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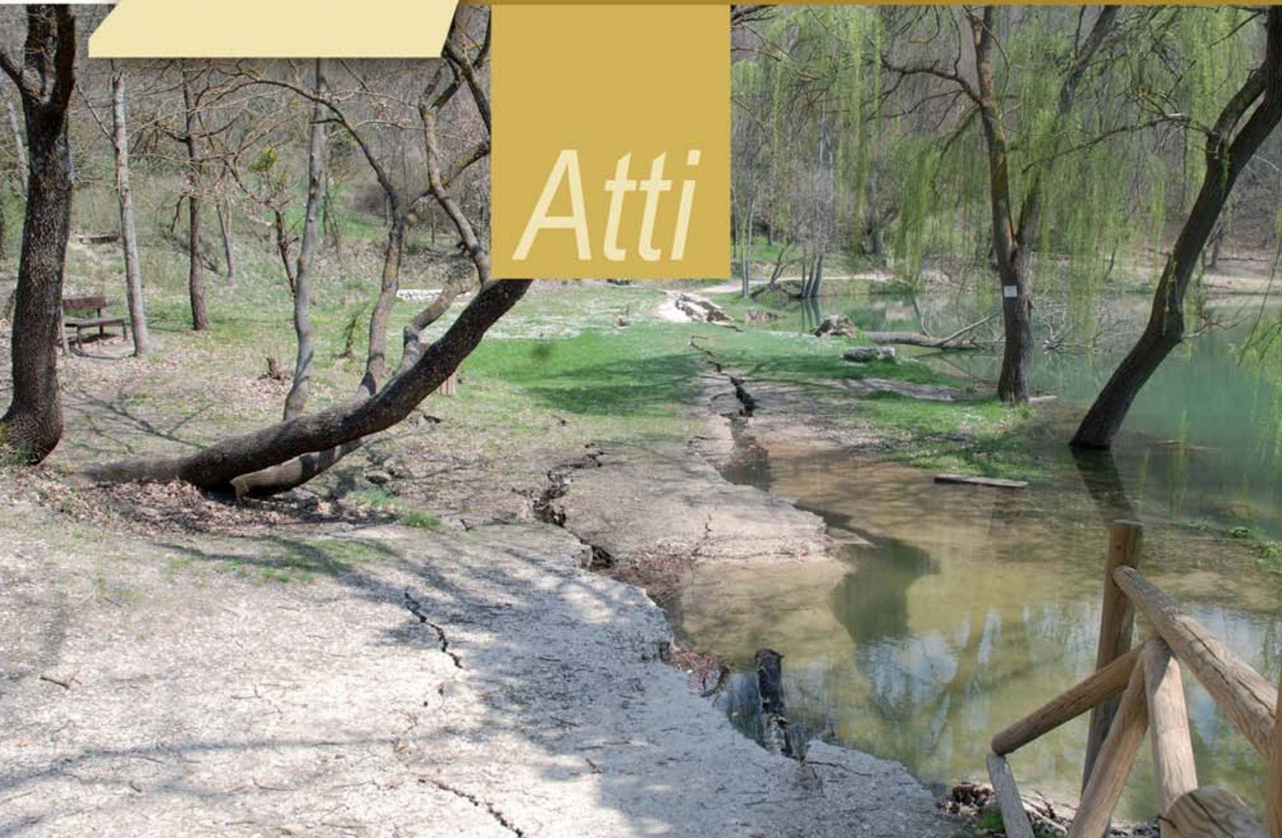
I SINKHOLES. GLI SPROFONDAMENTI CATASTROFICI NELL'AMBIENTE NATURALE ED IN QUELLO ANTROPIZZATO

ROMA 3 - 4 DICEMBRE 2009

Atti



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2° Workshop internazionale
I Sinkholes
Gli sprofondamenti catastrofici nell'ambiente naturale ed in quello antropizzato

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ACTIVITY OF THE ITALIAN NATIONAL RESEARCH COUNCIL IN THE AFTERMATH OF THE 6 APRIL 2009, ABRUZZO EARTHQUAKE: THE SINIZZO LAKE CASE STUDY

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ABSTRACT

The 6 April 2009, earthquake (Mw = 6.3) that hit L'Aquila and the Abruzzo region, central Italy, caused 306 fatalities, widespread damage to structures and infrastructure, ground deformations and multiple instability phenomena. The National Research Council (CNR) operated in the epicenter and the surrounding area immediately after the main shocks to complete field surveys and geomorphological and geophysical analyses aimed at the evaluation of individual hazards related to seismically-induced slope failures and ground instabilities. This work describes the research activities performed at the Sinizzo Lake, near San Demetrio ne' Vestini, a sinkhole where open cracks were observed immediately after the earthquake.Teams from different Institutions were involved in the study, under the general coordination of the CNR Department of Earth and Environmental Sciences. The Sinizzo lake is located less than 1 km east of the village of San Giovanni, in the San Demetrio ne' Vestini municipality. Circular in shape, and with a diameter of some 120 m, the lake has been subject to man made modifications, including an artificial barrier to increase the lake depth, currently around 10 m. Steep slopes that have been locally affected by small-volume rock falls, a consequence of the 6 April 2009 earthquake, characterize the surrounding area. Following the main shocks, open cracks and evident ground deformations formed on the lakeshore, and evolved rapidly in the following days. To characterize the geometry and structure of soils cropping out in the area, and to assess the integrity of the artificial barrier that raises the shoreline locally, four electric resistivity tomographies (ERT) were performed perpendicular and parallel to the western shore of the lake. The ERT highlighted terrains characterized by different geoelectrical properties, allowed estimating the thickness of the shallow layers, and to identify vertical and horizontal discontinuities in the subsoil. High-resolution, multi-beam bathymetry of the lake was performed, and the processed data used to generate a digital elevation model with a ground resolution of 5 cm x 5 cm. Comparison of the obtained results with pre-existing single-beam bathymetric data indicates no significant difference in the general configuration and depth of the lake-floor. The most relevant feature is an incipient instability along

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the eastern side of the lake, outlined by an irregular morphological step with a concave shape in plan-view, possibly locally evolving into an open fracture.

Riassunto

Il terremoto del 6 Aprile 2009 (Mw = 6.3) che ha colpito L'Aquila e l'Abruzzo ha causato 306 morti, danni ingenti agli edifici ed alle infrastrutture, deformazioni del suolo e diversi fenomeni di instabilità dei versanti. Immediatamente dopo il sisma, il Consiglio Nazionale delle Ricerche (CNR) ha operato nell'area epicentrale e nelle zone limitrofe, effettuando sopralluoghi e indagini geomorfologiche e geofisiche mirate a valutare la pericolosità connessa a specifici fenomeni di instabilità dei versanti indotti dal sisma. Questo lavoro descrive le attività di ricerca condotte al Lago Sinizzo, presso San Demetrio ne' Vestini, un'ampia dolina all'interno della quale subito dopo il terremoto si sono aperte evidenti fratture. Gruppi di ricerca di diverse Istituzioni hanno partecipato allo studio, con il coordinamento del Dipartimento Terra e Ambiente del CNR. Il Lago Sinizzo è situato a meno di 1 km a Est dall'abitato di San Giovanni, frazione di San Demetrio ne' Vestini. Di forma circolare, e con un diametro di circa 120 metri, il lago è stato in passato oggetto di modifiche antropiche, fra le quali la realizzazione di uno sbarramento che ha portato il lago alla profondità attuale di circa 10 metri. L'area circostante è caratterizzata da versanti acclivi, che sono stati interessati da crolli in roccia di volumi medio-piccoli in conseguenza del sisma del 6 Aprile 2009. A seguito delle scosse principali, lungo le sponde del lago si è formato un evidente sistema di fratture concentriche, associato a deformazioni del suolo, in rapida evoluzione. Per caratterizzare la geometria e la struttura dei terreni affioranti nell'area, e per valutare l'integrità dello sbarramento artificiale, sono state eseguite quattro tomografie elettriche (ERT), in direzione parallela e perpendicolare al margine occidentale del lago. Le tomografie hanno consentito di individuare terreni con diverse proprietà geo-elettriche, di stimare lo spessore degli strati superficiali, e di identificare discontinuità verticali e orizzontali presenti nel sottosuolo. E' stata realizzata una batimetria ad alta risoluzione nel lago, e i dati ottenuti hanno permesso di generare un modello digitale con risoluzione di 5 cm x 5 cm. Il confronto con una batimetria del lago precedente non ha rilevato differenze sostanziali nella configurazione e nella profondità del fondo del lago. L'elemento più significativo è un fenomeno di instabilità incipiente lungo la sponda orientale, evidenziato da un gradino morfologico irregolare di forma concava in pianta, che localmente pare evolvere in una frattura.

1. Introduction

In addition to the direct effects caused to the built up environment, earthquakes can trigger multiple types of ground instabilities, and produce indirect – locally severe – effects to the natural environment (Keefer, 1984). Rockfalls and topples are the most common type of seismically induced slope failures, that can be triggered by earthquakes of magnitude 4.0, or larger (Mc Calpin & Nelson, 1996). Among the other possible ground instabilities, reactivation and formation of sinkholes have also been observed (Yule & Grau, 2003; Waltham *et alii*, 2005, and references therein; Parise, 2008).

On 6 April 2009, at 01:32:39 UTC (03:32:39 local time), the Abruzzo Region, central Italy, was shaken by a severe earthquake of local magnitude M_L = 5.8 (moment magnitude M_w = 6.3). The epicenter of the earthquake was located WSW of l'Aquila at a depth of about 8.8 km. On April 7 and April 9, two earthquakes of $M_L > 5$ occurred in the same general area: the first ($M_L = 5.3$) was located 11 km SSE of l'Aquila, and the second ($M_L = 5.1$) 15 km NNW of l'Aquila. The 6 April 2009 earthquake ($M_W = 6.3$) that hit l'Aquila and the Abruzzo Region caused multiple ground deformations and widespread slope instabilities, chiefly rockfalls. The main seismic event took place along a normal fault trending NW-SE, and dipping southwest. The earthquake was the largest event in a seismic sequence that had started a few months earlier and had its most significant previous event on March 30, 2009.

The Italian National Research Council (CNR) operated in the epicentral area and the surrounding region immediately after the main shocks, to complete field surveys and geomorphological and geophysical analyses aimed at the evaluation of individual hazards posed by earthquake induced slope failures and ground instabilities. In this work, we describe the activities conducted at the Sinizzo Lake, near San Demetrio ne' Vestini, a sinkhole where open cracks were observed immediately after the main shocks. Teams from multiple Institutions contributed to the study, under the general coordination of CNR Department of Earth and Environmental Sciences. The study area is located less than one kilometre east of the village of San Giovanni, in the San Demetrio ne' Vestini Municipality. The Sinizzo Lake is one of several karst landforms present in the middle reach of the Aterno river valley (Nisio, 2008).

2. Geological setting

The epicentral area of the 6 April 2009 earthquake sequence is located in the Central Italian Apennines. In the area crop out stiff, carbonate platform limestone and turbidite sediments deposited in fore-deep basins, and progressively incorporated in the Apennines fold-and-thrust belt during its migration from West to East (Accordi *et alii*, 1988; Meletti *et alii*, 2000; Patacca *et alii*, 2008). In the area, Quaternary terrains were deposited in large morphological depressions, intra-mountain basins located in the uplifting mountain chain. The intra-mountain sedimentary basins are delimited primarily by high-angle normal faults (Bagnaia *et alii*, 1989). In general, the intra-mountain basins are delimited by master faults and associated synthetic faults on the eastern sides of the depressions and by antithetic faults on the western sides (Cavinato & De Celles, 1999; Tondi & Cello, 2003). During the Quaternary the middle valley of the Aterno River was therefore affected by phases of sedimentation of fluvio-lacustrine deposits, alternating with erosion phases caused by tectonics and climatic changes.

San Demetrio ne' Vestini is located on the left side of the Aterno River, on a small ridge trending NW-SE consisting of limestone, Cretaceous to Miocene in age. The limestone is covered by alluvial and lake deposits, mostly sand and gravel, Quaternary in age. Several sinkholes have been recognized in the Aterno valley and its flanks, most of which are located on lake and alluvial sediments, and distant from the limestone ridges (Nisio, 2008). Near San Demetrio, several sub-circular landforms are present in the plain, and have no direct relation with Cretaceous limestone. Some of them are clearly elongated along an apenninic trend, and include from SE to NW: the Sinizzo lake, another unnamed depression, Fossa Cupa, and Fossa Prinesca (Fig. 1). All these landforms have a diameter greater than 100 m, and a thickness of alluvial deposits of at least 30 m.

The local stratigraphy in the surrounding of the Sinizzo Lake consists of a limestone bedrock of Jurassic - Cretaceous age, overlain by Eocene-Miocene deposits (Bosi & Bertini,

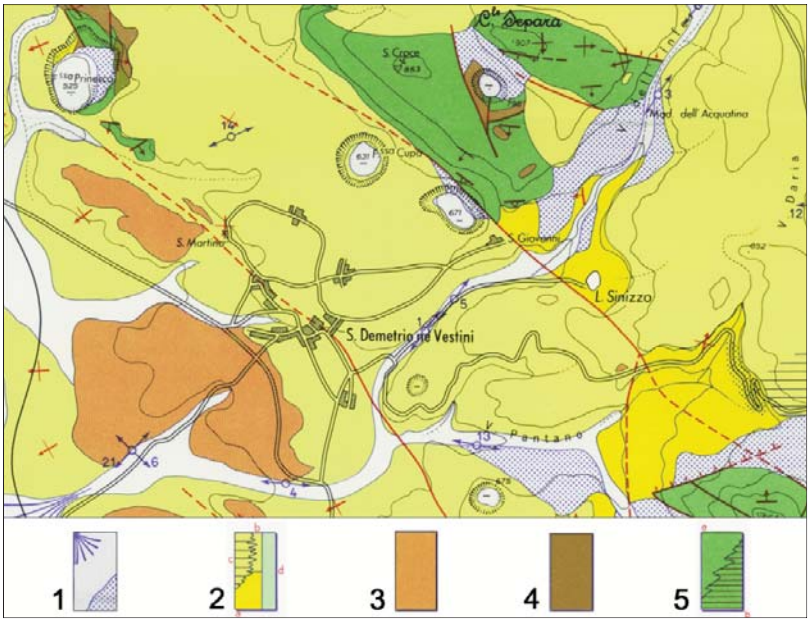

Fig. 1 – Geology of the area (simplified after Bosi & Bertini, 1970). Key: 1) recent alluvial deposits (Holocene); 2) lower fluvio-lacustrine complex (Lower-Middle Pleistocene); 3) breccias and conglomerates (Upper Pliocene – Lower Pleistocene); 4) Marl limestones (Lower-Middle Miocene); 5) Limestones (Jurassic – Cretaceous).

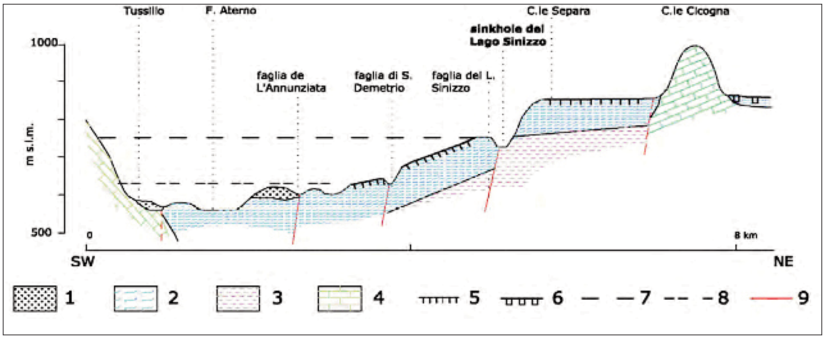

Fig. 2 – Schematic geological cross section of the Aterno valley (modified by Nisio, 2008, after Bosi & Bertini, 1970). Key: 1) upper fluvio-lacustrine complex; 2) Fossa dell'Inferno conglomerates; 3) S. Nicandro calcareous silts; 4) Cretaceous limestones; 5) Valle Daria surface; 6) Ansidonia surface; 7) position of Valle Daria surface; 8) terrace; 9) fault.

1970; Bertini *et alii*, 1989). For the goals of the present study, the most important lithologies are the Quaternary deposits, and in particular the so-called "lower fluvio-lacustrine complex", consisting of the San Nicandro calcareous silts, and the overlying Fosso dell'Inferno Conglomerates.

The San Nicandro calcareous silts crop out extensively in the area, and are a soft rock, that locally may become more competent because of the greater degree of calcite cementation. Locally, the silts pass upward to whitish marls, due to an increase in the content of clay minerals. The calcareous silts represent the lower member of the complex, with thickness ranging from 2 m to more than 50 m. The largest thickness is in the central part of the basin, which includes the area between San Demetrio, San Nicandro, and the Sinizzo Lake. The passage to the overlying Fosso dell'Inferno Conglomerates is gradually marked by gravel lenses with calcareous clasts, increasing in number and dimensions towards the top.

The Fosso dell'Inferno Conglomerates show rounded, prevailingly calcareous, clasts, in beds ranging from 0.5 to several meters, with local intercalations of light calcareous sands and silty sands (maximum thickness 1m). Generally in sub-horizontal bedding, and with 110-120 m overall thickness, the conglomerates represent a filling episode of the lacustrine basin, being related to sedimentation deriving from intense erosion of the surrounding areas, with great amounts of coarse debris materials which reached the basin, and deposited above the San Nicandro calcareous silts. Upward, the conglomerates end with a typical horizontal surface (named Valle Daria surface, at elevation about 850 m a.s.l.), the likely filling surface of the Aquilan lacustrine basin (Bosi & Bertini, 1970).

On the opposite (W) valleyside of the Aterno River, there is the Ansidonia surface, which according to a number of geometric and stratigraphic considerations by the same Authors, does not coincide with the Valle Daria, and corresponds to an older surface, even though similar in genesis (Bosi & Bertini, 1970).

Several portions of the Valle Daria surface are identifiable at different sites and heights, which testify to the occurrence of tectonic movements after the last phase of filling of the lacustrine basin. To summarize, the evolution of the middle reach of the Aterno River is characterized by a large lacustrine basin (Lago Aquilano), where filling ends with a wide surface extending from San Pelino to the Conca Subequana. A smaller basin (Sant'Eusanio Lake), probably resulting from tectonic events, originates afterwards within the boundaries of the previous lake; the Sant'Eusanio lake has its eastern margin just below the area where nowadays the inhabited area of San Demetrio is located.

The tectonic setting of the area is quite interesting, especially in terms of the evidence of recent movements: the reliefs on the left valleyside of the Aterno River are elongated in NW-SE direction, and correspond to monoclinal ridges dipping mostly to the N (locally, the NE and NW), bounded on the southwestern side by highly dipping (>50°) normal faults. The overall tectonic setting is completed by another fault system (NNE-SSW or NE-SW directed, with sub-vertical dip) that dislocates the area in a number of blocks.

The calcareous bedrock has been reconstructed in the middle reach of the Aterno River by means of geoelectric surveys, presented by Bosi & Bertini (1970). In regard to the study area, the bedrock (showing ρ > 1000 Ωm) has been identified at depths greater than 500 m. In describing the geophysical results, the Authors found it was not possible to identify with certainty the nature of the conductive cover above the bedrock: in fact, below a surface horizon of the recent alluvial deposits, the low measured values of resis-

Fig. 3 – Overall view, looking SE, from the northern side of the like: in the foreground, some of the cracks on the lake shores. Note in the background, in the upper left of the picture, the source areas of rock falls, that follow the strata attitude, affecting the same layer of conglomerate.

Fig. 4 – Rock falls triggered by the April 6, 2009, earthquake at the eastern slope of the lake, and the deriving debris talus. Note the two main source areas, corresponding to a conglomerate layer overhanging because of selective erosion in the underlying finer materials.

Fig. 5 – North-western corner of the lake, showing the man-made outlet realized after the impounding embankment.

tivity ($\rho < 40\ \Omega$m) could correspond to the San Nicandro calcareous silts, but also to the marls of the upper Miocene (Bosi & Bertini, 1970).

In regard to the geo-structural setting, fault systems have separated in the area many monoclinal ridges that, on the left valley of the Aterno River, dip to the NE, bounded by normal faults dipping SW (Bosi & Bertini, 1970). Starting from the Pliocene, a distensional phase begins, which is testified by movements and dislocations occurring after the lacustrine sedimentation in lower Pliocene (Blumetti *et alii*, 1996), such as the disconformities in the fluvial conglomerates overlying the lacustrine deposits near San Demetrio ne' Vestini.

The fault of Sinizzo Lake, located on the prolongation of the Paganica fault, belongs to the fault system that also includes the Annunziata and the San Demetrio faults (see Fig. 2). The Sinizzo Lake fault cuts Fosso dell'Inferno just downslope from the lake, and its main evidence is represented by the abrupt lateral contact between the San Nicandro calcareous silts, cropping out to the NE on both the flanks of Fosso dell'Inferno and along the road to San Nicandro, and the conglomerates to the SW. In addition, the fault is also testified by the Valle Daria surface (Fig. 2). The fault system creates a step structure, progressively uplifted toward the NE. Within this structure, some insights on the amount of the uplift related to the fault movements can be obtained by analysis of the original position of the filling surface of the lacustrine basin: in detail, the plate between the San

Fig. 6 – Pictures showing the cracks developed after the seismic shocks along the lake shorelines.

Demetrio and the Sinizzo Lake faults should had been lowered irregularly, and at increasing rate toward the NW (from a few meters in the area S of Sinizzo Lake, to some 70 m at Fossa Cupa). The upslope plate, comprised between the lake and the Colle Cicogna fault, is, on the other hand, uplifted in average about 100 m. In regard to chronology, it seems that these dislocations occurred after the development of the Valle Daria surface, but before the sedimentation of the upper fluvio-lacustrine complex, the deposits of which do not present any offset.

3. The Sinizzo Lake

Lake Sinizzo is located east of the inhabited area of San Demetrio ne' Vestini (Fig. 3). Circular in plan view, the lake has an average diameter of approximately 120 m. The slopes around the lake are very steep at the southern and the eastern margin, where a sub-vertical ridge is present. From the latter, medium-sized rock falls detached as a consequence of the 6 April 2009 earthquake (Fig. 4). The affected slope consists of alternations of gravel and conglomerate layers with intercalations of finer horizons. The differences in the physical characters of the materials determine selective erosion in correspondence of the less resistant horizons, which cause some conglomerate, more compact layers, to overhang and occasionally fall, as experienced during the 6 April 2009 earthquake.

Fig. 7 – Sets of cracks dislocating the shore on the northern margin of the lake.

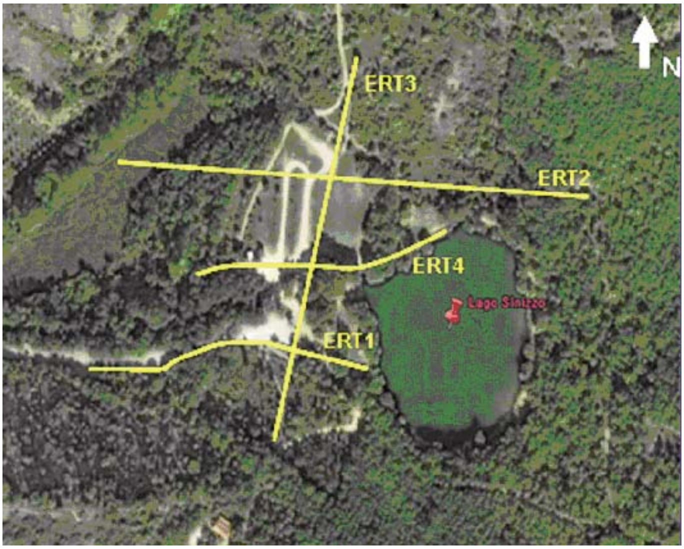

Fig. 8 – Sinizzo Lake (modified by Google Earth) with location of profiles along which the ERTs were performed.

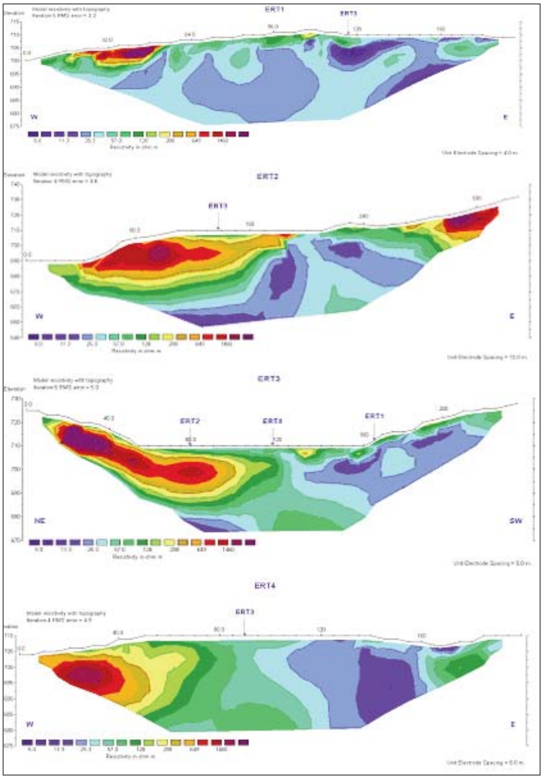

Fig. 9 – Electro Resistivity Tomographies (ERT) at Sinizzo Lake (location shown in figure 8): ERT1 carried out with direction perpendicular to the lake and parallel to the access road to the area; ERT2 carried out with direction perpendicular to the lake, across the artificial barrier built in the western side of the lake; ERT3 carried out with direction parallel to the lake, across the artificial barrier; ERT4, performed with direction perpendicular to the lake, crosses the artificial barrier and can be considered as a zoom of the ERT2.

Originally, the lake probably had a depth of about 7 meters, that was increased to 10 m after realization of a 22.5 m-long impounding embankment (Tetè *et alii*, 1984) at its north-western margin (Fig. 5). During the 16th century the lake was used to work hemp and linen, and as a hydric resource as well. Remnants of the aqueduct, which reached the ancient town of Corfinio in the Peligna Valley, were still visible in the 18th century (Tetè *et alii*, 1984). In 1974 the lake was partly drained. A small spring is located at the northern perimeter of the lake; some Authors report that discharge of the spring was strongly diminished, and its minimum value was recorded in July 1975, with 0.02 l/sec.

In regard to the origin of the lake, the geographer Roberto Almagià, describing the lakes in the Abruzzi region, refers that *"the small lake at San Raniero near Civita di Bagno was produced by a sinkhole that occurred in 1352 or in 1353, and a similar genesis is probably also at the origin of the nearby lake of San Giovanni and the Sinizzo Lake near San Demetrio"* (Almagià, 1919); he therefore describes the Sinizzo Lake as an alluvial doline. Marini (1976), claiming that the lake originated from a small spring, and that it is hosted in a Quaternary lacustrine clay-filled basin, disagrees with Almagià's hypothesis, and affirms that the potential sinkhole would have been originated below the clay cover.

As a consequence of the 6 April 2009 earthquake, several displacements occurred along the lake shores, and a number of open cracks developed (Figs. 6 and 7). The largest permanent displacements (ranging from a few mm to more than 1,5 m) were registered on the north and south shores respectively, which are also the sectors where the slopes

are more flat and gently sloping. The cracks had a rapid evolution during the 3-4 days following the main seismic shock, with progressive enlargement, and extension at distances of more than 20 m from the shore. Based upon our direct field surveys, further confirmed by other research groups (i.e., the Geotechnical Earthquake Engineering Reconnaissance; GEER Association, 2009), it was clear that the deformations were limited to the Quaternary cover materials, and did not affect the nearby limestone deposits.
The entire perimeter of the lake was affected by open cracks, with a trend sub-parallel to the shore. At several locations, anastomosing crack arrays were observed. They generally bounded individual slides that moved into the lake (see also farther on, the section on lake bathymetry).

4. Geophysical surveys

After fractures were observed along the shore of the Sinizzo Lake in the aftermath of the 6 April 2009 l'Aquila earthquake, the main concern was to ascertain the integrity and to determine the stability of the artificial levee located at the north-western corner of the lake. Local authorities and the national Department for Civil Protection (DPC) feared that a sudden failure of the dam could result in an inundation of the areas downstream from the lake. To evaluate the potential hazard, a preliminary set of topographic measurements, to be periodically controlled, was suggested, and geophysical surveys performed. The latter consisted of electrical resistivity tomography and a high-resolution multi-beam bathymetry of the lake, and are described in the section.

4.1 Electric Resistivity Tomography

To characterize the geometric structure of the terrains cropping out in the area and, in particular, to assess the integrity of the artificial barrier, 4 electric resistivity tomographies (ERTs) were performed: three are oriented in W-E direction, whilst the fourth is along the western side of the lake (Fig. 8). To acquire the measurements, dipole-dipole and Wenner-Schlumberger arrays were applied and an electrode spacing varying between 4 – 10 m was used to change the spatial resolution and the investigation depth. The ERTs obtained with different arrays were fully comparable and enabled identification of layers with different geo-electrical properties. In particular, this enabled estimation of the thickness of the shallow layers and to identify both vertical and horizontal discontinuities in the subsoil.
In particular, ERT1 (Fig. 9) was carried out by using 48 electrodes, spaced 4 m apart. The ERT reaches an investigation depth of about 25 m and reveals very low resistivity values ($\rho < 50\ \Omega$m). The shallow western part of the ERT shows higher resistivity values ($\rho > 600\ \Omega$m) that could be associated with the presence of more competent material or plant roots. The blue arrow indicates where ERT1 crosses ERT3.
ERT2 (Fig. 9) was carried out by using 36 electrodes, spaced 10 m apart. It reached an investigation depth of about 50 m and shows high resistivity contrasts. In particular, the western area of the ERT reveals resistive material ($\rho > 200\ \Omega$m), with a thickness of about 25 – 30 m, overlying more conductive material ($\rho < 50\ \Omega$m). The latter characterizes the central and deeper part of the ERT. The eastern side of ERT2 reveals a very high resistive core ($\rho > 600\ \Omega$m) that could be associated with conglomerate terrains outcropping in the area. The resistive material in the western side of the ERT could be associated with the materials used to built the artificial barrier of the lake.

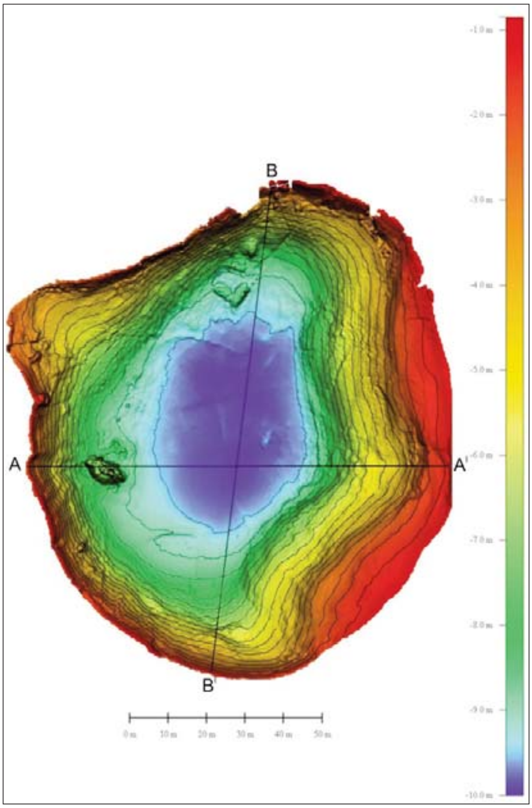

Fig. 10 –Shaded relief map and contour lines of Sinizzo Lake obtained from swath bathymetry data and traces of bathymetric profiles (see Fig. 14).

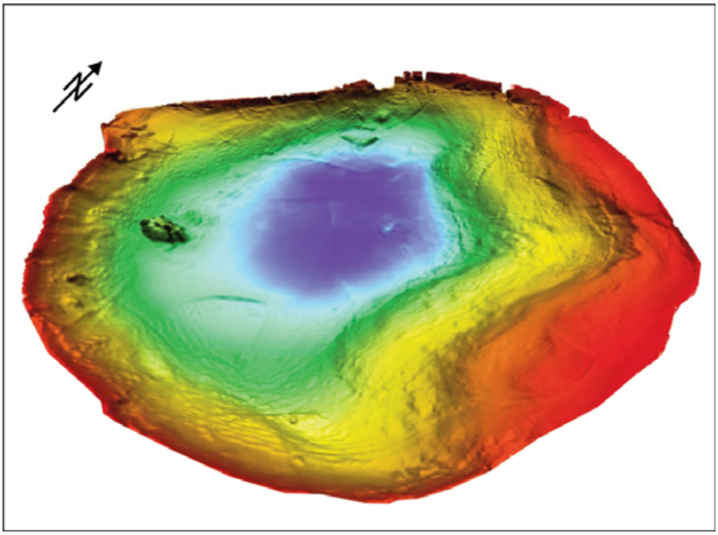

Fig. 11 – Perspective 3D view of the lake looking from the south-east. Note the sector where the main block was detached.

Fig. 12 – The rubber boat "Bombo" equipped with the 8101 multibeam system.

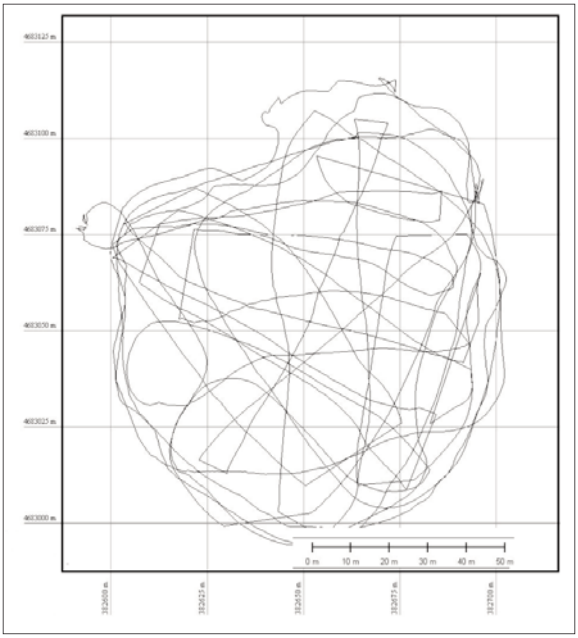

Fig. 13 – Navigation plan for the Sinizzo Lake bathymetric survey.

ERT4 (Fig. 9) was performed in direction parallel to the ERT2 by using 40 electrodes, spaced 5 m apart. Reaching an investigation depth of about 25 m, it can be considered a blow up image of ERT2. ERT4 reveals resistive material ($\rho > 200$ Ωm) in the western side and conductive material ($\rho < 50$ Ωm) in the eastern side. Also in this case, the resistive material could be associated with the materials used to built the artificial barrier.
ERT3 (Fig. 9) was performed by using 44 electrodes, spaced 5 m apart. It reaches an investigation depth of about 35 m and shows high resistivity contrasts. In particular, the extreme north-eastern side is characterized by very high resistive material ($\rho > 600$ Ω m) that could be associated with calcareous terrains. The central part of the ERT shows a vertical discontinuity between high resistive material (200 Ωm $< \rho <$ 600 Ωm), associ-

ated with the materials used to built the artificial barrier, and low resistive materials (ρ < 50 Ωm), associated with silts cropping out in the area. The ERT shows these low resistive materials also on the south-western side of the lake.

ERT3 crosses all the other ERTs, as shown in figure 9 by the blue arrows. The comparison between all the performed ERTs helps to better define the geological setting of the Sinizzo lake. In particular, surficial materials in the southern area of the Sinizzo Lake appears to be relatively less competent. This is consistent with surficial observations of silts in this zone. The other areas around the lake are constituted by more competent material, as conglomerates and alluvial terrains.

The ERTs interpretation highlights vertical and horizontal discontinuities in the stratigraphy and provides estimate of the thickness of the materials within the artificial barrier on the western side of the lake. Moreover, the ERTs provide information on the integrity of the western edge of the lake; it seems that the cracks involving this edge involve only the surface materials, since the ERTs do not highlight the presence of cracks at depth.

4.2 Swath Bathymetry

High-resolution multi-beam bathymetry of Lake Sinizzo (Figs. 10 and 11) was performed on 8 May 2009, 32 days following the main shock. The multi-beam system was equipped with a transducer head with operating frequency of 240 kHz, a processing unit (PU), a gyrocompass and a Dynamic Motion Sensor (TSS). Both heading and attitude data were acquired via a MAHRS inertial navigation system, manufactured by Teledyne. Positioning was obtained through a Topcon GPS equipped with a RTK system. All the instruments were interfaced with the PDS 2000 software package used for survey planning, data acquisition and processing.

Multi-beam bathymetric data were collected from a rubber boat equipped with a dedicated pole and flange used to operate the sonar head (Fig. 12). Vessel tracks were positioned so as to insonify 100 percent of the lake floor, with significant overlap (Fig. 13). Patch test to determine and correct biases from positioning time delay (latency), pitch offset, azimuthal (yaw) offset and roll offset were performed after system installation in accordance with standard procedures. Multi-beam data were edited to eliminate spurious bathymetric and navigation points, and processed using PDS 2000 software from Reson. Subsequently, the processed data were used to generate a digital elevation model (DEM) with cell size of 5 cm x 5 cm, with an accuracy meeting the requirements of the International Hydrographic Organization (IHO).

The collected data revealed morphological features of the lake floor, at metre and decimetre-scale, including features related to slope instability. Overall, the lake is about 10 m deep (9,99m), circular in shape, and with a mean diameter of 120.7 m (Fig. 10, Table 1). The lake bottom is nearly flat, with an asymmetric east-west profile, a concave western slope and a gentle morphologic step along the eastern side (Fig. 14). Hazard-related morphologies include centimetric waves and lobes probably connected to a very shallow creeping of the western slope, arcuate forms, linear depressions, fissures and steps indicating incipient slope instabilities (Fig. 15).

A comparison of the new swath bathymetry data with an existing single-beam bathymetry (Fig. 16; Tetè *et alii*, 1984) did not reveal any significant difference in the general lake-floor configuration and relative depth distribution. The most relevant feature is an incip-

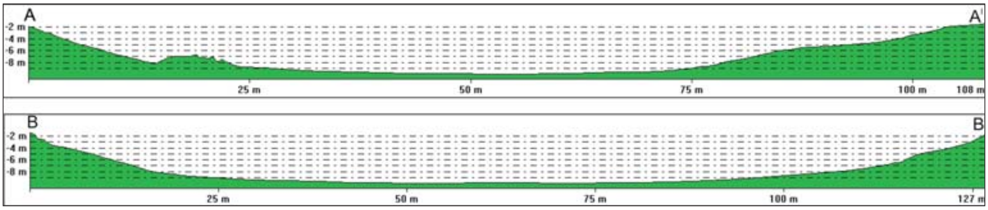

Fig. 14 – Cross sections of the Sinizzo Lake. Trace of the sections shown in figure 10.

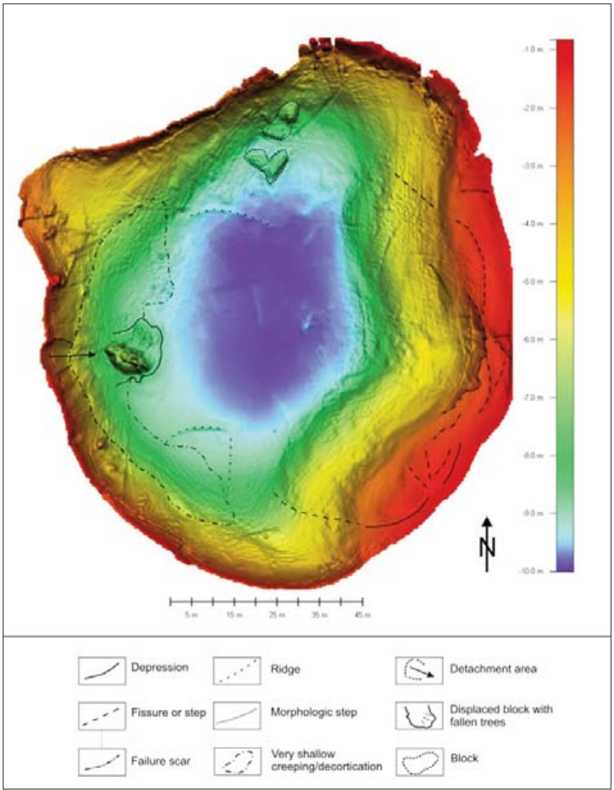

Fig. 15 – Interpretative geomorphologic map of the Sinizzo Lake, based upon the results from the multi-beam bathymetric survey.

ient slope instability revealed by an irregular morphological step (1 to 25 cm in height), of concave shape in plan view, developing for about 120 m along the eastern side of the lake between -1.5 and -7.5 m, and possibly evolving locally into an open crack (Fig. 17). Some of these features may represent the extension underwater of the cracks observed at the lake banks after the main shock. Other lake-floor morphologies induced by the earthquake include a possible shallow creep or decortication of the lacustrine sedimentary cover and a landslide, both located along the western side of the lake. The multi-beam data clearly show the area affected by slope displacement along the western bank (Fig. 17) featured by submerged trees and an arcuate failure scar (see E-W section in Figs. 14 and 15). The landslide mobilized a cohesive mass of material, probably sustained by

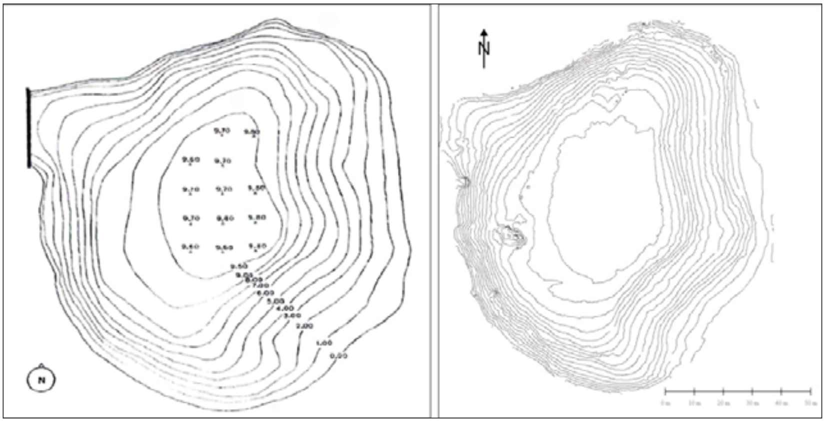

Fig. 16 – Bathymetry of Sinizzo Lake: left, single-beam bathymetry, as surveyed in the 1980's (after Tetè et alii, 1984); right, swath bathymetry data, as surveyed on May 8, 2009.

tree roots and internal cementation, with a total volume of 431.6 m^3. The available data also indicate that the displaced block induced a deformation of the lake sedimentary cover occurring at the lake bottom.

The significant similarity between the previous single-beam bathymetry and the new multi-beam data (Fig. 16; Table 1) suggests a highly localized character of the earthquake-induced effects, almost exclusively confined at the lake banks. Scarce underwater evidence for the widespread cracking and fissuring observed above-water, and lack of well-developed ground deformations at the lake floor indicate very superficial, not evolved toppling of the lakeshore. Nevertheless, minor vertical displacement observed locally, along with volume increase of the lake basin (Table 1) may indicate that, after the main shock, minor "sinking" movements affected the lake.

5. Conclusions

The geophysical surveys carried out at the Sinizzo Lake after the 6 April 2009 earthquake provided information on the effects induced by the seismic shocks in the sinkhole area and its immediate surroundings. Development of an extensive network of cracks around the lake shores, in particular, pushed to investigate the likely continuation of these features at depth, and the occurrence of mass movements as well. Results from both the electrical resistivity tomography and the lake bathymetry indicated that the cracks seem to involve only the Quaternary deposits at shallow depths. Some individual slides were identified, the most striking of which occurred on the western shore of the lake. However, no indications of deeper mass instabilities, or problems related to integrity of the impounding embankment, were observed. This is supported by the overall consistency between the 2009 swath bathymetry and that previously obtained in 1984 with a single-beam technique.

In regard to the sinkhole origin, in order to ascertain whether the Sinizzo Lake originated as a result of a collapse or of a slower process (e.g., suffosion-type) further analyses are needed to reconstruct in greater detail the overburden thickness. In the first case, given

Fig. 17 – Failure of the lake shore occurred soon after the main shock. Note the displaced picnic table in the foreground and the submerged trees in the background.

Table 1 – Morphometric features of Sinizzo lake resulting from multi-beam investigation compared with measurements reported by Tetè et alii (1984).

	TETÈ *et alii*, 1984	This paper	Difference
Perimeter (m)	395	401.8	+6.8
Mean length (m)	135.5	120.7	-14.8
Mean width (m)	87.25	89.78	+2.53
Surface area (m^2)	11,822.38	11,580.82	-241.56
Mean diameter (m)	122.69	120.7	-1.99
Max depth (m)	9.8	9.99	+0.19
Volume (m^3)	66,627.14	68,331.78	+1704.64

the nature of the cover deposits, the collapse may have been originated in voids within the soluble bedrock below, with upward propagation until reaching the ground surface. However, it has to be noted that the overall morphology of the lakeshore may indicate the likely possibility of a suffosion-type sinkhole (WALTHAM *et alii*, 2005), related to downward transport of material into the network of fissures and joints in the limestone bedrock.

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References

Almagià R. (1919) – *Alcuni fenomeni carsici nell'Abruzzo aquilano.* Bollettino della Società Geografica Italiana, **9**, 937-955.

Accordi G., Carbone F., Parotto M., Praturlon A., Civitelli G., Corda L., De Rita D., Esu D., Funiciello R., Kotsakis T., Mariotti G. & Sposato A. (1988) – *Carta delle litofacies del Lazio-Abruzzo ed aree limitrofe.* CNR, Prog. Fin. Geodinamica, Quaderni della Ricerca Scientifica, **114**, 223 pp.

Bagnaia R., D'Epifanio A. & Sylos Sabini S. (1989) – *Aquilan and Subequan basins: an example of Quaternary evolution in central Apennines, Italy.* Quaternaria Nova, **2**, 187-209.

Bertini T., Bosi C. & Galadini F. (1989) – *La conca di Fossa – S. Demetrio de' Vestini.* In: CNR, Centro di Studio per la Geologia Tecnica, ENEA, *Elementi di tettonica pliocenico-quaternaria ed indizi di sismicità olocenica nell'Appennino laziale-abruzzese.* Società Geologica Italiana, 26-58.

Bosi C. & Bertini T. (1970) – *Geologia della media valle dell'Aterno.* Memorie della Società Geologica Italiana, **9**, 719-777.

Blumetti A.M., Cavinato G.P. & Tallini M. (1996) – *Evoluzione Plio-Quaternaria della conca di Aquila-Scoppito: studio preliminare.* Il Quaternario, **9** (1), 281-286.

Cavinato G.P. & De Celles P.G. (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.

GEER Association (2009) – *Preliminary report on the seismological and geotechnical aspects of the April 6 2009 L'Aquila earthquake in central Italy.* GEER Association report no. GEER-016.

Keefer D.K. (1984) – *Landslides caused by earthquakes.* Geol. Soc. America Bulletin, **95**, 406-421.

Marini G. (1976) – *Il fenomeno carsico nella conca dell'Aquila.* Quad. Museo Speleologico V. Rivera, **1** (3), 41-56.

Mc Calpin J.P. & Nelson A.R. (1996) – *Introduction to paleoseismology.* In: Mc Calpin J.P. (ed.) Paleoseismology. Academic Press, San Diego, 1-28.

Meletti C., Patacca E. & Scandone P. (2000) – *Construction of a seismotectonic model: the case of Italy.* Pure and Applied Geophysics, **157**, 11-35.

Nisio S. (2008) – *I sinkholes in Abruzzo.* Mem. Desc. Carta Geol. d'Italia, **85**, 269-308.

Parise M. (2008) - *Rock failures in karst.* In: Cheng Z., Zhang J., Li Z., Wu F. & Ho K. (a cura di), *Landslides and Engineered Slopes*. Proc. 10th Int. Symp. Landslides, Xi'an (China), June 30 – July 4, 2008, **1**, 275-280.

Patacca E., Scandone P., Di Luzio E., Cavinato G.P. & Parotto M. (2008) – *Structural architecture of the Central Apennines: interpretation of the CROP 11 seismic profile from the Adriatic coast to the orographic divide.* Tectonics, **27** (3), doi: 10.1029/2005TC001917.

Tetè P., Pesce G.L. & Leonardis B. (1984) – *Il lago Sinizzo nei pressi di San Demetrio ne' Vestini (L'Aquila).* Natura, **74**, 195-206.

TONDI E. & CELLO G. (2003) – *Spatio-temporal evolution of the Central Apennines fault system (Italy).* Journal of Geodynamics, **36**, 113-128.

WALTHAM T. & LU Z. (2007) - *Natural and anthropogenic rock collapse over open caves.* In: PARISE M. & GUNN J. (Eds.), *Natural and anthropogenic hazards in karst areas: recognition, analysis, and mitigation.* Geological Society of London, sp. publ., **279**, 13-21.

WALTHAM T., BELL F. & CULSHAW M. (2005) – *Sinkholes and subsidence.* Springer, Praxis Publishing, 382 pp.

YULE D.E. & GRAU T.H. (2003) – *Earthquake event report for the North Alabama 29 April 2003 Mw = 4.6 earthquake.* Engineer Research and Development Center, Geotechnical and Structures Laboratory, 21 pp.

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