Geological Field Trips and Maps

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Geological map of the Mt. Vettoretto–Capodacqua area (Central Apennines, Italy) and cross-cutting relationships between Sibillini Mts. Thrust and Mt. Vettore normal faults system

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Geological map of the Mt. Vettoretto–Capodacqua area (Central Apennines, Italy) and cross-cutting relationships between Sibillini Mts. Thrust and Mt. Vettore normal faults system

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Cover page Figure
Panoramic view of Mt. Vettoretto and Mt. Vettore taken from Mt. Forciglietta. The Mt. Vettoretto Fault ribbon is apparent.

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Abstract

We present the results of a geological mapping project performed in the southern portion of the Sibillini Mts., aimed at defining the structural relationships between the Sibillini Mts. Thrust front and the Mt. Vettore normal fault system, reactivated during the 2016-2017 central Italy seismic sequence. The Sibillini Mts. Thrust is characterised by a hanging wall where the Meso-Cenozoic Umbria-Marche succession crops out, while the footwall is represented by the Messinian Laga foredeep unit. The Mt. Vettore extensional fault system is formed by two main normal faults, the "Castelluccio Plain" and "Mt. Vettoretto" faults. Being the cross-cutting relationships between the structural elements hidden by a thick debris cover, they have been reconstructed analyzing the geometries of the hanging wall anticline of the Sibillini Mts. Thrust and other field constrains. This allowed us to conclude that the Sibillini Mts. Thrust was displaced by the Castelluccio Plain normal fault with a max throw of ~ 250 m. Both the Castelluccio Plain normal fault and the Sibillini Mts. Thrust are subsequently cut by the Mt. Vettoretto fault, which is inferred to reuse in part the inverted Sibillini Mts. Thrust plane.

Keywords: Geological map, Umbria-Marche Apennines, 2016 Amatrice-Norcia Earthquake, thrust, normal fault, inversion tectonics.

Introduction

The study area is located in the southernmost part of the Sibillini Mts. (Fig. 1), which is the most prominent (Mt. Vettore, 2476 m a.s.l.) chain of the Umbria-Marche Apennines (central Italy).
The area is characterised by the occurrence of two main tectonic structures, the Sibillini Mts. Thrust front, which is one of the longest compressional structures of the Apennines, and the Mt. Vettore normal fault system, which was responsible of the destructive main shock (Mw 6.5, 30 October 2016) of the 2016-2017 Amatrice-Norcia seismic sequence, which is still ongoing (Chiaraluce et al., 2017; Scognamiglio et al., 2018).
The cross-cutting relationships between the active Mt. Vettore normal fault system and the Sibillini Mts. Thrust is controversial and object of a long lasting scientific debate: some authors report that the normal faults cut and displace the Sibillini Mts. Thrust (e.g., Lavecchia, 1985; Lavecchia et al., 1994; 2016; Pierantoni et al., 2005) while others suggest that normal faults detached on the thrust plane instead of displacing it (e.g., Bally et al., 1986; Calamita et al., 1994; Di Domenica et al., 2012). This debate grew up after the 2016–2017 seismic sequence (e.g. Bonini et al., 2016; Chiaraluce et al., 2017; Buttinelli et al., 2018; Brozzetti et al., 2019).
Such different interpretations are due to the almost total lack of good outcrops in the area where the Mt. Vettore fault system intersects the Sibillini Mts. Thrust, preventing any direct observation of the structural relationships (Pierantoni et al., 2013). In addition, available seismic lines are not detailed enough, and do not allow the visualization of any possible displacement of less than 150-200 m.
After the mentioned 2016-2017 seismic sequence which affected the area, despite a fresh set of geophysical data are available for researchers, the controversy is still going on. Some authors, based on different approaches and dataset, infer that the Mt. Vettore fault system cut only the succession at the hanging wall of the Sibillini Mts. Thrust, producing the negative inversion of the thrust plane at depth (Bonini et al., 2016; Pizzi et al., 2017; Buttinelli et al., 2018; Scognamiglio et al., 2018); other authors, based on geophysical data and field analysis, infer that the Mt. Vettore normal fault system displaces the Sibillini Mts. Thrust (Lavecchia et al., 2016), with throws ranging from ~ 300 m (Brozzetti et al., 2019) to more than 1 km (Porreca et al., 2020).
We present a new geological map of the area between Mt. Vettoretto and the village of Capodacqua (AP), and provide a fresh interpretation of the thrust/normal faults relationships based on field evidence, also in light of the recent mentioned seismic activity.
This work supports the research activities of the RETRACE group that deals with the 3D modelling of the crustal volume affected by the 2016 Central Apennines seismic sequence.

Methods and techniques

The geological map of the area between the Mt. Vettoretto (more precisely Rifugio Zilioli, 2250 m a.s.l.) and the village of Capodacqua (850 m a.s.l.) (Fig. 1), has been surveyed on 1:10000 scale, using the classical field methods of geological mapping, with the aim to analyze the tectonic structures that characterise the area. To better constrain the stratigraphy and the structural elements, thin sections of rock samples were realised and analyzed.
The study area is within the 325 "Visso" and 337 "Norcia" Sheets of the Geological Map of Italy at 1:50000 scale; the latter is currently in preparation by the Geological Survey of Italy and CNR within the CARG Project, while the realization of the first one is planned for the near future. The topographic base-maps used for the geological survey described in the present work are portions of the sections 325 II "Monte Vettore" and 337 I "Arquata del Tronto" of the official topographic map of Italy at 1:25000 scale (IGM Serie 25 DB). The geological map, originally surveyed at 1:10000 scale, is accompanied by a stratigraphic log, a tectonic scheme and four geological cross-sections.

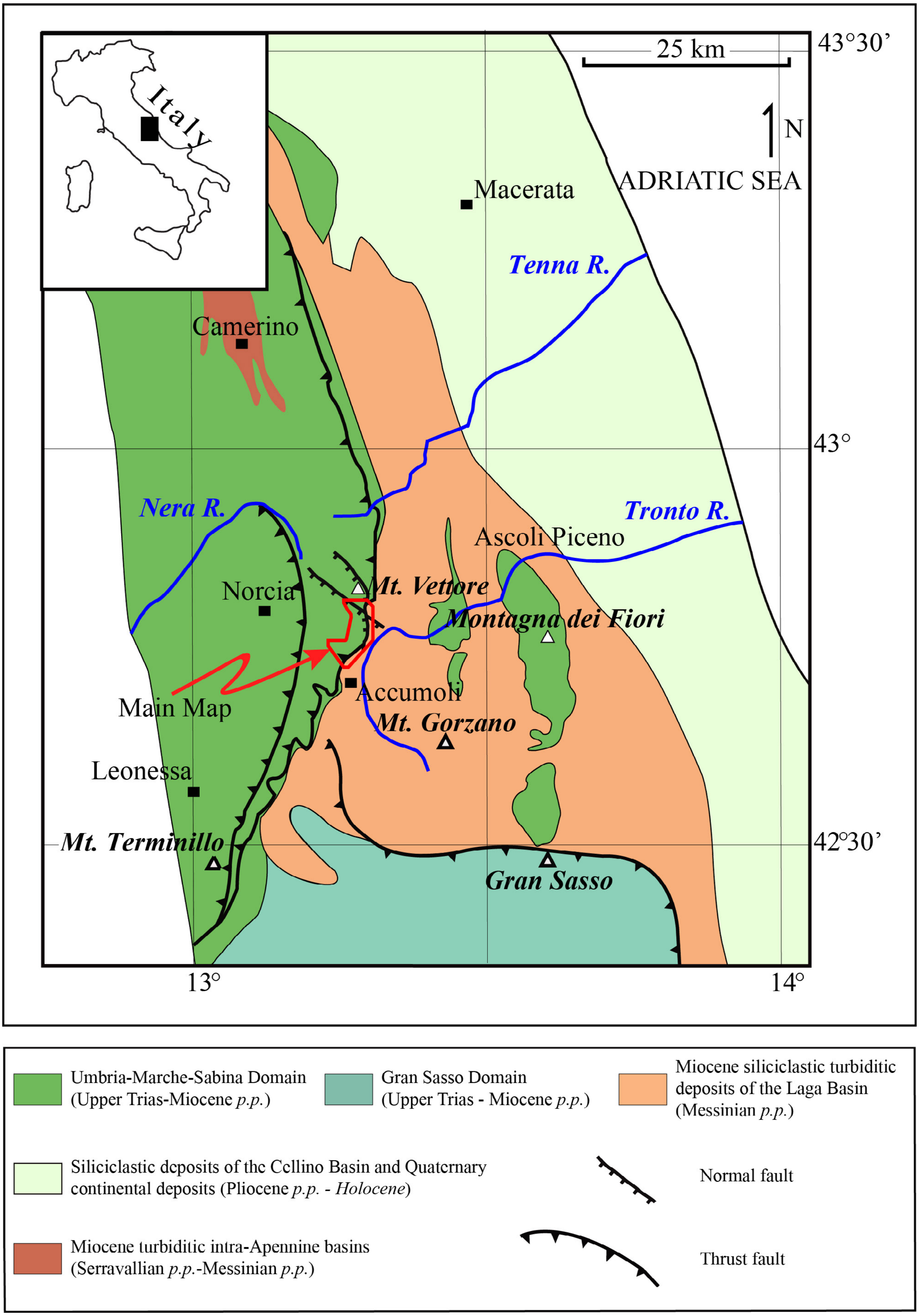

Fig. 1 – Location and regional setting of the study area (modified after Pierantoni et al., 2013).

The geological mapping process was supported by geo-localization and georeferencing methods that allowed to correctly define the location of the geological elements. The geological map has been georeferenced by the software opensource QGis, using the spatial reference system EPSG:23033 (ED50/UTM zone 33N). The final version of the map, the geological cross-sections and the structural scheme have been drawn with the software Adobe Illustrator.

Regional Setting

The Central Apennines is a fold and thrust belt produced by the deformation of two Meso-Cenozoic palaeogeographic domains (Umbria-Marche-Sabina and Latium-Abruzzi) belonging to the passive margin of the Adria domain (Royden et al., 1987; Patacca & Scandone, 1989; Patacca et al., 1992; Parotto & Praturlon, 2004).
The study area belongs to the Umbria-Marche-Sabina Domain, whose Mesozoic stratigraphy was controlled by the well-known Early Jurassic Western Tethys rift stage (Bernoulli, 1967; Centamore et al., 1971; Santantonio & Carminati, 2011; Fabbi & Santantonio, 2012). The vast supra-regional scale Calcare Massiccio carbonate platform was dismembered since the Hettangian-Sinemurian boundary by extensional tectonics, which caused the carbonate platform drowning and produced a horst and graben configuration (Morettini et al., 2002; Passeri & Venturi, 2005; Santantonio & Carminati, 2011). After the drowning of the carbonate platform, a dominantly pelagic sedimentation was established in the area, characterised by strong facies and thickness differentiation (Fig. 2), with thin pelagic condensed successions sedimented on footwall blocks (PCPs *sensu* Santantonio, 1993, 1994) and much thicker successions sedimented in hanging wall basins (Colacicchi et al., 1970; Centamore at al., 1971; Santantonio, 1993; 1994; Galluzzo & Santantonio, 2002; Passeri & Venturi, 2005; Marino & Santantonio, 2010; Pierantoni et al., 2013; Fabbi, 2015; Cipriani, 2016).
In the earliest Cretaceous the paleobathimetric differences were levelled by the Maiolica (Centamore et al., 1971; Cipriani et al., 2019), and uniform pelagic sedimentation was established in the basin for the rest of the Cretaceous and Paleogene, characterised by a general increase in terrigenous content since the Eocene throughout the Miocene.
Since the late Miocene, the advancing of the Apennine chain caused the flexuring of the foreland, followed by the development of the Laga foredeep basin, which hosted a >3000 m-thick turbiditic succession (Cantalamessa et al., 1980; Calamita et al., 1998; Milli et al., 2007).
The chain building occurred through the eastward migration of thrust systems, which produced an arcuate mountain ridge since the late Miocene, overthrusting the foredeep deposits of the Laga Basin (Royden et al., 1987; Lavecchia et al., 1988; Calamita & Deiana, 1988; Patacca et al., 1992; Carminati & Doglioni, 2012; Pierantoni et al., 2013). The Sibillini Mts. Thrust is the main thrust front of the Central Apennines (Lavecchia, 1985; Pierantoni et al., 2005; Cosentino et al., 2010; Calamita et al., 2012). It has an arcuate shape, showing N140-160 strike in the northern portion, N 20-30 strike in the central portion (study area), and about N-S in the southern part where it is known as the Olevano-Antrodoco-Posta line (Salvini & Vittori, 1982; Cipollari & Cosentino, 1991; Mazzoli et al., 2005; Pierantoni et al., 2005; Calamita et al., 2012). After the compressional tectonic phase, as a consequence of the opening of the Tyrrhenian back-arc basin, the E-verging accretionary wedge was affected by Quaternary extensional tectonics (Patacca et al., 1992; Doglioni, 1995; Doglioni et al., 2006). Active normal faults mainly parallel the Apenninic strike (NNW-SSE), forming an angle with respect to the Sibillini Mts. Thrust and the other compressional structures (Lavecchia et al., 1988; Calamita et al., 1998; Bigi et al., 2002; Festa, 2002).
Significantly, before the active Quaternary extensional phase, the Central Apennines show evidences of multiple pre-orogenic extensional phases, during the Early Jurassic (see above), Middle/Upper Jurassic (Bartoccini & Rettori, 1991; Galluzzo and Santantonio, 2002; Di Francesco et al., 2010), Early Cretaceous (Fabbi et al., 2016; Cipriani & Bottini, 2019), Late Cretaceous/Paleogene (Capotorti et al., 1995; Bice et al., 2007) and Miocene (Calamita et al., 1998; Tavarnelli & Peacock, 2002; Bigi et al., 2003; Carminati et al., 2014; Calamita et al., 2018). The latter phase is well-documented, because it produced a significant control on the sedimentation in foredeep basins (Calamita et al., 1998; Fabbi & Rossi, 2014; Fabbi et al., 2014), and on the trajectory and geometry of thrusts (Tavarnelli., 1995; Calamita et al., 2012). The Miocene extensional activity can explain the occurrence of normal faults with large stratigraphic throw, coupled with few present-day topographic evidence (Compagnoni et al., 1990; Bigi et al., 2003; Fabbi et al., 2014; Fabbi & Rossi, 2014; Fabbi, 2016; 2018). Finally, a last pre-Quaternary syn-compressional extensional phase has also been described in the Sibillini Mts. by Tavani et al. (2012), related to the gravitational collapse along fold limbs during the late stage of thrust propagation and fold growth. A superposition of such different extensional phases in the same area can explain puzzling structural relationships or incongruent throws in different sections of a single normal fault.

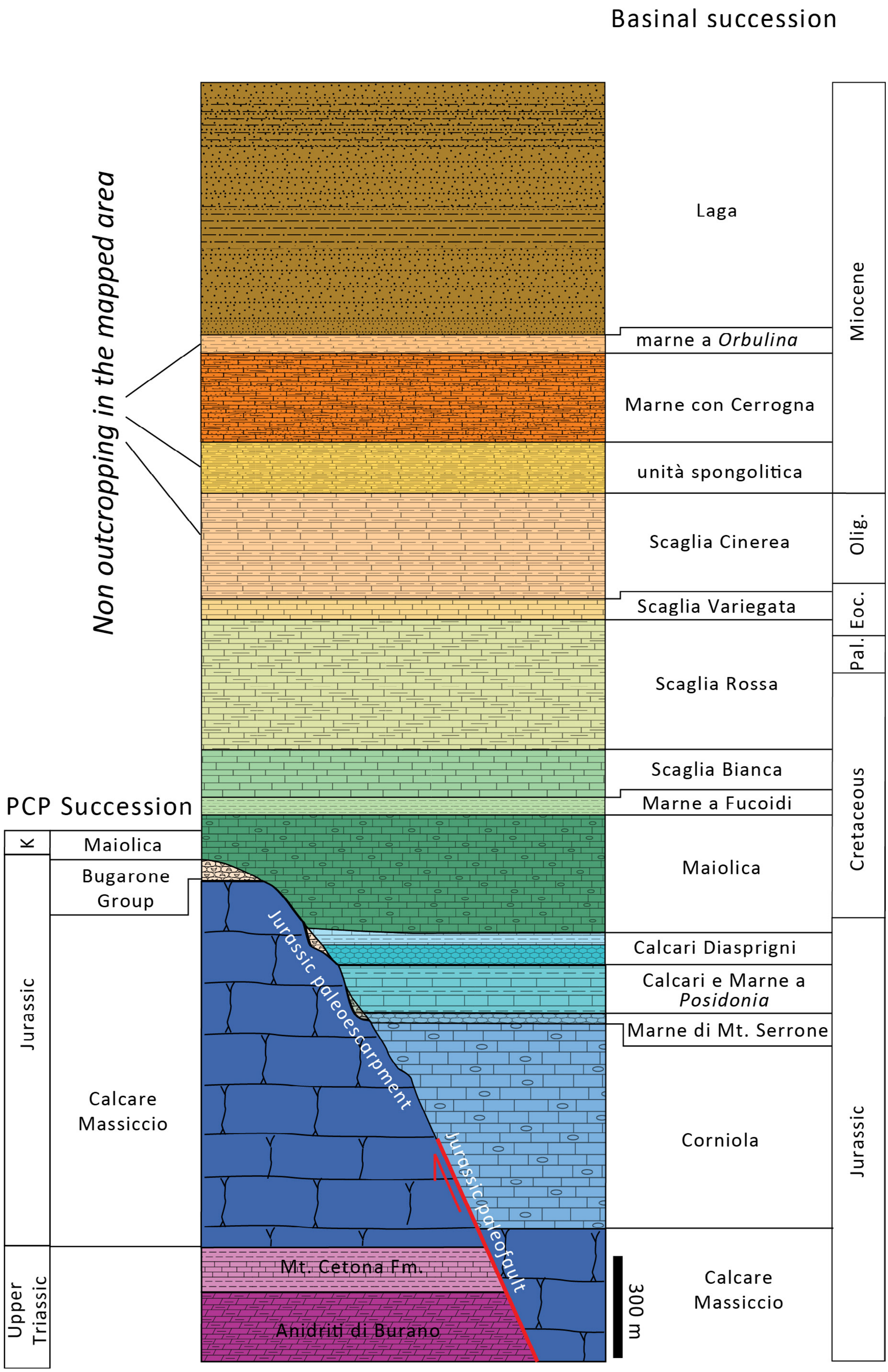

Fig. 2 – Stratigraphy of the study area (modified after Fabbi et al., 2019).

Map Description

Stratigraphy (Fig. 2)

The older stratigraphic unit exposed in the study area is the Calcare Massiccio (MAS - Hettangian – lower Sinemurian) which is characterised by cyclic sedimentation in a carbonate platform setting. It consists of white, thick bedded to massive grainstone and packstone, containing molluscs, oncoids, peloids, rare ooids, benthic forams (Valvulinidae, Lagenidae, Nubecularidae) and algae (*Palaeodasycladus* sp., Solenoporaceae, *Cayeuxia* sp.). It corresponds to the Calcare Massiccio A Lithofacies (Cita et al., 2007; Fabbi, 2015) and crops out only along the eastern side of Mt. Vettore (Fig. 3a). The thickness is not detectable but in the region it exceeds 600 m (Bice & Stewart, 1985).

The Corniola (COI - lower Sinemurian-lowermost Toarcian) marks the switch to a pelagic basinal sedimentation, due to the rapid deepening of hanging wall blocks of Jurassic faults (Fig. 2). The lower part of the COI is the syn-rift portion of the succession (Cecca et al., 1990; Fabbi & Santantonio, 2012; Santantonio et al., 2017), evidenced by abundant clastic deposits, derived from the small carbonate platform that survived on the structural highs until the lower Pliensbachian (Marino & Santantonio, 2010), and to tectonic-related dismantling of the structural highs escarpments, which produced large olistoliths (Di Francesco et al., 2010; Fabbi, 2015; Cipriani, 2016; Santantonio et al., 2017). The COI is made of dark grey-brownish lime-mud/wackestone (Fig. 3b), in decimetric to metric beds, containing abundant nodules of grey chert. The microskeletal content is made of radiolaria and sponge spicules, while macrofossils are essentially rare ammonoids and thin-shelled bivalves. The COI widely crops out in the study area, and along the western side of Mt. Vettore it is characterised by megabreccias and olistoliths derived from pre-rifting MAS. The thickness is variable and reaches 500-600 m.

The following Marne di Monte Serrone (RSN - Toarcian *p.p.*), consists of brown, centimetric to decametric well-bedded marly limestones, interlayered with marls and clayey marls. RSN contains clastic material with shallow-water grains, that most likely derives from the nearby Latium-Abruzzi Platform. Microfauna is mostly composed of thin shelled bivalves (*Bositra buchii* and *Lentilla humilis*) (Conti & Monari, 1992). Outcrop conditions are often very poor, due to tectonics and intense weathering; the thickness reaches about 70 m.

The overlying Calcari e Marne a Posidonia (POD - uppermost Toarcian-lower Bajocian) are composed of lime-mud/wackestones and brownish marly intervals, organised in decimetric to pluridecimetric beds (Fig. 3c); bioclastic content consists of thin-shelled bivalves (*Posidonia* auctt.). The lower part of the formation is characterised by the occurrence of centimetric to metric resedimented horizons of carbonate grains sourced from the adjacent Latium-Abruzzi Platform. The main components of these layers are ooids, peloids, echinoid fragments and algal remains. The number of calcarenite layers decrease upwards, with the parallel reduction of bed thickness. The maximum thickness of the formation is about 200 m.

The following Calcari Diasprigni is subdivided in two members (Cita et al., 2007). The lower member, the Calcari Diasprigni Mb. (CDU_1 - upper Bajocian-lower Kimmeridgian), is made up of well stratified white to polychrome chert, interlayered with subordinate limestones and marly limestones (Fig. 3d,e). The skeletal content is mostly composed of radiolarians. In the lower part, resedimented carbonate material occurs (Fig. 3d). The thickness of this member ranges between 50 and 100 m. The upper member, the Calcari a Saccocoma ed Aptici Mb. (CDU_2 – upper Kimmeridgian-lower Tithonian), consists of greyish cherty limestone in 5-10 cm-thick beds, with grey-pink chert layers and nodules (Fig. 3f,g); chert content rapidly decreases towards the top of the unit. Fossil content is made up of abundant remains of *Saccocoma*, radiolarians, aptychi and rare ammonoids. The thickness of this member ranges from 50 to 100 m.

The Maiolica (MAI - upper Tithonian–lower Aptian) is a white, well-bedded lime-mudstone with chert (Fig. 4 a,c), organised in 10/40 cm-thick beds, resulting from the calcareous nannoplankton bloom which occurred in the latest Jurassic (Erba, 2006). The microfauna is also composed of calpionellids and radiolarians. Chert colour is white and turns to black at the top of the unit. The formation widely crops out in the study area. The thickness is about 300 m.

The following Marne a Fucoidi (FUC - lower Aptian-upper Albian) marks a significant increase of the clay content linked to significant climatic changes (Coccioni et al., 1987). It is composed of green/grey and pink marly limestone in decimetric beds, with rare black, reddish, and greenish chert nodules (Fig. 4b). Paleontological content is represented by abundant planktonic forams (*Ticinella* spp., *Hedbergella* spp.). Its thickness is variable, ranging from ~10 m to few tens of meters.

The Scaglia Bianca (SBI - upper Albian–lower Turonian) consists of white well-bedded (10/30 cm-thick) limestones and marly- limestones (Fig. 4d), with black and pink 5-10 cm-thick chert bands and nodules. The Bonarelli anoxic level (Premoli Silva et al., 1999) was not detected at the top of the SBI in the study area. The fossil content is characterised by

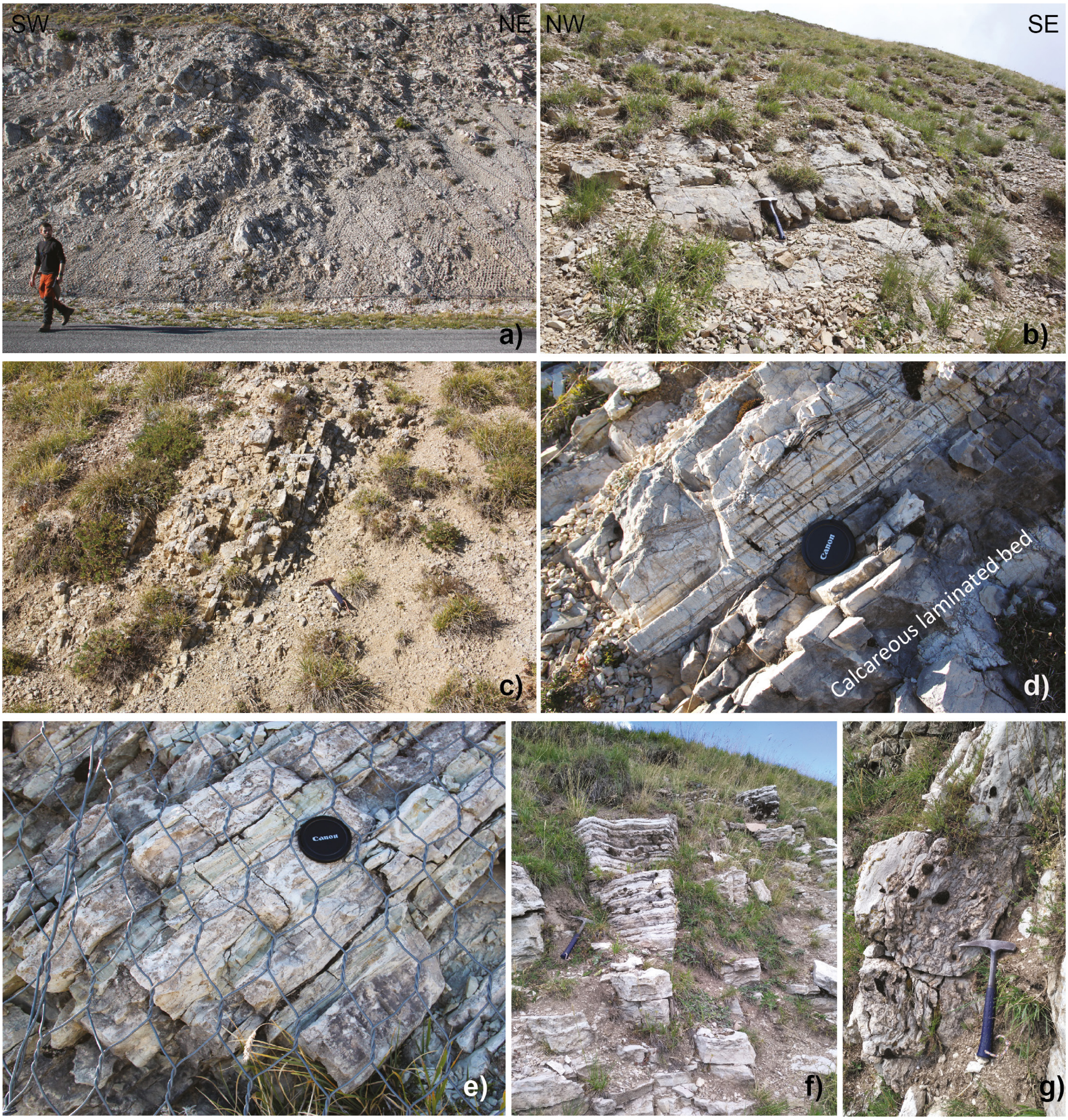

Fig. 3 – a) Fractured MAS outcrop along the Forca di Presta road; b) COI outcrop along the southern slope of Mt. Vettoretto; c) POD outcropping near the Mt. Vettoretto fault, along the Forca di Presta road; d) CDU_1 with resedimented laminated calcareous bed; e) typical aspect of the CDU_1 member outcropping along the Forca di Presta Road; f, g) Typical aspect of CDU_2 in the neighbors of Mt. Macchialta.

planktonic foraminifera (*Thalmanninella appenninica*, *Planomalina buxtorfi*). The thickness does not exceed 100 m.

The overlying Scaglia Rossa (SAA - lower Turonian-lower Eocene) comprises two main facies: a lower calcareous one, made up of 10/25 cm-thick reddish beds (Fig. 4e) with red chert in bands and nodules, and an upper calcareous-marly one, characterised by plurimetric marl/white limestone alternations and by a decrease in chert content (Fig. 4f). The SAA is characterised by very abundant planktonic forams assemblages ("Globotruncanids" *s.l.*, and "Globorotalids" *s.l.*) which allow to discriminate between the Cretaceous and the Paleogene portions of the Unit. The

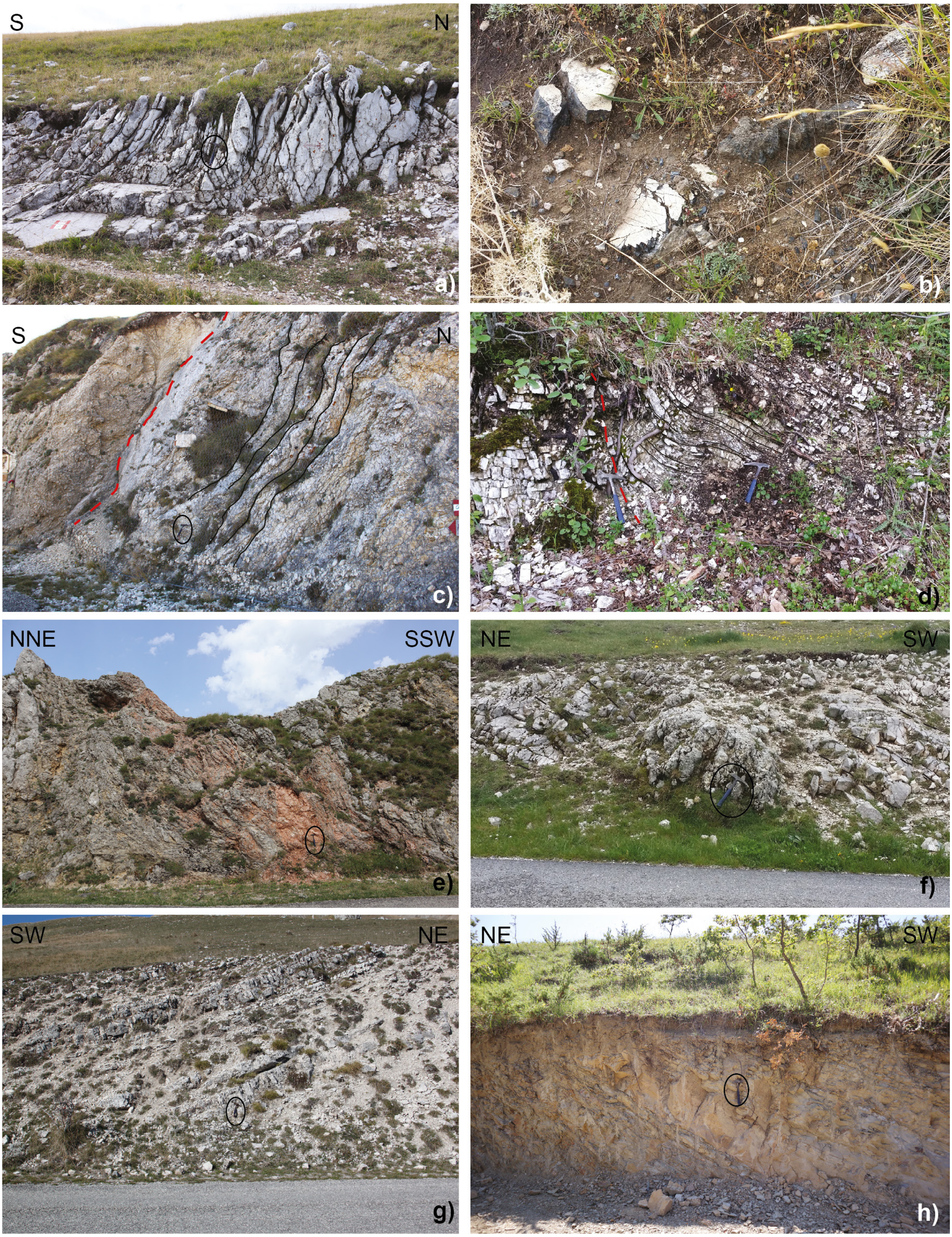

Fig. 4 – a) Typical aspect of MAI near Mt. Macchialta.; b) Rare example of FUC with black chert; c) Minor fault plane cutting the MAI at Forca di Presta; d) Deformed SBI outcropping at Macchia Marinella; e) Cretaceous SAA outcropping at Forca di Presta, strongly deformed by the CPF conjugate faults; f) Calcareous Paleogene SAA at Forca di Presta; g) Typical aspect of VAS at Forca di Presta; h) Typical aspect of LAG outcropping in the neighbors of Pescara del Tronto. Black ovals indicate hammer for scale.

Cretaceous portion of the SAA is rich in planktonic foraminifera *(Helvetoglobotruncana helvetica, Dicarinella* sp., *Globotruncana* sp., *Marginotruncana* sp., *Contusotruncana contusa*), and bears abundant resedimented layers of variable thickness, intercalated to pelagic deposits. The Paleogene portion of the Scaglia Rossa is marked by the almost total lack of chert. Fossil content is characterised by planktonic forams (*Acarinina* sp., *Morozovella* sp., *Subbotina* sp.,). Orbitoid (derived from dismantled Cretaceous beds) and nummulitid rich resedimented layers occur in this portion. The thickness ranges between 200 and 250 m.
The overlying Scaglia Variegata (VAS - Lower Eocene-Upper Eocene) is made up of polychrome limestone and marly limestone in dm-thick beds, intercalated with clayey marl layers (Fig. 4g); chert is very rare. The palaeontological content includes planktonic foraminifera (*Turborotalia cerroazulensis*, *Turborotalia sp*., Globigerinoids). Within the study area the estimated thickness is few tens of metres.
Overthrusted by the above described Jurassic to Eocene succession, the Marne con Cerrogna (CRR - Langhian-Tortonian *p.p.*) consist of grey marls, marly limestones and siltstones bearing planktonic foraminifers (*Orbulina* sp.), and characterised by abundant calcareous turbiditic beds sourced from the Latium-Abruzzi Platform. Its thickness is not detectable due to limited fault-bounded outcrops.
Overthrusted by all the previous units, the Laga Fm. (LAG - lower Messinian) consists of massive sandstones and pelite alternations (Fig. 4h), representing a turbidite succession infilling troughs within the Laga Basin (Milli et al., 2007; 2013). The surveyed succession belongs only to the first (pre-evaporitic) member of the LAG, regionally observed and described in adjacent areas. The LAG always crops out at the footwall of the Sibillini Mts. thrust, in the lowermost tectonic position in the investigated area. The thickness is not detectable.
Slope debris (a - Quaternary) represents the youngest deposits surveyed in the area. The high topographic gradient favoured their sedimentation at the toe of most prominent and steep slopes (e.g.: Mt. Vettore). Slope debris comprises large sharp boulders in an abundant pebble-size matrix. Debris hides most of the tectonic contacts, and prevent a direct observation of the relationships between compressional structures and normal faults (Fig. 5).

Structural data

Compressional structures

I. Sibillini Mts. Thrust
The main structure exposed in the study area is the Sibillini Mts. Thrust, which from SW to NE has been divided into three main segments: Costa le Cese Segment (CCS) from Capodacqua to the intersection with the Costa Ferrone Structure; Costa Pacino Segment (CPS), from the intersection with the Costa Ferrone Structure to the Mt. Vettoretto Fault; Mt. Vettore Segment (MVS), at the footwall of the Mt. Vettoretto normal fault (Fig. 6).

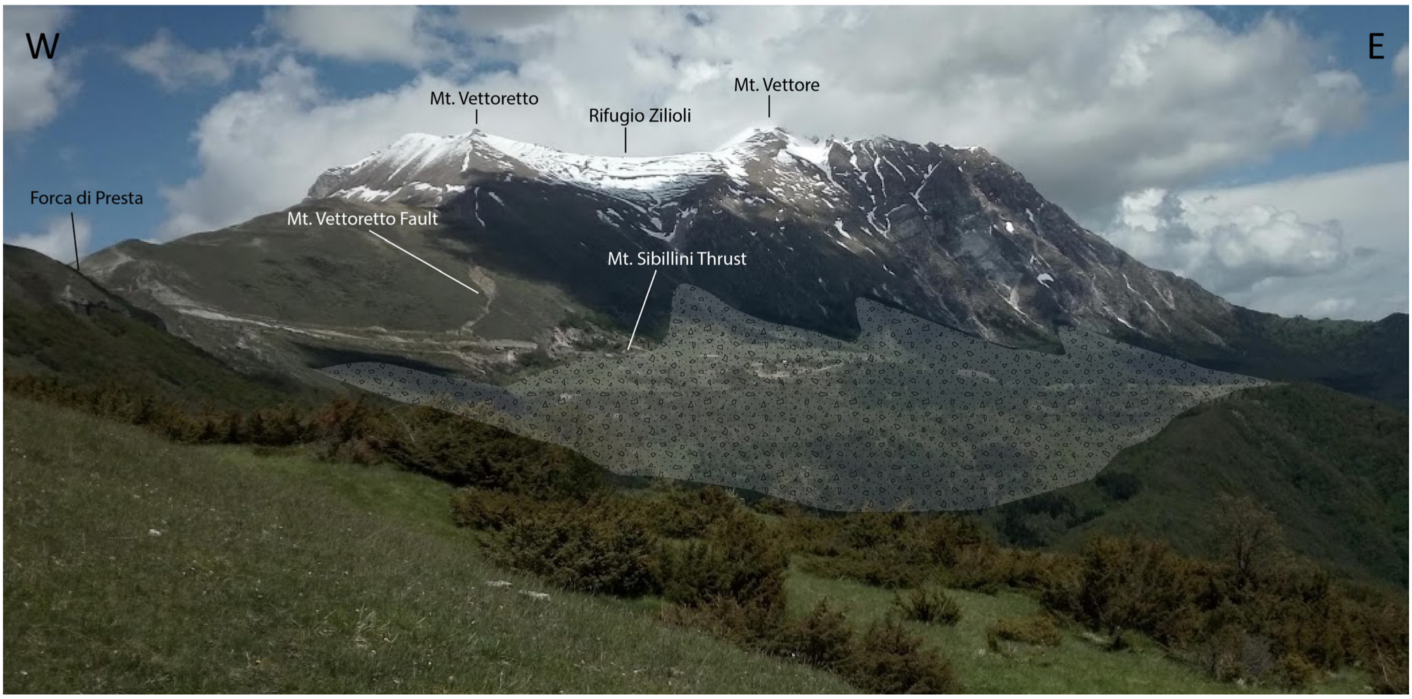

Fig. 5 – Panoramic view of the southern slope of Mt. Vettore-Vettoretto, the thick and wide debris cover is indicated.

Costa le Cese Segment (CCS)

This segment is an about three km-long, arcuate shaped, NE-SW striking low-angle structure, located in the south-eastern sector of the geological map (Fig. 6). At the hanging wall of the thrust, between Capodacqua and Fosso della Lama, an anticline fold showing NE-SW trending axis occurs, involving the Maiolica and Scaglia Rossa Fms. Only the overturned anticline forelimb crops out, with bed attitude ranging from N 310/30 to N 315/56 (dip/dip angle); this is in turn cut by a secondary hanging wall splay of the main thrust. The footwall of the main thrust is represented by the Laga Fm., having general overturned bed attitudes N 320/50. We envisage that the Laga Fm., deformed by the Costa le Cese Segment, forms an overturned syncline fold (see also Pierantoni et al., 2005).

Costa Pacino Segment (CPS)

The central segment of the Sibillini Mts. Thrust is about three km-long and also shows an arcuate shape, with strike ranging from NE-SW to roughly N-S. The northern end of the CPS is represented by the intersection with the Mt. Vettoretto normal fault (Fig. 6). The hanging wall anticline of the CPS shows an arcuate axis subparallel to the thrust trend, and it is characterised by a strongly deformed backlimb. The forelimb can be observed in the central and southern portion of the anticline where the Maiolica steeply dips towards S-SE and also overturns in proximity of the thrust plane, with bed attitudes ranging from N 120/52 to N 260/50. The footwall of the CPS is characterised by an overturned syncline in the Laga Fm. with beds dipping towards W-NW (Cross-section A-A' in the main map). In the southern portion of the CPS a small outcrop of the Marne con Cerrogna is tectonically interposed between the Maiolica and Laga formations.

Mt. Vettore Segment (MVS)

The Mt. Vettore Segment crops out at the footwall of the Mt. Vettoretto normal fault, and is exposed along the Forca di Presta mountain road, which connects Arquata del Tronto and the Castelluccio Plain (Fig. 7). The NE-SW striking MVS has been mapped for about 2.2 km, in the northern portions of the geological map (Fig. 6). The thrust fault plane shows a gradual steepening, observable between 1420 m and 1450 m a.s.l. At the hanging wall of the MVS a NE-SW trending anticline occurs, characterizing the "overlapping zone" of the Sibillini Mountains (Chiocchini et al., 1976), where the Calcare Massiccio thrusts on the Laga Fm. (Fig. 7). The anticline involves the Corniola and Calcare Massiccio Fms and is displaced by the Mt. Vettoretto normal Fault. Due to the occurrence of such tectonic structures, the units are strongly fractured (see Fig. 3a) and are affected by mesoscale folds. The western portion of the MVS hanging wall is characterised by a syncline which involves the succession from the Marne of M. Serrone to the Maiolica Fms. Such units are strongly deformed by mesoscale folds and strongly fractured. At the footwall of the MVS, just below the thrust plane, the Laga Fm. crops out with bed attitudes ranging between N230/29 and N305/33, while elsewhere it is commonly hidden by a thick cover of slope debris.

II. Hanging wall structures

The Sibillini Mts. Thrust branches out in two mains hanging wall structures in the southern-central part of the study area (Fig. 6), characterised by vertical to overturned hanging wall anticline forelimbs: the Colle Giove Splay (CGS) and the Costa Ferrone Structure (CFS).

Colle Giove Splay (CGS)

CGS is a NE-SW trending, 2.5 km-long, low- angle thrust, cropping out in the south-eastern portion of the study area (Fig. 6). West of Capodacqua the CGS crops out as a vast fractured zone having the Maiolica at the footwall and the Corniola at the hanging wall. Northward of Capodacqua the splay is displaced by a W-dipping high angle normal fault showing about 40 m throw. Such fault plane does never clearly crop out. The hanging wall of the splay is an anticline with a NE-SW trending axis, which involves the stratigraphic succession from the Corniola to the Maiolica Fms. At the footwall of the Colle Giove Splay the succession is intensely deformed by chevron folds.

Costa Ferrone Structure (CFS)

The CFS is a N-S striking, 3 km-long, low-angle fault, cropping out in the south-eastern and central sectors of the study area. This structure was previously interpreted as a normal fault (Pierantoni et al., 2013) but in the present map it has been considered as a fault with uncertain kinematic; the low-angle geometry of the fault plane could be interpreted as a thrust, but the younger-on-older relationships in the southern portion suggest a more complex history, such as a reactivation of a pre-existent normal fault, or the displacement of a previously faulted succession (i.e. the overthrusting of the former hanging wall of a pre-orogenic normal fault on its footwall). The southern portion of the CFS juxtaposes the Scaglia Bianca and Scaglia Rossa formations with the Maiolica. Moving northward the Marne a Fucoidi at the footwall are extremely thinned or absent, suggesting the development of second order decollement plane within this formation, or, alternatively, a pre-existent stratigraphic unconformity: this contact is indicated in the map as "undefined boundary". At Fosso Santa Lucia (Fig. 6) the CFS is displaced by a S-dipping high-angle fault, with a ~50 m throw. Northward, the CFS produced the thrusting of the Maiolica on the Marne a Fucoidi to Scaglia Rossa

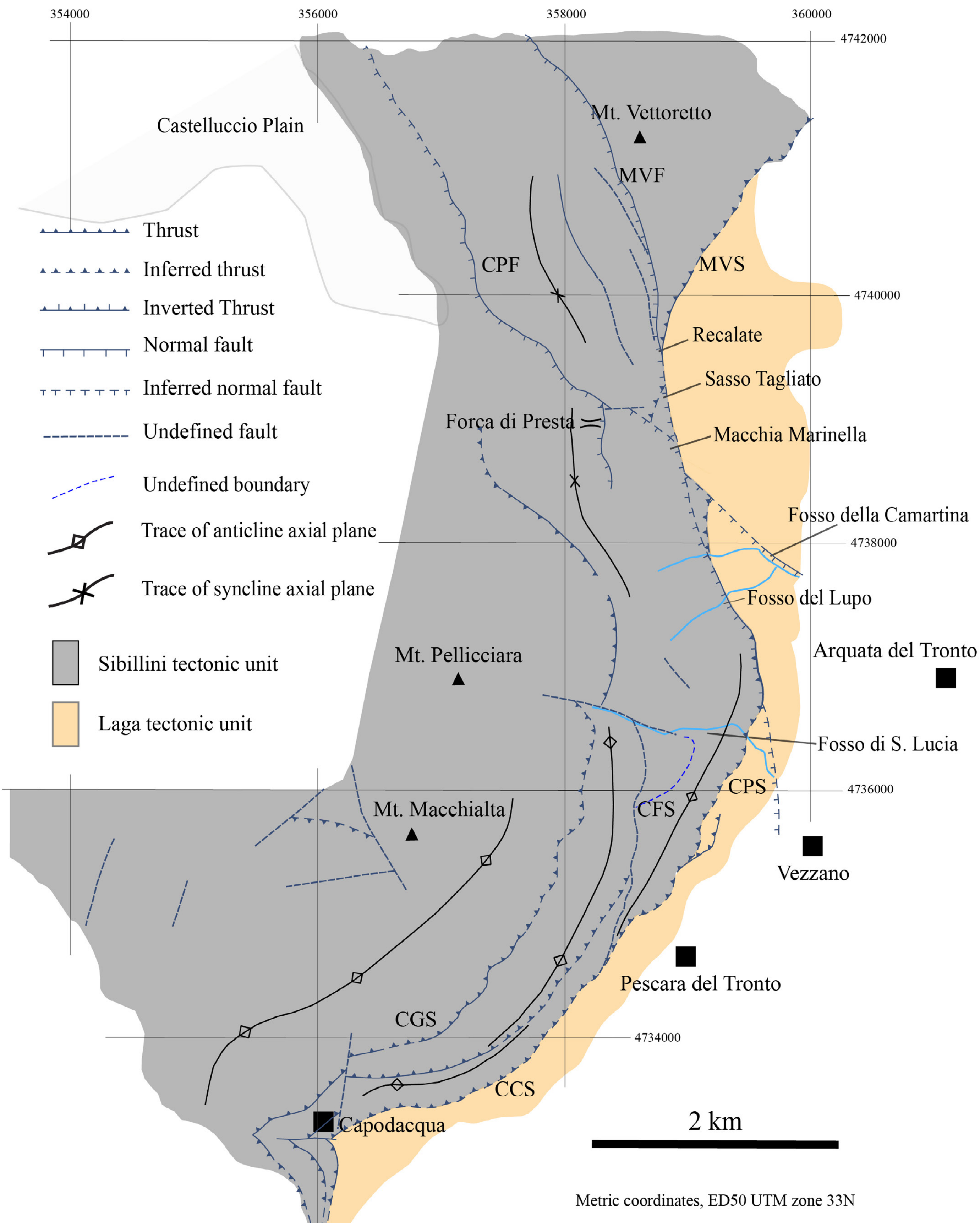

Fig. 6 – Tectonic scheme of the study area, the main localities mentioned in the text are indicated.

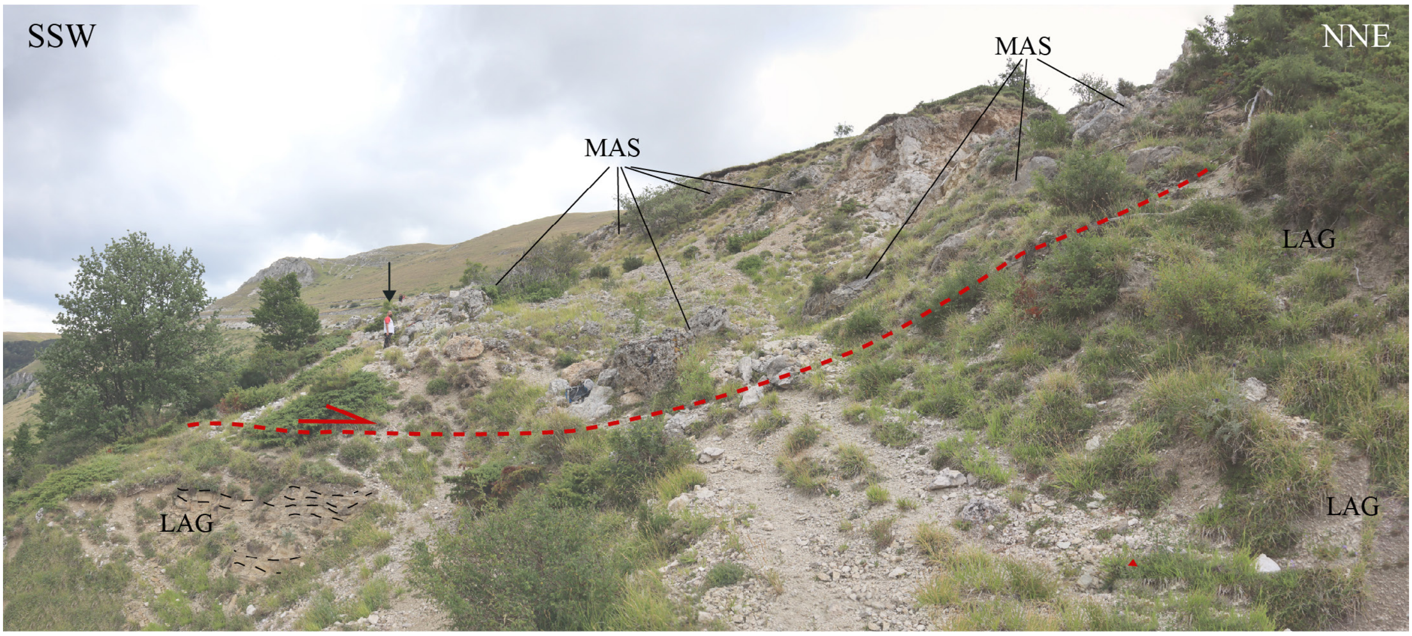

Fig. 7 – Main outcrop of the Mt. Sibillini Thrust below the Forca di Presta road. The high angle thrust plane is between the MAS and the LAG. The arrow indicates geologist for scale.

succession, generating the syncline which crops out at Forca di Presta, having the Scaglia Variegata at its core.

Extensional structures

The Mt. Vettore normal fault system is composed of two main faults (Fig. 8) outcropping in the northern portion of the study area (Fig. 6), which cut the western slope of the Mt. Vettore ridge, facing the Castelluccio Plain: The western one is the Castelluccio Plain Fault (CPF) while the eastern one is the Mt. Vettoretto Fault (MVF).
The NW-SE striking, SW-dipping Castelluccio Plain normal fault (CPF), has been mapped for a length of about 6 km, but it extends northwards for a length of more than 10 km (Porreca et al., 2020). The Quaternary tectonic activity of this fault caused the formation of the Castelluccio Plain. At the hanging wall, the Maiolica to Scaglia Variegata succession crops out; showing a predominantly E-dipping bed attitude, with dip angles ranging between 56° to 35°, but at Forca di Presta the succession is folded in the mentioned syncline at the footwall of the CPS (see above). At the footwall, the Calcari e Marne a Posidonia to Maiolica succession crops out, representing the western side of a syncline fold which is cut by the CPF. The normal fault plane is not clearly visible, but it is marked by a strongly deformed belt, characterised by several variously oriented secondary fault planes (Fig. 4c,e). Although the Quaternary throw of the CPF is about 250 m, based on the thickness of the Castelluccio Plain infill (Di Nezza et al., 2018), the stratigraphic throw of such fault is far larger and reach >500 m in the study area (cross-section B-B') and >1000 m in the northern portion (Porreca et al., 2020). This suggests that the CPF records the cumulative displacement of the Quaternary activity superimposed on pre-Quaternary extension, possibly late Miocene as is the case of several known faults in the Apennines (Bigi et al., 2003; Fabbi & Rossi, 2014; Fabbi, 2016).
The other main normal fault of the study area is the NW-SE striking, SW dipping Mt. Vettoretto Fault (MVF). It was mapped for about 4 km (Fig. 6) and corresponds to the fault scarp well-visible along the south-western slopes of Mt. Vettore (Fig. 8, 9a), rejuvenated by the 2016 seismic sequence with variable coseismic throw, which ranges from ~80 cm in the study area (Fig. 9a) to more than 2 m (Brozzetti et al., 2019). The MVF juxtaposes the Corniola, forming its footwall, and Marne del M. Serrone and Calcari e marne a Posidonia Fms. lowered towards SW, at the hanging wall (Fig. 9b), with a throw of about 50 m (see below). The main fault plane, which is clearly visible at the Corniola-Marne del M. Serrone Fms. contact, shows a N223/55 attitude, measured along the Forca di Presta - Mt. Vettore pathway at 1925 m a.s.l. Minor conjugate faults characterised by fractured belts with unclear kinematics occur at the hanging wall. We infer that the MVF displaces the thrust fault of only about 50 m, but the stratigraphic throw is undeterminable and seems to increase northward. As for the CPF fault it can be accounted that also the MVF, and the whole Mt. Vettore Quaternary extensional system could be superimposed to pre-Quaternary extensional faults which would explain the incongruence between the Quaternary and stratigraphic throws (see above).

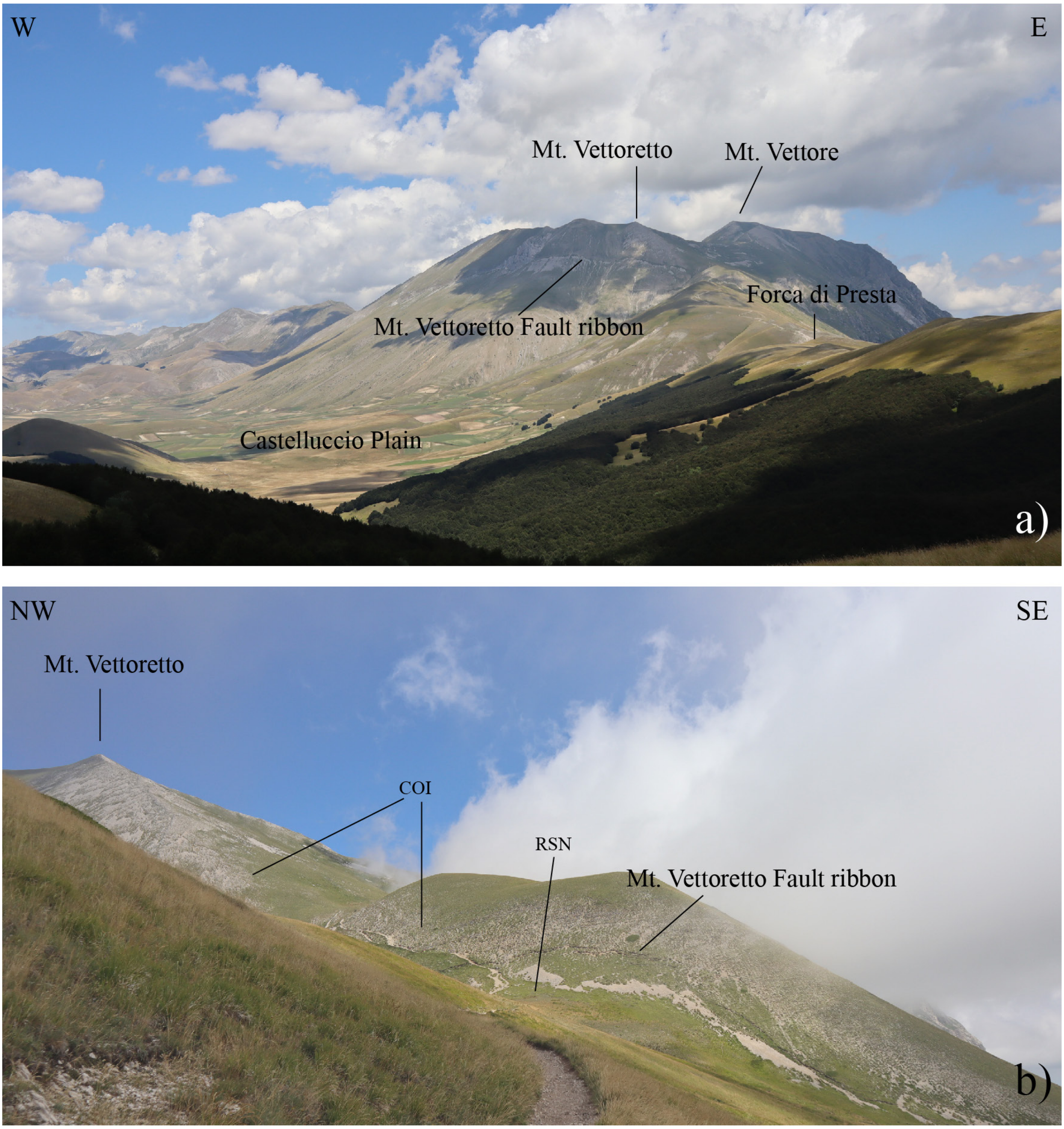

Fig. 8 – Panoramic views of the Mt. Vettoretto fault.

Discussion and conclusions

In order to determine the position of the Sibillini Mts. Thrust and its relationships with the normal faults mostly covered by thick Quaternary debris, several data have been considered:

- the thrust plane attitude
- the position of the LAG outcrops at the footwall of the thrust
- the hanging wall anticline geometry
- the normal faults geometry and their reactivation during the 2016-2017 seismic sequence
- the thickness of the Castelluccio Plain Quaternary infill at the hanging wall of CPF
- scientific papers published after the 2016 earthquake

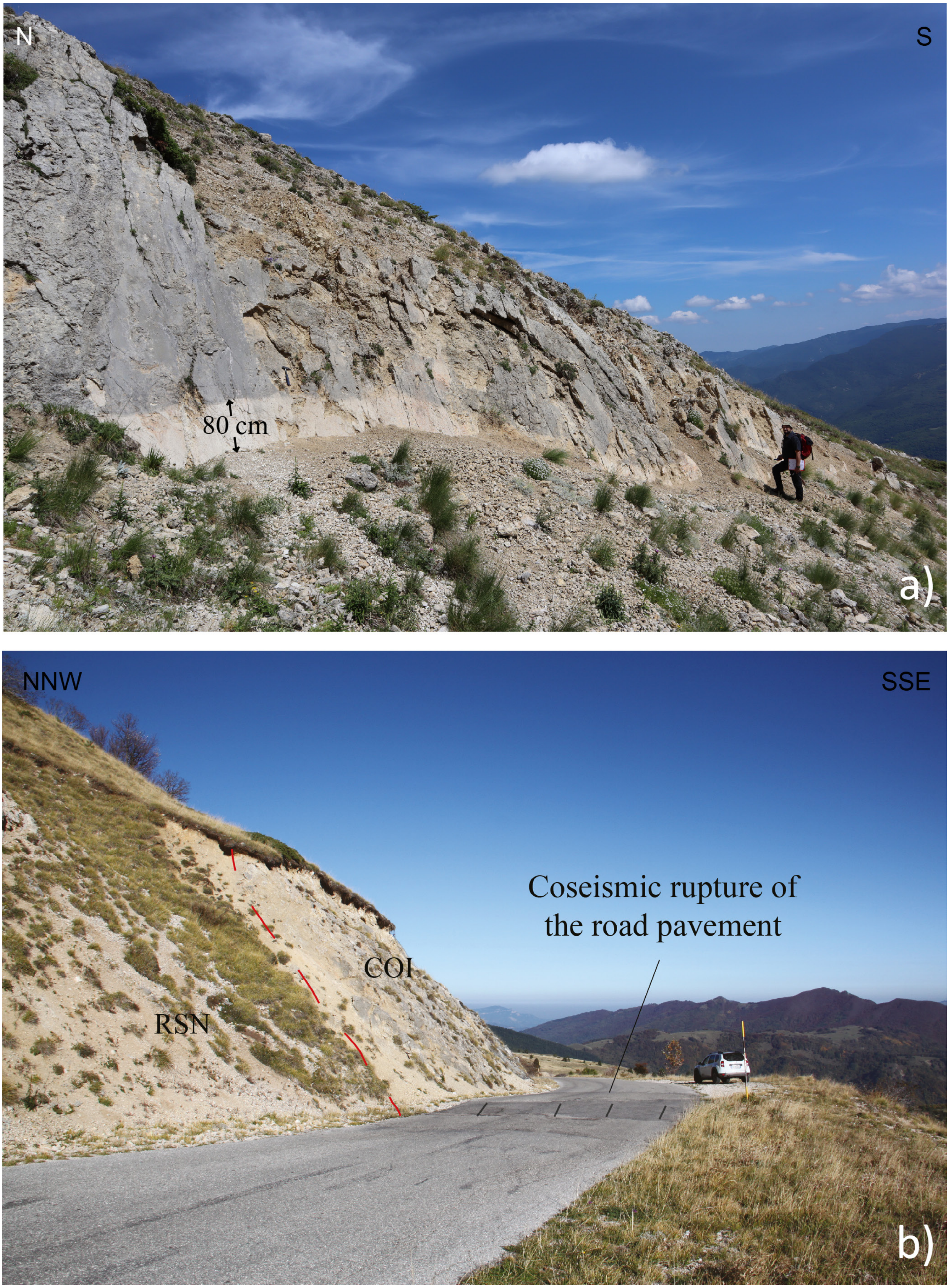

Fig. 9 – a) Rejuvenated Mt. Vettoretto fault ribbon. b) The Mt. Vettoretto fault outcropping along the Forca di Presta road. Note the rupture of the road pavement produced by the 2016 Mw 6.5 earthquake.

It was observed that, where the Sibillini Mts. Thrust crops out it dips towards WSW. In addition, while in the MVS tract only a faint hanging wall anticline occurs, due to the presence of the rigid Calcare Massiccio, in the southern portion, where the Jurassic-Paleogene basinal formations crop out, the anticline is well developed, with vertical to overturned or recumbent forelimb. Such folds show axis approximately parallel to the thrust trend. The latter datum was very important because the grade of preservation of the vertical to overturned geometry of the hanging wall anticline forelimb is a robust clue for reconstructing how close is the thrust plane. This kind of observation allows to infer the location of the same thrust plane also at the hanging wall of normal faults, where, as said, all the structural elements are hidden by the thick Quaternary debris. Away from the rigid Calcare Massiccio, in fact, the basinal succession steeply dips towards the thrust vergence direction, and the same succession overturns close to the thrust plane. For this reason, the occurrence of either vertical to overturned beds or differently W-dipping beds belonging to the hanging wall anticline backlimb are interpreted as clues of proximity or distance from the thrust plane respectively.

The determination of the possible thrust plane position under the Quaternary debris, based on such field data, allows to infer the continuity/discontinuity of the thrust, and to estimate normal faults throws.

At Forca di Presta, a complex fault pattern cut the basinal succession; the main normal fault here is the CPF, which juxtaposes the Maiolica to the uppermost Scaglia Rossa, in the neighboring Sasso Tagliato locality; at the footwall of the CPF, the Maiolica shows a rapid increase of beds dip angle, up to become subvertical in the last outcrops not covered by debris. This is interpreted as a clue of proximity of the MVS thrust plane (Fig. 6).

Moving southwards, at Macchia Marinella, the succession at the hanging wall of the CPF dips towards W-NW and represents the backlimb of the MVS hanging wall anticline. This is inconsistent with any hypothesis of continuity of the thrust plane between Sasso Tagliato and Vena Marinella, because there is not enough space for the development of the complete hanging wall anticline geometry. Such field evidence suggests that the CPF cut the M.Vettore Segment (MVS) of the Sibillini Mts. Thrust between Sasso Tagliato and Macchia Marinella, with an estimated throw of of ca. 250 m, and continues in the footwall within the Laga Fm. as observable at Fosso della Camartina (Fig. 6). The amount of this throw is supported as said by the almost total elision of the hanging wall anticline forelimb, and is fully correlable with the thickness of the Quaternary infillings of the Castelluccio Plain (Di Nezza et al., 2018).

The MVF, having oblique direction with respect to the Sibillini Mts. Thrust and to the CPF (Fig. 6), is the fault which has shown the more evident clues of reactivation during the 2016 earthquake (e.g. Brozzetti et al., 2019), and this suggests that it is the younger tectonic element. A total displacement of ~50 m of the Sibillini Mts. Thrust has been inferred for such fault just below the Forca di Presta road (Recalate locality), where the MVF is also inferred to displace the CPF, below the debris cover. Such exiguous throw is congruent with inferred position of the thrust at Sasso Tagliato, while the little stratigraphic throw of the fault along the SW slope of Mt. Vettoretto is not precisely determinable. The Marne del Monte Serrone and Calcari e Marne a Posidonia Fms. are in fact juxtaposed to the Corniola (Fig. 9) which in turn onlaps the Calcare Massiccio paleoescarpment (e.g. Santantonio et al., 2017), but it was not possible to determine which portion of the Corniola is cut by the fault.

The MVF has been considered as continuing towards the South, partly along the inverted Sibillini Mts. Thrust plane (e.g., Bonini et al., 2016; Scognamiglio et al., 2018). This seems to be confirmed by the grade of preservation of the hanging wall anticline geometry, which shows a steep E-dipping to overturned forelimb (Fig. 10), suggesting the proximity to the thrust plane, also where the MVF should displace it. This suggest that the MVF could reuse the Sibillini Mts. Thrust plane. Such inversion most likely occurred only where the geometry of the thrust plane was suitable for extensional reuse.

It cannot be ruled out in fact that the MVF could cut again the thrust plane, possibly due to dip angle variation, and then could be linked with the normal fault observable near the Vezzano village (Fig. 6), which displaces the Laga Fm. in the footwall with very little throw (Cristina Muraro, pers. comm.).

In conclusion, based on a detailed geological mapping it is possible to infer how the lower Pliocene Sibillini Mts. Thrust (Cipollari & Cosentino, 1991), characterised by a complex hanging wall composed of stratigraphic units with different rheology variously faulted by Jurassic - late Miocene pre-orogenic tectonic phases, controlled the onset of subsequent (Quaternary) extensional faults. Where the hanging wall is composed of weak formations, the deformation produced a subvertical to overturned frontal anticline that was subsequently segmented and displaced by Quaternary-Holocene faults formed during the final extensional phase of the chain. Such extension also seems to cause a partial negative inversion along the above mentioned thrust in the study area. Our study represents a “third way” supported by field data with respect to the two dominant interpretations of the cross-cutting relationships between the Mt. Vettore

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Fig. 10 – SE- steeply dipping MAI beds in the neighbours of the MVF at Fosso del Lupo. The Sibillini Mts. Thrust hanging wall anticline forelimb geometry is here almost complete.

normal fault system and the Sibillini Mts. Thrust in literature. The calculated throws of the normal faults are in fact by far less than the >300/>1000 m published by various authors (e.g., Brozzetti et al., 2019; Porreca et al., 2020); on the other hand they are obviously larger than those inferred by the authors (Pierantoni et al., 2013; Pizzi et al., 2017; Scognamiglio et al., 2018; Bonini et al., 2019) which consider the normal faults having a tip in correspondence of the Sibillini Mts. Thrust.

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