Rend. Online Soc. Geol. It., Vol. 52 (2020), pp. ...-..., 16 Figs., 1 Tab. (https://doi.org/10.3301/ROL.2020.16)

The dolines of Campoli Appennino (Frosinone, Italy): a geo-historical overview

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Document type: Article.
Manuscript received 23 April 2020; accepted 14 July 2020; editorial responsibility and handling by M. Del Monte.

ABSTRACT

The spectacular karst morphologies of the area between Campoli Appennino and Alvito (Southern Lazio, Italy) represent an emblematic example of karst processes acting on different types of substrate. Hypogean forms are subordinated to epigean ones, with dolines as undiscussed leaders. Imposing and famous are the dolines of "*Fossa Maiura*" (also known as "*Fossa Majura*" or "*Fossa Majora*") and "*Il Tomolo*", around which the town of Campoli Appennino is built in a semi-circle, but are 8 the karst depressions with a diameter greater than 200 m ("main macrodolines") in this area. These forms of landscape controlled the cultural and socio-economic aspects of this corner of Ciociaria. Starting from the second half of the 19th century, the hydrogeological, structural, stratigraphic and geomorphological features of the Campoli Appennino area, attracted the interest of geologists, allowing to recognize a "site of geological memory". However, the geological heritage of this area worth greater visibility, as indicated by the poorly-developed geo-tourism, and for a greater dissemination, making the geo-morphological features more accessible and understandable, even for non-geologists.

KEY WORDS: karst; dolines; Central Apennines; Meso-Cenozoic limestones; "*conglomerati di Campoli Appennino*"; History of Geology.

INTRODUCTION

Karst forms, both hypogean and epigean, are those morphologies produced by the chemical interaction between the water and the carbonate rocky substrate. The water containing CO_2 reacts with the calcium/magnesium carbonate bringing it into chemical dissolution. Dolines are the most emblematic expression of the karst process on the surface (Sauro, 2003), in relation to the convergence of the water towards a particularly absorbent point or area (Ferrarese & Sauro, 2001). Based on morphological features, dolines can be bowl-, funnel- or pit-shaped; hemispheric, conical or cylindrical in 3D; circular, elliptical, polygonal or irregular in plant-view. Based on the size, dolines can be classified in small, medium and large. According to the classification by Ferrarese & Sauro (2001), modified by Sauro (2003), dolines can be classified in: a) normal solution dolines; b) collapse dolines; c) subsidence dolines; d) cover dolines; e) intersection dolines; f) anthropogenic dolines. Other epigean karst morphologies, for a detailed description of which we refer to Ford & Williams (2007), are:

- poljes (i.e. large, flat-floored depressions);
- karrens (i.e. small- to large-scale dissolution pits, grooves and channels at the surface and underground);
- gorges, suspended and blind valleys;
- towers karst, represented by residual carbonate hills scattered across a karst plain.

The study area corresponds with a carbonate ridge at the western edge of the Western Marsica (Central Apennines), characterized by the outcrop of Meso-Cenozoic shallow-water limestones. Epigean and hypogean karst landforms are extremely widespread in the surroundings of Campoli Appennino, and are mainly represented by dolines/poljes, sinkholes, karst highlands and karren fields. Examples are the "*I Pozzi*" (SE of M. Cornacchia, Pescosolido), Serra Traversa-Serra del Re and Macchiarvana-Forca d'Acero (Alvito and San Donato Val di Comino – D'Andrea et al., 2003) karst highlands, at the top of the Western Marsica mountain ridge, and the dolines of Pescosolido ("*Fossa della Defensa*" or "*Fossa Difensa*" in Cacciamali, 1892; "*Prato Valle Folesca*"), Posta Fibreno ("*La Prece*" and "*Madonna della Vittoria*"), Alvito ("*Pratola inferiore*" and "*Pratola superiore*", "*Fossa Livora*", "*Santa Maria del Campo*"), Vicalvi ("*Fossa Licia*" or "*Fossa Lisa*" in Cacciamali, 1892) and of the adjoining municipalities falling within the National Park of Abruzzo, Lazio and Molise (Villani, 1973). Clear was the influence of the local dialect on the names used for geomorphological features and natural landscapes. This is, for instance, the case of the dolines, which were usually called "*fossa*" ("pit"), "*pozzo*" ("hole") and "*prece*" as local term/abbreviation of "*precipizio*" ("precipice"). Wider karst morphologies, as poljes, were usually indicated with the term "*pratola*" or "*prata*", to indicate 'wide grassy fields both natural and cultivated'. Nevertheless, most of these names are now disused and there are no traces of them as toponyms in the topographic maps.

The peculiar geomorphological features of the Campoli Appennino area (Frosinone, South-eastern Lazio, Italy) have, since historical times, controlled the socio-economic and cultural aspects of this corner of Ciociaria (Ricca, 1865) (Fig. 1). An example is represented by the town of Campoli Appennino itself, developed in a ring on the edge of a karst doline with a typical funnel structure, called "*Il*

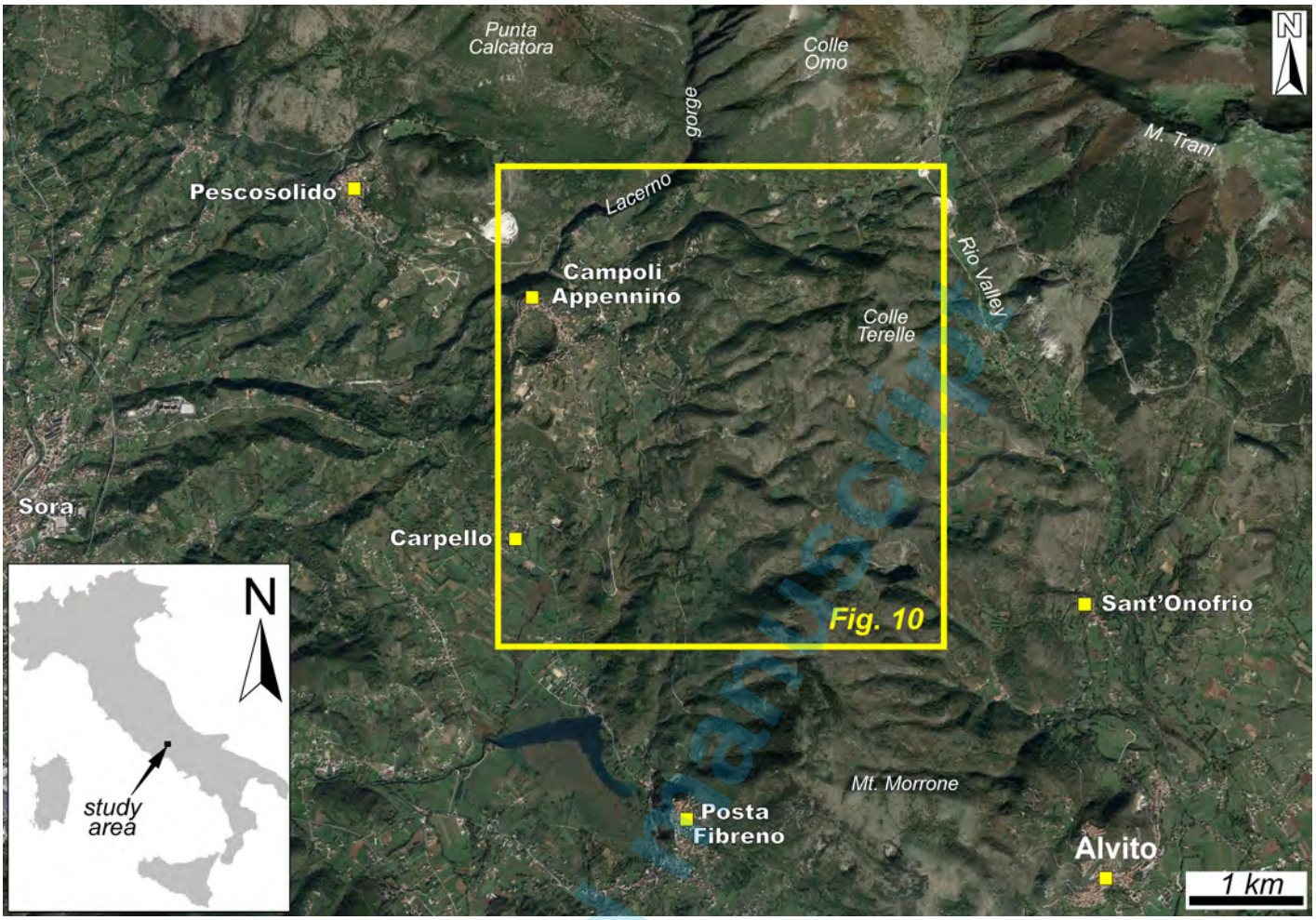

Fig. 1 - Geographic localization of the study area (modified from Google Earth©2018).

Tomolo" or "*Fossa*", which has always been mistakenly considered a volcanic caldera by locals. Due to its size (see below) and its grandiose appearance, "*Il Tomolo*" can be counted among the largest dolines of Italy and the only one with inhabited edges. Furthermore, the flat bottom of the Campoli Appennino karst morphologies was exploited as cultivable land at high altitude. The name "Campoli" probably derives from "*campulus*" or "*campora*", an archaic plural ending in *-ora* of the Latin word "*campus*", meaning "cultivated plain" (Lovato, 2018). The name of "*Camporam*" is reported since the 1150 in the "*Catalogus Baronum*" ("*Landulfus de Aquino sicut dixit Actenulfus Casertanus tenet de eodem Comite Albitum, et Camporam, et quarterium Aquini quod feuda x militum et cum augment obtulit milites xx et servientes xxx*" - Jamison, 1972).

The most interesting feature of the Campoli Appennino karst landscape is that both epigean and hypogean morphologies affect not only pure carbonate rocks, but also well-cemented, continental, clastic deposits. The latter are Pleistocene polygenic conglomerates, sands and sandy conglomerates ("*conglomerati di Campoli Appennino*" - Zuccari, 1963), bearing Meso-Cenozoic limestone/marl/sandstone clasts bound by carbonate cement. The high carbonate content of the "*conglomerati of Campoli Appennino*", as well as the intense fracturing, favored the weathering and dissolution processes of the carbonate component by acidic waters. Karst phenomena in continental clastic deposits characterized by a high percentage of carbonate pebbles are frequent, although much less studied than their counterparts in pure limestones. Examples are from northern Italy (Colle del Montello, Venice - Ferrarese & Sauro, 2005), Slovenia (Lipar & Ferk, 2011), Alpine molassic basins to the Austria-Germany border (Goeppert et al., 2011) and Pyrenean Catalonia (Bergadà et al., 1997).

The aim of this contribution is to provide a geo-historical *excursus* of the epigean karst complex of the whole Campoli Appennino area, that attracted the interest of several naturalists and geologists since the XIX century, and to provide a description of the main karst depressions. A special section is dedicated to Achille Zuccari which, in 1963, produced a monumental (one and only) paper on the karst morphologies of Campoli Appennino, albeit the Author focused only on the landforms affecting the "*conglomerati di Campoli Appennino*" (see below).

The study area has recently been proposed as a "site of geological memory" (*sensu* Martini, 2000; Console et al., 2018; Pantaloni & Console, 2019; Cipriani, 2020a, 2020b). In addition, the dolines "*Il Tomolo*" (Campoli Appennino - 41° 44› 5,98›› N, 13° 40› 47,27›› E) and «*Fossa Maiura*" (mostly falling in the municipality of Alvito, but partly involved in the municipality of Campoli Appennino - 41°

42› 50,37›› N, 13° 43› 18,21›› E) are already listed among the geosites of regional interest (respectively, ID no. 2548 and 2332 - https://sgi1.isprambiente.it/GeositiWeb) due to the high geomorphological interest of the sites. Despite this, the karst landscape of Campoli Appennino is characterized by a poorly-valorized geological-naturalistic tourism. As a consequence, the geo-morphological heritage of this area needs for a greater visibility and for a greater dissemination. The latter could i) enhance the diffusion of the stunning geo-naturalistic peculiarities, ii) make the geo-morphological features more accessible and understandable, even for a wider audience, iii) promote the need for a geo-conservation of this geological heritage, and iv) promote a greater people (non-geologists) awareness about hydro-geo-morphological risks.

GEOLOGICAL SETTING

The stratigraphic record of Central Apennines mirrors the complex tectonic and stratigraphic evolution that affected the Adriatic lithosphere since the Late Triassic-earliest Jurassic. Epeiric and evaporitic environments, Norian-Rhaetian in age, switched to Bahamian-type shallow water, peritidal, carbonate platform settings in the Hettangian (Ciarapica, 2007; Ciarapica & Passeri, 2008; Chiocchini et al., 2008, 2012, 2019). This super-regional and sub-tropical carbonate platform was dismembered into fault-bounded blocks by the Early Jurassic Tethyan rifting (Colacicchi & Praturlon, 1965; Bernoulli & Renz, 1970; Bernoulli & Jenkyns, 1974; Chiocchini & Mancinelli, 1978; Centamore et al., 2009; Carminati et al., 2013), which led to a complex paleogeographic differentiation of this part of Tethys. A carbonate platform-basin system characterized the present-day Central Apennines (e.g. Zappaterra, 1990; Carminati et al., 2013). Shallow water conditions survived on the footwall blocks of Jurassic master faults, represented by the Lazio-Abruzzo (e.g. Damiani et al., 1991; D'Argenio et al., 1997; Chiocchini et al., 2008, 2012; Carminati et al., 2013; Romano et al., 2019c) or Apennine (*sensu* Mostardini & Merlini, 1986) Carbonate Platform. By contrast, pelagic environments developed on the hangingwall blocks of rift faults. This is the case of the well-known Umbria-Marche-Sabina (Centamore et al., 1971; Cantelli et al., 1978; Farinacci et al., 1981; Corda & Mariotti, 1986; Cecca et al., 1990; Cosentino & Parotto, 1992; Santantonio, 1993, 1994; Galluzzo & Santantonio, 2002; Rusciadelli et al., 2009; Santantonio & Carminati, 2011; Rusciadelli & Ricci, 2013; Cipriani, 2016, 2019; Fabbi et al., 2016; Romano et al., 2018, 2019a, 2019b; Cipriani & Bottini, 2019a, 2019b; Citton et al., 2019, 2020; Cipriani et al., 2019, 2020a, 2020b) and Molise-Lagonegro (Ghisetti & Vizzani, 1998; Festa et al., 2006) basins surrounding the Apennine Carbonate Platform. The neritic environments passed to the surrounding pelagic basins through tectonic-related slopes/margins (Praturlon, 1968; Parotto, 1969, 1971; Cantelli et al., 1978). Nevertheless, renewed (i.e. post-rift) phases of synsedimentary tectonics affected the carbonate platform during the Meso-Cenozoic and produced significant variations of the depositional architecture, as well as paleogeographic modifications (e.g. Praturlon, 1965; Accordi et al., 1988; Damiani et al., 1991; Capotorti et al., 1991; Mindszenty et al., 1996; D'Andrea et al., 2003; Praturlon & Madonna, 2004; Centamore et al., 2007, 2009).

More than 3 km of dolostones and limestones record the Triassic to Cretaceous peritidal settings of the Apennine Carbonate Platform (Damiani et al., 1991; D'Argenio et al., 1997; Chiocchini et al., 2008, 2012; Carminati et al., 2014; Fabbi, 2016, 2018). A stratigraphic gap (i.e. Paleogene hiatus *sensu* Parotto & Praturlon, 1975), likely related to subaerial exposure and erosion of large sectors of the platform (Damiani et al., 1991) and more than 40 m.y. long, separates the Mesozoic rocks from the overlying Miocene carbonates, accumulated in a carbonate ramp context (Civitelli & Brandano, 2005).

The Neogene development and propagation of the Apennine fold-thrust belt led to the drowning of the Miocene benthic factory in the Tortonian and caused the deposition of terrigenous facies (e.g. Bergomi & Damiani, 1976; Fabbi et al., 2014). The orogenic uplift was followed normal faulting, related to the opening of the Tyrrhenian back-arc basin as a result of the roll-back of west-subducting slab (Carminati et al., 2012). This extensional phase caused the exhumation of the Meso-Cenozoic succession, as well as the accumulation of terrigenous continental successions (e.g. Saroli et al., 2003).

GEOLOGICAL FRAMEWORK OF CAMPOLI APPENNINO

The study area is located on a NW-SE trending hilly area between Alvito (SE) and Pescosolido (NW), at the southern end of the Roveto Valley. This area corresponds with a small carbonate ridge at the south-eastern edge of the Western Marsica mountains (Mt. Cornacchia-Punta Calcatora ridge), and is bounded to the west by the Quaternary Sora plain and to the east by the Colle Omo-Mt. Trani mountainous range (see Fig. 1). The attention will be focused on the Colle Terelle-Campoli Appennino (hereafter, CTCA) area, for a total of about 15 km², characterized by the study karst forms. This sector corresponds with the south-eastern part of the Colle Rotondo-Colle Terelle tectonic unit by Saroli et al. (2003), and is characterized by two main hills: the Campoli Appennino-San Pancrazio to the NW, and the Colle Terelle-Mt. Morrone to the SE. In the CTCA area, a SW-dipping monocline of Cretaceous and Miocene rocks crops out, unconformably overlain by Pleistocene clastic rocks (Zuccari, 1963; Servizio Geologico d'Italia, 1967 - Fig. 2). Unfortunately, the study area is still not involved in the new geo-cartographic project of the Italian Geological Survey (CARG Project at 1:50,000 scale); consequently, it lacks a detailed and updated stratigraphic study. According to Servizio Geologico d'Italia (1967) and Saroli et al. (2003), the back-bone of the CTCA is made of a Cretaceous carbonate platform succession characterized by abundant rudist bivalves and the typical, regionally known, bauxitic horizons (Paradisi & Sirna, 1965; Praturlon, 1968; Cipriani, 2020a). This succession pass southwestwards to the Miocene "*Calcari a Briozoi e Litotamni*", in turn followed by the terrigenous "*Marne a Orbulina*" and "*Flysch Argilloso-Arenaceo*" units. The NW-trending monocline is at the hangingwall of a low-angle, SW-dipping, out-of-sequence thrust (Saroli et al., 2003). A Quaternary high-angle fault system

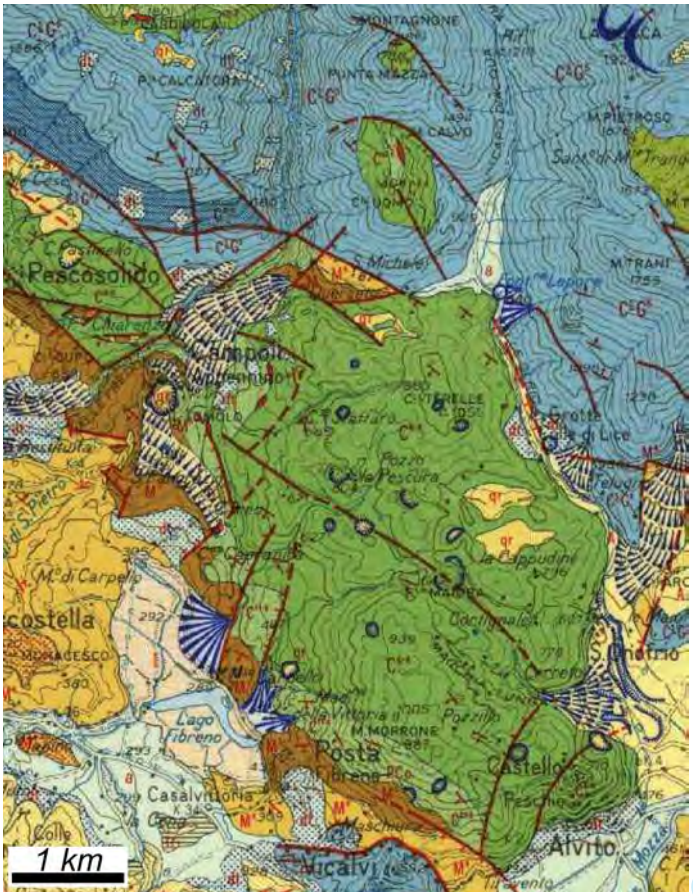

Fig. 2 - Part of the Sheet 152 "Sora" of the Italian Geological Map at 1:100,000 scale (2nd edition - Servizio Geologico d'Italia, 1967), encompassing the study area. The blue lines represent the main karst depressions. Legend: G^{4-2}= whitish, nut and pink well-bedded, micritic or grained, limestones with dolomitic interbeds (Toarcian-Pliensbachian); C^3-G^5= nut, white and grey, well-bedded, grained limestones with dolomitic interbeds (Barremian-Aalenian); C^{6-4}= grained nut, well-bedded or sometimes massive, limestones bearing oolites or thinly-bedded micrites. Bauxites at the top (upper Cenomanian-Aptian); C^{11-4}= white and sand, rudistid-rich, limestones, locally dolomitized, bearing bauxitic and emersion facies (Upper Cretaceous); M^3= bioclastic limestones, bearing bryozoans and red algae (Elvetian-upper Langhian?); M^4= alternation of marly sandstones and clayey marls grey-yellowish (Tortonian); M^{5-4}= lensoid polygenic conglomerates bearing carbonate and siliciclastic clasts (Messinian?-Tortonian); travertines (tr_2) and lacustrine carbonate loams (l) (Pleistocene); A= old and terraced alluvial deposits (Pleistocene); qr= *terre rosse* (Holocene); dt= scree (Holocene); a= recent alluvial deposits and alluvial fans (Holocene); red lines= faults.

(Roveto Valley-Atina-Cassino system) displaces the orogenic fault and downthrows the Tortonian-Messinian terrigenous deposits on the Cretaceous limestones. This fault system shows evidence of polyphase activity with different kinematics (strike slip in the early Pleistocene - Saroli et al., 2003; dip-slip in the middle Pleistocene-Holocene - Galadini & Galli, 2000; Roberts & Michetti, 2004; Papanikolaou et al., 2005; Fabbi & Smeraglia, 2019) and displaces the Pleistocene *"conglomerati di Campoli Appennino"* (Serafini & Vittori, 1986, 1988). This peculiar continental unit was introduced by Zuccari (1963) and is made of polygenic conglomerates and sands, locally very well-cemented, bearing limestone clasts sourced from the mountain slopes surrounding Campoli Appennino. These deposits accumulated in an alluvial fan system, with local lake episodes (Zuccari, 1963; Saroli & Moro, 2012). Based on paleomagnetic data, an early-middle Pleistocene age has been estimated for these deposits (Saroli et al., 2015).

THE DOLINES OF CAMPOLI APPENNINO IN LITERATURE AND CARTOGRAPHY

The first morphological description of the doline around which Campoli Appennino is built (i.e. *"Il Tomolo"*), is provided by Giovanni Paolo Mattia Castrucci in his *"Descrittione del Ducato d'Alvito nel Regno di Napoli, in Campagna Felice"* ("Description of the Alvito Duchy in the Kingdom of Naples, in Campagna Felice" – Castrucci, 1633). The Author describes the karst form as *"una valle di figura circolare molto profonda, detta il tomolo; ha la sua bocca e larghezza di ogni parte uguale che nella sua maggior'altura cominciando a ristringersi pian piano per uno stadio, si termina nel profondo, che è simile ad un orto"* ("a very deep circular depression, called il tomolo; its opening and width is equal in each part and slowly begins to shrink from its highest point to the base, where it is similar to a vegetable garden" - Castrucci, 1633, p. 127).

One fascinating representation of the Campoli Appennino doline is a low relief of the XVII century, today stored in the Villa Mazzenga at Alvito (Fig. 3). The Medieval configuration of Campoli Appennino (here indicated with the name *"Canpoli"*), with the town wall and the buildings outside the walls built on the edge of the karst depression, is spectacularly reported. It is also possible to appreciate the use for agro-pastoral purposes of the doline bottom, marked by small incisions which represent the boundaries between cultivated lands.

Gaetano Tenore (1826-1903) provides the first geological information on the study area in a series of documents, written after an intense fieldwork conducted in the San Donato Val di Comino-Alvito mountains, that was aimed at discovering exploitable mineral deposits under the Kingdom of the two Sicilies (Bassani, 1904; Mercalli, 1907; Cipriani, 2020a). In a preliminary report, Tenore (1856a, 1856b) identifies the *"catena del castello di Alvito e di Campoli"* ("Alvito castle and Campoli range") "geomorphological unit", the northern part of which

Fig. 3 - A 1600 low relief of Campoli Appennino (called *"Canpoli"*) and *"Il Tomolo"*, preserved in Villa Mazzenga (Alvito) (Photo: Tonino Bernardelli; www.atinaitaly.com); note the cultivated plots of land represented in the bottom of the doline.

corresponds to the CTCA area described in this paper. For this NW-trending hilly range, Tenore reports several topographic information, most of which missing in the modern cartography (i.e. sections II SW "Alvito" and III SE "Sora" at 1:25,000 scale of the Topographic Map of Italy at 1:100,000 scale, Sheet 152 "Sora" - Istituto Geografico Militare, 1963; *Carta Tecnica Regionale* at 1:10,000 scale, section n. 391050 "Campoli Appennino" - Regione Lazio, 1991; *Carta Tecnica Regionale Numerica* at 1:5,000 scale, sections n. 391051, 391052, 391053, 391054 - Regione Lazio, 2009, available online at http://dati.lazio.it/catalog/it/dataset?category=Territorio+e+urbanistica). An example is the "*Pratola*" locality, described as a "*piccolo bacino, circondato da varii monticelli a dossi rotondati e disposti in cerchio ad un dipresso*" ("small basin surrounded by small rounded mountains arranged roughly in a circle around the depression" - Tenore, 1856a, p. 48). This locality is also reported by Cacciamali (1892) and is recognizable in an area about 2 km NW of Sant'Onofrio, characterized by a series of poljes. Gaetano Tenore mentions the toponym "*Monte di Pratoroveto*", a small mount to the W of "*Pratola*". It could correspond with the unnamed small mount (874 m a.s.l) W of Fossa Micciola on the Istituto Geografico Militare section II SW "Alvito". The toponym "*Colle Tamburo*" corresponds with the southern slope of Colle Terelle mount. These localities are key-localities for the geographic comprehension of the geological cross-section provided in Tenore (1867; see below).

According to Tenore (1856a, 1856b), the carbonate back-bone of the "Alvito castle and Campoli range" is represented by compact and brecciated limestones ("*calcarea compatta*" and "*brecciata*"), the latter bearing carbonate clasts in an iron-rich matrix to form a "*marmo-breccia*" (Tenore, 1856a, p. 50). This breccia, called "*breccia di Campoli*" by locals, was cut in the surroundings of Colle Terelle to be used as ornamental rock (the main altar and the mosaics of the Campoli Appennino church are made of "*breccia di Campoli*" - Conflitti, 1928). Limonite deposits dispersed in dark red clays are also associated with limestones "*in forma di globetti sciolti di varia grandezza disseminati e rimaneggiati alla superficie di quei terreni coltivati*" ("in the form of loose globes of various sizes, scattered and rearranged on the surface of those cultivated land" - Tenore, 1856b, pp. 119-120). The Author refers to the cultivated bottom of the karst depressions characterizing this area, made of *terre rosse*, as insoluble material resulting from the carbonate dissolution. Furthermore, Tenore understands the post-depositional nature of these deposits, which are not embedded in the "*calcarea*" but covering unconformably the limestones. As a result, the Author attributes a "*diluvian*" age (i.e. Pleistocene-Holocene) to these iron-rich continental clays.

The first geological iconography concerning the study area known to date is a table with two geological cross sections drawn by Tenore (1867 -Fig. 4A). This table is supposed to be associated to the "*Carta geologica del Bacino del Melfa*" ("Geological map of the Melfa Basin"),

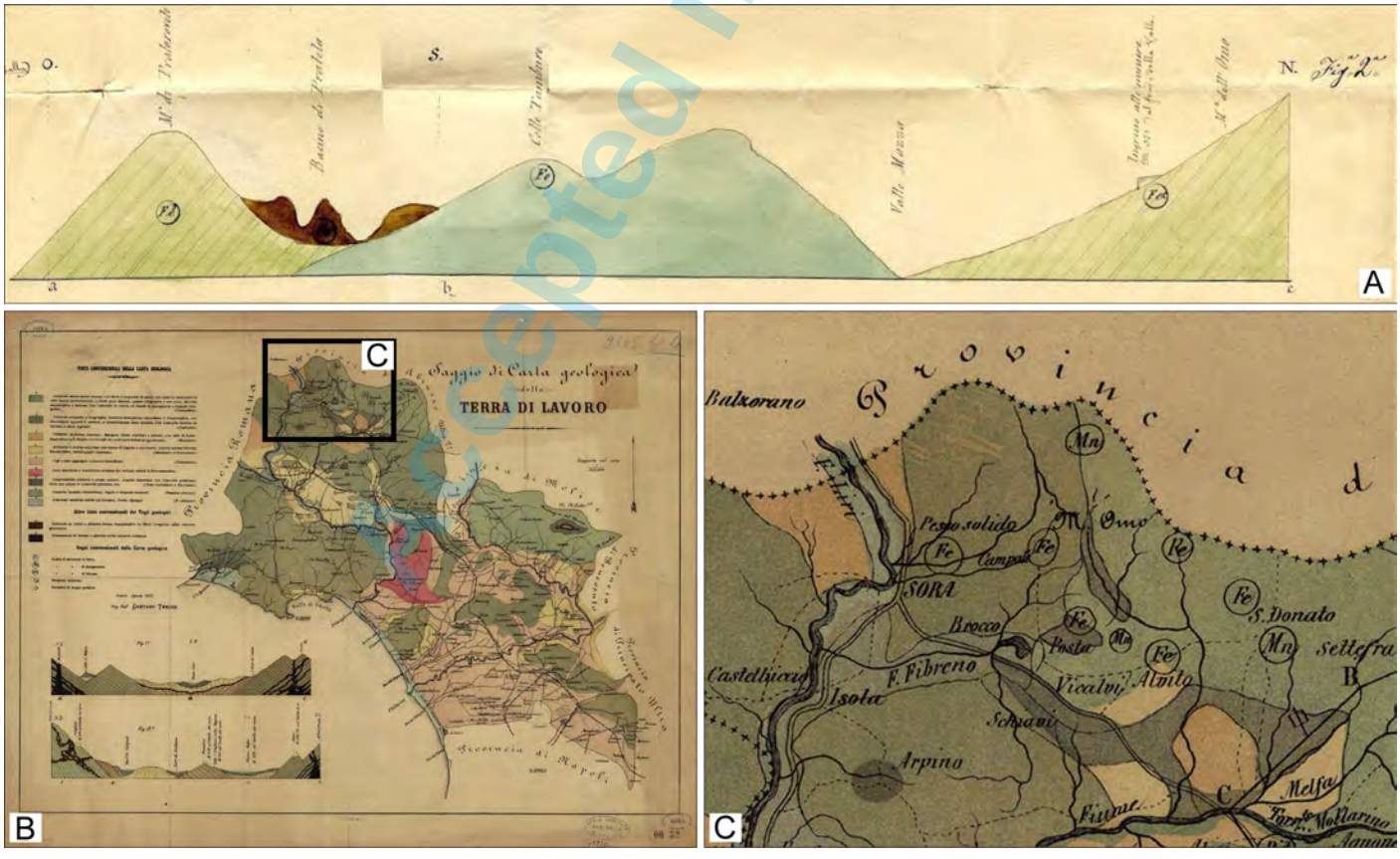

Fig. 4 - Part of the table companion of the "*Geological map of the Melfa Basin*" (Tenore, 1867), where the hand-made geological cross section ("*Fig. 2*") involving the "*Pratola*" Quaternary deposits and dolines is reported. B) "*Essay of geological map of Terra di Lavoro*" (Tenore, 1872). C) Enlargement of Fig. 4B involving the study area. Cartographic collection, ISPRA Library.

mentioned in Tenore (1863), and presented at the Paris International Exposition in 1867 (Bassani, 1904; see also Cipriani, 2020a, 2020c), a document that seems to have been unfortunately lost.. Geological information is reported on the table, as a legend subdivided in ten units and the localization of the main iron-rich deposits (see Pantaloni et al., 2016, and Cipriani, 2020a, for further details). One composite geological section (i.e. *"Fig. 2"*) involves CTCA and the *"Pratola"* karst area (see Fig. 4A). This section begins at *"Monte di Pratoroveto"* (to the W), where the *"calcarea compatta e brecciforme"* ("compact and breccia-shaped limestone") is reported by the Author, and moves east-ward, where the *"argille diluviane con Limonite pisiforme"* ("diluvian clays bearing pea-shaped limonite") are reported in the *"Pratola"* basin. Here, Tenore represents two U-shaped depressions, maybe coincident with the "Pratola inferiore" and "Pratola superiore" cavities reported by Cacciamali (1892). East of Pratola, the orientation of the geological section turns from W-E to N-S, involving the slopes of *"Colle Tamburo"* (i.e. Colle Terelle) and of *"Monte dell'Omo"*, passing through *"Valle Mozza"* (see Cipriani, 2020a, for further details about the northern part of the section).

In 1872, Tenore published the *"Saggio di carta geologica della Terra di Lavoro"* (*"Essay of geological map of Terra di Lavoro"*) at 1: 280,000 scale, involving the (present-day) northern part of Campania and the southern part of Lazio regions. This "simplified" geological map is the first available geological map for the study area (Tenore, 1872; see also Cipriani, 2020a, 2020c – Fig. 4B, 4C), and represents the physiological (bibliographic and cartographic) evolution of the data presented in Tenore (1856a, 1856b, 1863, 1867). Nine main geological units are reported on the map: i) *"Calcarea salina"* (*"saline limestones"*), "Jurassic" in age; ii) *"Calcarea compatta o litografica, Calcarea brecciforme varicolore, Calcarea bituminifera"* (*"compact or lithographic, polychrome brecciated or bituminous limestones"*), Cretaceous in age; iii) the *"Eocene" "Calcarea idraulica; Macigno; Scisti argillosi e selciosi"* (*"Hydraulic limestones; Macigno; Clayey and cherty schists"*); iv) the *"Miocene and Pliocene" "Arenaria e marna argillosa; Argille scistose; Sabbie gialle"* (*"Sandstone and clayey marl; Schistose clays; Yellow sands"*); v) the *"Pliocene"* tuffs and vi) lavas; vii) the *"post-Pliocene or diluvian"* to Recent calcareous conglomerates (*"Conglomerato calcareo a grossi ciottoli)* and *terre rosse* (*"Argilla diluviana"*), viii) travertines (*"Calcarea lacustre [travertino]; Laghi e Sorgenti minerali"*), and ix) alluvial deposits, peat and beaches. Reported are also the localities where the main iron- and manganese-rich deposits (indicated with *"Fe"* and *"Mn"* on the map, respectively) and bituminous emanations (*"Bit"* on the map) occur. In addition to what already quoted in the works of the 1856, here Tenore introduces deposits of *"Argilla diluviana spesso con Limonite pisiforme o in grani"* (*"Diluvian clay often bearing pea-shaped and grainy limonites"*) characterizing the *"collicelli a dossi rotondati delle contrade di Pratola e della Posta in quel di Alvito"* (*"rounded hills in the districts of Pratola and La Posta in Alvito"* - Tenore, 1872, p. 33). In spite of the limited knowledges about the karst geomorphology at that time, the Author seem to have perceived the relevance of karst processes on that landscape, highlighting the principal features.

Subsequently, Kiepert (1881) reports for the first time the toponym *"Fossa Majura"* on his chorographic and archaeological map of Central Italy (Fig. 5A), while the toponyms of the main dolines of Campoli Appennino (*"Tomolo"*, *"P.zo la Pescura"* and *"Fossa Majura"*) are mapped in the first edition of Sheet 152 "Sora" of the Topographical Map of Italy at 1:100,000 scale (Ministero di Agricoltura, Industria e Commercio, Direzione Generale dell'Agricoltura, 1890). The toponyms *"Tomolo"* and *"Fossa Majura"* were then changed to *"Il Tumolo"* and *"Fossa Maiura"* in the updated version of the Sheet 152 "Sora" Topographic Map of Italy at 1:100,000 scale, as reported in the sections II SW "Alvito" and III SE "Sora" at 1:25,000 scale (Istituto Geografico Militare, 1963).

The first geomorphological description of some of the Campoli Appennino karst dolines, as part of a wider work involving the Alvito-Pescosolido area, was provided by Cacciamali (1892). Giovanni Battista Cacciamali (1857-1934) recognizes the naturalistic interest of the area, characterized by *"cavità naturali imbutiformi che richiamano il così detto fenomeno del Carso"* ("natural, funnel-shaped, depressions that recall the so-called Carso phenomenon" - Cacciamali, 1892, p. 334). Associated to the work is a 1: 100,000 scale topographic map of the area (Fig. 5B), where the toponyms of the main dolines, called *"anticrateri"* (*"anticraters"*), are reported; as said for Tenore (1856a, 1856b), most of this information are missing or different in the modern cartography. The Author provides a geographic and morphological description of each doline, which will be reported below. It is worth noting how Cacciamali (1892) grasps the "sinking" nature of these morphologies, by differentiating them from the volcano calderas. In fact, the Author describes a *"trasporto di materia dal di sopra al di sotto, ecco un inghiottimento con corrosione, ecco un avvallamento intorno alla fessura o formazione di cono negativo (azione antivulcanica)"* ["transport of matter from above to below, here is a sinkhole with corrosion, here is a depression around the crack or formation of a negative cone (anti-volcanic action)"] for the dolines, contrasting with the *"trasporto di materia dal di sotto al di sopra, ecco una eruzione con espandimento, ecco un rialzo attorno alla fessura o formazione di cono positivo (azione vulcanica)"* ["transport of matter from below to above, here is an eruption with enlargment, here is a rise around the crack or formation of a positive cone (volcanic action)"] (Cacciamali, 1892, p. 340). Here the decision to use the term *"anticrater"* for these karst, funnel-shaped, morphologies. Furthermore, the Author distinguishes four types of karst forms: cave-shaped, well-shaped, funnel-shaped and floor-shaped, referring the Campoli Appennino dolines to the third and fourth type. Interesting is the intuition about the genetic reconstruction of the conglomeratic facies and of the morphological setting of the Campoli Appennino hill (mainly made of that conglomerates). According to Cacciamali (1892), *"in origine doveva far parte d'un gran talus addossato alla montagna di Pescosolido; il Lacerno, che forse prima decorreva più a mattina dirigendosi a S, avrebbe più tardi inciso profondamente quel talus isolando così la collina; ed ora noi vediamo il torrente scorrere a N di Campoli in una profonda e stretta gola prodotta da erosione, ed uscito da essa distendere a sera dello stesso paese un'ampia e bellissima conoide alluvionale"* ("[The Campoli Appennino hill] *originally was part of a great talus leaning against the*

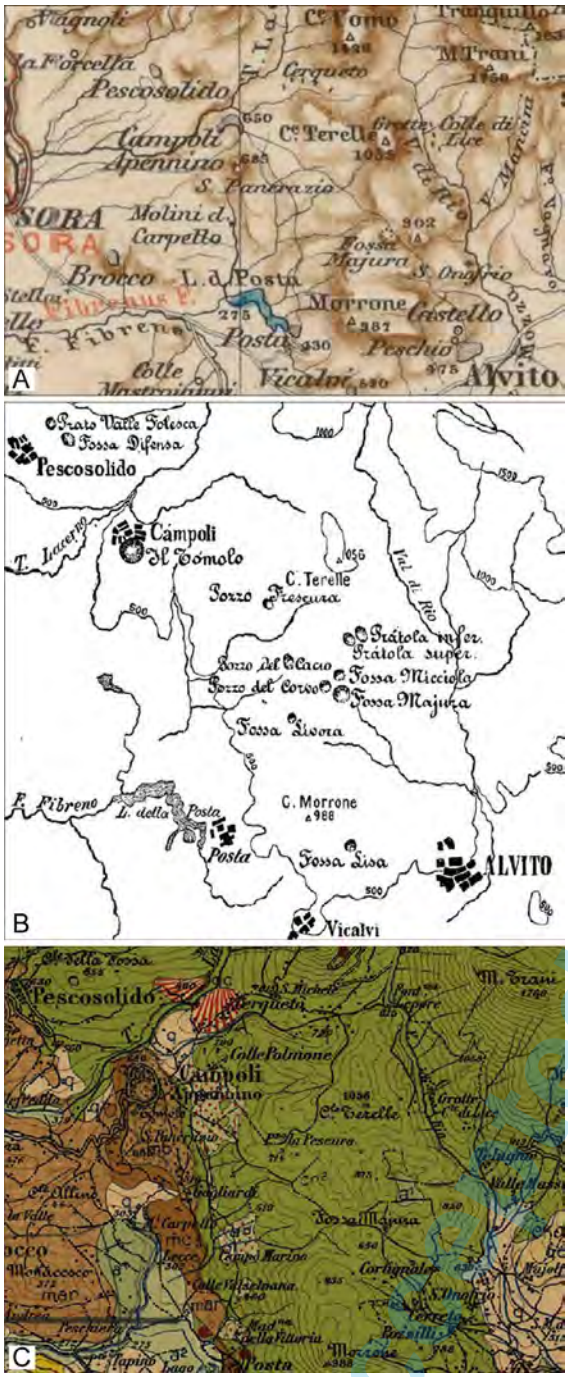

Fig. 5 - Historical cartography concerning the Colle Terelle-Campoli Appennino area and its dolines. A) Small part of the chorographic map by Kiepert (1881). B) Topographic map by Cacciamali (1892), where the Vicalvi-Alvito-Campoli Appennino-Pescosolido main dolines are reported. C) Excerpt of the first edition of the Geological Map of Italy at 1: 100,000 scale (Regio Ufficio Geologico, 1928) involving the study area. The base map of this sheet was the first edition of the Topographical Map of Italy at 1:100,000 scale (Ministero di Agricoltura, Industria e Commercio, Direzione Generale dell'Agricoltura, 1890). Note the "*Tomolo*", "*P.zo la Pescura*" and "*Fossa Majura*" toponyms. Legend: cr^2= light colored, compact and well bedded, limestones bearing gastropods, chondrodontids, rudistids ("*Neocretaceo*"); mc= lime marls and marly limestones, yellowish and whitish compact limestones (middle Miocene); mar= yellowish-greyish sandstones (middle Miocene); mb= breccias and conglomerates overlying, or interbedded with, the sandstones (middle Miocene); pl= sandy conglomerates and yellow sands (Pliocene); q^c= suspended alluvial ("*diluviali*") fans (Quaternary); q= terraced alluvial deposits (Quaternary); a^1= old terraced alluvial deposits (Quaternary); a^2= recent alluvial deposits (Quaternary); red circle= bauxitic deposits.

mountain of Pescosolido; the Lacerno, which perhaps earlier flowed more in the morning heading S, would later engrave deeply that talus thus isolating the hill; and now we see the stream flowing N of Campoli in a deep and narrow gorge produced by erosion, and come out of it to stretch in the evening [i.e flowing towards E] *of the same country a large and beautiful alluvial fan*" - Cacciamali, 1892, p. 342).

In the late 1800s and earliest 1900s, Cassetti performed field-works in the Simbruini-Marsica area aimed at realizing the first edition of Sheet 152 "Sora" of the Geological Map of Italy (Regio Ufficio Geologico, 1928 - Fig. 5C). In particular, the Campoli Appennino territory was mapped in the 1898 and discussed in his annual report on the "*Bollettino del Regio Ufficio Geologico*" (Cassetti, 1899). Here, the Author describes the main lithological aspects of the exposed rocks, whereas only touches upon the geomorphological features of "*Il Tomolo*" and "*Fossa Maiura*".

In a pioneering work on the geology of Abruzzo region, Sacco (1907) refers to "*Il Tomolo*" and "*Fossa Majura*" as part of the Holocene deposits and geomorphic phenomena, even though these dolines are out of the Abruzzo border.

Secondo Franchi (1859-1932), in the spring of 1915, visited the villages of the upper Liri valley affected by the Fucino earthquake, in order to indicate the new sites for reconstruction, and made some geological observations on the Quaternary glacial morphologies of the Simbruini and Cantari Mts. These data were published years later (Franchi, 1918, 1920). In an appendix concerning other quaternary phenomena besides the glacial ones (i.e. volcanic eruptions, landslides in the Liri valley, floodings and alluvial fans), Franchi (1920) discusses on karst phenomena occurring in the Western Marsica slopes. He quotes the Pescosolido, Fontanaliri and Posta Fibreno dolines, as well as "*Fossa Majora*", emphasizing its ancient fame. Franchi also describes "*Il Tomolo*" of Campoli Appennino, defining it "*bella, grandiosa e regolarissima fossa carsica*" ("*beautiful, grandiose and very regular karst depression*"), providing its first known photographic representation (Fig. 6A).

In a work on the well-known "Pulo" of Altamura, one of the most spectacular dolines of Apulia, Segre (1954) compares its morphological features (width, depth, etc.) with numerous other impressive dolines of peninsular Italy. Among them he mentions "*Fossa Majura*" and "*Il Tomolo*", considered among the most important dolines of the Apennines.

The monumental work by Zuccari (1963), accompanied by a geological map and an important photographic record (Fig. 6B, 6C), represents the only note focused on the analysis of karst phenomena affecting the Pleistocene "*conglomerato di Campoli Appennino*". Further details will be described below, in a dedicated section.

After the law n. 15 of 3 January 1960 ("*Completion and updating of the Geological Map of Italy*"), commonly known as "*Legge Sullo*", the entire national territory was covered by an "official" geological map at 1:100,000 scale; this project was completed in 1976. The second edition of the Sheet 152 "Sora" of the Geological Map of Italy at 1: 100,000 scale was published in 1967 (Servizio Geologico d'Italia, 1967), whereas the field mapping carried out on the 1: 25,000 scale by Alessandro Paradisi and Gianfranco Francioni (Fig. 7A, 7B) was completed in 1966. On the original field maps, as well as on the official sheet, the edge of the main dolines is marked by blue lines, and

Fig. 6 - Historical pictures of "*Il Tomolo*" and Campoli Appennino by A) Secondo Franchi (1920) and B-C) Achille Zuccari (1963).

the *terre rosse* at the bottom of them are reported (when wide enough to be mappable at 1:100,000 scale). In the explanatory notes of the aforementioned sheet, Praturlon (1968) discusses the karst structures of the northern Comino Valley area, quoting the "*impressive Tomolo*". The same goes for Accordi et al. (1969), with the seminal work on the hydrogeology of the upper Liri River basin.

Sirna & Mastroianni (1993) describe several Jurassic-Cretaceous nerineid specimens sampled in the surroundings of Campoli Appennino, most of which "sourced" from the clasts of the "*conglomerato di Campoli Appennino*" exposed along the edge of "*Il Tomolo*".

Since the early 2000s, this portion of Italy experienced a revived phase of scientific interest. In particular, it was attentioned for what concerns hydrogeological risk assessment, due to the numbers of sinkholes and gas emissions (i.e. hydrogeological hazards) developed in historical times. New geological data obtained through remote sensing and geological mapping are provided by Saroli et al. (2003 - Fig. 7C). The Authors purpose a new structural framework, identifying a previously unreported structural unit in the Colle Rotondo-Colle Terelle area (see "Geological framework of Campoli Appennino" chapter). In a work concerning the collapse cavities at

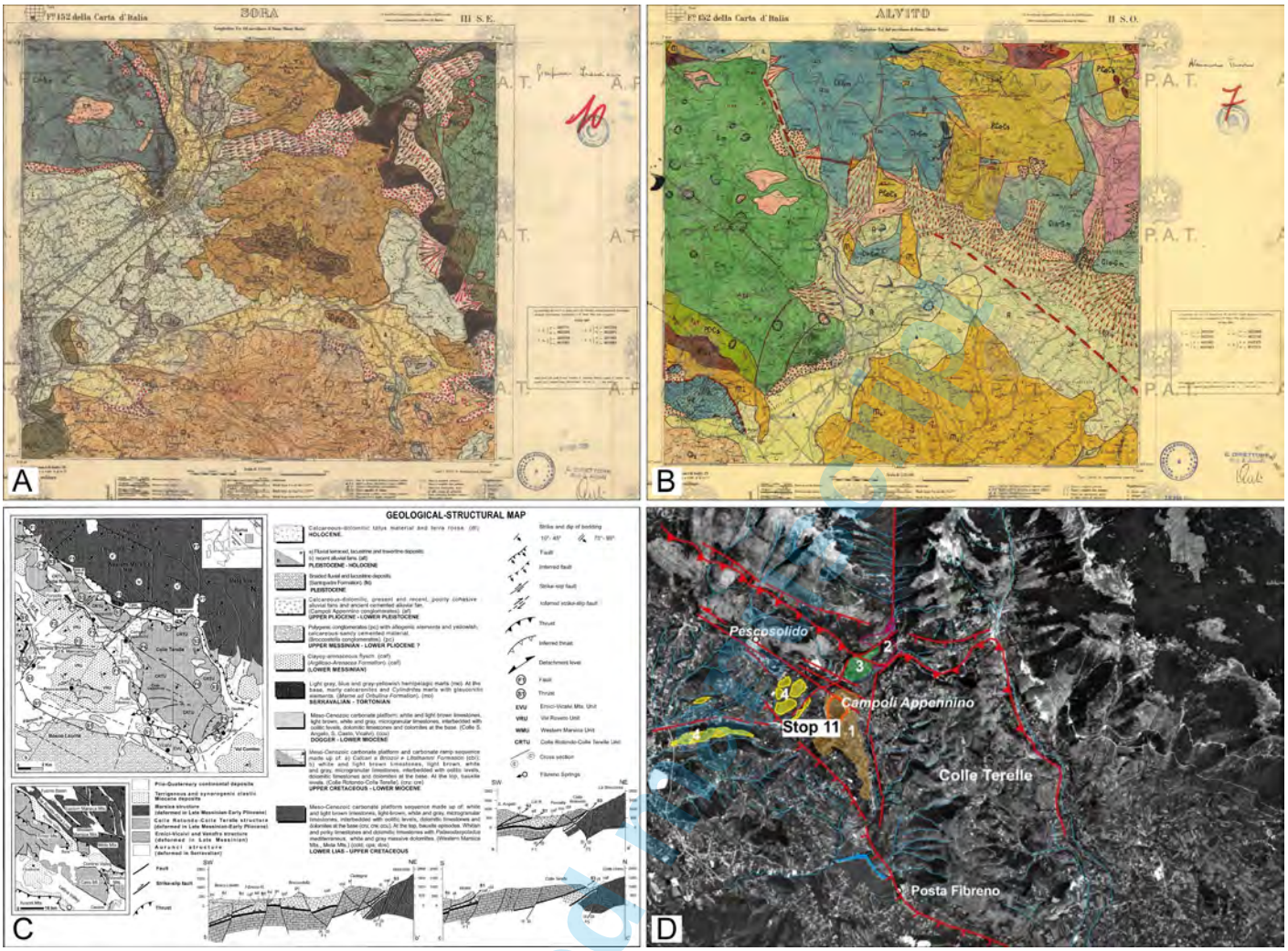

Fig. 7 - A-B) Originals field maps at 1: 25,000 scale of the sections III SE "Sora", by Gianfranco Francioni, and II SO "Alvito", by Alessandro Paradisi, completed in the 1966. Cartographic collection, ISPRA Library. C) Geological map of the southern Roveto Valley involving the study area by Saroli et al. (2003). D) Morphotectonic map of Campoli Appennino by Saroli & Moro (2012). The exposures of the Pleistocene conglomerates and their sedimentary cycles are reported. Legend: 1= first sedimentary cycle; 2= second sedimentary cycle; 3= third sedimentary cycle; 4= fourth sedimentary cycle; orange line= doline; red lines= main thrust and normal faults.

Posta Fibreno, Agrillo et al. (2004) provide a description of the main karst features of Western Marsica. The Authors focus the discussion on "*Il Tomolo*", the main karst form of the study area, providing its main morphological characters in agreement with Zuccari (1963). Agrillo et al. (2004) refer the genesis of "*Il Tomolo*", and of all the epi- and hypogean cavities of the area, to: i) the concomitant action of extensional tectonics, which controlled the topographic elevation of the main fresh-water springs; ii) the stability, in space and time, of the flow lines of the large karst aquifer, which displays its main springs in the Posta Fibreno Lake, referable to the Western Marsica hydrogeological unit *sensu* Boni et al. (1986); and iii) the aggressive capacity of groundwater, favoured by the release of deep gas fluids rich in CO_2 content, enhancing the chemical dissolution of highly-porous (due to primary and secondary porosity) carbonate rocks. Santo et al. (2011) refer the area between Campoli Appennino and Alvito to a "*High Sinkhole Concentration Area*". Here, the Authors recognize 33 sinkholes, of which 31 in carbonate rocks and 2 in Quaternary conglomerates covering the carbonate bedrock.

Saroli & Moro (2012) well define the karst landscape of Campoli Appennino, made of dolines, karst conducts and abandoned valleys originated from the rims of the karst depressions (Fig. 7D). The Authors recognize and discuss the coexistence of karst forms showing different degrees of evolution. These occurrences are referred to the oscillations of the hydrological base level of the Posta Fibreno springs, connected with extensional activity of the "Posta Fibreno Fault" (a segment of the Roveto Valley-Atina-Cassino fault system) during the Pleistocene-Holocene. According to Saroli & Moro (2012), the abandoned valleys and dolines of CTCA correspond with paleo-topographically higher springs ("paleo-springs") of the Posta Fibreno karst system, subsequently sunk with the downthrowing of the Posta Fibreno plain and, as a consequence, lowering of the hydrological base level.

ACHILLE ZUCCARI AND THE "FENOMENI CARSICI NEI

CONGLOMERATI DI CAMPOLI APPENNINO"

The figure of Achille Zuccari (1926-2015) as a geologist is less known to the Italian geological community than that of General Secretary of the Italian Geological Society, a role he held for about half a century (Argentieri et al., 2018, to which we refer to a detailed biographical description). His (albeit limited) scientific publications were, however, always pioneering in the geomorphological field. The one concerning the karst phenomena of Campoli Appennino is an example (i.e. *"Fenomeni carsici nei conglomerati di Campoli Appennino"* - Zuccari, 1963). The right mix of stratigraphy and sedimentology, structural geology and geomorphological information makes this work a milestone for the comprehension and description of "anomalous" karst morphologies, not only for the study area, but also for comparable geo-morphological settings. The paper is accompanied by a geological map, which highlights the field-based nature of this manuscript (Fig. 8A-E).

The "anomaly" is that the karst forms studied by Zuccari do not affect limestones, but conglomeratic deposits unconformably covering the Meso-Cenozoic carbonate bedrock. These deposits, called *"conglomerati di Campoli Appennino"* (see above), are described as up to 150 m-thick, well-bedded, polygenic conglomerates, bearing heterometric (from sand to boulder in size) carbonate and arenaceous clasts dispersed in a sandy matrix made of limestone/dolostone/quartzitic microclasts (Zuccari , 1963 Fig. 9A, 9B). Microcrystalline calcite related to circulation of meteoric waters is considered to be the main cement, albeit sandy and clayey cements are also discussed. The top of the unit is described as very well-cemented, whereas the base is poorly lithoid being dominated by clayey-sandy cements, suggesting various degrees of cementation (Fig. 9C, 9D). Zuccari identified sandy-silty lenses and travertine deposits, as well as diatomites. From a genetic point of view, the Author refers the deposition of the *"conglomerati di Campoli Appennino"* to alluvial fans sourced from the (paleo-)Lacerno stream, which drained towards S (whereas at present it drains towards E), filling lacustrine environments. This interpretation supports the earlier intuition by Cacciamali (1892). Zuccari estimated a *"Quaternario antico"* (*"early Quaternary"*) age for these conglomerates (recently refined to early-middle Pleistocene by Saroli et al., 2015).

Concerning the karst morphologies developed in the conglomerates, Zuccari identifies a main epigean nature of these forms, represented by dolines, karrens, caves and micro-karst forms (Fig. 9E, 9F). Three main dolines without sinkholes are described from a morphological and genetic point of view: *"Il Tomolo"*, *"San Pancrazio"* and *"Case Treo"* (see Fig. 8C), whereas other collapsed dolines (defined as *"truncated dolines"*) are mentioned. The funnel shape and the high depth of *"Il Tomolo"* are referred to the structural and lithological differences between the conglomerates and the underlying limestones, the latter characterizing the base of the doline. By contrast, the *"San Pancrazio"* and *"Case Treo"* dolines display a bowl-shaped morphology and are defined as *"doline di pendio"* (*"slope dolines"*). The latter are at maximum 50 m-depth, and Zuccari refers this feature to the presence of poorly permeable rocks (i.e. Miocene terrigenous deposits) below the conglomerates, which limits the flow of the groundwater and reduces the in-depth chemical processes of dissolution. An exceptional photographic record is provided of each doline and of the main karst forms. According to the Author, the karst processes are driven by: i) the very high $CaCO_3$ content of the conglomerates, due to the pebbles composition (mainly limestones) and the high degree of cementation; ii) the presence of *"diaclasi"* (fractures) which facilitates the weathering; iii) the presence of *"leptoclasi"*, i.e, small fissures in the clasts that cause a differential chemical alteration between the clasts (high rates) and the cement (low rates) (see Fig. 9E, 9F).

THE DOLINES OF COLLE TERELLE-CAMPOLI APPENNINO AREA

The dominant karst forms of the Colle Terelle-Campoli Appennino area (CTCA) are the dolines, but karst conduits and abandoned valleys also occur. Abandoned valleys originated from the edges of the dolines characterize a poorly developed hydrographic network on the karst field of Colle Terelle (Zuccari, 1963; Saroli & Moro, 2012). Hypogean forms are less abundant. In accordance with Mecchia et al. (2003), the only underground cavity reported for the area by the speleological register is the Treo Cave (see below). Another unregistered pothole, known as *"Grotta del Lupo"*, occurs close to a small church ("San Michele") at the southern slopes of Colle Omo.

In the CTCA, 21 dolines having an average diameter >100 m, thus falling within the field of large dolines or "macrodolines", are recognized (Fig. 10). Almost all dolines are normal solution dolines and do not display pits or sinkholes, as they are masked by the dissolution products of the involved limestones or carbonate-rich clastic rocks. The only exception is represented by the *"Pozzo La Pescura"* doline (see below). Most of the Campoli Appennino dolines have bowl-shaped morphologies *sensu* Sauro (1991), i.e., with steep and inclined slopes and a flat bottom, generally filled with a blanket of residual soil. Flat-shaped, funnel-shaped, well-shaped or complex morphologies also occur. In plant-view, they are sub-circular or ellipsoidal. The tectonics influence on the development of these karst forms is clear, the dolines being aligned with the Apennine-trending structural discontinuities affecting the study area, as also highlighted by the geological maps of Zuccari (1963), Servizio Geologico d'Italia (1967) and Saroli et al. (2003).

Of the 21 macrodolines, 5 are superimposed on the Pleistocene conglomerate deposits, 15 are linked to the dissolution of Cretaceous limestones, whereas *"Il Tomolo"* is linked to the karst of both the Meso-Cenozoic carbonate bedrock and the Pleistocene *"conglomerati di Campoli Appennino"* unconformably covering the latter. Furthermore, 8 dolines present an average diameter >200 m and are here defined *"main macrodolines"*; their principal morphological characters are reported in Table 1. Some of these forms coincide with those described by Cacciamali (1892), i.e., *"Il Tomolo"*, *"Pozzo Frescura"*, *"Pozzo del Cacio"*, *"Fossa Micciola"* and *"Fossa Majura"*.

The description of the *"main macrodolines"* is provided below; the numbers are the same reported in Fig. 10.

1. *"Il Tomolo"* doline (Fig. 11; see also Fig. 6): it is the largest doline of the Campoli Appennino karst complex and has an ovoid shape (Fig. 11A, 11B). Its maximum

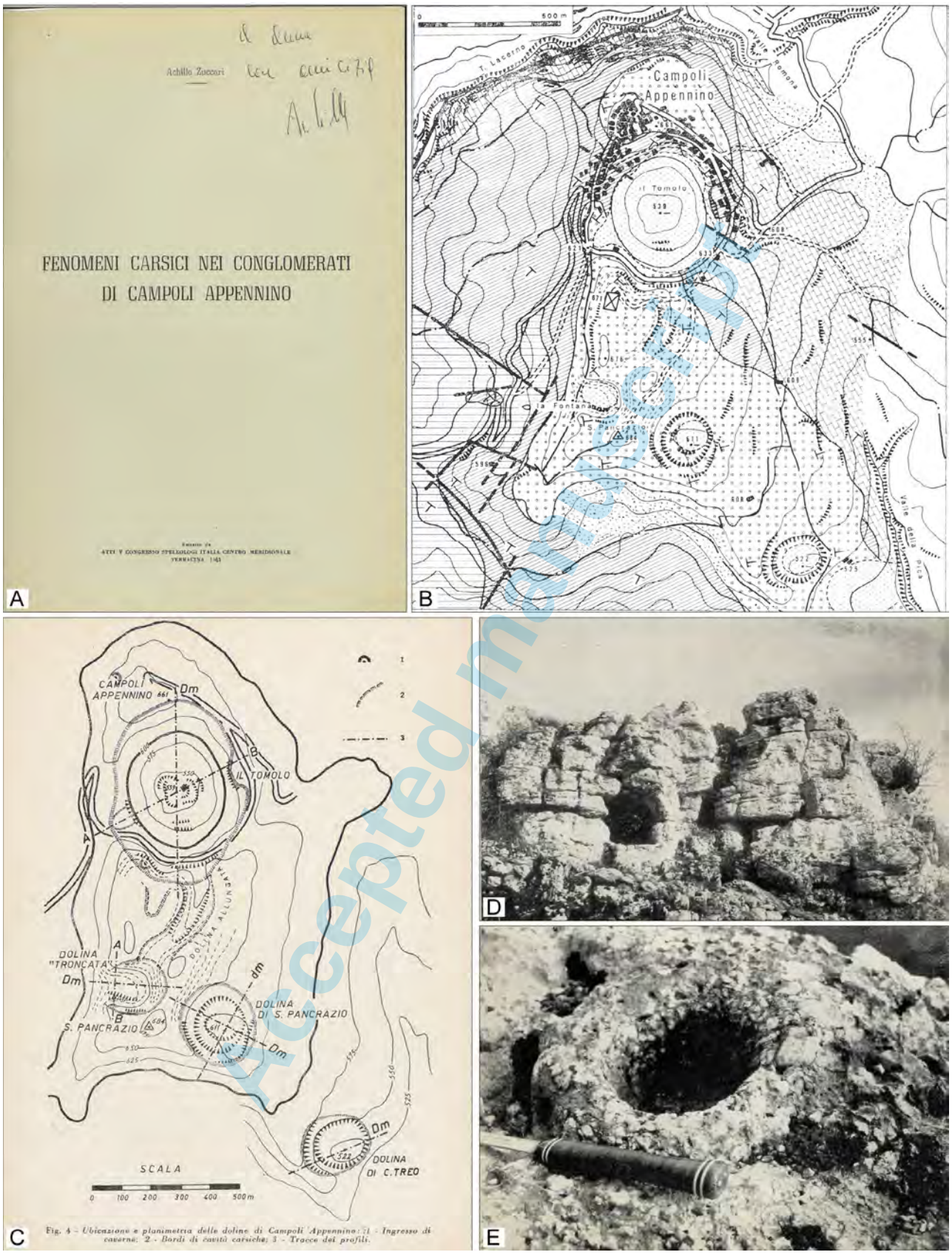

Fig. 4 - Ubicazione e planimetria delle doline di Campoli Appennino: 1 - Ingresso di caverne; 2 - Bordi di cavità carsiche; 3 - Tracce dei profili.

Fig. 8 - Excerpts of the work *"Fenomeni carsici nei conglomerati di Campoli Appennino"* by Achille Zuccari (1963). A) Cover page; note the dedication to Prof. Anna Farinacci with autograph signature. Courtesy by Alessandro Zuccari. B) Geological map of Campoli Appennino. C) Localization and topographic representation of the Campoli Appennino dolines. Legend: 1= entrance of caves; 2= edges of the karst depressions; 3= traces of the topographic profiles in figures 11, 12 and 13. D) Original field picture of fractured conglomerates cropping out at the edge of the *"Case Treo I"* doline and displaying small-scale caves. E) Field view of an elliptical dissolution pothole in well-cemented conglomerates.

Fig. 9 - Field view of the "*conglomerati di Campoli Appennino*". A) Well-cemented, massive and fractured, facies cropping out in a steep cliff (*circa* 10 m in height) near the San Pancrazio church. B) Heterolithic, poorly-cemented, facies bearing heterometric and sub-rounded carbonate clasts (up to 40 cm across), exposed along the southern slopes of the "*Il Tomolo*" doline. The slope is continuously subject to erosion and backstepping due to the scarce consolidation by carbonate cement of the conglomerates. C) Coarse-grained deposits of the "*conglomerati di Campoli Appennino*" cropping out near the San Pancrazio church. Selective erosion highlights the differences in cementation degree. In particular, the poorly-consolidated deposits are carved (intervening bed) in respect of the well-cemented and scarcely erodible facies (uppermost and lowermost beds), which form steep cliffs in the weathering profile. D) Small-scale cave affecting well-cemented conglomeratic/breccias facies. Note the two antithetical fractures at the margins of the cave, which have enhanced the chemical weathering processes, and the sub-vertical walls of the karst form. The progressive widening of the cave will weaken the cave roof, causing its collapse to form a small-scale collapse cave. This outcrop is comparable with a 2D section of a collapse doline. E) Small pits (up to 5 cm across - blue arrows) in well-cemented facies exposed near the San Pancrazio church. F) Selective weathering in well-cemented facies at San Pancrazio. The red arrows indicate dissolved carbonate clasts forming small depressions; the margins of these depressions are made of the less-erodible calcitic cement (blue arrow) binding the clasts.

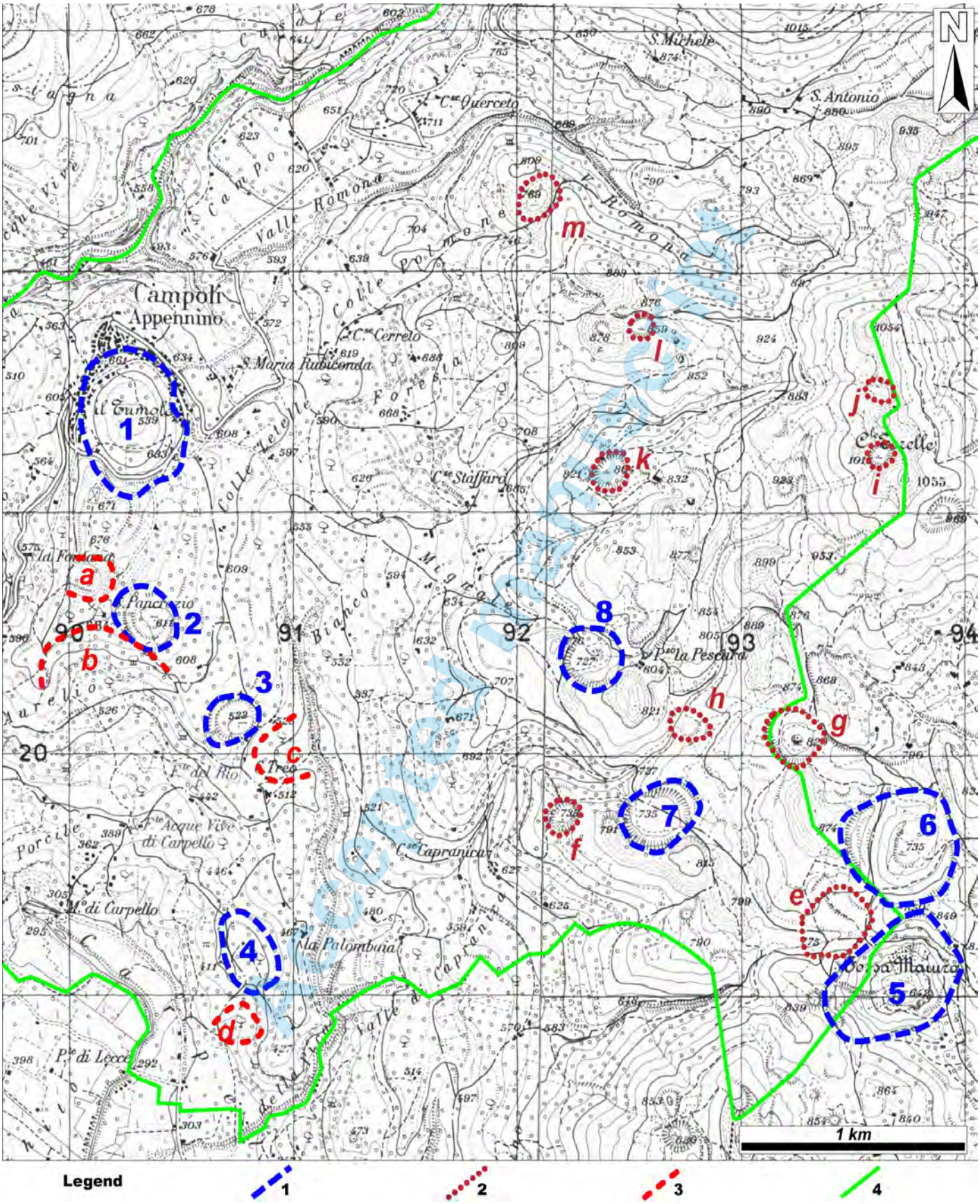

Fig. 10 - Part of the Sheet 152 "Sora" of the Italian Topographic Map at 1:25,000 scale (II SO "Alvito" and III SE "Sora" - Istituto Geografico Militare, 1963) encompassing Campoli Appennino and its dolines. Legend: 1) margins of the main "macrodolines"; 2) margins of the sub-circular and elliptical karst forms ranging between 100 and 200 m in diameter; 3) preserved margins of the "truncated macrodolines"; 4) boundary of the Campoli Appennino municipality.

TABLE 1

Topographic and morphometric parameters of the 8 "main macrodolines". Altitudes are referred to the *Carta Tecnica Regionale Numerica* at 1:5,000 scale (Regione Lazio, 2009).

Name of the doline	Maximum diameter (m)	Minimum diameter (m)	Maximum altitude (m)	Minumum altitude (m)	Maximum depth (m)	Bedrock
Il Tomolo (41°44'6.05"N; 13°40'46.70"E)	630	450	670	539	130	Pleistocene conglomerates + Meso-Cenozoic limestones
San Pancrazio (41°43'40"N; 13°40'53"E)	270	245	660	610	50	Pleistocene conglomerates
Case Treo I (41°43'26"N; 13°41'9"E)	245	209	580	519	61	Pleistocene conglomerates
La Palombaia (41°42'54"N; 13°41'12"E)	366	203	420	388	32	Meso-Cenozoic limestones
Fossa Maiura (41°42'49"N; 13°43'17"E)	560	408	840	642	202	Meso-Cenozoic limestones
Fossa Micciola (41°43'11"N; 13°43'20"E)	475	345	872	735	137	Meso-Cenozoic limestones
Pozzo del Cacio (41°43'13"N; 13°42'30"E)	400	280	791	735	56	Meso-Cenozoic limestones
Pozzo la Pescura (41°43'35"N; 13°42'16.50"E)	295	285	810	723,3	77	Meso-Cenozoic limestones

diameter is 630 m and is roughly N-S-trending, whereas the maximum depth is about 130 m (see Table 1). The dip angle of the slopes ranges between 19° and 25°, except for the eastern flank where an about 40 m-height cliff made of Miocene limestones occurs. Zuccari (1963) considers "*Il Tomolo*" an intermediate form between the "funnel" and "bowl" shapes (Fig. 11C). The thick detrital / residual blanket that characterizes the steep slopes and the bottom of the doline, has allowed an agro-forestry-pastoral exploitation of this depression since historical times, as evidenced by the seventeenth-century low relief preserved in the Villa Mazzenga (see Fig. 3), up to the end of the 1980s (Fig. 11D, 11E). Since 2010, part of the "*Il Tomolo*" (about 15 hectares) has been converted into a wildlife area (Fig. 11F). Campoli Appennino is built on the northern edge of the doline, even though the whole perimeter is anthropized. Cacciamali (1892) provides an incisive description of Campoli Appennino: "*in una pittoresca posizione sulla vetta di un colle isolato [...] e circondante un profondo avvallamento circolare imbutiforme, a guisa di un cono vulcanico che circonda il proprio cratere*" ("*in a picturesque location on the top of an isolated hill [...] surrounding a deep funnel-shaped circular depression, like a volcanic cone that surrounds its crater*" - Cacciamali, 1892, p. 307). The same Author hypothesizes a geomorphic evolution of the doline made of "*un colle primitivamente ammantato di detrito, e la cui cima sprofondò poi, trascinando seco nella voragine, come grano in una tramoggia, parte del detrito stesso*" ("a hill originally covered with debris, the top of which then sank, dragging part of the debris like wheat in a hopper" - Cacciamali, 1892, p. 312).

2. "*San Pancrazio*" doline (Fig. 12): it occurs about 1 km S of the town, in the highest elevation of the hill on which Campoli Appennino is built (called "Colle San Pancrazio" due to the presence of the church in honour of San Pancrazio, the patron saint of Campoli Appennino). This karst form only affects the Pleistocene conglomerates, has an elliptical shape in plant view (Fig. 12A, 12B), with a diameter ranging from 245 and 270 m (NW-trending maximum diameter), whereas the maximum depth is 50 m (see Table 1). It has a strongly asymmetric characteristic

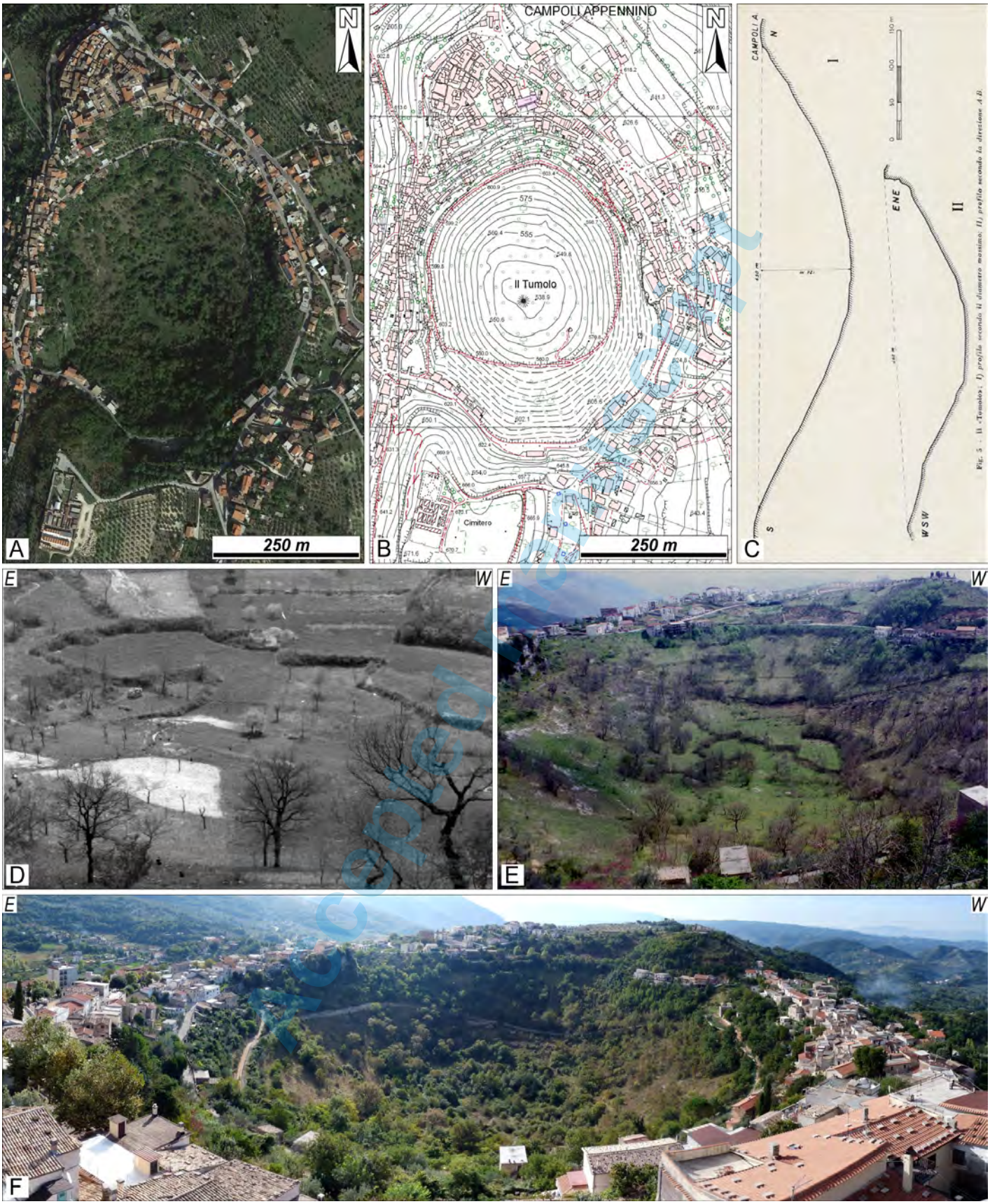

Fig. 11 - *"Il Tomolo"*. A) Aerial photo and B) cartographic detail from the *Carta Tecnica Regionale Numerica* at 1:5,000 scale (Regione Lazio, 2009) of the doline. C) Topographic sections of *"Il Tomolo"* by Zuccari (1963; see Fig. 8C for their orientation). D) Cultivated bottom of the doline in the 1950s and E) in 1986 (courtesy by Bernardino Serapiglia). F) Present-day landscape of *"Il Tomolo"* taken from the north (courtesy by Bernardino Serapiglia); part of the karst depression is now a faunistic area bearing brown bears, also marked by anthropic engravings along the doline slopes.

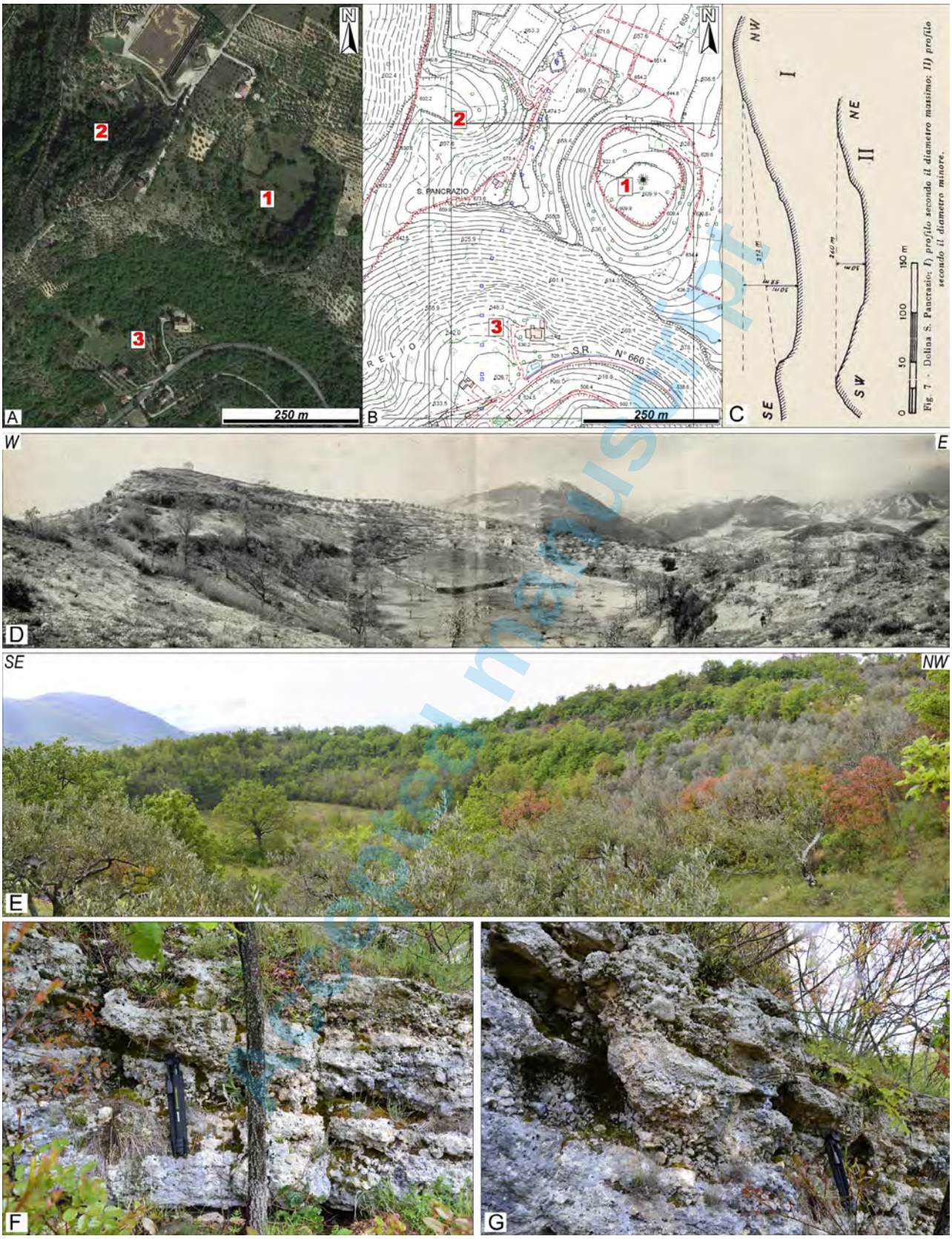

Fig. 12 - *"San Pancrazio"* doline. A) Aerial photo and B) cartographic detail from the *Carta Tecnica Regionale Numerica* at 1:5,000 scale (Regione Lazio, 2009) of the doline. Legend: 1= *"San Pancrazio"* doline; 2= *"Valle Civieri"* truncated doline; 3= *"Colle Aurelio"* ?paleo-doline. C) Topographic sections of the *"San Pancrazio"* doline by Zuccari (1963; see Fig. 8C for their orientation). D) Historical photo of the *"San Pancrazio"* doline taken from the south (modified from Zuccari, 1963). E) Photo of the doline landscape taken from the north-east. Note how most of the karst depression is now wooded. F-G) Field view of the well-cemented and karstified *"conglomerati di Campoli Appennino"* facies cropping out on the slopes of the doline. The small-scale karst forms as micro-caves and *tafoni* follow the main fractures and bed surfaces (height of the tripod= 50 cm).

"bowl" morphology; this asymmetry is related to the back-stepping of the conglomeratic slope of the San Pancrazio hill, which affects the south-eastern flank of the doline (Fig. 12C-E). According to Zuccari (1963), this karst form displays stepped slopes in its western part and sub-vertical in the eastern sectors, due to the E-dipping bed attitude (i.e., slope direction) of the "*conglomerati di Campoli Appennino*". The well-cemented conglomerates cropping out along the doline slopes show intense fracturaction, associated with micro-karst forms (i.e. small caves, funnel-shaped "microdolines", *tafoni* - Fig. 12F, 12G). The bottom is wide and sub-horizontal, and is made of *terre rosse* and gravels sourced from the flanks of the doline.

3. "*Case Treo I*" doline (Fig. 13): it occurs in the homonymous locality, about 1.5 km SSE of Campoli Appennino. The "*Case Treo I*" form affects only the "*conglomerati di Campoli Appennino*" and has an ellipsoidal morphology. The maximum diameter is 245 m-long and is *circa* E-W-trending, whereas the maximum depth is about 60 m (see Table 1). Like the "*San Pancrazio*" doline, this karst form is bowl-shaped and has an asymmetrical profile (Fig. 13A-C). The edge of the doline is anthropized, the houses that characterize the hamlet "Case Treo" being built on it, as well as the *terre rosse*-bearing bottom (Fig. 13D). Zuccari (1963) describes intense fracturation and the occurrence of caves along the conglomerate-made slopes. Few tens of meters W of the doline, along the road built on the NW-edge of the karst form and that connects Sora with Pescasseroli, Serafini & Vittori (1986) discusses on the presence of a WNW-trending, right-lateral, transcurrent fault system affecting the "*conglomerati di Campoli Appennino*", the ESE prosecution of which involves the doline itself. Recently, the "Treo Cave" was discovered on the southern margin of the doline (Mecchia et al., 2003); it represents the only hypogean form of the study area and is a straight karst conduit, about 50 m long and up to 25 m high.
4. "*La Palombaia*" doline (Fig. 13E, 13F): this karst form occurs about 2.5 km SSE of Campoli Appennino, affecting Cretaceous-Miocene limestones and has an elliptical contour. The maximum diameter trends towards NNW and is (at present) 366 m long, whereas the depth is about 90 m. This doline displays a bowl morphology and a pronounced asymmetry, related to the collapse of its western flank. The eastern slope is steep and quickly connects to a large flat and cultivated bottom, made of *terre rosse*. The topographic elevation of the bottom is 388 m a.s.l. and is important to note because the doline is engraved to the S by a karst valley that connects it with another small truncated karst form *sensu* Zuccari (1963) ("*d*" in Fig. 4; see Fig. 13E, 13F). In fact, the south-eastern margin is missing, due to erosion or collapse. This smaller hemispherical depression has its bottom at 346 m and could testify a younger karst phase, connected to the tectonic-related lowering of the hydrological base level of the Posta Fibreno springs system.
5. "*Fossa Maiura*" doline ("*maggiore*", which means "bigger" - Fig. 14): it represents, coupled with "*Il Tomolo*", the most spectacular macrodoline of the study area. This depression occurs 3.5 km SE of Campoli Appennino, at the border between the latter and Alvito municipalities (see Fig. 4). It has an elliptical shape, with its WNW-trending maximum diameter by 560 m, and a maximum depth of about 200 m (see Table 1; Fig. 14A-C). The doline develops on Cretaceous limestones bearing an abundant rudist fauna (Fig. 14D); the carbonate bedrock is displaced by NW-SE-trending Quaternary normal faults, and is extremely fractured in the whole area (Fig. 14E). "*Fossa Maiura*" shows a complex morphology, made of a "funnel" shape at the top and the bottom of the depression, and an intervening "pit" morphology (Fig. 14C). This architecture is also reported in Cacciamali, who says: "*mostrasi formata come di due imbuti concentrici: l'imbuto più grande ha un diametro massimo di circa 250 m. e le sue pareti rocciose mostrano evidente l'azione erosiva delle acque scorrenti; queste pareti scendono poi per breve tratto a picco, indi vi fa seguito il secondo imbuto, a pareti arenose per franamento: il fondo infine non è che una semplice striscia di terreno erboso*" ("*it appears to be formed of two concentric funnels: the largest funnel has a maximum diameter of about 250 m. and its rocky slopes clearly show the erosive action of flowing waters; these slopes become very steep for a short tract, then the second funnel follows, with blocky slopes due to landslide; the bottom is a strip of grassy ground*" - Cacciamali, 1892, p. 336). This configuration could testify to several karst erosive phases, with the formation of a probable normal solution doline in the initial stage of karstification (funnel shape), and of a collapse doline *sensu* Ford & Williams (2007) in the last stage (pit shape). The basal funnel morphology is almost related to the presence of residual deposits and scree sourced by gravity-related phenomena affecting the steep slopes of the doline, which make the slopes smoother at the bottom. The latters could encrypt a potential sinkhole, towards which the runoff waters are funneled. The steep walls of the "pit-type" sector are affected by secondary karst forms, like small-scale caves (Fig. 14C).
6. "*Fossa Micciola*" doline ("*piccola*", which means "small" - Fig. 15): just to the N of "*Fossa Maiura*", with which shares the southern edge, this depression is an ovoid bowl-shaped doline (Fig. 15A-B). The maximum diameter trends *circa* E-W and is 475 m long, whereas the maximum depth is 137 m (see Table 1). The steep slopes quickly connect to the flat, cultivated, bottom rich in *terre rosse* (Fig. 15C). The northern margin is missing, and this allowed Giovan Battista Cacciamali to describe this doline as "*la platea di una specie di anfiteatro roccioso, aperto a N*" ("*the parterre of a rocky amphitheater, open to the N*" - Cacciamali, 1892, p. 307).
7. "*Pozzo del Cacio*" doline (Fig. 16A-C): about 1 km E of Case Capranica locality and 2.5 km SE of Campoli Appennino, this is an elliptical (in plant view), bowl-shaped morphostructure (Fig. 16A, 16B). The maximum diameter is about 400 m and trends roughly WSW-ENE, whereas the depth is of about 60 m (see Table 1). The steep slopes of the doline pass suddenly to a flat, cultivated, bottom made of a residual soil (Fig. 16C). Two suspended karst valleys incise the margins of the depression to WNW and ESE respectively, possibly in correspondence with the main structural discontinuity which also affects the "*Fossa Maiura*" doline. Cacciamali writes: "è attraversata per il lungo dalla strada mulattiera,

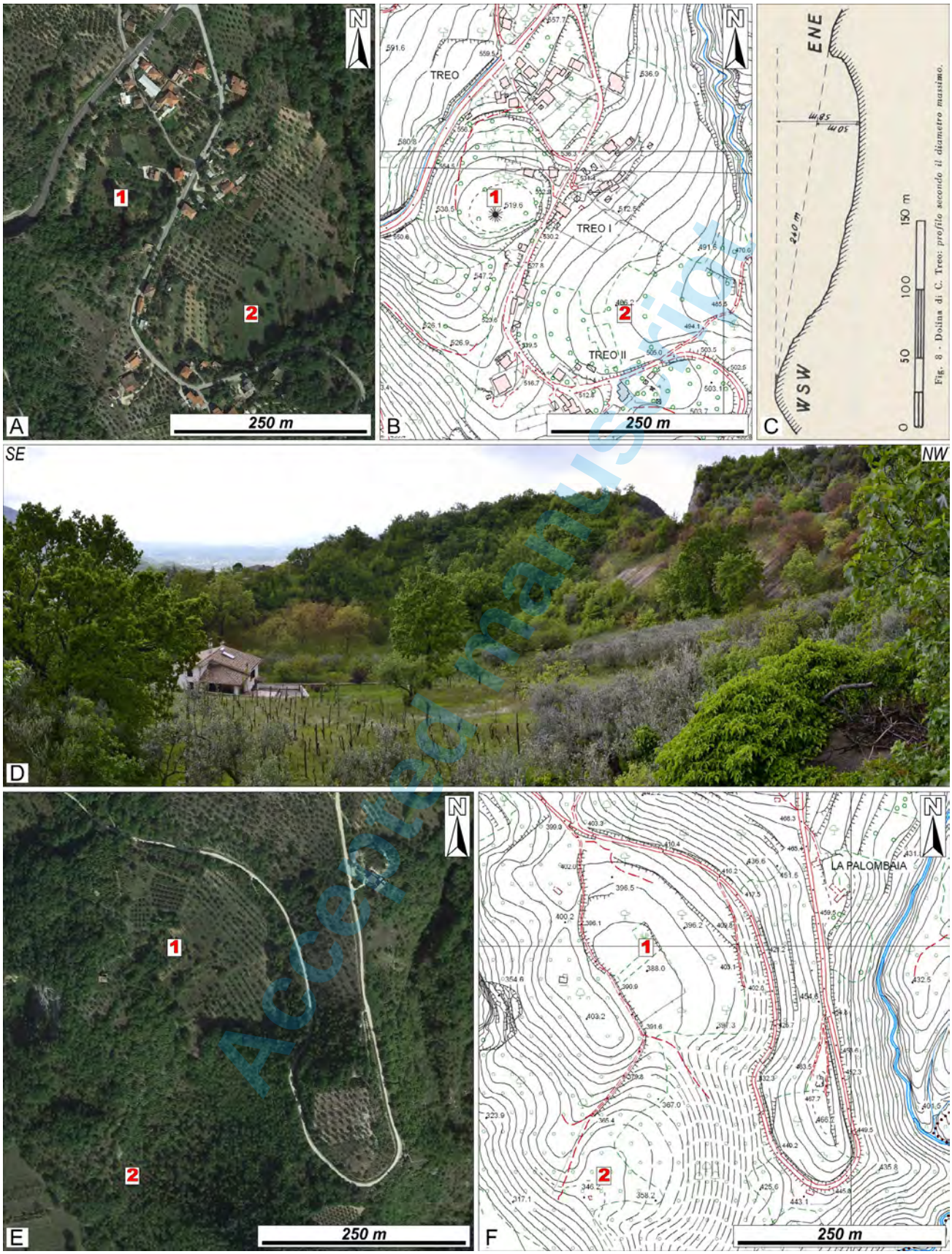

Fig. 13 - A-D) *"Case Treo I"* doline. A) Aerial photo and B) cartographic detail from the *Carta Tecnica Regionale Numerica* at 1:5,000 scale (Regione Lazio, 2009) of the doline. Legend: 1= *"Case Treo I"* doline; 2= *"Case Treo II"* truncated doline. C) Topographic section of the *"Case Treo I"* doline by Zuccari (1963; see Fig. 8C for its orientation). D) Panoramic view of the karst depression taken from the north-east. E-F) *"La Palombaia"* doline. F) Aerial photo and G) cartographic detail from the *Carta Tecnica Regionale Numerica* at 1:5,000 scale (Regione Lazio, 2009) of the doline. Legend: 1= *"La Palombaia"* depression; 2= truncated doline.

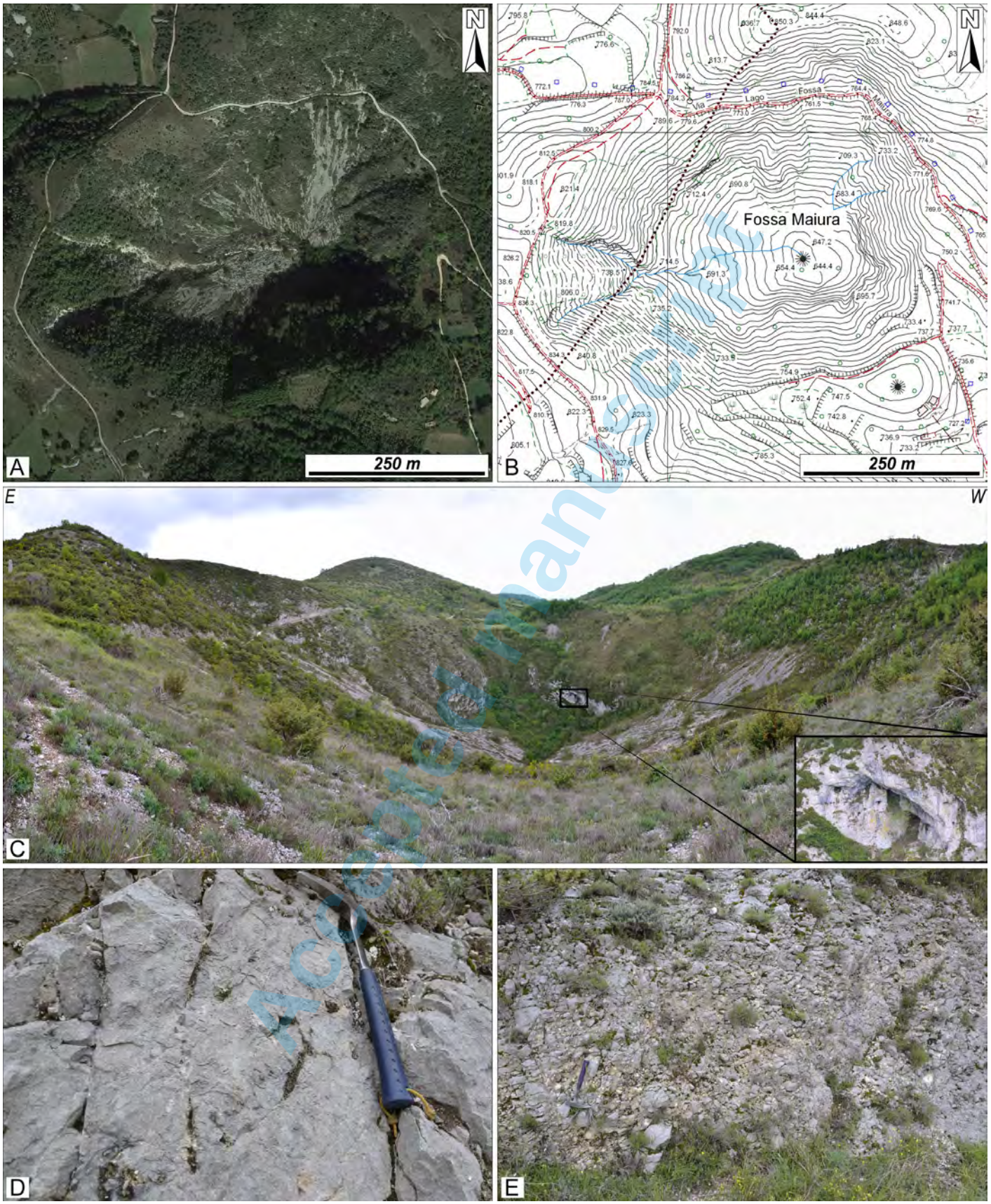

Fig. 14 - "*Fossa Maiura*". A) Aerial photo and B) cartographic detail from the *Carta Tecnica Regionale Numerica* at 1:5,000 scale (Regione Lazio, 2009) of the doline. C) Panoramic view of the majestic "*Fossa Maiura*" taken from the north; note the difference in steepness between the highest slopes (funnel shape) and the bottom (pit shape) of the doline. An enlargement of the karst cave occurring on the southern wall of the "pit" is provided. D) Rudist-rich Cretaceous limestones exposed along the road surrounding the karst depression. E) Field view of highly-fractured limestones cropping out along the slopes of "*Fossa Maiura*".

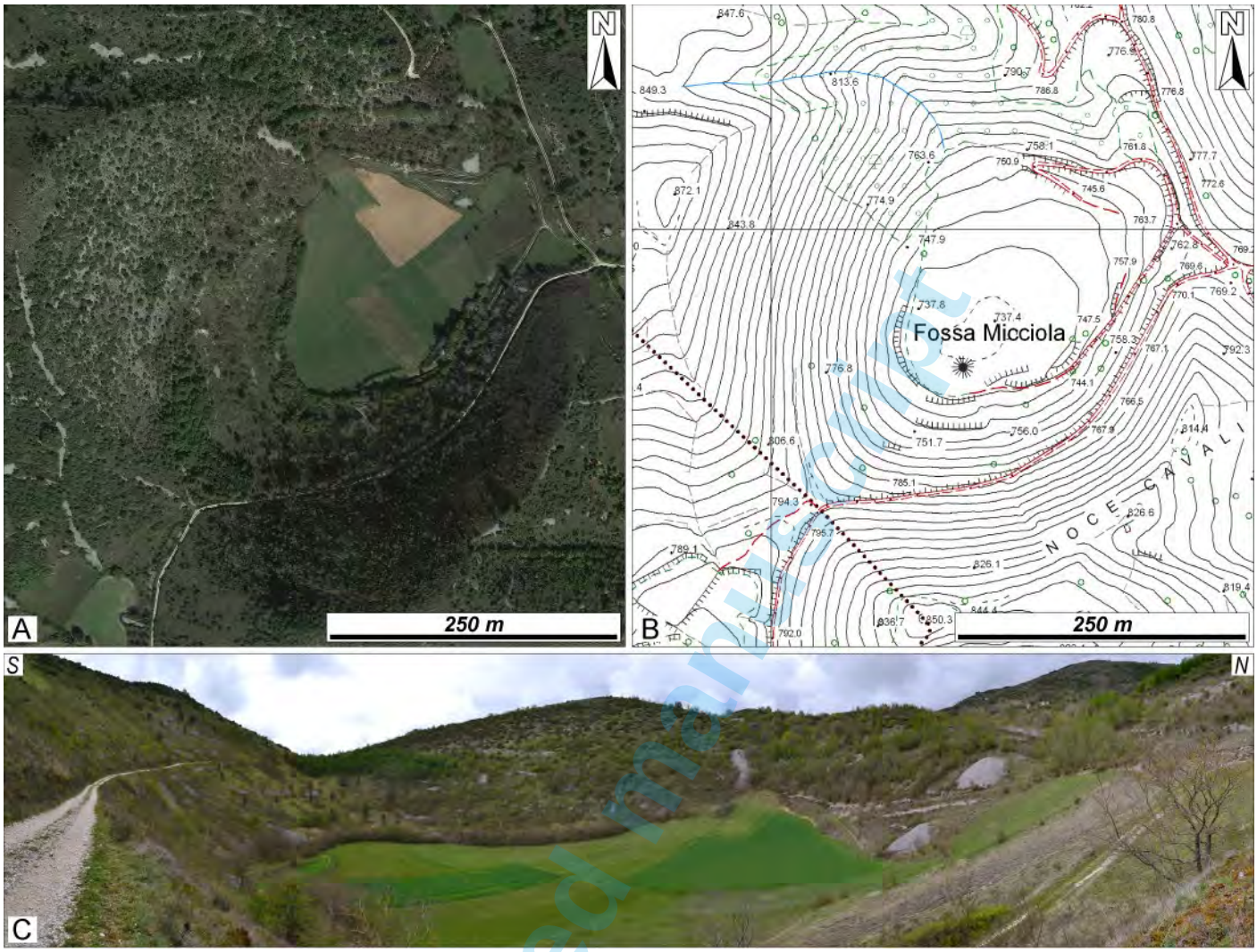

Fig. 15 - *"Fossa Micciola"*. A) Aerial photo and B) cartographic detail from the *Carta Tecnica Regionale Numerica* at 1:5,000 scale (Regione Lazio, 2009) of the doline. C) Panoramic view of *"Fossa Micciola"* taken from the east; note the "bowl" morphology of the doline, with the steep slopes suddenly joined with the flat bottom where the fertile *"terre rosse"* are anthropically exploited.

e vi esiste un pozzo di acqua perenne" (*"it is crossed by a road mule track, and there is a perennial water well"* - Cacciamali, 1892, p. 307).

8. *"Pozzo la Pescura"* doline (Fig. 16D-F): the name derives from *"frescura"* (*"Pozzo Frescura"* in Cacciamali, 1892), which means "freshness" and is related to the peculiar microclimatic conditions occurring in this karst depression, especially during the warm seasons. *"Pozzo la Pescura"* is 0.6 km NNW of *"Pozzo del Cacio"*, 1.5 km NW of *"Fossa Maiura"* and 2 km ESE of Campoli Appennino (see Fig. 10). This doline is ovoidal, with steep slopes connected to a wide karst plain made of *terre rosse* (Fig. 16D-F). The margins are interrupted to the E and to the NW by karst valleys. The maximum diameter is oriented ENE-WSW and is *circa* 300 m long, whereas its depth is 77 m (see Table 1). A peculiar feature of this depression is the presence, at the bottom, of a sinkhole formed in historical times. Giovanni Battista Cacciamali refers: *"in questo ripiano esiste una pozzanghera larga circa 15 m. Si racconta che questo stagno siasi formato improvvisamente, un 30 anni addietro, per sprofondamento del suolo, e che anzi in quel posto esistesse prima un noce: appena formatosi, lo stagno era più profondo, méntre ora vi possono entrare le bestie a bagnarsi"* (*"in this level ground is a puddle about 15 m wide. It is said that this pond was formed suddenly, 30 years ago, by sinking the soil, and indeed in that place there was first a walnut: as soon as it formed, the pond was deeper, while now the beasts can enter to bathe"* - Cacciamali, 1892, p. 307). A more detailed description is by Maestro Basilio Conflitti, one of the most relevant and appreciated personalities of the Campoli Appennino community in the first decades of XX century. Conflitti (1928) tells of local shepherds who on the evening of August 14, 1865 heard a strong underground thunder coming from the clearing that characterizes the bottom of the doline. At the center of the depression was a large walnut tree that, after the thunder, was disappeared and in its place there was a small karst lake of about 30 m in diameter. The testimonies of this lake remain in the stories of the inhabitants of Campoli Appennino and in the book

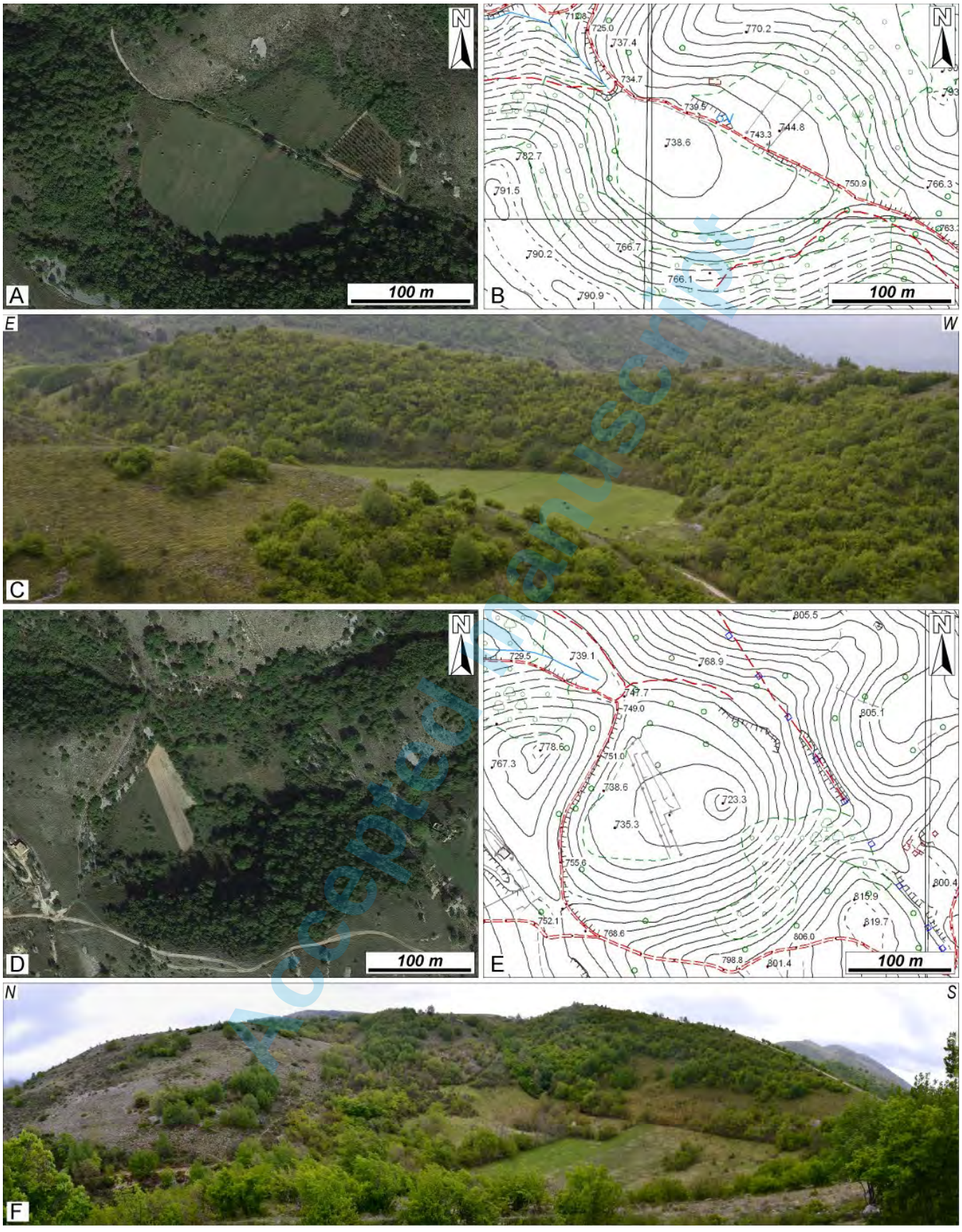

Fig. 16 - A-C) *"Pozzo del Cacio"* doline. A) Aerial photo and B) cartographic detail from the *Carta Tecnica Regionale Numerica* at 1:5,000 scale (Regione Lazio, 2009) of the doline. C) Landscape of the *"Pozzo del Cacio"* doline with the characteristic "bowl" form; here too, the near-level bottom of the karst depression is cultivated. Photo taken from the north. D-F) *"Pozzo la Pescura"* doline. D) Aerial photo and E) cartographic detail from the *Carta Tecnica Regionale Numerica* at 1:5,000 scale (Regione Lazio, 2009) of the doline. F) Panoramic view of the *"Pozzo la Pescura"* doline taken from the west.

of Conflitti (1928) until 1915, when, after the Fucino earthquake, the water disappeared. Today remains a funnel-shaped depression.

Four "truncated" dolines *sensu* Zuccari (1963) are added to the 8 main macrodolines, having the main axis longer than 200 m. The peculiar feature of these forms is the lacking of part of their margins due to gravitational collapse or erosive backstepping of the slope on which are superimposed. Three of these are "*Valle Civieri*", "*Colle Aurelio*" and "*Colle Treo II*" dolines ("a-c" in Fig. 10) and affect the Pleistocene "*conglomerati di Campoli Appennino*", whereas the fourth has already been described earlier (see "Palombaina doline" - "d" in Fig. 10; #2 in Fig. 13E, 13F).

1. "*Valle Civieri*" doline ("a" in Fig. 10; "*dolina troncata*" in Zuccari, 1963; #2 in Fig. 12A, 12B): this karst form occurs 0.1 km N of the San Pancrazio church, on the homonymous hill. It is a U-shaped depression with its western margin collapsed due to erosional backstepping of the north-western hill slopes. The doline has a more than 200 m-long maximum diameter, and a depth of about 35 m; its morphology is bowl-shaped, with steep slopes and flat bottom.
2. "*Colle Aurelio*" ?paleo-doline ("b" in Fig. 10; #3 in Fig. 12A, 12B): an enormous amphitheater-shaped morphology facing towards S, about 1.5 km S of Campoli Appennino and bounding to the S the San Pancrazio hill. Nowadays, this morphology shows clear evidence of gravity-driven backstepping, forming a wide collapse niche. Nevertheless, it cannot be excluded the superimposition of gravity features on a karst ancestor.
3. "*Case Treo II*" doline ("c" in fig 10; #2 in Fig. 13A, 13B)): wide U-shaped morphology flanking to SE the "*Case Treo I*" doline and with the main axis trending ENE-WSW. This karst morphology is also quoted by Zuccari (1963) and presents the north-eastern margin collapsed.

The remaining 9 karst forms are scattered on the Colle Terelle hilly range. These depressions are sub-circular or elliptical in plant-view, have a maximum diameter ranging between 100 and 200 m, and affect only Mesozoic carbonate rocks ("e-m" in Fig. 10). One of these ("e" in Fig. 10), just to the W of "*Fossa Maiura*" and "*Fossa Micciola*", is called "*Pozzo del Corvo*" by Cacciamali (1892).

THE UNDER-ESTIMATED RELEVANCE OF THE CAMPOLI APPENNINO KARST LANDSCAPE

In spite of the geological heritage of Campoli Appennino, which have attracted the interest of geologists and naturalists since the end of the XIX century (allowing to define an areal "site of the geological memory" for the study area - Cipriani, 2020b), its historical overview stresses a clear under-estimation of these various karst forms during most of the XX century. This is also marked by the spotted dissemination of scientific geodata, making the fascinating Campoli Appennino karst landscape "trascurated" for a too long time from a geomorphological and hydrogeological point of view. This has led to a poor enhancement of the scientific, cultural, social and aesthetic characters of this part of Italy, as well as to a limitation of the people's awareness of natural processes and risks (which, instead, must be increased). In fact, it must be stressed that the Campoli Appennino area falls in a "high sinkhole concentration area" *sensu* Santo et al. (2011), and, as a consequence, is more prone to collapse phenomena. Moreover, the risk of karst collapses is enlarged by the presence of seismogenic sources in the area, which can produce large earthquakes (Galadini & Galli, 2000; Roberts & Michetti, 2004; Papanikolaou et al., 2005). Both the identification of a collapse prone area and of the high seismic hazard (which can facilitate the collapse itself) require a greater consideration in the territorial planning (Santo et al., 2011). However,

people's awareness of the seismic and hydrogeological hazards is still not at a very high level.

The lack of geotourism, in the sense of promotion of the geological heritage (e.g. Piacentini et al., 2019), also remarks the low interest towards these treasures of the Western Marsica, albeit Campoli Appennino is part of the Lazio-Abruzzo-Molise National Park, and "*Il Tomolo*" and "*Fossa Maiura*" are two geosites.

With this work, we want to "reverse this course" and disseminate the relevance of the geological heritage of Campoli Appennino in particular, and of the Western Marsica as a whole. New strategies of geological information must be adopted in the future to give value to these landscapes. Geological tourist maps should be produced to favouring the territorial knowledges not only to geologists, but also to tourists and locals (e.g. Giardino et al., 2004; Piacentini et al., 2019).

Geological and naturalist paths equipped with explanatory panels should be developed. In the city plan of the Campoli Appennino municipality, the construction of a cycle-pedestrian path connecting areas with a high historical and naturalistic value, called "*Piano Urbano delle Doline*" ("Doline urban park"), is envisaged. This hiking trails network, coupled with the dissemination of the geological peculiarities of the territory, could give more value to the multifaceted geological heritage of this area, also favouring the promotion and development of geotourism.

The realization of a shared database hosting three-dimensional virtual outcrops/landscapes could represent a fundamental tool for communication, dissemination and exchange of geological information (Cipriani et al., 2016; Ferraby & Powlesland, 2019; Romano et al., 2019b). The use of laser scanners or of cheap drones bearing high-quality cameras could permit to produce 3D models for the study dolines (e.g Petti et al., 2008, 2018; Falkingham, 2012; Citton et al., 2017). High-resolution photogrammetric models obtained with laser scanning or photogrammetric techniques allow to digitally preserve geological data, and make them available for a wider community, education and public engagement (e.g. Falkingham, 2012; Cipriani et al., 2016, Romano et al., 2019b), favoring their visibility. This is particularly important when the sites are susceptible to the natural geomorphic evolution as observed and described for the studied area (e.g. karst, weathering, gravity-driven phenomena).

All the above-discussed points should also be supported by a policy focused on the enhancement and promotion of the territory, intended as a resource both for tourism and for greater awareness of geological risks.

CONCLUSIONS

The Campoli Appennino karst landscape represents an emblematic example of karst processes acting on different types of rocks, not only carbonate but also clastic. In particular, karst forms affecting conglomerate deposits represent a under-investigated topic in literature, whereas are peculiar in the Campoli Appennino area. Their detailed description made Achille Zuccari one of the pioneers of the karst geomorphology affecting carbonate-rich clastics (i.e. "*conglomerati di Campoli Appennino*"). The study area is characterized by 21 macrodolines (i.e. having maximum diameter >100 m), 8 of which present a more than 200 m-long main axis and are called "main macrodolines". The "*conglomerati di Campoli Appennino*" are affected by 3 main macrodolines, whereas the remaining 5 forms occur on Meso-Cenozoic limestones cropping out in the Colle Terelle-Mt. Morrone carbonate ridge. Associated with the main macrodolines are 4 "truncated" dolines having the main axis longer than 200 m and lacking of a margin to form amphitheater-shaped morphologies. From a historical point of view, since the second half of 1800 the hydrogeological, structural, stratigraphic and geomorphological aspects of the karst depressions of Campoli Appennino have attracted the interest of geologists. This allowed to identify and to propose a "site of the geological memory" for the Campoli Appennino karst landscape. Nevertheless, the biblio-cartographic historical overview displays a limited interest in these karst forms, evidenced by the few publications. The latter, coupled with a territorial policy not focused on the promotion of the geological heritage, caused a poor advertising of the geological wonders of Campoli Appennino, not favoring geotourism.

ACKNOWLEDGEMENTS

AC wants to warmly acknowledge Alessandro Zuccari for providing the original (and invaluable) copy of his father's, Achille Zuccari, manuscript "*Fenomeni carsici nei conglomerati di Campoli Appennino*". Giovanni "Giannino" Corgnale, Maria Pagnani, Tonino Cipriani and our daughter Matilde are thanked for the support on the field, as well as Barbara Conflitti for providing information about the work by Basilio Conflitti (1928). A special thanks goes to Bernardino Serapiglia for providing us unique iconographic data. Fabiana Console, Marco Pantaloni and Alessio Argentieri are warmly acknowledged for providing iconographic and bibliographic data, and for involving AC in the project "*sites of the geological memory*" ideated and developed by *ISPRA - Servizio Geologico d'Italia*, *Regione Lazio - Direzione Regionale Capitale Naturale, Parchi e Aree Protette* and *Città Metropolitana di Roma Capitale*. The authors are grateful to the Editor-in-Chief Domenico Calcaterra, the Associate Editor Maurizio del Monte, Simone Fabbi and an anonymous reviewer for their editorial and revision work.

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