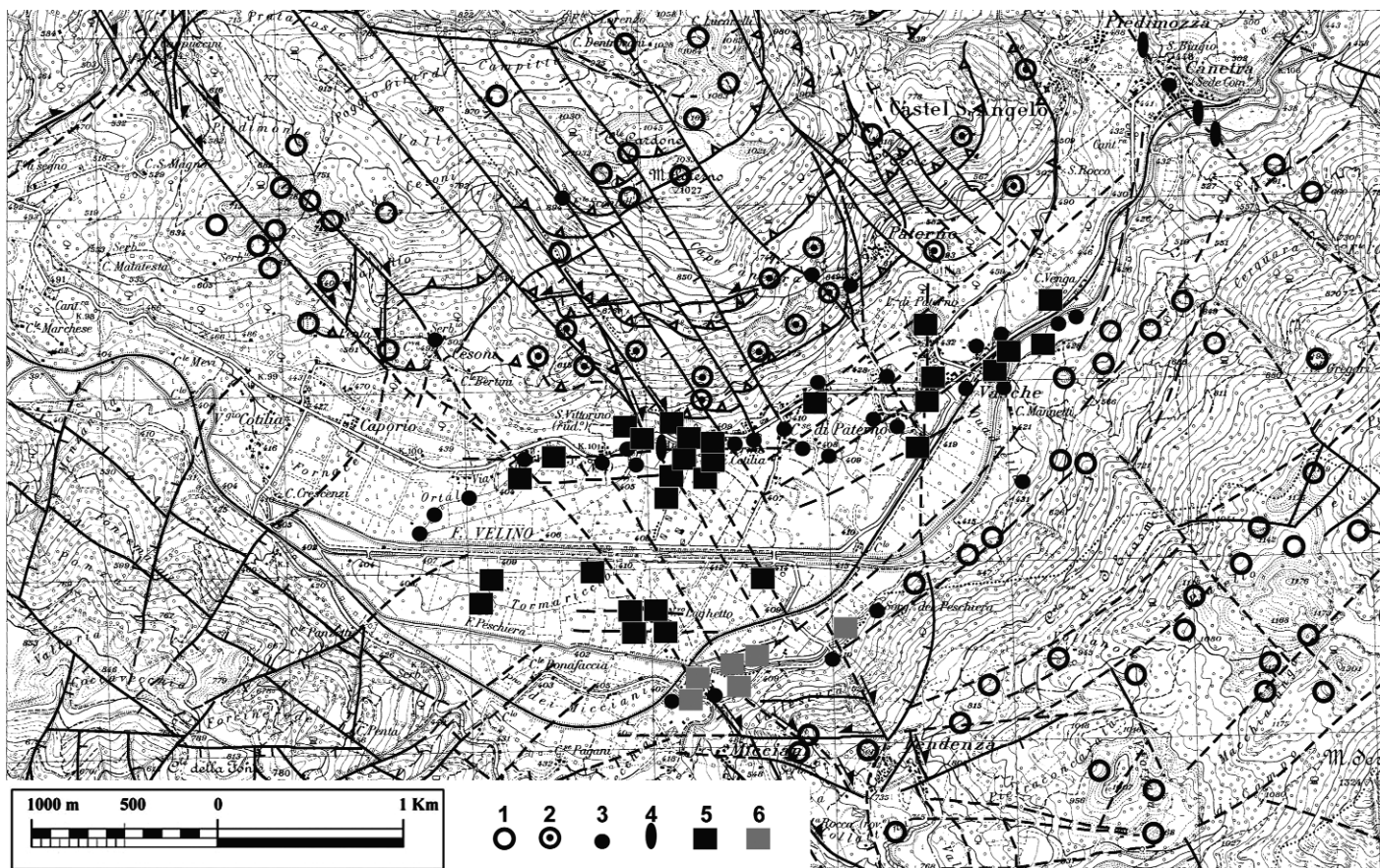


Fig. 6 - Distribution sketch of: dolines, sinkholes and springs: 1) dolines; 2) collapsed dolines; 3) springs; 4) sulphurous springs; 5) sinkholes; 6) inactive sinkholes; 7) borehole logs.

- Schema della distribuzione delle doline, dei sinkholes e delle sorgenti: 1) doline; 2) doline sfondate; 3) sorgenti; 4) sorgenti solfuree; 5) sinkholes; 6) sinkholes «estinti»; 7) ubicazione dei sondaggi.

important element of this system is the *River Velino Fault* (bordering the Mt. Nuria Ridge). Also belonging to this system are the faults affecting the north-western edge of Calciariola Ridge and the Valle Ottara-Fosso delle Valli sectors, which show considerable displacement.

The E-W faults system dislocate several sectors such as the Calciariola Ridge, between Mt. Paterno-Fosso delle Valli, the Cimata del Castello-Fontanelle, Pendenza sector, and the south-eastern slope of the Montagna dei Cesoni.

The N10° system is recognized in the Calciariola Ridge, near Paterno, and in the Valle Santa depression.

These faults testify a very intense Quaternary activity, dislocating paleo-surfaces and recent continental deposits. This is evident from the presence of triangular or trapezoidal facets, scarplets, hanging valleys, and by the alignments of dolines (fig. 6). Recent and historical seismicity is related to this tectonic activity (MICHETTI *et alii*, 1994). In the San Vittorino Plain the fault network, dissecting the bedrock buried under a thick alluvial cover, is highlighted by the alignments of sinkholes, springs and gassy fluid anomalies (fig. 6).

3. GEOMORPHOLOGICAL OVERVIEW

The study area is located to the east of the Rieti Plain, between the southern side of the Reatini Mts. and

the north-western sector of the Mt. Nuria Ridge. In this area, from a geomorphological point of view, four sectors, with their own geomorphological features, have been distinguished: A north-western sector, including the southern sector of the Reatini Mts; A central flat zone, characterized by the San Vittorino triangular shaped plain, with a SE facing apex; A south-eastern mountain sector, including the north-western edge of the Mt. Nuria Ridge and the Pendenza-Colle Impicciavera blocks; A south-western foothill sector represented by the Calciariola Ridge.

In the highest parts of the mountain sectors, remnants of low-relief paleo-surfaces can be identified: the *summit surface* (*surface de sommets* in DEMANGEOT, 1965), and two other paleo-surfaces, entrenched in the former one and arranged in two levels of altitude.

The north-western sector presents a very complex morphology, characterized by widespread paleo-surfaces, markedly dissected by the Quaternary extensional tectonics. In the study area the 1st order paleo-surface is well defined at Cimata del Castello (1503 m a.s.l.), Prato Miccio-Colle Riofagio (1319 m a.s.l.), Colle Cesarini (1454 m a.s.l.), and Colle Falsata-Fontanelle (1310 m a.s.l.). The 2nd order paleo-surface is represented at Fontanelle (1050 m a.s.l., where it is characterized by the occurrence of paleo-landslide and breccia deposits (*Fontanelle breccias*), and in the Paterno sector (1027 m a.s.l.).

The hydrographic network is superimposed on the main Middle Pleistocene faults. It is characterized by two deep V-shaped valleys, the Valle Ottara-Fosso delle Valli and the Valle Santa, whose slopes are incised by a dense rectangular pattern of small valleys. The Valle Santa is a remarkable tectonic depression, in which paleo-landslide and breccia deposits (*Fontanelle breccias*) have been dislocated by NNW-SSE, EW and NW-SE trending faults.

The central sector, corresponding to the San Vittorino Plain, has since the 1890 undergone drastic land works which have markedly modified the original landscape including the course of the Velino River which has been straightened at several localities. Along the right-hand of the plain two orders of alluvial terraces, overlain by travertine deposits, are present: the 1st order is located between 500 m and 450 m a.s.l. (Canetra, San Rocco, Cittaducale) while the 2nd order is located between 440 m and 420 m a.s.l. (Terme di Vespasiano, Caporio). The plain is filled with Upper Pleistocene-Holocene continental deposits. The main peculiarity of this sector is represented by the presence of sinkholes, mineralized (sulfuric and ferric) waters and gassy fluid anomalies.

The south-eastern sector, corresponding to the Colle Impicciavera-Pendenza block, belonging to the external north-western carbonate Nuria Ridge, is subdivided into a set of smaller blocks, consisting of a staircase of NE trending ridges and narrow depressions gradually lowering towards the Velino River (fig. 2). On the very steep north-western slope several small trenches and triangular facets can be observed. Between Colle Impicciavera and Pendenza, a step-wise sequence of SW-wards lowering blocks, evidenced by triangular facets and scarplets, is present. Close to Cerquara, at the extreme north-western edge of the above mentioned sector, deep-seated gravitational deformations (CENTAMORE & NISIO, 2002a) occurred causing the formation of several trenches and the collapse of slopes.

The NW-SE trending Calcariola Ridge, is separated from Mt. Nuria by a deep narrow valley, cutting the carbonate deposits of the *Mt. Navegna Unit*. Its top is characterized by limited flat or smoothly undulated surfaces, separated by shallow E-W trending depressions, filled with eluvial-colluvial deposits. Its steep slopes are cut by numerous NE trending small valleys. On the north-eastern slope, triangular facets, limited slope-ruptures, and trenches are present. These features are linked to the activity of the NW-trending faults and, sometimes, to the reactivation of tectonic elements that controlled the evolution of the Rieti Basin during the Early Villafranchian (BARBERI & CAVINATO, 1992; CAVINATO, 1993; CENTAMORE & NISIO, 2002b). Also the NE-wards step-wise block pattern and the priming of several deep-seated gravitational deformations may be related to the activity of this fault system. In the extreme north-western sector of the Calcariola Ridge a prominent NE trending fault scarp occurs, it represents the south-western prolongation of the *Valle Ottara-Valle dei Fossi Fault*, on the right-hand side of the Velino River Valley.

In the study area, where carbonate rocks largely outcrop, karst landforms (hypogene and epigene) are widespread. These features show different evolution, arrangement and typology from one sector to the other, in relation to the structural setting of the sector. Generally they formed on the paleo-surfaces, especially on the 2nd order *Fontanelle surface* (CENTAMORE & NISIO, 2000a;

NISIO & ROSSI, 2003). In the Montagna dei Cesoni-Cimata del Castello sector, where the umbrian-marchean-sabine successions outcrop, numerous dolines of variable dimensions were formed at the intersection of a NE-SW fault system with a NW-SE fault system (fig. 6). They tend to be deepening suggesting a young karst, developed in an area affected by an intense uplift and a fast valley down-cutting. In the Mt. Paterno-Castel S. Angelo sector, at the footwall of the *Reatini Mts. Thrust*, the karst landforms are mainly represented by laterally collapsed dolines, located on the splay hangingwalls, at the limestone-marls contact, and at the intersection of the main fault systems (fig. 6).

The karst morphology of the Colle Impicciavera-Pendenza sector is very similar to that of the Montagna dei Cesoni-Cimata del Castello sector (fig. 6).

The present landscape of the study area is the result of a long lasting geomorphological evolution started with the initial stages of the Apennine chain emergence (Early Pliocene) when a first continental landscape, characterized by low-relief topography, was formed. Small remnants of this ancient landscape are still present on top of the highest mountains (*summit surface*). Further uplift and erosion processes gave rise to other two low-relief surfaces, entrenched in the summit surface, and arranged at different topographic heights (*relict surfaces* or *orographic terraces*, CENTAMORE & NISIO, 2003). In the final Early Villafranchian, a first remarkable impulse of extensional tectonics, linked to a sharp increase of the regional uplift, occurred. In this context, surface faulting heavily modified the previous landscape with the formation of high fault slopes bordering tectonic depressions. On these slopes, large-scale landslides and deep-seated gravitational deformations (CENTAMORE & NISIO, 2002a, 2002b, 2003) were triggered. Cold climate conditions were responsible for widespread frost-shattering processes on bare slopes and the accumulation of thick breccia deposits (CENTAMORE & NISIO, 2002a, 2002b, 2003 and references therein).

By the end of the Lower Pleistocene, an intense increase of regional uplift and extensional tectonics and a sharp change to cold-arid climatic conditions occurred, causing the deep entrenching of the hydrographic network, with the development of deep narrow V-shaped valleys where the alternating cold/temperate climate phases favoured the formation of several orders of alluvial terraces (CENTAMORE & NISIO, 2002a, 2002b, 2003).

Travertine deposits, likely formed by the emergence of mineralized water (BRANCACCIO *et alii*, 1988) are widespread in the study area. In particular, the (Canetra, S. Rocco, Cittaducale) travertine has been deposited in a set of step-wise arranged basins, lowering towards the Rieti Basin. Waterfall travertine lithofacies, outcropping along faults at San Rocco and Cittaducale (CARRARA *et alii*, 1992), can highlight the formation of fault scarplets (CENTAMORE & NISIO, 2002b).

These events could be related to a phase of intense tectonic activity, which occurred in the area in the late stages of Middle Pleistocene, causing the reactivation of the *Fiamignano-Micciani Fault*, and the displacement of the *Piedimozza-Cerquara Fault* (FACCENNA *et alii*, 1993; CENTAMORE & NISIO, 2002a, 2002b, 2003). These events were responsible for the triangular-shaped morphostructural pattern of the San Vittorino Plain, which can be considered a sort of a pull-apart basin, with an irregular



Fig. 7 - Detailed photo of one of the several sinkholes filled by sulphurous water and gas.
 - Dettaglio di uno dei numerosi sinkhole riempiti con acque sulfuree e gas.

geometry (CENTAMORE & NISIO, 2002a). In the same context, a part of the Mt. Paterno sector collapsed towards the SE and SW through a set of down-stepping blocks, which largely occupied the San Vittorino depression, later filled with 180-200 m thick lacustrine-alluvial sediments. Downfaulted blocks of travertine, previously outcropping in the collapsed sector, have been recognized in drilling cores close to Mt. Paterno Ridge, under a thick cover of more recent sediments.

4. THE SINKHOLES

In the San Vittorino Plain at least 35 sub-circular sinkholes are present (fig. 6); some of them are extinct, while others host small lakes or ponds, formed through drowning processes (CARAMANNA *et alii*, 2004; NISIO, 2003, 2004; NISIO *et alii*, 2004; CARAMANNA *et alii*, 2008) (fig. 7). One of these, the Lago Paterno sinkhole, (characterized by a floating island) was already present in Roman times, when religious ceremonies were officiated at its borders. The first recorded sinking occurred in 1705, following an earthquake. This event caused the formation of a 20 m wide and 2 m deep cavity which heavily affected the San Vittorino church (built between 1604 and 1614). In 1787 further failures involved the church foundations which were submerged by four palms-width of spring water. Five other sinkholes, among which are two small lakes (Lago di Mezzo and Pozzo Burino), seem to have formed between 1700 and 1850. The Lago di Mezzo sinkhole seems to be the more recent: it is, in fact, not reported in a 1808 atlas (RIZZI ZANNONI, 1808), while it is present in a map of 1815 (IGM, 1815). On the contrary, Pozzo Burino, a cylindrically shaped, 55 m deep small lake, is already present in the same 1808 atlas (BERSANI & CASTELLANO, 2002). This sinkhole formed within 1st order terrace alluvial deposits; its base is located on the footwall of one of the Mt. Paterno splays.

Several collapses occurred in August 2002 along the Salaria Road, giving rise to cavities later filled through

restoration works. The latest sinkhole opened in September 2003, at 100 metres from the Salaria Road, near the Consorzio Agrario; this cavity, 4 metres in diameter, still hosts a pond.

In 1886, after an intense rainfall period, three cavities, with diameters ranging between 5 and 60 m and 10m depth, were formed in the Sciamagutta area.

Several sinkholes (including Lago Paterno, Lago di Mezzo, Pozzo Burino) have been reactivated between 1985 and 1951 (RICCARDI, 1951; MORI, 1895); their dimensions are variable, with diameters of 204, 130, 80, 50, 15m, and depth from 45 to a few metres (COLOMBI *et alii*, 1999; CAPELLI *et alii*, 2000). In 1893 five new sinkholes, with 100 m to 8 m diameters and 10 to 15 m depth, suddenly opened. Five other small (a few metres wide) cavities opened in 1903. Reactivation or enlargement of sinkholes were observed in coincidence with seismic shocks (MICETTI *et alii*, 1994), as occurred for the 1915 Avezzano earthquake, when Pozzo Gustavo opened.

The sinkholes are concentrated in the northern sector of the San Vittorino Plain, bounded by the *Fiamignano-Micciani* and *Piedimozza-Cerquara* faults. They are aligned along different trends: NE-SW between Vasche and Case Paterno; E-W between Terme di Cotilia and San Vittorino; NW-SE in the belt between the Peschiera Springs-Micciani and Cotilia-San Vittorino, coinciding in part with the north-western prolongation of the *Fiamignano-Micciani Fault* (FACCENNA *et alii*, 1993; NOLASCO, 1996). West of the *Fiamignano-Micciani Fault* no collapse processes are recorded (FACCENNA *et alii*, 1993; CIOTOLI *et alii*, 1998; CENTAMORE *et alii*, 2002, 2004).

The mineralized waters, filling the cavities, are mainly characterized by a sulphurous and ferruginous composition. They are mainly concentrated at the foot of the Mt. Paterno, between San Vittorino and Vasche, but others are located on the left-hand of the Velino River Valley, along the NW-SE Piedimozza-Cerquara alignment. In particular, the ferruginous waters emerge in several ponds at San Vittorino SE, along the *Fiamignano-Micciani Fault* prolongation, while the sulphurous ones are aligned E-W, between San Vittorino and Vasche, NW-SE trending between Pendenza and San Vittorino and between Piedimozza and Cerquara (FACCENNA *et alii*, 1993; NOLASCO, 1996; CIOTOLI *et alii*, 2001).

5. HYDROGEOLOGICAL SETTING

The *Fiamignano-Micciani Fault*, the *Piedimozza-Cerquara Fault* and the *Velino Fault* subdivide the study area into different sectors with different hydrogeological behaviour: the Calcariola Ridge sector, corresponding to the south-western part of the study; the south-eastern Colle Impicciavera-Mt. Serrasecca sector and the Montagna dei Cesoni-Mt. Paterno sector.

The Calcariola Ridge bedrock consists of three piled up tectonic units (*Reatini Unit*, *Navegna Unit* and *Salto Unit*) locally composed of feeble permeability formations (Scaglia cinerea, Guadagnolo Unit, argilloso-marnosa unit, and Messinian siliciclastic turbidites; Pl. 1), bounded to NE by the *Fiamignano-Micciani Fault*, and buried under the Rieti Basin Villafranchian deposits. This block exerts a sort of plugging action for the fluid circulation and is not affected by karst processes.

The-Colle Impicciavera-Mt. Serrasecca bedrock consists of a thick, densely fractured carbonate succession, characterized by a high permeability and by the presence of numerous karst landforms. It makes part of the Mt. Giano-Mt. Nuria-Mt. Velino hydrogeological system, the most important aquifer of Latium (BONI *et alii*, 1995). The main emergences of this aquifer are the Peschiera Springs, whose flow reaches 18,000 l/s (BONI *et alii*, 1995). These springs are located in the maximum convexity plane, at the convergence between the *Velino* and the *Fiamignano-Micciani Faults* (fig. 2), their emergence is linked to the plug effects of the aquicludes located in the hangingwall of the two structural elements.

In the Montagna dei Cesoni-Mt. Paterno sector, the upper subunit of the *Reatini Unit*, formed by the Jurassic pelagic carbonate succession, arranged in a gentle syncline, represents a good aquifer. This is plugged at its base by the Scaglia cinerea aquiclude and is drained toward northern sectors. The underlying Mt. Paterno sector, subdivided internally three splays, represents a very complex hydrogeological system, formed by a set of aquifers, bounded to the hangingwall and to the footwall by aquicludes (Pl. 1). The most important of these is constituted by the siliciclastic turbidites located in the footwall of the lower splays. Along the Mt. Paterno slope, these aquifers feed small springs located at the splays emergences, while along the southern slope borders, emerge fresh-water springs, with 2000 l/s flow, belonging to the Mt. Paterno hydrological system. In the plain sector, under the thick alluvial cover, lies the collapsed Mt. Paterno splays system. This system represents a set of confined aquifers, with significant hydraulic pressure (Pl. 1).

The continental deposits, filling the San Vittorino depression, represent a feeble permeability hydrological system that hosts small ground-water bodies. Confining between the two main hydrogeological facies is observed: bicarbonate-sulphate-calcic, prevailing in the northern border, and the bicarbonate-calcic, prevailing in the southern area. Moreover a well developed mixing is recorded in the northern sector, while it is almost absent in the southern one, with a reduced mixing along the main Apennine trending dislocations (CIOTOLI *et alii*, 2001).

Mineralized waters, Helium/Radon anomalies and ascending gases are concentrated mainly in the extreme northern sector of the plain, between San Vittorino-Cerquara and San Vittorino-Micciani alignments (CIOTOLI *et alii*, 2001; CENTAMORE & NISIO, 2002a). All the above elements seem to be linked to a deep thermal circuit, connected with the surface through the deep faults or fractures, such as the *Fiamignano-Micciani* or the *Velino Faults*. The ascending fluids may be connected with a late phase of local magmatism, possibly the one that caused the eruption of Cupaello 491±3 ka (STOPPA & CUNDARI, 1995), not far from the study area, alternatively, they may belong to fossil waters, belonging to the hydrocarbon accumulation.

The catastrophic sinkhole collapses are commonly joined with fluid and gas anomalies along the main tectonic elements and sometimes are accompanied by roars and trembling.

6. DISCUSSION AND CONCLUSIONS

The spatial distribution of sinkholes, mineralized waters and gas anomalies clearly indicates a net concen-

tration in the northern-central sector of the San Vittorino Plain, where geologic-structural and hydrogeological features of that block seem to favour the formation and arrangement of the collapses. This sector, in particular, is characterized by: a karst affected carbonate bedrock, arranged in a set of splays with clayey-marly or siliciclastic footwall, and dislocated by a dense fault network; a structural system retaining confined aquifers with substantial hydraulic pressure; a thick siliciclastic horizon, located at the base of the lower splays and representing an important aquiclude, which plays a significant role in dividing the northern sector waters from those of the southern one, and in controlling the ascending flow of waters belonging to the deep thermal circuit, and the limited mixing between the northern and southern sectors; a thick continental heterogeneous, feebly permeable cover.

As regards to the lack of recent collapses in the southern sector and in the sector located on the south-western side of the Micciani-San Vittorino alignment (prolongation of the *Fiamignano-Micciani Fault*), an explanation may be found in their geological-structural and hydrogeological patterns, very different from that of the northern-central sector. In the south-eastern sector several structures, filled by collapsed deposits or levelled through anthropic reworking, have been referred to former sinkholes. These features are aligned along the *Velino River Fault*, where a lowered block of the *Mt. Nuria Unit* is located. Deep piping processes would have developed there in past climatic conditions characterized by higher piezometric levels.

In the sector at SW of the *Fiamignano-Micciani Fault*, characterized by feeble permeability, the collapse processes cannot develop due the absence of the necessary predisposing factors.

The above data allow us to define the tight relationships between the sinkhole development and the geological-structural/hydrogeological context. In particular the San Vittorino sinkholes are located in a limited area of the wider plain, where a fault lowered block of the Mt. Paterno Ridge lies under a thick, feebly permeable continental cover.

The main triggering factors of the sinkhole collapses may be referred to deep piping processes, developed by the ascending waters through bedrock faults and fractures and responsible for the erosion and the upwards transportation of the overlying continental deposits. These phenomena are accompanied by dissolution processes linked to CO₂ and H₂S ascending through the same dislocations (NISIO, 2003). These processes would record significant increases during seismic shocks or very intense meteoric events, from the pressure variations in the confined aquifers.

The role of travertine dissolution in inducing sinkhole collapses seems entirely irrelevant since they are discontinuously distributed or completely absent in some of the sinkhole affected areas.

Among the predisposing factors to the priming and propagation of sinkholes in the Plain, a predominant role has certainly been played by the presence of an intersecting fault system and of a fracturing network that favoured the communication between the carbonate substratum and the thick alluvial cover. In the specialist literature the possible relationships between seismic events and sinkhole development has been invoked for many cases, but there is not, up to now, a sound test of the intercon-

N of events	sinkhole development date	earthquake date	epicenter	distance	<i>I</i> s to the epicenter	<i>I</i> s to the site	days from the seismic event
1	14-1-1703	14-1-1703 2-2-1703	Norcia l'Aquila	32km 21km	100 90	95	0
2	19-9-1891	14-7-1891 1-10-1891 9-4-1895	Trevi	50km	65		66?
2	26-12-1902	17-12-1902	Rieti Castelritaldi	4km 56km	60 60	60 ?	9
3	25-11-1903	2-11-1903	Rieti Norcia	11km 57km	50-60 60-70		23
7	31-1-1915 2-2-1915 3-2-1915	13-1-1915	Avezzano	55km	110	75-80	18-21
1	5-7-1933	3-7-1933	Lama dei Peligni	95km	90	?	2
1	1962	25-6-1962 20-10-1962 12-9-1962 14-12-1962	Serravalle Baiano Alvito Alvito	51km 43km 100km 100km	60 70 55 60	? ? ? ?	? ? ? ?
3	17-2-1986	3-2-1986 7-2-1986	Reatini M. Reatini M.	1-2km 1-2km	28-30	28-30	10 12
1	30-9-2004	27-9-2004 28-9-2004	Reatini M. Reatini M.	1-2km 1-2km	30	30 30	3 2

Fig. 8 - Distribution and frequency of earthquakes related to the development of the sinkholes.
- *Distribuzione e frequenza dei principali eventi sismici in relazione allo sviluppo dei sinkhole.*

tion among earthquake timing, epicentre distance, shaking intensity and cavity forming. The research on seismic catalogs (fig. 8) points out that almost all sinkhole collapses developed in connection with an earthquake (generally within twenty days after the shock). Unfortunately, in many cases, the collapse dates are uncertain making the connection weak. It is highlighted that on occasion of very high soil macroseismic intensity (*I*s), generally 95-110, the response is immediate: the cavity forms in a day, also for 30-50 km distant epicentres. However it is possible that several cavities were formed also in connection with instrumental earthquakes (*I*s 30).

ACKNOWLEDGEMENTS

We are grateful to Francesco Dramis and to the anonymous reviewer for their constructive reviews of this paper that improved the final version of the manuscript. We are also grateful to Dott. David Turner for his detailed revision of the English language form and style. This contribution has been supported through CARG Lazio Project Grant to Ernesto Centamore.

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