“Walk along the Mt. Vettore Fault”

Field Trip Guidebook

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Emanuele Tondi

Tiziano Volatili

Pietro Paolo Pierantoni

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**** The present guidebook has been extracted and modified from the international field trip guidebook:***

FROM 1997 TO 2016:

THREE DESTRUCTIVE EARTHQUAKES

ALONG THE CENTRAL APENNINE FAULT SYSTEM, ITALY

https://convegni.unicam.it/TDEq_centralItaly

1. Geological and geodynamic framework of Central Apennines

1. 1. Central Apennines

The Central Apennines (Fig. 1.1) are part of a post-collisional segment of the Mediterranean Africa-vergent mountain system which is made up of several tectonic units emplaced since the Oligocene, as a result of convergence and collision between the continental margins of the Corsica-Sardinia block, European origin, and of the Adriatic block, African affinity, (Vai and Martini, 2001 and references therein).

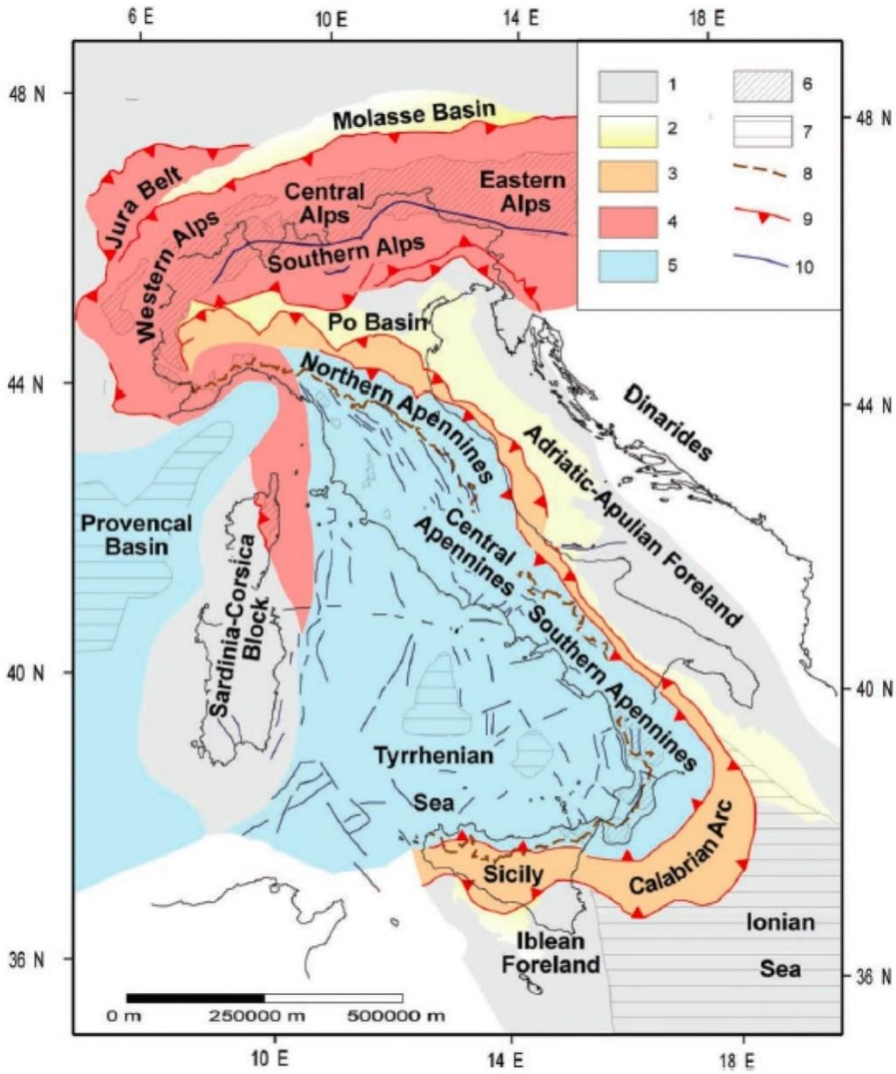

Fig. 1.1. Synthetic tectonic map of Italy and surrounding seas; 1) Foreland areas; 2) foredeep deposits; 3) domains characterized by a compressional tectonic regime; 4) Alpine orogen; 5) areas affected by extensional tectonics: these areas can be considered as a back-arc basin system developed in response to the eastward roll-back of the west-directed Apenninic

subduction; 6) crystalline basement; 7) oceanic crust in the Provençal Basin (Miocene in age) and in the Tyrrhenian Sea (Plio-Pleistocene in age) and old Mesozoic oceanic crust in the Ionian Basin; 8) Apenninic water divide; 9) main thrusts; 10) faults. From Scrocca et al., 2003.

The Meso-Cenozoic stratigraphic successions exposed in the Central Apennines are composed by different environments and depositional systems. During the Triassic, a shallow water carbonate platform and euxinic basins paleo-environments controlled the depositions of shallow-marine carbonates, dolostones and sulphates about 1.5-2 km thick (Bally et al., 1986). During the lower Jurassic, a rifting stage took place in the whole Neotethyan region causing a basin-platform system. The paleogeography related to this period was persistent until early Tertiary times. The shallow-water platform domain was broken-up and new platform-basin systems developed, characterized by downthrown sectors dominated by transitional to deep-water sedimentation, with deposition of limestones, marly limestones, and marls, and upthrown sectors with shallow-water carbonate platform deposits. The early-middle Cretaceous regional paleogeography was quite similar to that of the late Jurassic. The platform-basin systems led to the deposition of thick, shallow- and deep-water carbonate successions (up to 4-6 km thick, Bally et al., 1986). In the platform domain, a late Cretaceous-early Miocene hiatus was followed by deposition of early Miocene paraconformable carbonates, deposited along a carbonate ramp (Civitelli and Brandano, 2005), while in the deeper domains sedimentation continued throughout the Paleogene. During Eocene-Oligocene times a critical scenario developed in the proto-western Mediterranean area, with the existence of the S-SE-directed Alpine subduction system (approaching the end of its existence) and the young NW-dipping Apennines subduction system starting its activity (Carminati et al., 2012), which possibly developed along the retrobelt of the Alpine orogeny (Fig. 1.2). This means that two subduction systems, with nearly opposite polarity, were present in a relatively narrow area for a short time.

During the late Miocene, the southern Neotethyan passive margin was involved in the evolution of the Apennines, that accreted the sedimentary cover of the passive margin during the "eastward" roll-back of the NW-dipping Apennines subduction system (Fig.

1.2; Carminati and Doglioni, 2005). The Apennine slab roll-back induced subsidence and boudinage of large portions of the Alps that have been scattered and dismembered into the Apennines-related backarc basin: the Provencal and the Thyrrenian (Fig. 1.2). Within this geodynamical setting, tectonically-controlled sedimentary basins developed with the deposition of hemipelagic marls in a foreland environment in the Central Apennines, followed by deposition of turbidites composed of siliciclastic sandstones in a foredeep setting ahead the propagating deformative front (Patacca and Scandone, 1989; Cipollari and Cosentino, 1991; Patacca et al., 1991; Milli and Moscatelli, 2000; Critelli et al., 2007). North-eastward migration of thrust fronts (Cipollari et al., 1995) developed different tectonic units that pushed carbonate ridges, oriented NW-SE, onto turbiditic basins (Ricci Lucchi, 1986; Boccaletti et al., 1990; Cipollari et al., 1995; Patacca and Scandone, 2001; Cosentino et al., 2010).

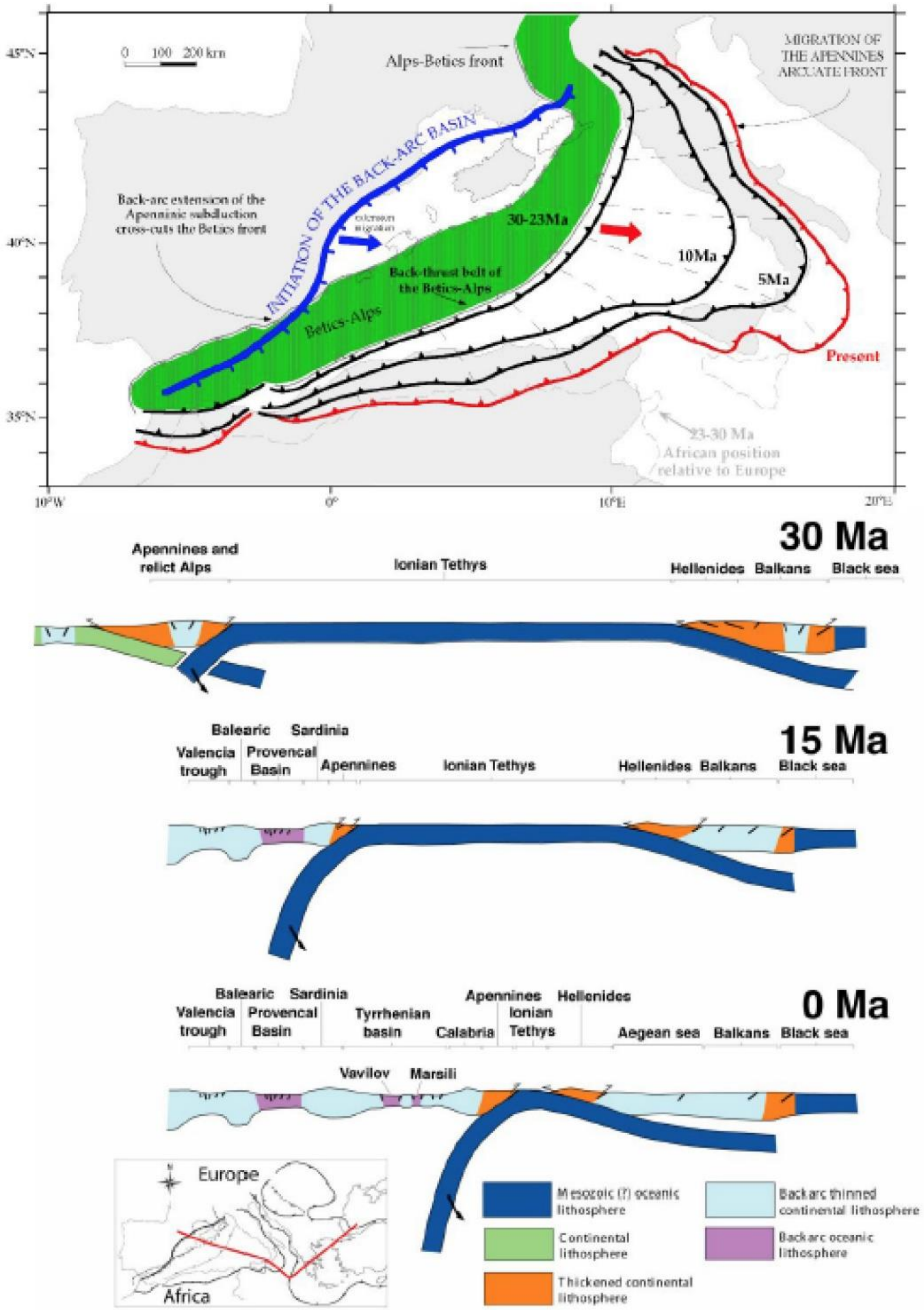

Fig. 1.2. The early "east"-directed Alpine subduction was followed by the Apennines "west"-directed subduction, which developed along the retrobelt of the pre-existing Alps. The slab is steeper underneath the Apennines, possibly due to the "westward" drift of the lithosphere relative to the mantle (From Carminati and Doglioni, 2005).

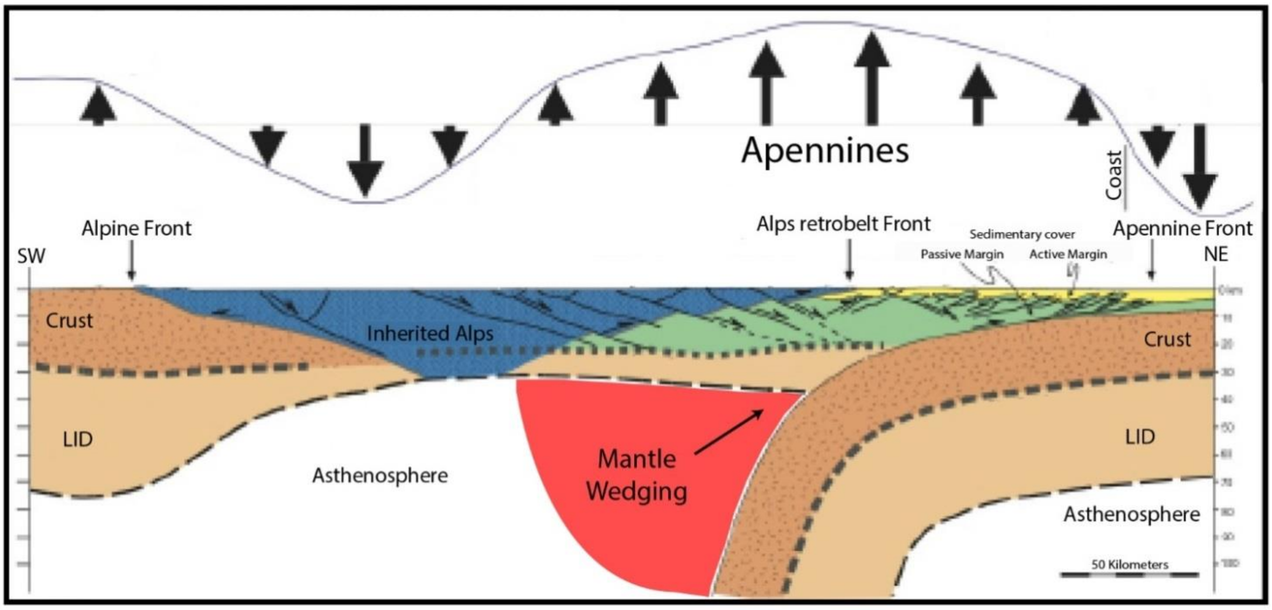

Fig. 1.3. Cross section from Corsica (SW), through Tyrrhenian Sea and across the Apennines (NE). The Apennine prism (light green) developed along the retrobelt of the alpine orogen (the blue double-wedge in the center of the section). The alpine orogen was boudinaged and stretched by the backarc rift. Above the cross section are reported the vertical movements. From Carminati et al., 2010.

Following the kinematics of W-dipping subduction and applying the westward drift of the lithosphere, the Apennines should float above a new asthenospheric mantle, which replaced the subducted lithosphere, causing the uplift of the accretionary wedge of the Apennines chain (Fig. 1.3; Carminati et al., 2010). Nowadays the Apennines are characterized by a frontal active accretionary wedge, below the Adriatic Sea, whereas the inland elevated ridge is instead in uplift and extension, controlled by tensional regime oriented about NE-SW (Fig. 1.1; Calamita et al., 1994; Lavecchia et al., 1994; Doglioni and Flores, 1995; Cello et al., 1997).This is generally inferred from the age of the different intramontane sedimentary basins filled by alluvial and lacustrine sediments (e.g., Fucino, Sulmona and L'Aquila basins), initiated by the extensional tectonic activity affecting the Central Apennine area since the late Messinian and still active. New stratigraphic data on the depositional sequences filling the L'Aquila and Rieti Basin shows common inception of these extensional structures in the upper Pliocene (Cosentino et al., 2017). These intramontane basins are mainly bordered by NW-SE oriented and SW-dipping normal to transtensional faults cutting throughout the crust, generating most of the seismicity in the region (Fig.1.4; Cavinato et al., 2002; Barchi et al., 2000; Tondi and Cello, 2003).

Tondi and Cello (2003), integrating the geological information on exposed active faults in the area together with the historical earthquakes, reconstructed the seismic cycle of the entire active fault system for the last millennium (Tab. 1). These authors estimated the displacement rate of the whole system in the last 700 ka to be 1.6 cm/year and the average recurrence time for M>6.5 events to be about 350 years, with Faure Walker et al. (2010) suggesting ~3mm/yr. In Fig. 1.4 are reported the main active faults and the three seismic sequences occurred in the area from 1997 to 2016.

Tab.1. Historical earthquakes associated to the active faults in Fig. 1.4 (Rovida et al., Eds., 2015)

Year	Lat.	Long.	Epicentral zone	Imax	Me (MW)
1279	43.093	12.872	Appennino Umbro-Marchigiano	9	6.20
1328	42.857	13.018	Valnerina	10	6.49
1349	42.270	13.118	Appennino Laziale-Abruzzese	9	6.27
1599	42.724	13.021	Valnerina	9	6.07
1639	42.639	13.261	Amatrice	9-10	6.21
1703	42.708	13.071	Valnerina	11	6.92
1703	42.620	13.100	Appennino Laziale-Abruzzese	8	6.00
1703	42.434	13.292	Aquilano	10	6.67
1730	42.753	13.120	Valnerina	9	6.04
1859	42.825	13.097	Norcia	8-9	5.73
1979	42.730	12.956	Valnerina	8-9	5.83
1997	43.014	12.853	Colfiorito	8-9	6.00

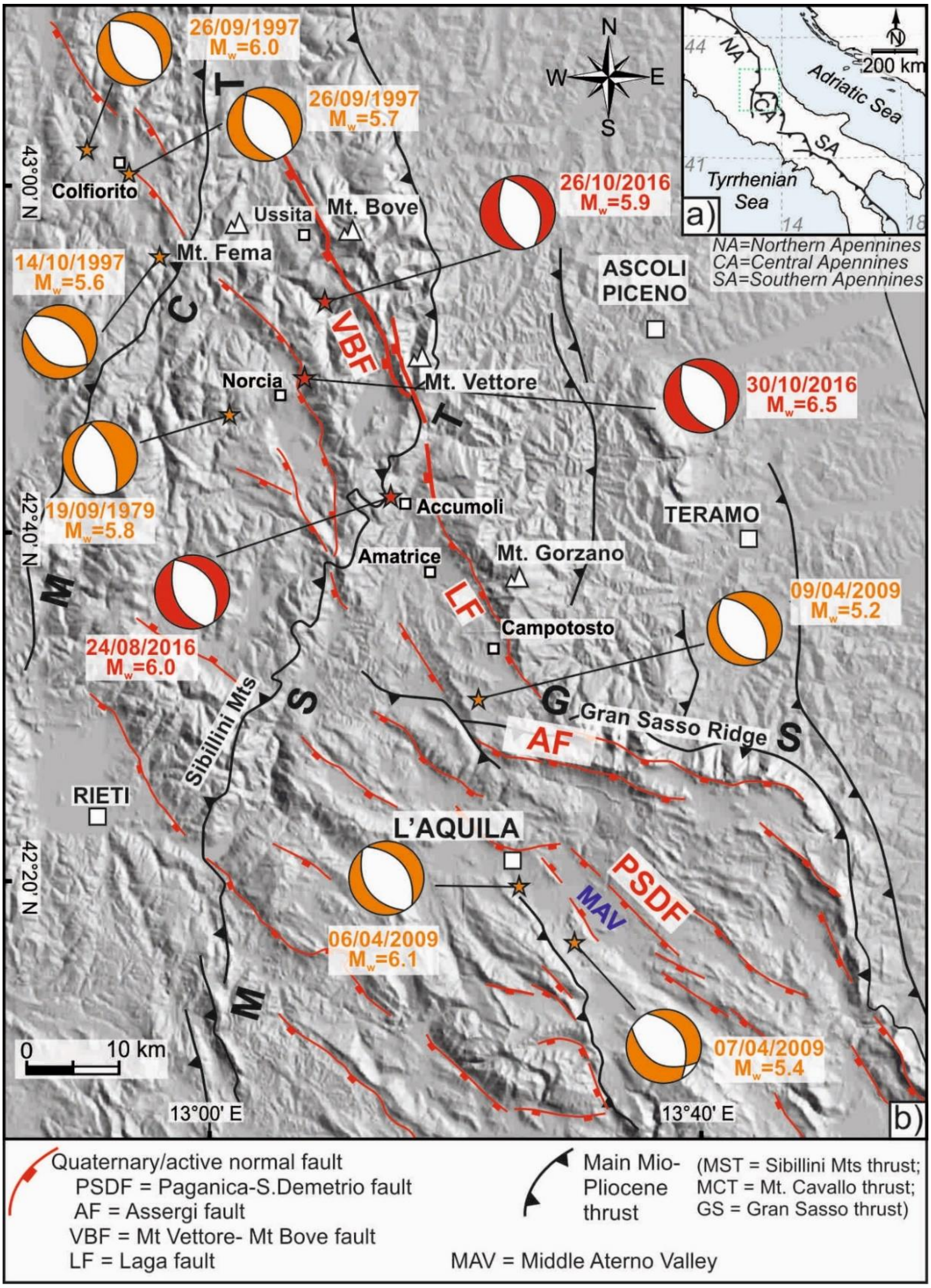

Fig. 1.4. a) Location map of Figure 1b with the three main arcs of the Apennine chain. b) Seismotectonic sketch of the field trip area with the main Neogene thrusts (black lines) and Quaternary/active normal fault systems (red lines). The Mt. Cavallo (MCT), Sibillini Mts (MST) and Gran Sasso (GS) thrust ramps are oblique to the main (N)NW–(S)SE trend of the normal fault systems (modified from Di Domenica and Pizzi, 2017).

2. Field Trip to the epicentral area of 2016 Amatrice, Visso, and Norcia earthquake

2.1 Introduction

Along the axial zone of the Apennine, the main active tectonic structures in the area are the Mt. Vettore - Mt. Bove fault systems (VBFS, hereinafter; Calamita et al., 1992; Calamita and Pizzi, 1992, 1994; Cello et al., 1997; Pizzi et al., 2002, Pizzi and Galadini 2009), the Laga Mountains (Galadini and Galli, 2000, 2003; Galli et al., 2008), the Norcia (Galli et al., 2005) and the Montereale (Civico et al., 2016) fault systems.).

The recent activity of the VBFS has been indicated by geomorphological and paleoseismological studies (Calamita et al., 1992; Brozzetti and Lavecchia, 1994; Calamita and Pizzi, 1994; Blumetti, 1995; Coltorti and Farabollini, 1995; Cello et al., 1998; Galadini and Galli, 2003; Galli et al., 2005). The VBFS is the easternmost fault system in the Central Apennines; it is characterized by WSW dipping normal faults about 5-7km long with en-echelon pattern, and in some cases linked by transfer faults. The VBFS is extended from Mt. Bove, to the north, till Mt. Vettore to the south intersecting the Olevano–Antrodoco–Sibillini Mts. thrust (OAST). In particular, the amount of displacement related to the Quaternary activity of the 30 km long VBFS abruptly decreases near its intersection with the OAST-ramp (Pizzi and Scisciani, 2000). Here, the SE termination of the fault system is made up of two segments. The tip of the eastern segment, although covered by Quaternary slope deposits, is not present as far as 1.5 km SE from the intersection with the OAST trace, where the outcropping strata of the Messinian sandstones (OAST footwall unit) are not displaced by the fault. The strike of the western segment clearly deflects parallel to the trace of the OAST and the displacement progressively dies out 3 km to the south (Pizzi and Galadini, 2009).

Since August 2016, a series of moderate to large earthquakes hit the central Apennines generating important damage in numerous towns (e.g. Amatrice, Castelluccio di Norcia, Visso) and causing almost 300 casualties and more than 20,000 homeless (Civico et al. & Open EMERGEO_WG 2018; Villani et al. & Open EMERGEO_WG 2018). The seismic sequence (Chiaraluce et al., 2017 and references therein) started with an Mw 6.0 mainshock on 24 August at 1km west of Accumoli. After two months (26 October), a new mainshock of Mw 5.9 occurred at 3 km NW of Castel Sant’Angelo sul Nera, followed by the largest shock of the sequence, a Mw 6.5 on 30 October 2016 at 5 km NE of Norcia. These have been the strongest seismic event in Italy since the Irpinia earthquake (Ms 6.9) in 1980 (Westaway and Jackson, 1987; Bernard and Zollo, 1989). Additional events occurred in the southern sector of the sequence on 18 January 2017, with a maximum Mw of 5.5. Aftershocks are confined to the upper crust (10-12 km maximum depth) and follow a roughly NW-SE trend for about80 km between the towns of Camerino to the north and Pizzoli to the south (Chiaraluce et al., 2017).

The affected area has been repeatedly struck by 5.3 > Mw < 6.9 earthquakes in the last 400 years, with the largest local earthquake occurring in 1639 at Amatrice with an Io 9–10 MCS and an estimated M 6.2 (Rovida et al., 2016). In recent times, moderate-sized earthquakes struck Norcia in 1979 with a Mw 5.8 (Deschamps et al., 1984), Colfiorito in 1997 with a Mw 6.0(Amato et al., 1998; Tondi and Cello, 2003; Tondi et al., 2009), and L’Aquila in 2009 with a Mw 6.1 (Chiaraluce et al., 2011; Valoroso et al., 2013).

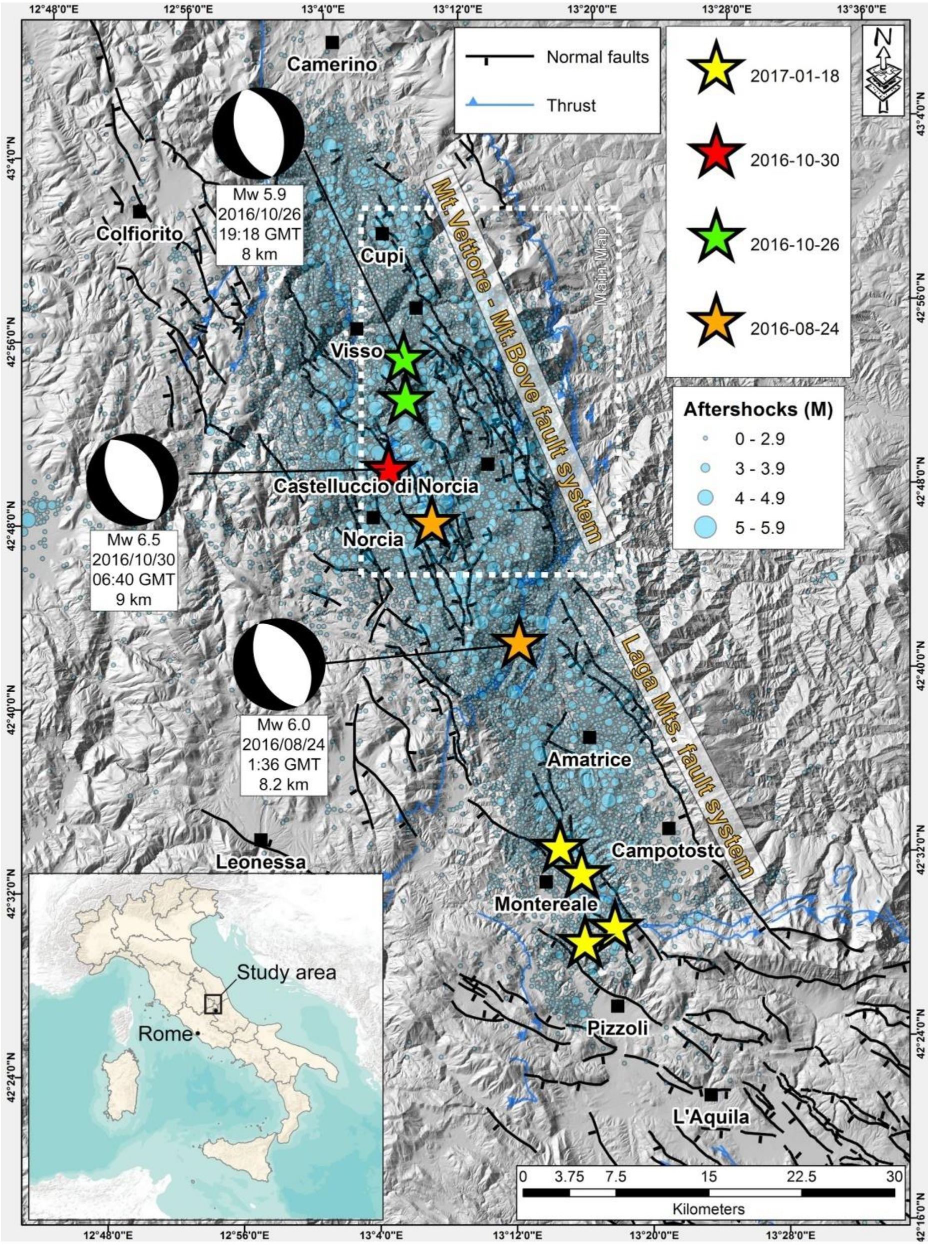

Fig 2.1. The 2016-2017 central Italy seismic sequence as recorded by the INGV Italian National Seismic Network (data from ISIDe - Italian Seismological Instrumental and Parametric Data-Base - http://iside.rm.ingv.it) for the time period of 24 August 2016 through 23 January 2017. Time Domain Moment Tensor focal mechanisms are from the INGV web page (http://cnt.rm.ingv.it). Faults are compiled from Centamore et al. (1992) and Pierantoni et al. (2013) and Galli et al. (2008). The white dashed box encloses the area of the Main Map.

After the most important seismic events, important surface ruptures were observed along the VBFS by different groups and institutions mainly conglomerated in the Open EMERGEO Group.

After the 24 August 2016, Mw 6.0 normal-faulting Amatrice earthquake (Fig. 2.1): ~N155°-trending surface ruptures, mostly SW dip-slip kinematics (average displacement of 0.15 m), were recorded for several kilometers along the southern portion of the VBFS (EMERGEO Working Group, 2016; Lavecchia et al., 2016). These coseismic features were interpreted as the response of primary surface faulting by Livio et al., 2016, Aringoli et al., 2016 and Pucci et al., 2017, while unclear and discontinuous coseismic features were recorded along the Laga Mts. fault system by most of the research groups working in the area. The earthquake of 26 October 2016, Mw 5.9, near Castel Sant'Angelo sul Nera, caused sparse and discontinuous (few hundred of meters long) ground ruptures along the northern portion of the VBFS (average vertical displacement of 0.15 m). Unfortunately, the field survey on the coseismic effects of this latter event was not fully achieved due to the 30 October Mw 6.5 mainshock close to Norcia (Fig. 2.1). This seismic event produced coseismic effects on an area of nearly 450 km^2 mainly consisting of primary surface ruptures (Fig. 2.2), accompanied with other secondary effects like landslides. An almost continuous pattern of surface ruptures was observed for an overall length of 20-25 km along the whole VBFS, generally reactivating the 24 August and the 26 October 2016 ground ruptures (Fig.2.2). Surface rupture displacement exhibits predominantly normal dip-slip kinematics, with an average 0.5 m vertical offset. Notably, the ~N155° striking alignment of ground ruptures typically follows the trace of mapped faults (Pierantoni et al., 2013 and references therein), while in some locations the coseismic ruptures occurred along fault splays that were not previously recognized.

Remote surveys verified and integrated with field data evidenced an almost continuous alignment of ground ruptures along closely-spaced, parallel or subparallel, overlapping or step-like synthetic and antithetic fault splays pertaining to the VBFS (20-25 km long). Field observations after the 30 October 2016 earthquake reveal that its coseismic surface rupture pattern can be considered one of the most complex recorded in Italy and in the Mediterranean in the past 40 years in terms of number of involved fault splays, in a normal faulting earthquake context (Civico et al. & Open EMERGEO_WG 2018; Villani et al. & Open EMERGEO_WG 2018).

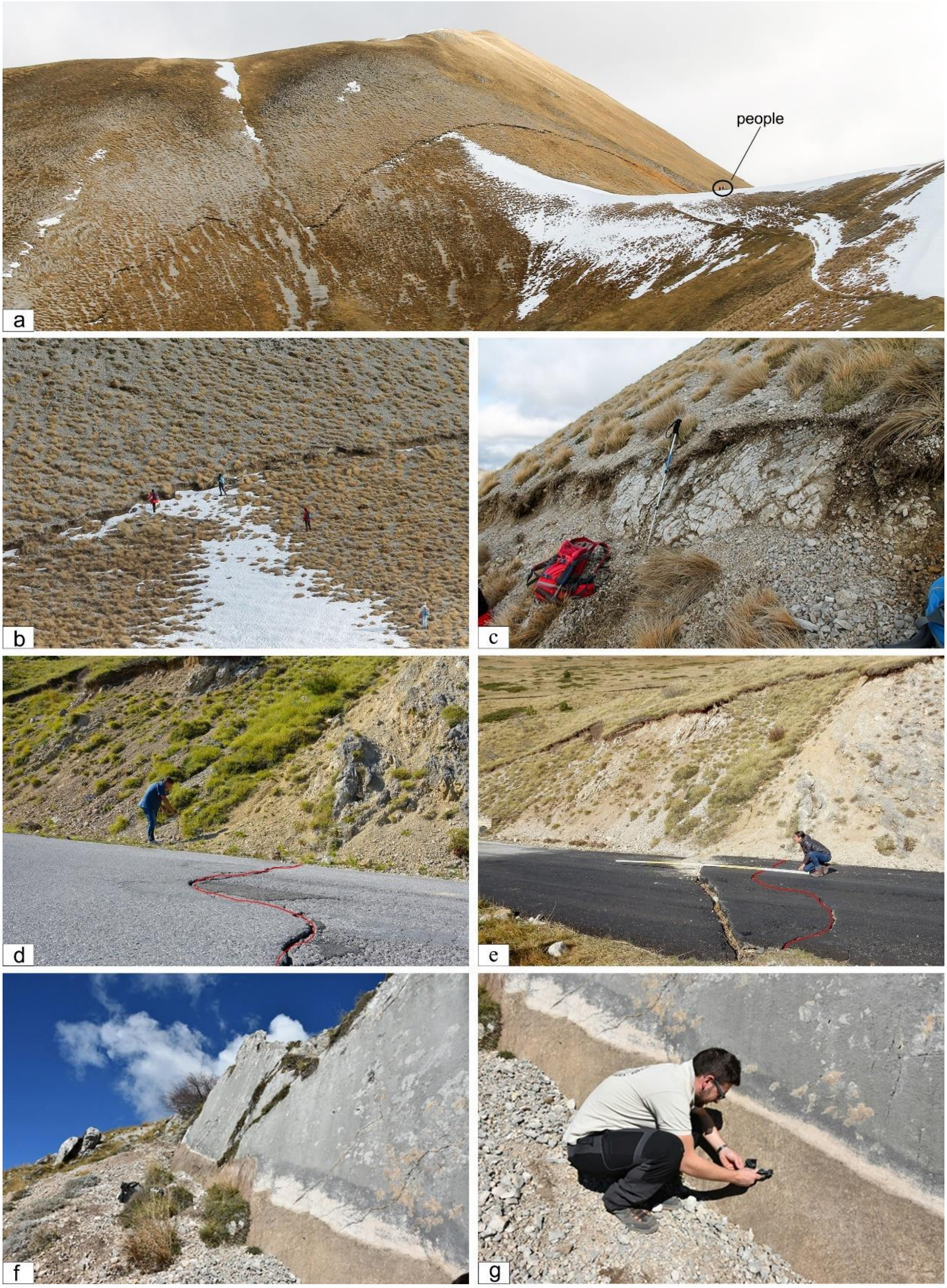

Fig. 2.2. Examples of coseismic ruptures along the Mt. Vettore - Mt.Bove fault system as seen in the field. (a) panoramic view of the Mt. Porche coseismic rupture; (b) close up of the Mt. Porche rupture; (c) detail of decametric throw; (d, e) evidences of coseismic rupture of the same location on different time (d, 24/06/2016; e, 19/11/2016) (f, g) metric coseismic vertical dislocation along a fault plane located in Colli Alti e Bassi.

2.2 Field Trip

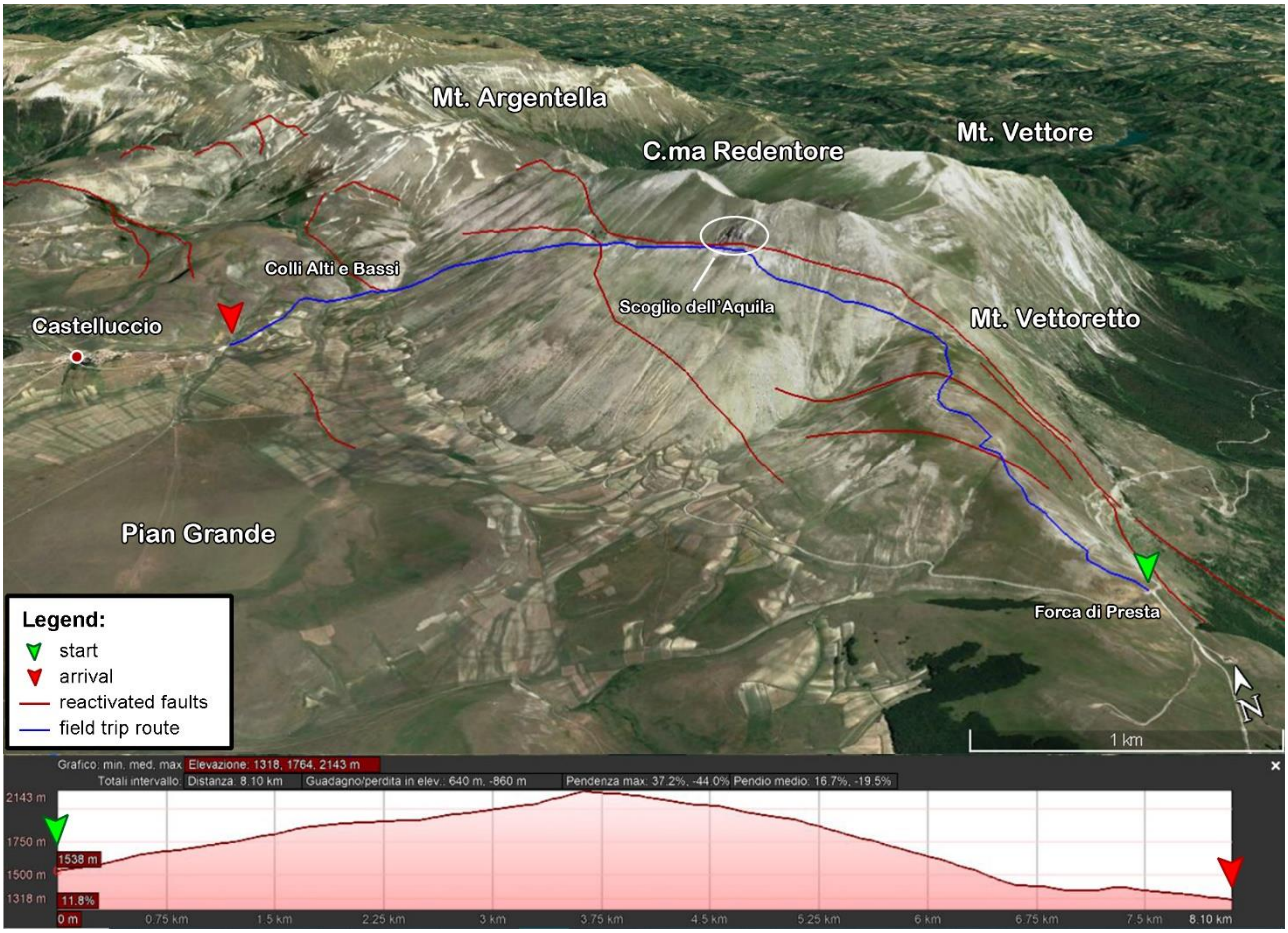

Fig. 2.3. Oblique view from satellite of the Southern part of the Sibillini Mountains where the reactivated faults (red lines) and the field trip route (blue line) are displayed. At the bottom of the figure the trail elevation profile is shown.

From the satellite image in Fig. 2.3, it is possible to observe the landscape of the Southern area of the Sibillini Mountains, where surface expressions of the VBFS are visible from satellite. Mt. Vettore is the highest peak of the Sibillini Mountains (2476 m a.s.l.), followed by Cima del Redentore (2449 m a.s.l.). The villages in this area have been severely damaged by the October 30 mainshock, with an Is from 9 to 10.5 (MCS local intensity; Galli et al., 2017).

The first stop is located at Forca di Presta locality, an introduction of the geological

framework of this area will be given, taking advantage of an exceptional panoramic view where it is possible to see the main fault surface expressions affecting the western slope of Mt. Vettore.
Then the hike starting from Forca di presta will continue along the "Cordone del Vettore" fault scarp (Fig. 2.6) also known as "la Strada delle fate". This name has taken from a myth.

"The legend says that beautiful sparkling fairies, linked by a spell to the Sibyl, an evil sorceress, descended into the valley during the night to dance with the local shepherds. Each fairy represented an element of nature, fire, snow, water, flowers and so on. The fairies were beautiful from the waist up, but they had goat feet. They could dance all night but before dawn they had to return to the underworld. One night, amazed by the music they did not notice the rising of the sun and, when the first rays of the sun hit the tops of the mountains, they gave themselves to a mad race towards the entrance of their kingdom (the cave of the Sibyl). With their goat feet, in their mad run, they forever marked the face of Monte Vettore, creating what is still called "la Strada delle Fate".

After leaving the main fault scarp the group head downslope to "Colli Alti e Bassi" locality (CAB), about 1km east from Castelluccio di Norcia. In this location, we can appreciate a fault scarp related to a synthetic splay (Fig. 2.8) and finally the field trip ends in the Pian Grande.

Forca di Presta: introduction to the geology of the Monte Vettore area

The Castelluccio basin is an intramontane depression, located in the central Apennines, and filled by Pleistocene to Holocene fluvial-lacustrine deposits; bedrock units are instead represented by limestone and pelagic marls of Jurassic to Miocene age. The main geomorphological modeling of the landscape started during the Late Pliocene, when arid or sub-tropical humid climatic conditions, favorable to planation processes, created a "paleo"-landscape with gentle relief. The subsequent tectonic phase, active since the Early-Middle Pleistocene until now, is characterized by dip- and oblique-slip faults and strong uplift. These processes interrupted and dissected the previous landscape, forming the tectonic depression, same as the other nearby basins (Colfiorito, Norcia, Cascia, Leonessa, ecc.) within the central Apennines (Aringoli et al., 2012, and references therein).

The western slope of Mt. Vettore is marked by at least two major normal faults: the lower fault runs at the base of the Vettore escarpment and bounds the Castelluccio basin. The upper fault runs very close to the top of Mt. Redentore, marked by a clearly visible fault scarplet ("*Cordone del Vettore*", Fig. 2.6a) crosscutting the Upper Triassic-Lower Liassic carbonates Corniola and Calcare Massiccio (Pierantoni et al. 2013). In the area of Palazzo Borghese-Mt. Porche, a E-W trending Jurassic fault causes the sharp juxtaposition of the basinal sequence of Mt. Porche (north) with the condensed sequence of Palazzo Borghese (south). In the latter structure, the condensed sequence's beds are also unconformable on the upper fault scarp.

The seismicity that affected Central Italy since August 24 was attributed to the activation of the entire VBFS, between the northern slope of the Tronto River valley and the area of Ussita. It includes segments identified along the western slopes of Mt. Vettore, Mt. Argentella, Palazzo Borghese, Mt. Porche and Mt. Bove (Calamita and Pizzi, 1992, Coltorti and Farabollini, 1995, Cello et al., 1997, Pizzi et al., 2002; Galadini and Galli, 2003; Pizzi and Galadini, 2009). Considering the evidence of local activity and the lack of historical earthquakes associated with it, the fault was previously considered "silent", assuming that it was presumably tied to a seismic gap (Galadini and Galli, 2000).

A recent geological map (Pierantoni et al., 2013) provides a detailed trace of these faults (Fig. 2.4). The Mt. Vettore normal fault crosses and displaces the Sibillini thrust fault for some hundred meters. According to some authors, normal faulting may have locally reutilized some steeper shallow planes of the thrust zone (Calamita et al., 1994; Di Domenica et al., 2012 and bibliography therein). Recent activity on the normal faults was described by Scarsella (1947) and confirmed by several Authors in more recent times, who studied the geomorphic evolution of the Castelluccio Basin (e.g. Blumetti, 1991; Calamita et al., 1994; Coltorti and Farabollini, 1995), pointing out the occurrence of fault escarpments and scarplets. According to these Authors, the Castelluccio Basin is produced by extensional tectonics with slight left lateral component.

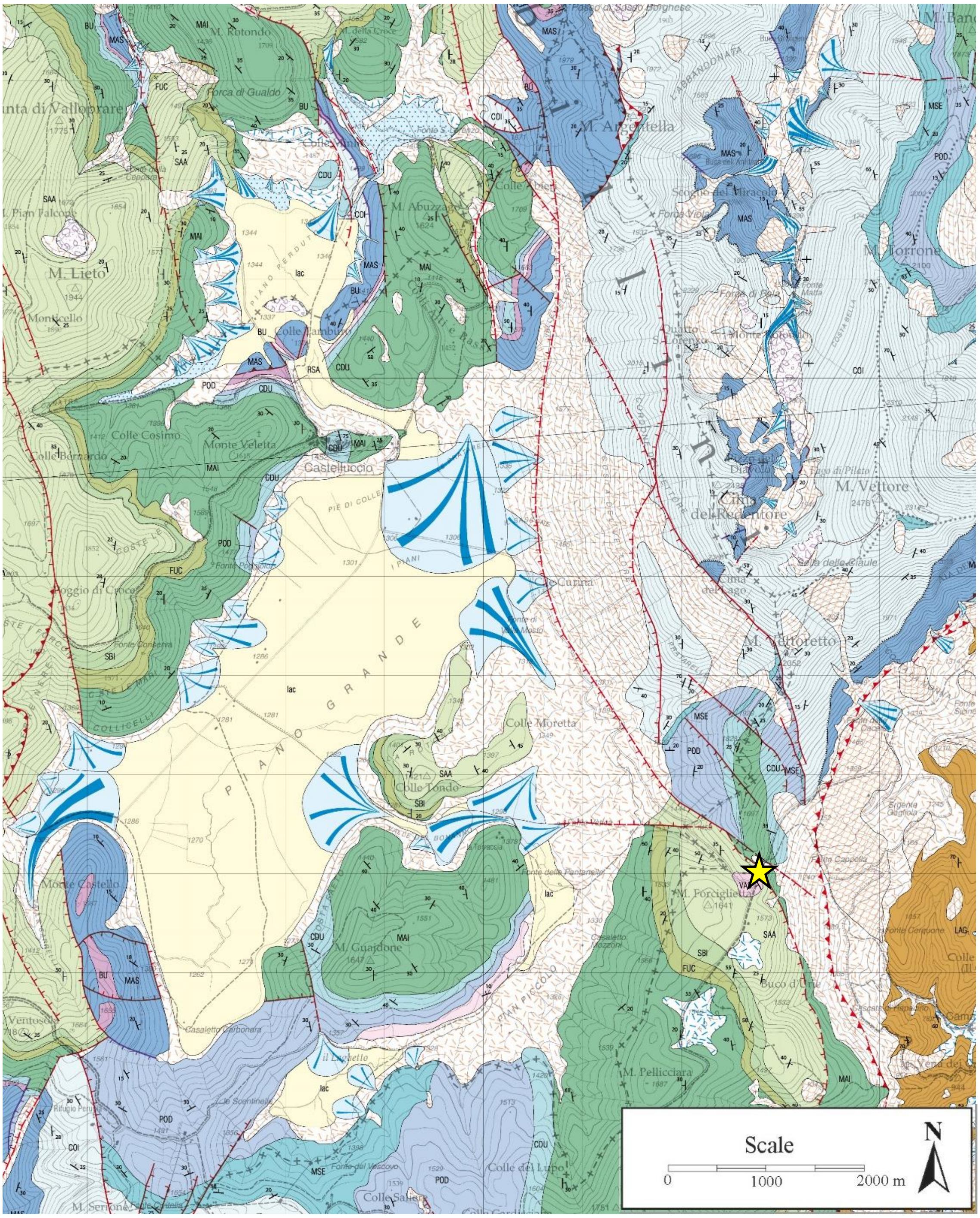

Fig. 2.4. Geological map of the western slope of Mt. Vettore (from: Pierantoni et al., 2013). The yellow star shows your location.

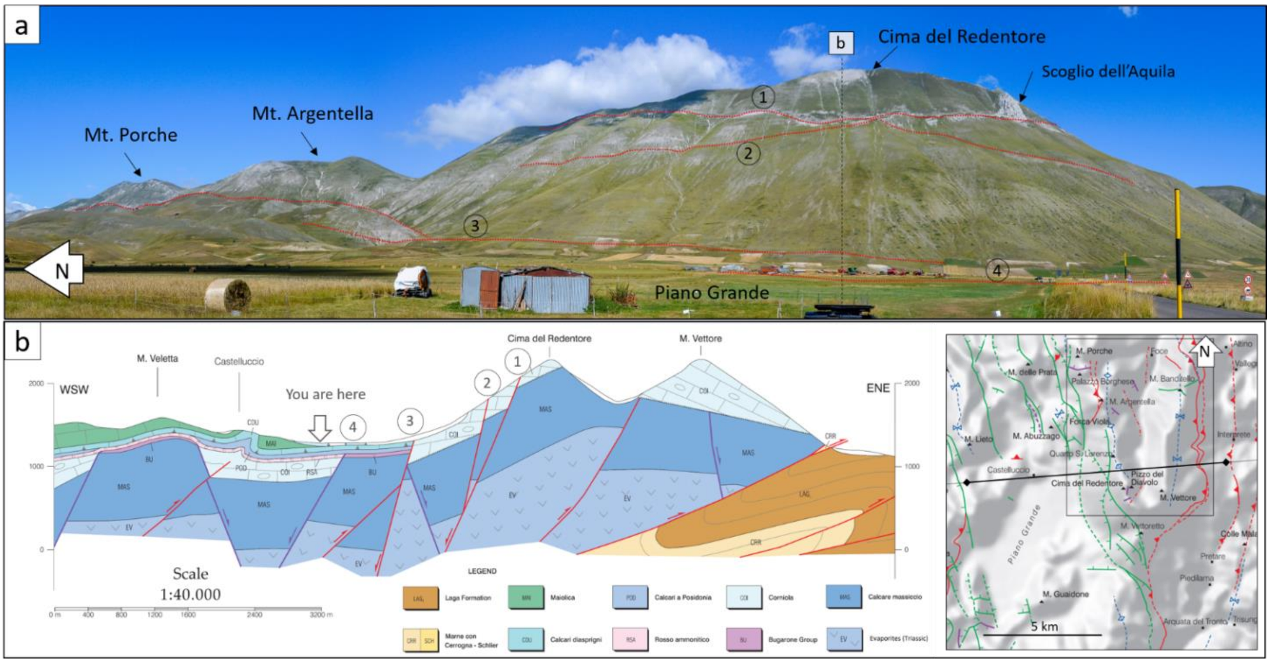

Fig. 2.5. Outline of the fault scarps related to the main normal faults of the Mt. Vettore-Mt. Bove system. a) Panoramic view of the Sibillini Mountains indicating the surface expression of major faults activated during the last earthquake sequence of 2016. b) Cross-section orthogonal to the panoramic view indicating the continuation of the faults in depth, which crosscut the Umbro-Marchigiana succession. The most evident expression of the coseismal rupture is given along (1) the Cordone del Vettore where the maximum offset (nearly 2m) is present at Scoglio dell'Aquila, (2) fault splay also reactivated, (3) the main fault with a cumulative offset of about 2000m, and (4) a Jurassic fault also reactivated.

Mt. Vettore Fault: walk along the "Cordone del Vettore" fault scarp

This stop consists on a walk along the fault segment located on the southern slope of Mt. Vettoretto in order to arrive just below the top of Cima Redentore, where we can appreciate the metric fault scarp commonly named “Cordone del Vettore”.

A set of very clear ground ruptures are visible on the southern slope of Mt. Vettoretto. These ruptures mainly strike between NNW-SSE, with a slight left-lateral horizontal component. They generally affect colluvium and soil, often very close to the bedrock fault plane, but sometimes at a distance of several meters. These ruptures can be followed almost without interruption from the SP34 (province road) to the end of Mt. Vettoretto slope. The province road shows an offset about 10-20 cm (Fig.2.6b). Going a few meters to uphill, even more evidence of coseismic ruptures are found and the offset increases to 50-60 cm (Fig. 2.6c). Continuing up to the end of Mt. Vettoretto the observable offset gradually increases up to 60-80 cm (Fig. 2.6d). Archiving the “Cordone del Vettore” fault scarp, the offset largely increases showing a “free face” with about 2 m vertical throw close to Scoglio dell’Aquila (Fig. 2.6e).

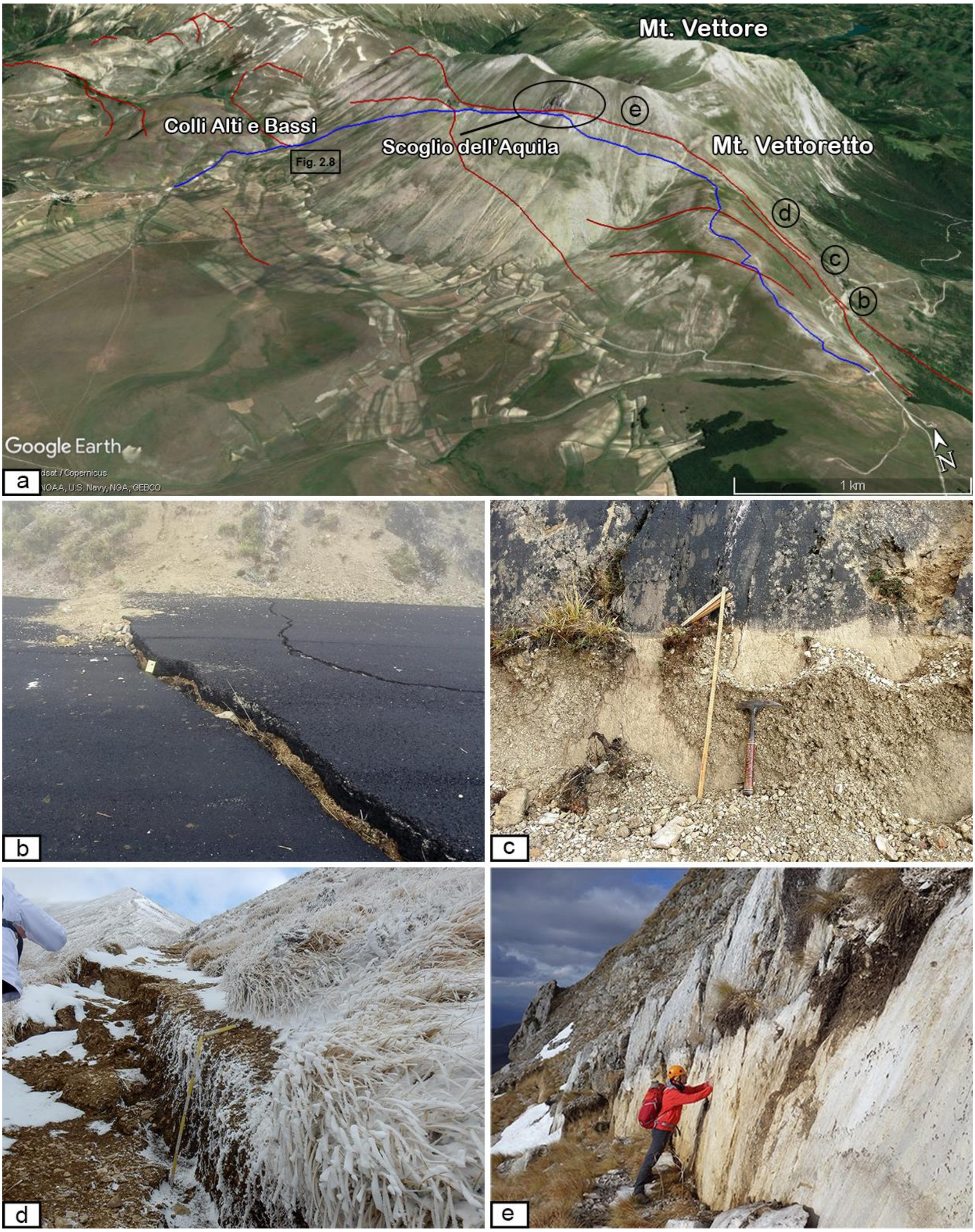

Fig. 2.6. a) Satellite view of the location, blue line: hike route, red lines: reactivated faults extracted by Pierantoni et al. 2013; b, c, d, e) coseismic structures encountered along the walk.

Colli Alti e Bassi: free face observation along a bedrock fault scarp

This stop is located along the NS-striking "Colli Alti e Bassi" normal fault (CAB), a synthetic structure of the Mt. Vettore master fault (Fig. 2.7a).

The CAB lowers westward the Early Cretaceous pelagic "Maiolica" Fm (hanging wall block), with respect to the Early Jurassic shelf carbonates of the Calcare Massiccio Fm (footwall) (Fig. 2.7b, section B-B1). The CAB dips on average, to W - SW, with sharp changes of attitude, from to 255-42 to 215-70, on an extent of a few hundred meters. The observed stratigraphic omission allows to assess a long-term displacement of 380 m (throw of ~355 m).

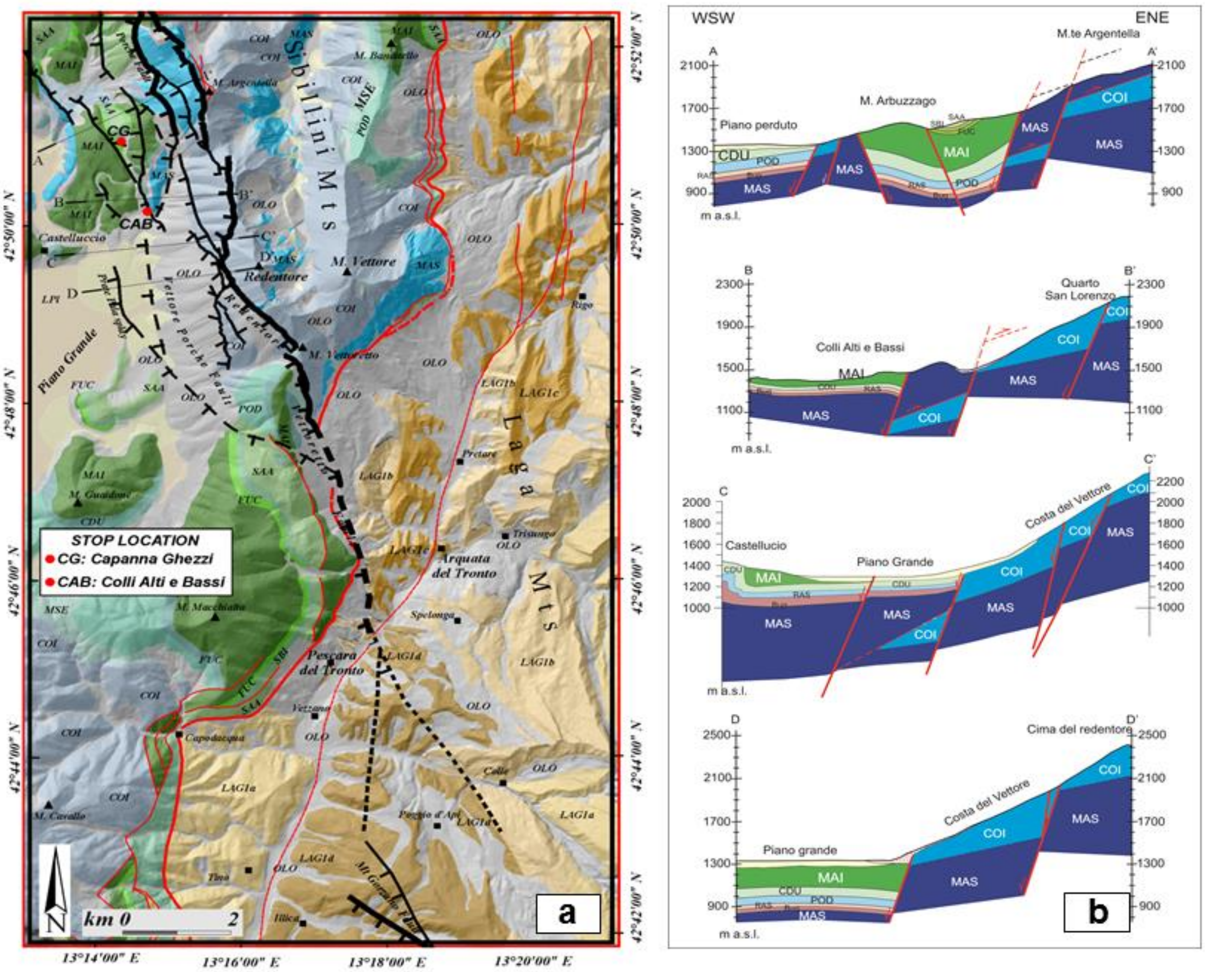

Fig 2.7. Structural-geological sketch of the Mt Vettore - Piano Grande area with stop locations (red full circles); CAB: Colli Alti e Bassi site, CG: Capanna Ghezzi sit. Blue and green colors

refer to outcrop of Jurassic and Cretaceous Fms (respectively) of the Umbria-Marche carbonatic succession; brown colors refer to outcrop of Miocene ramp muds and turbidite foredeep successions. b) Geological sections across the western slope of Mt. Vettore showing the west-dipping normal fault system driving the Quaternary evolution of the study area.

On the CAB site, we can observe an exposure of a continuous fault scarp, some hundred meters-long, showing a spectacular free face, 50 to 100 cm-high (Fig. 2.8). The latter can be entirely attributed to the surface faulting event of the MW 6.6, 30 October 2016 Earthquake. In fact, the detailed field mapping performed by our research unit, in the 24 August-29 October interval, led us to exclude any reactivation of tye CAB during the Mw 6.0, Amatrice, and 26 October Mw 5.9, Visso, earthquakes.
Both striations on the fault plane and correlation of piercing points, recognizable on the two faulted blocks, record normal kinematic, locally with a minor left-lateral component (Fig. 2.8).

Fig. 2.8: Spectacular outcrop of the Colli Alti e Bassi normal fault showing the free face due to coseismic slip of the October 30 Mw 6.5 earthquake.

From a structural point of view, this valley corresponds to a narrow graben delimited by the CAB to the east and by the East-dipping antithetical fault of Mt. Arbuzzago, to the west (Fig. 2.7a).

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