FROM 1997 TO 2016:

THREE DESTRUCTIVE EARTHQUAKES

ALONG THE CENTRAL APENNINE FAULT SYSTEM, ITALY

Field Trip Guide Book

International Field Trip

July 19th - 22nd 2017

Patronage to:

Front cover image:

Upper Left: Falling houses of the Costa village (MC) during the mainshock of Mw = 6.0, 1997 Umbria - Marche Earthquake. Upper Right: Faulted water pipeline at Paganica, 2009 L'Aquila Earthquake, Mw = 6.3. Bottom: Panoramic view of the western slope of Monte Vettore. Here is shown the scarp related to the causative fault of the mainshock of Mw = 6.5, 2016 Amatrice - Visso - Norcia earthquake.

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Summary and Acknowledgements

From 1997 to 2016, three earthquakes: Umbria-Marche 1997 of Mw=6.0, L'Aquila 2009 of Mw=6.3 and Amatrice-Norcia-Visso 2016 of Mw=6.5, destroyed a large area along the central Apennines. This International Field Trip will provide a unique opportunity to observe the causative active faults belonging to a coherent and interacting fault system. On the basis of the geological studies carried out mainly prior to the last earthquakes, participants will be able to evaluate the contribution of active fault-field-based studies on seismic hazard analysis.

Participants will be led on a three-day field trip organized as follows:

Day 1: Field Trip to the epicentral area of the 1997 Umbria-Marche earthquake (Mw=6.0)

Day 2: Field Trip to the epicentral area of the 2016 Amatrice, Visso, and Norcia earthquake (Mw=6.5)

Day 3: Field Trip to the epicentral area of the 2009 L'Aquila earthquake (Mw=6.3)

Our sincere acknowledgements to all who have helped in the organization of the TDEq2017. This field trip has been prepared thanks to the collaboration of many researchers from seventeen different institutes. We especially would like to thank Hannah, Danica, Tiziano, Miller, and Alan, Ph.D. Students and post-docs of the Geology Division of the University of Camerino, for the excellent work done for the field trip organization. Also, many thanks to the participants, who are the actual sponsors of this event, for making this fieldtrip possible.
We hope the TDEq2017 will substantially contribute to better understanding one of the most relevant active fault systems in Europe. We also expect this fieldtrip will provide an opportunity to increase professional networking and foster future research collaborations through the active participation of all the attendants.

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, of European origin, and of the Adriatic block of African affinity (Vai and Martini, 2001 and references therein).

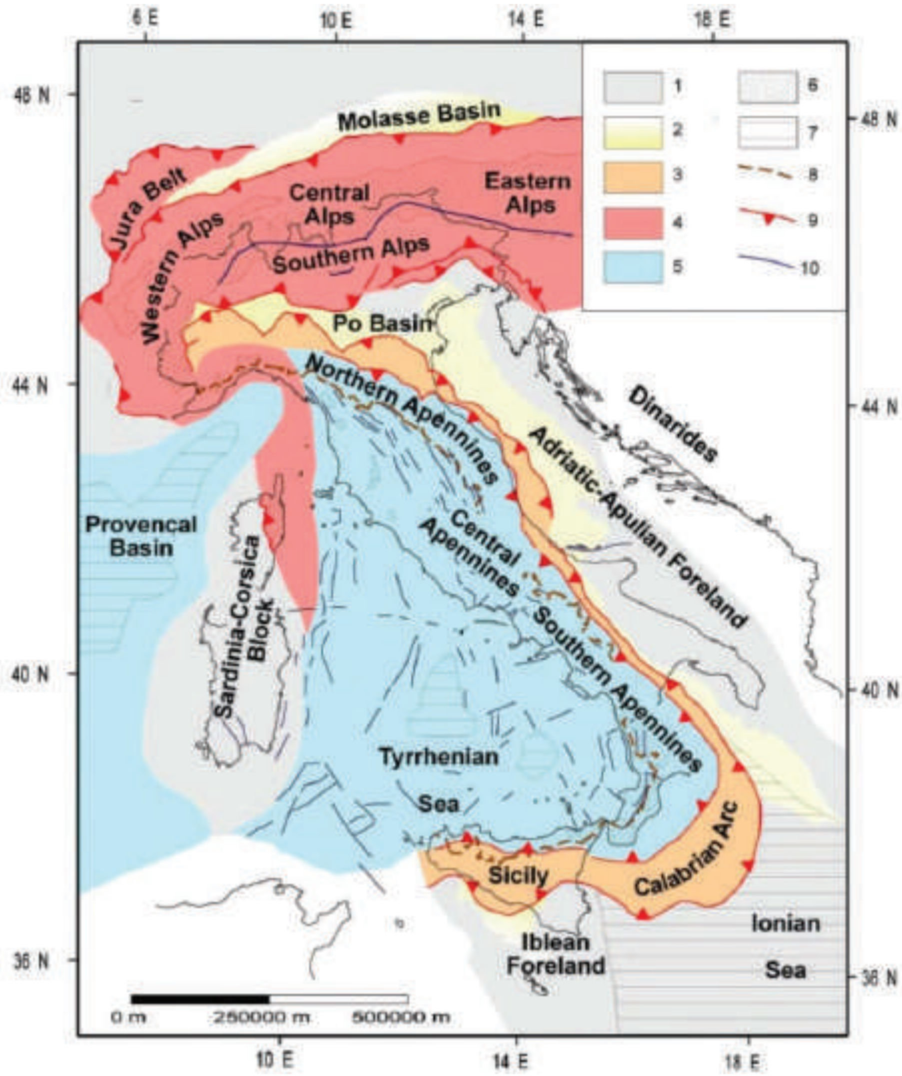


Fig. 1.1. Synthetic tectonic map of Italy and surrounding seas; 1) Foreland areas; 2) foredeep deposits; 3) domains characterized by a compressional tectonic regime; 4) Alpine orogen; 5) areas affected by extensional tectonics: these areas can be considered as a back-arc basin system developed in response 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 of 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 Provencal and Thyrrenian backarc basins (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

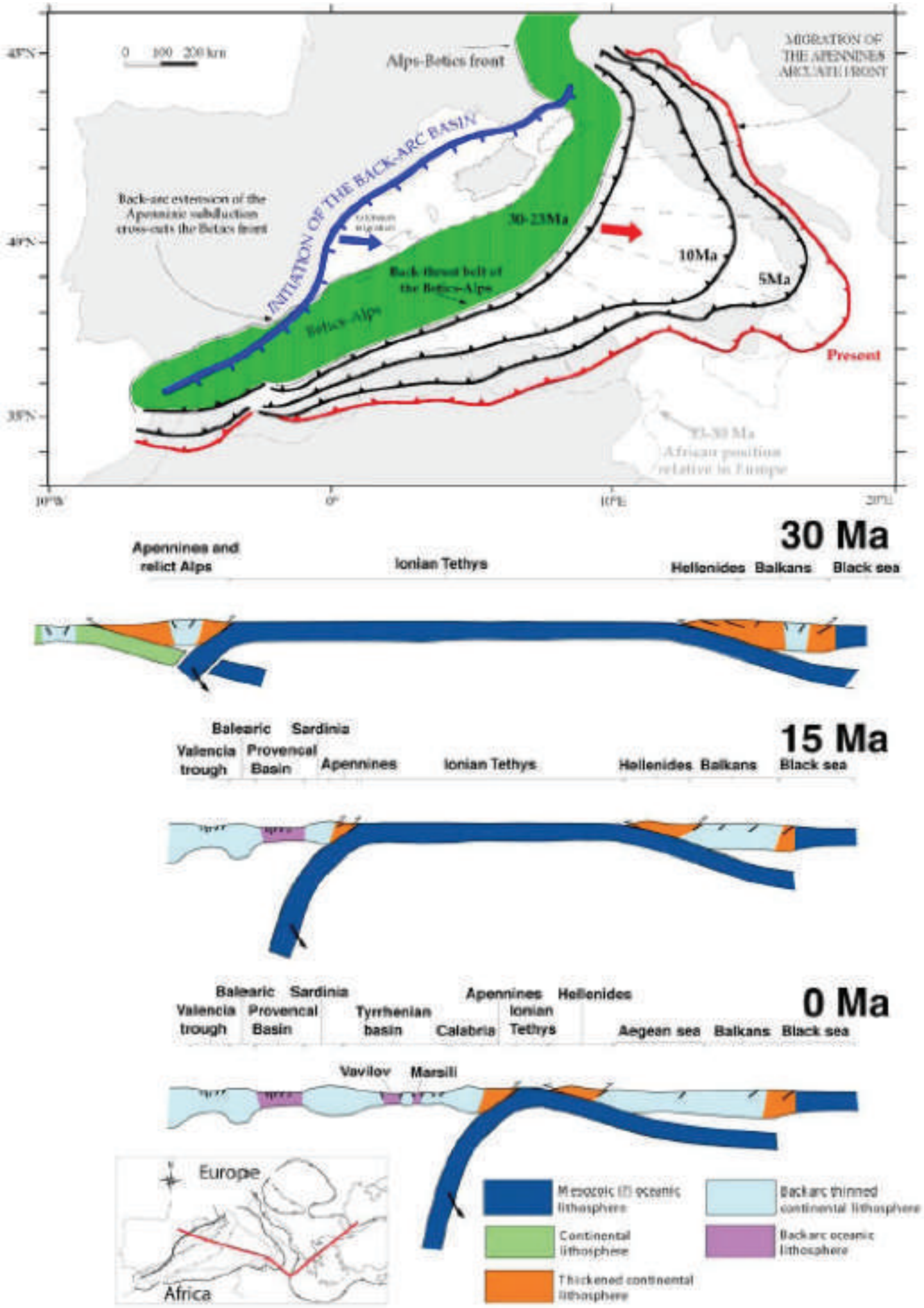


Fig. 1.2. The early "east"-directed Alpine subduction was followed by the Apennines "west"-directed subduction, which developed along the retrobelt of the pre-existing Alps. The slab is steeper underneath the Apennines, possibly due to the "westward" drift of the lithosphere relative to the mantle (From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

of siliciclastic sandstones in a foredeep setting ahead the propagating deformation 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).

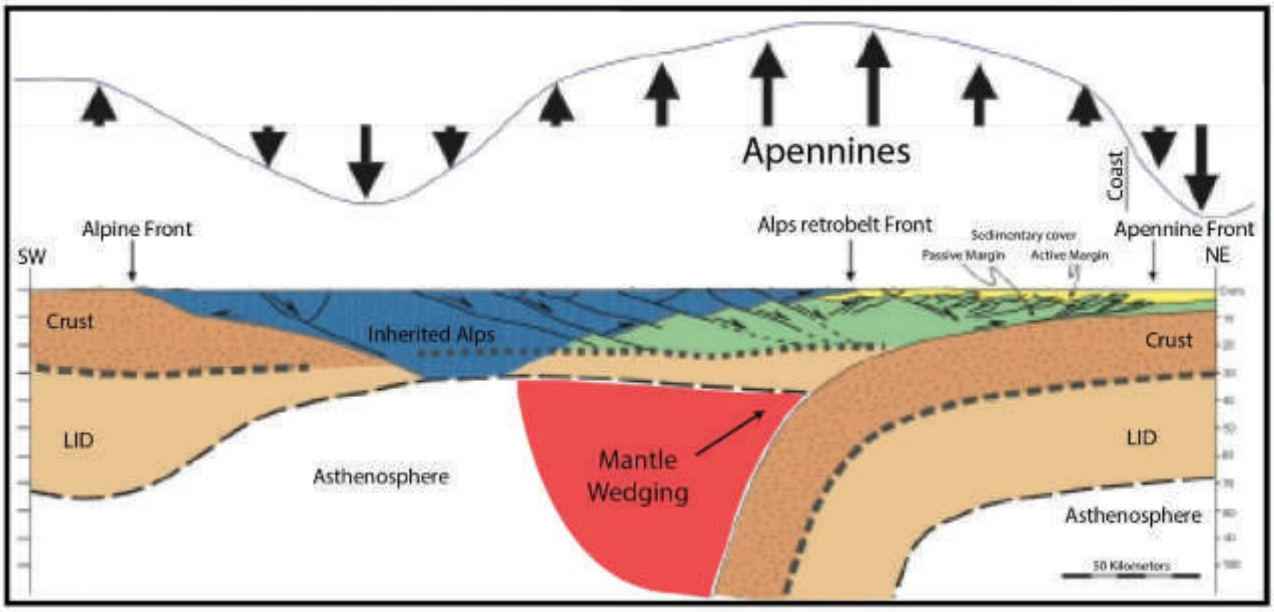


Fig. 1.3. Cross section from Corsica (SW), through Tyrrhenian Sea and across the Apennines (NE). The Apennine prism (light green) developed along the retrobelt of the alpine orogen (the blue double-wedge in the center of the section). The alpine orogen was boudinaged and stretched by the backarc rift.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

Following the kinematics of west-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. Fig. 1.4 shows the main active faults and the three seismic sequences in the Central Apennines 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

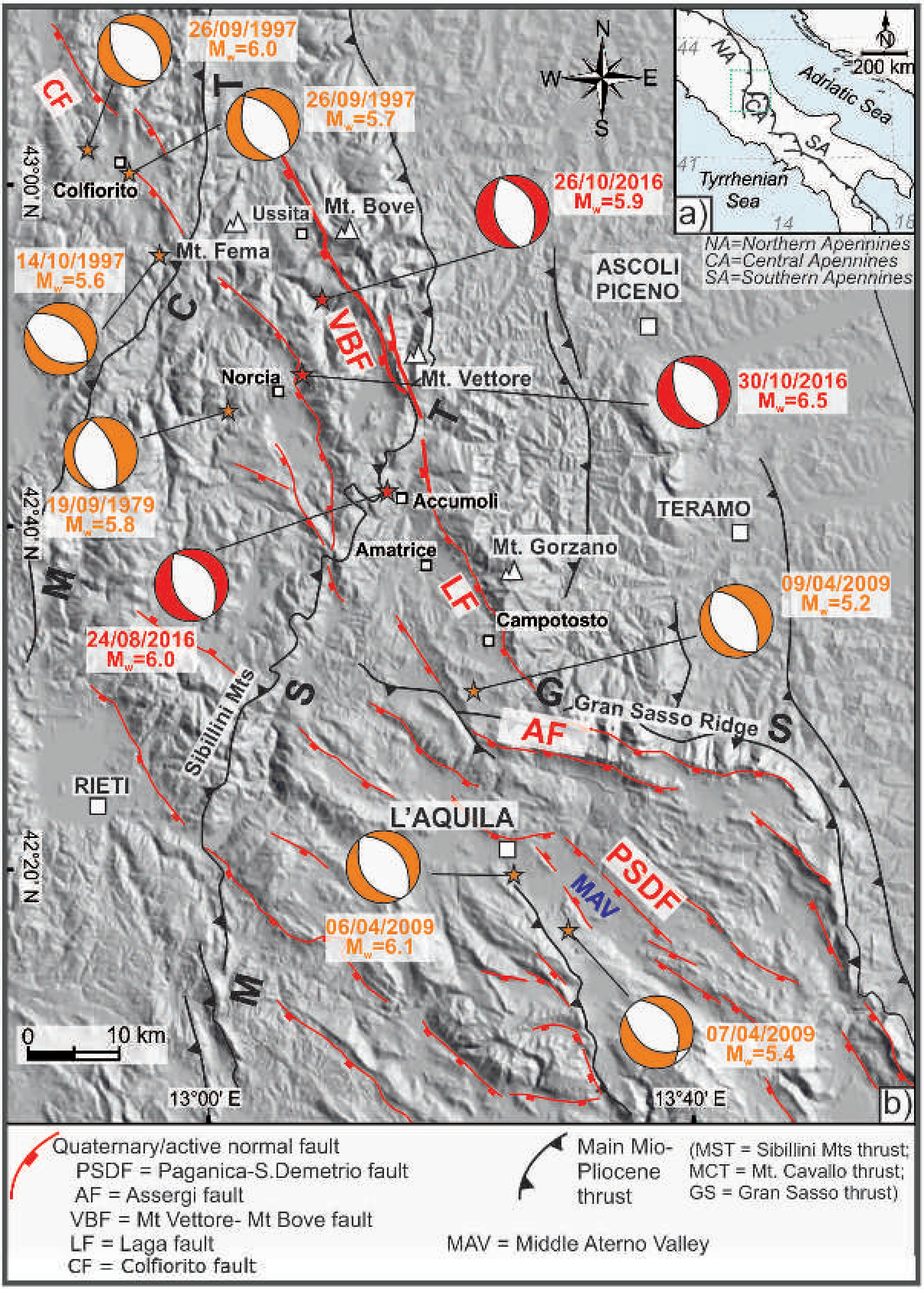


Fig. 1.4. a) Location map of Figure 1b with the three main arcs of the Apennine chain. b) Seismotectonic sketch of the field trip area with the main Neogene thrusts (black lines) and Quaternary/active normal fault systems (red lines). The Mt. Cavallo (MCT), Sibillini Mts (MST) and Gran Sasso (GS) thrust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

2. Day 1: Field trip to the epicentral area of 1997 Umbria-Marche earthquake

2. 1. Introduction

On September 26, 1997, at 00:33 and 09.40 GMT (Fig. 2.1) two moderate earthquakes (Mw = 5.7 and Mw = 6.0) struck several historical towns and monuments (including the San Francesco Monastery in Assisi) in the Umbria and Marche regions of Central Italy (Fig. 2.2) causing the death of 12 people, injuries to 140 people and leaving about 80.000 people homeless. The epicenter of the first shock was located midway between Cesi and Costa (some 20 km south of Camerino; Fig. 2.2), whereas the second shock occurred south of Annifo (about 6 km to the NNW of the first event). Both these events occurred within the Colfiorito basin, a quaternary tectonic depression infilled with fluvio-lacustrine deposits (Fig. 2.2). A major foreshock (Ms = 4.8) also occured on September 4 in the Cesi area, recorded by the local seismic network of the University of Camerino, followed by many aftershocks (Ms < 4.7) that affected the whole epicentral area during the following months. The two major earthquakes were part of a seismic sequence which also included another mainshock recorded on October 14 (Mw = 5.7) in the Sellano area (some 15 km south of Colfiorito), and a roughly 45 km deep earthquake (Ms = 5) which occurred 25 km north of Colfiorito.

Fig. 2. 1. Falling houses at Costa village (Fig.2.2, fault 5). This photo was taken on the 26th September at 9.40 (GMT) during the mainshock of magnitude 6.0.

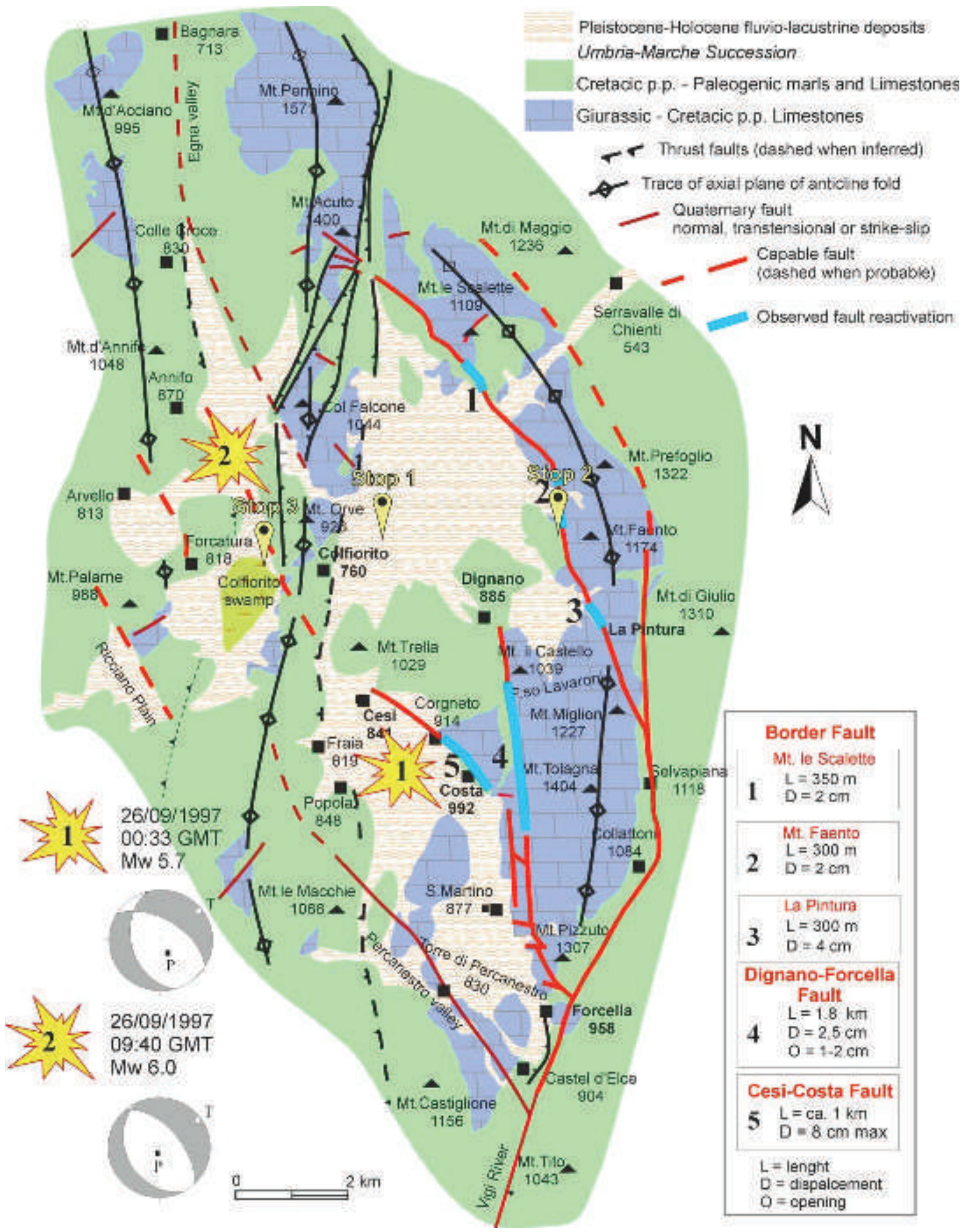


Fig. 2. 2. Fault data, focal mechanism solutions, and ground deformation within the mesoseismal area of the Colfiorito earthquake sequence (data from Amato et al., 1998b; Cello et al., 1997, 1998).

Field surveys aimed at detailing the ground effects lated to the mainshocks of September 26, 1997 and were initiated soon after the first event.

During the surveys we observed systematic reactivations of the mapped capable faults, with offsets on the order of a few centimeters and discontinuous ruptures measuring a few hundred meters over a distance of ca. 8 km (Cello et al., 1998; Cello et al., 2000; Vittori et al., 2000, Mildon et al. 2016).

The epicentral area of the September 26 events is located within a Quaternary intramontane basin which is characterized by an array of nested tectonic depressions filled with lacustrine and alluvial deposits (Fig. 2.2). Mammal remains in the lake sediments suggest that the Colfiorito basin developed since, at least, the end of the early Pleistocene (Ficcarelli and Silvestrini, 1991). Evidence of Late-Pleistocene to Holocene offsets along many of the faults bordering the basin is provided by several authors, who also discuss their potential for coseismic ground displacement (Tondi et al., 1997 and references therein).

The 1997 seismic crisis is comparable to other historical and paleoseismological events of similar size that have affected the Umbria-Marche region over the last millennium (Rovida et al., 2015). According to the Italian seismic catalogues (Rovida et al., 2015), the strongest earthquake with an epicentral area close to that of the 1997 events, occurred in 1279 (I = X MCS). Furthermore, the available instrumental data show that the hypocentral depth for the moderate events known to occur in the Umbria-Marche region ranges from 8 to 15 km (Chiaraluce et al., 2005).

Additional information on the kinematics of the seismogenic structures of this sector of the Apennines can be inferred from the focal mechanism solutions which consistently show normal faulting on roughly NW - SE trending fault planes for most of the relevant events in the area (Calamita et al., 1999; Barchi et al., 2000; Boncio and Lavecchia, 2000). Likewise, seismological data of the 1997 mainshocks (refer to Fig. 2.2), suggest almost pure normal faulting on northwest-southeast trending planes, dipping 40°-50° to the southwest (Chiaraluce et al., 2003).

2. 2 Evidence of fault reactivations

Most of the fault segments mapped as capable faults within the epicentral area of the September 26, 1997 earthquakes (Cello et al., 1997; Tondi et al., 1997) typically mark the interface between bedrock and slope deposits occurring at the base of the range fronts bordering the Colfiorito basin (refer to Fig. 2.2 and 2.5). Observed surface ruptures due to the 1997 seismic sequence were mapped along three main faults (refer to Fig. 2.2):

1) the Colfiorito Border Fault

Surface fault reactivation at Mt. Le Scalette, Mt. Faento and La Pintura produced discontinuous free faces 2 to 4 cm high.

Fig.2.3. Fracture cutting the road along the Colfiorito Border Fault at La Pintura.

2) the Cesi-Costa

In proximity of the village of Costa, fault reactivation following the 00:33 GMT mainshock of September 26, is recorded by a newly-generated continuous free face (refer to Fig. 2.2 and Fig. 2.6). The coseismic break is marked by a slipped region where the presence of a strip of brown soil (which is still attached at the base of the pre-existing fault plane in bedrock) allowed us to measure a roughly constant value of the coseismic movements which occurred along this segment of the Cesi – Costa fault (Fig. 2.4).

3) the Dignano-Forcella

Fault reactivation along the Dignano - Forcella fault was characterized by the occurrence of a continuous, 2.5-3.0 cm high, free face exposed at Fosso Lavaroni over a length of about 200 m (Fig. 2.2); here, coseismic motion was almost pure dip-slip (refer to Fig. 2.6).

Fig. 2. 4. Phototgraphic mosaic of the fault scarp and of the Dignano - Forcella fault (a) panoramic view over the scarp, (b, c) free face from the 26th September event; and Cesi-Costa Fault (d-f) with 8 – 10 cm free face.

The 1997 earthquake sequence of central Italy offered an opportunity to study distributed coseismic surface faulting effects related to moderate-size seismic events originating within a highly anisotropic crustal volume incorporating a network of pre-existing faults and fractures inherited from older tectonic phases.

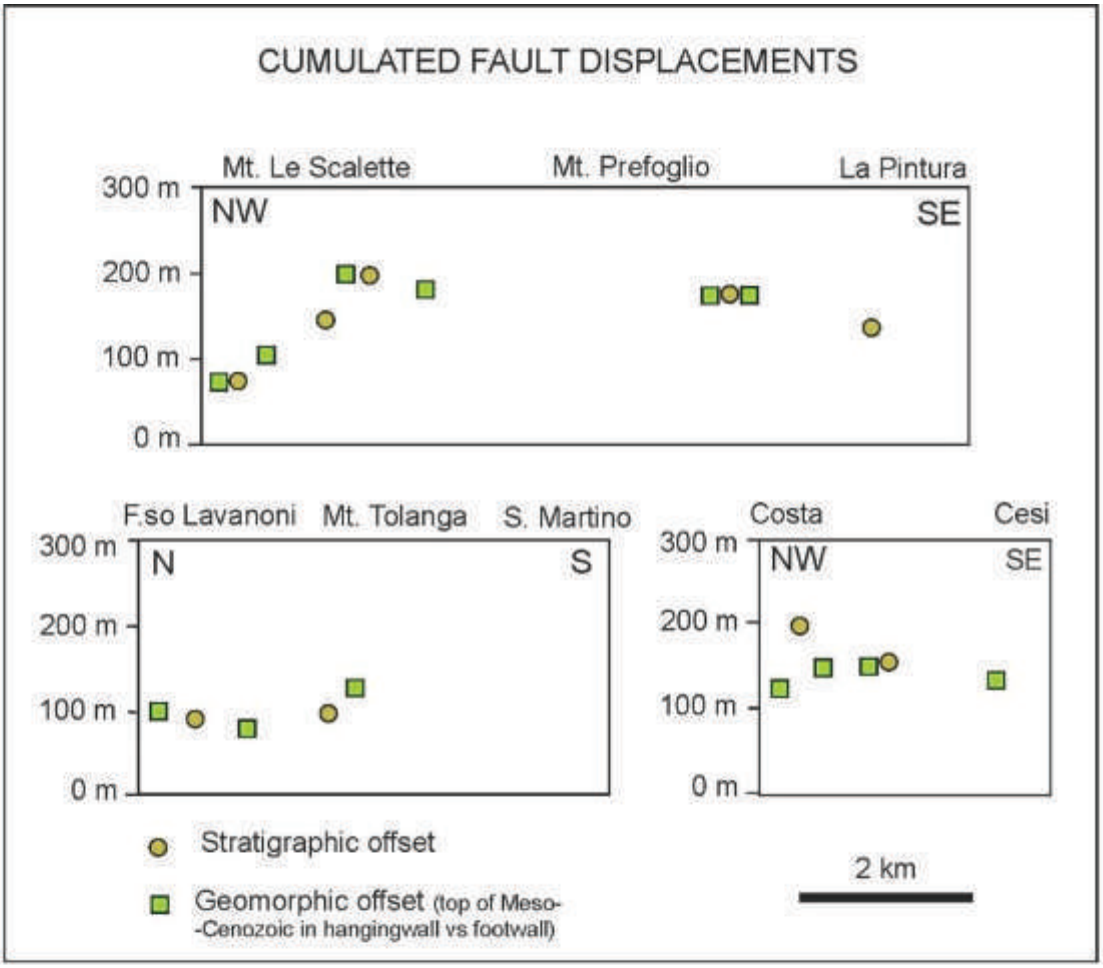


Fig. 2. 5. Comparison of stratigraphic and geomorphological displacements associated with the capable faults of the Colfiorito area. Sections are parallel to the fault traces shown in Fig. 2.2.

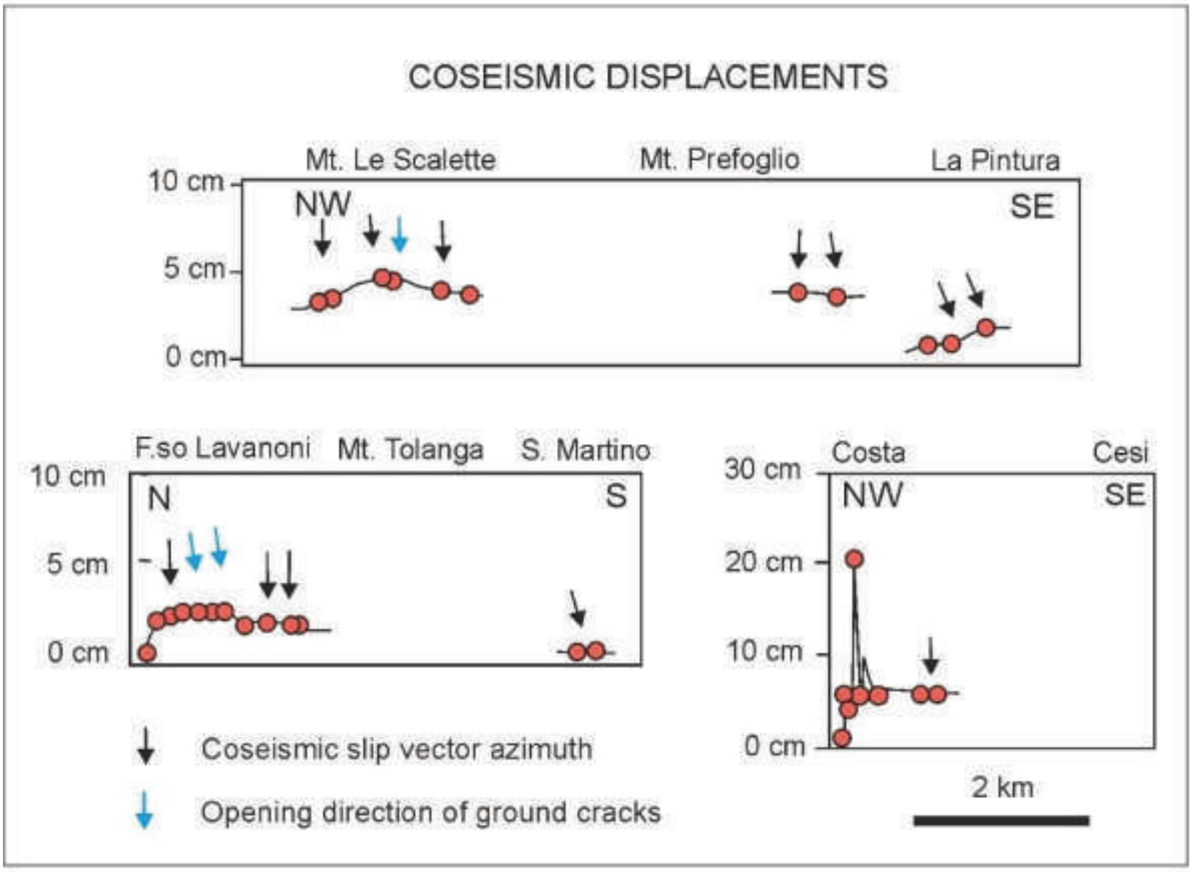


Fig. 2. 6. Coseismic displacements and coseismic slip-vector azimuth recorded along the capable faults of the Colfiorito basin area after the two mainshocks of the 26 September, 1997 earthquake sequence, refer to Figs. 2.4.

2.3. Field trip

STOP 1. The Church of Santa Maria in Plestia: panoramic view and introduction to the geology of the area

An early Romanesque church, built in the 5th century AD., is a sanctuary situated at the border between Umbria and Marche. The archaeological investigations conducted in this area have identified a pre-Roman sanctuary dedicated to goddess Cupra, built in the 4th century BC, near the village of Pistia, whose remains are covered. The resort Pistia refers to a very old village (IX-VII century BC), developed by the Roman Plestia. The Church of Santa Maria di Plestia, probably located on an existing early Christian basilica, has a spire and crypt dating from the eleventh century, nave with raised presbytery that has undergone several changes over the years and the porch, which seems to have been added in the fifteenth century.

Fig. 2. 2. a) Romanesque church from the 11^{th} century with portico b) columned crypt

The Colfiorito border Fault is characterized by differently oriented segments (refer to Fig. *2.2*). At Mt. Le Scalette, the fault trends from N130° to N150°, segment of Mt. Prefoglio and Mt. Faento trends from N160° to N 180°. All the fault segments are characterized by a 100-200m high fault scarp with the base at 2 - 5 m high slickenside-bedrock fault plane.

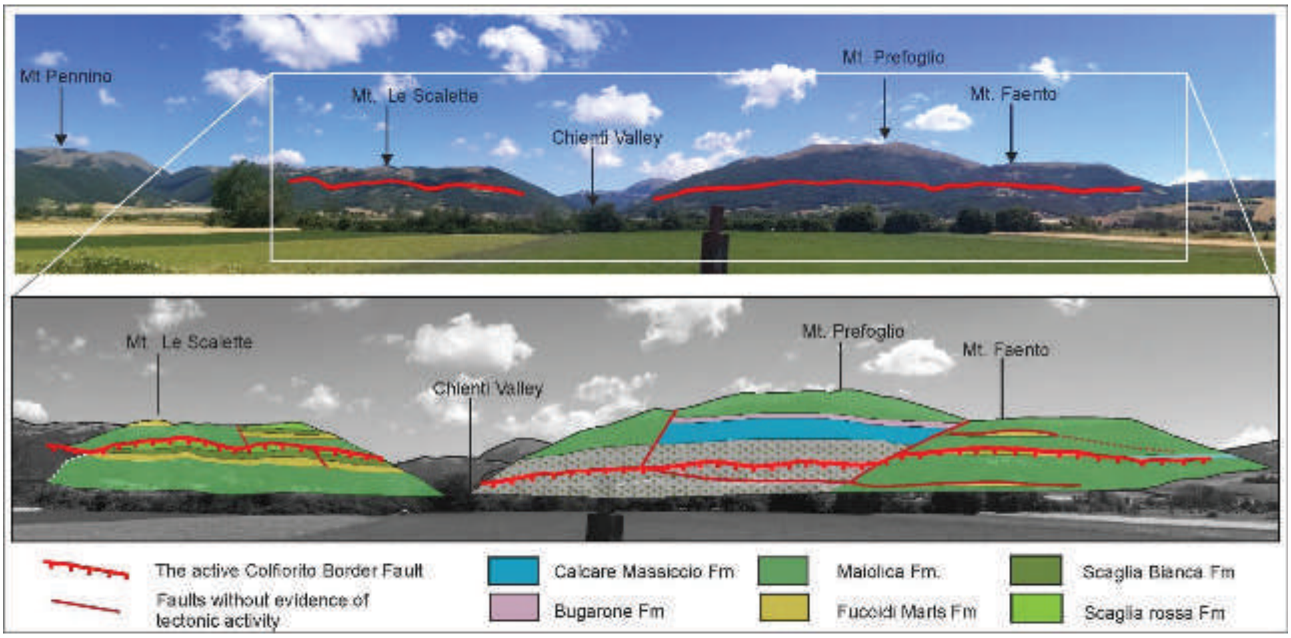


Fig. 2. 7. Panoramic view over the Colfiorito Border Fault and line-drawing of main segments with outcropping formations (for interpretation see the Fig.2.2)

The stratigraphic and geomorphological offset measured across the Colfiorito border fault is 150 to 200 m (Figs. 2.5, 2.7). The fault displaces middle Pleistocene and recent lake sediments, damming the drainage of the Colfiorito basin to the Chienti River valley (Fig. 2.1; Centamore et al., 1978; Tondi et al., 1997).

Surface fault reactivation in 1997 at Mt. Le Scalette, Mt. Faento and La Pintura produced discontinuous free faces 2 to 4 cm high over a length of ca. 550 m (Figs. 2.2, 2.6). At La Pintura the coseismic offset is evident along the dirty road to Selvapiana, where the ruptured fault segment cuts obliquely across the mountain slope and intersects the dirty road at two sites. Detailed observations at both sites show that slip has a significant left lateral component along the N150°-160° trending segments and is purely normal along the N 120°-130° trending ones.

STOP 2. Faento Mountain: the Colfiorito Border Fault scarp

At this stop we approach the fault scarp associated with the Colfiorito Border Fault. Here, the fault puts into contact the Maiolica formation of the footwall with the top of the Fucoidi Marls formation in the hanging-wall giving a cumulative stratigraphic offset across the fault of 150 - 200 m (Figs. 2.6, 2.8).

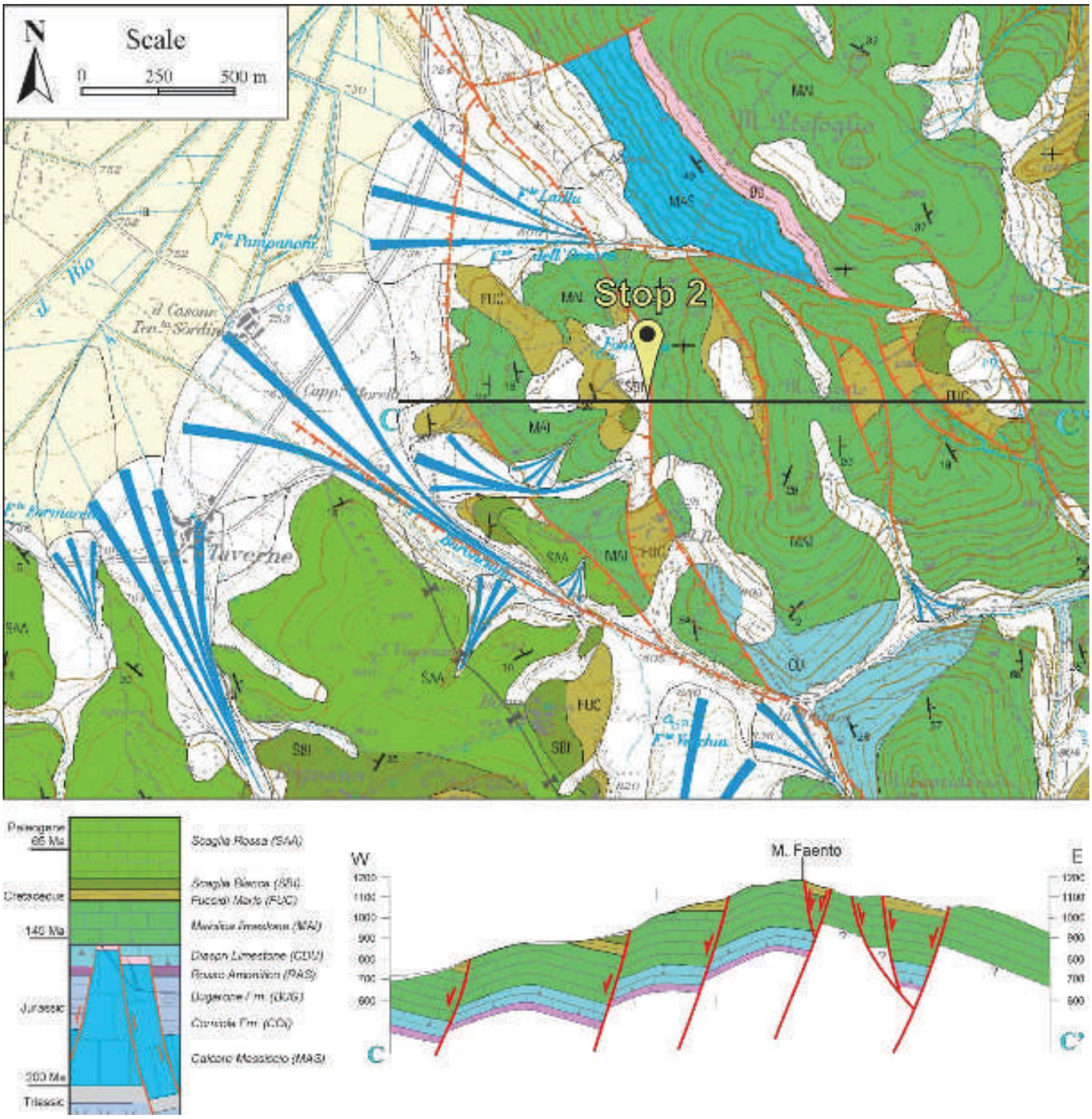


Fig. 2. 8. Geological map of the Monte Prefoglio and Monte Faento. Schematic stratigraphic column of the exposed formations with the geological cross-section (map from Barchi et al., 2011).

The fault scarp is characterized at the base by the occurrence of a continuous 2.0 -4.0 m high slickenside-bedrock fault plane (Fig. 2.10 a, b, c). This fault segment striking N160° and dips 50°-60° to the SW. The fault rock is composed of 10 -20 cm thick protocataclasite (Fig. 2.10d) and the damage zone is around ten meters in the footwall. The bedding within close proximity to the fault plane dips up to 48°, and gradually becomes more gentle (20°) when moving away from the fault plane.

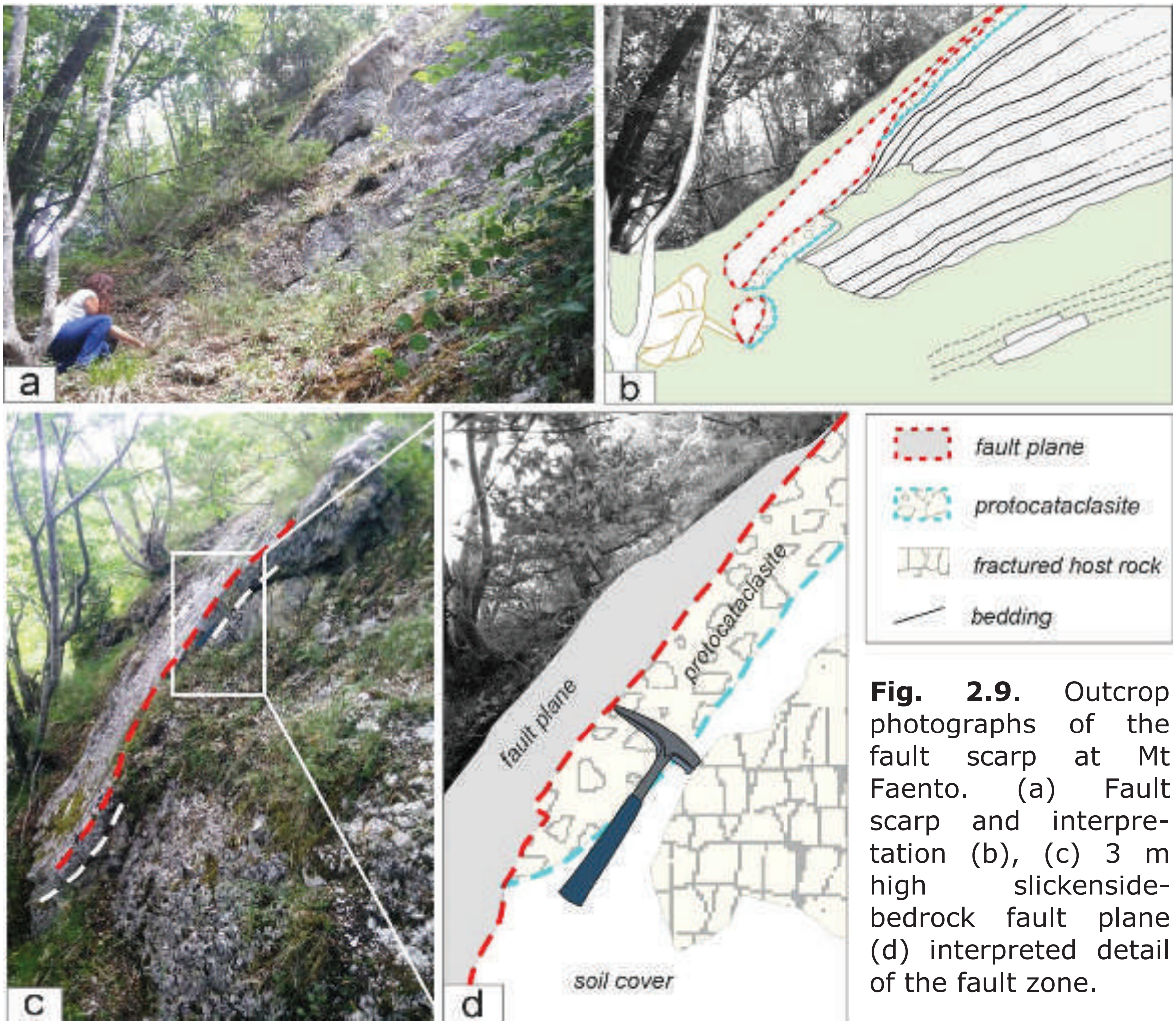


Fig. 2.9. Outcrop photographs of the fault scarp at Mt Faento. (a) Fault scarp and interpretation (b), (c) 3 m high slickenside-bedrock fault plane (d) interpreted detail of the fault zone.

After the 1997 event of Mw=6.0, along the fault scarp, a free face of 2-3 cm high over a length of 1.8 km was observed. These coseismic-surface displacements occur along pre-existing faults that are responsible for the recent evolution of the area and for the growth of fresh limestone scarps and slickensides characterized by geomorphic features unequivocally related to paleoseismic surface faulting. The observed offsets (a few centimeters) are remarkably constant over tens or hundreds of meters, and fit quite well with the empirical relations between fault displacements and lengths derived by Wells and Coppersmith (1994). A growth of the cumulative offset over millennia by progressive compaction of the hanging wall scree and soil sediments, particularly following seismic shaking, appears rather unlikely

STOP 3. Swamp of Colfiorito: morphological evidences of active tectonics and related karstic processes

At the Swamp of Colfiorito, geomorphological evidence of the activity related to a NNW – SSE trending dip-slip fault can be observed. The development Colfiorito-swamp basin and the swallow-hole provide such evidence.

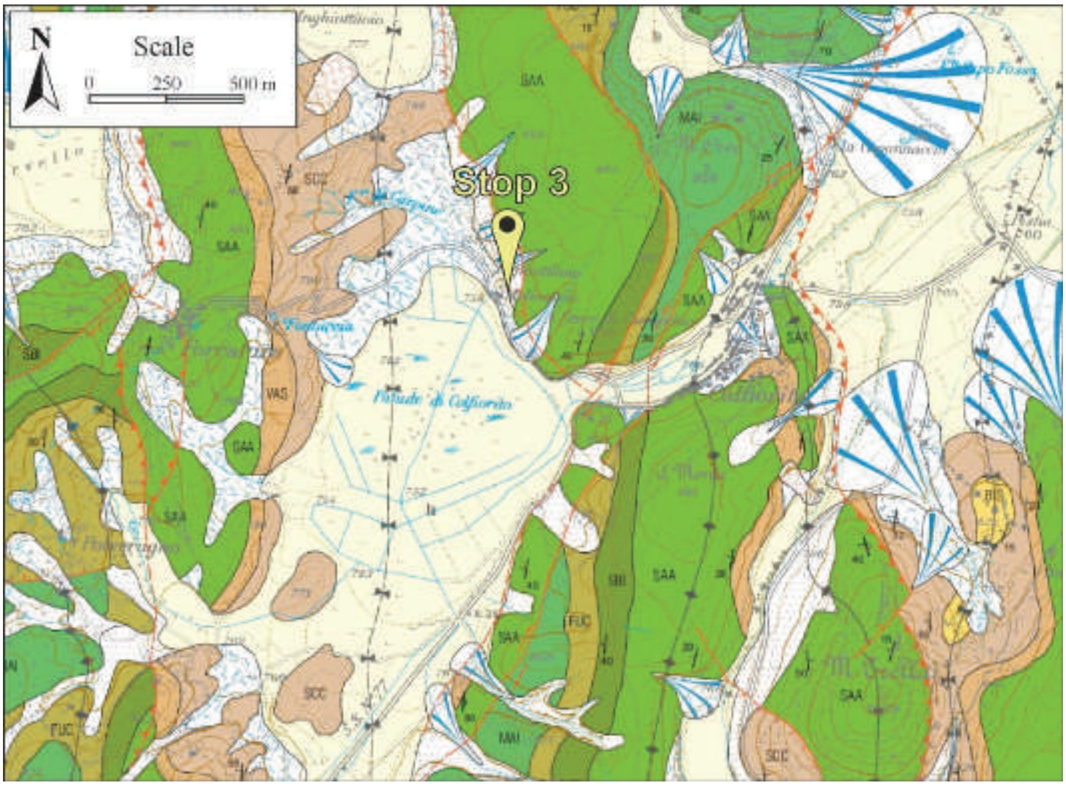


Fig. 2. 10. Geological map of the Colfiorito Swamp Area (Barchi et al., 2011).

The Colfiorito Swamp is a result of a natural ephemeral lake with a man-made canal system that directed all the water towards the swallow-hole. The gathered water was used for a mill in the 15th century. Later on, a dam was built in order to hinder the drainage through the swallow-hole. Situated at the foot of Mt. Orve, the "Molinaccio" sinkhole width ranges 10-20 m, the depth is 5 m and the swallow-hole drains 1.25 l/s. The sinkhole has developed in the damage zone of the fault that bounds the swamp basin.

Fig. 2. 12. Colfiorito Swamps

Karstism in the Umbro-Marche region is a common geomorphological phenomenon, due to widely present calcareous lithologies. The endokarstic features (caverns and secondary karstic features) are much more abundant than the exokarstic ones (sinkholes, swallow-holes) due to prevalent hypogenetic karstism and milder, dryer climate in this region. However, exokarstic features are found as sinkholes and swallow-holes. These are particularly related to areas with rocks of higher permeability, such as highly fractured rocks that enable the percolation of the meteoric water.

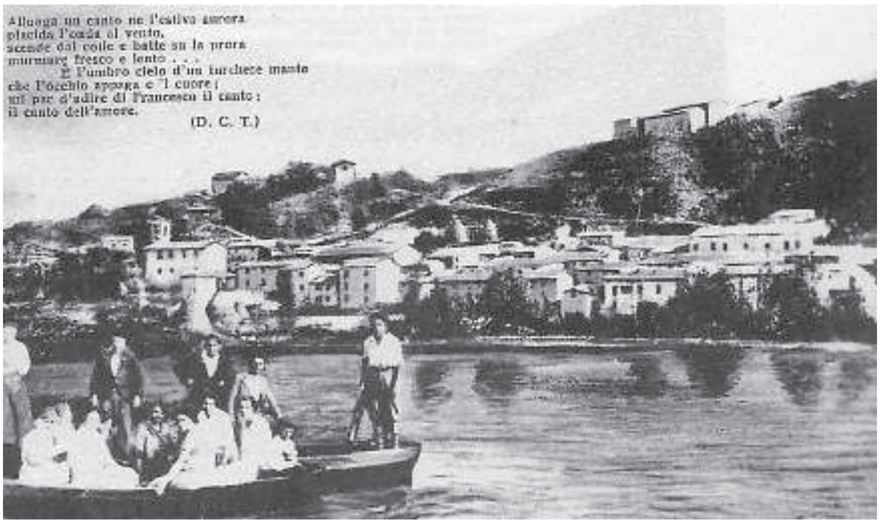


Fig. 2. 13. The Colfiorito Swamp around the year 1960. Notice the extent of the lake reaching Colfiorito town.

STOP 4: RED ZONE of the Camerino city: observation of damaged buildings related to the 2016 Amatrice, Visso and Norcia earthquake.

Photos refer to the Santa Maria in Via church that was highly damaged during the 26 October 2016 Visso earthquake of Mw 5.9.

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

3.1 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 (OpenEMERGEO_WG 2017). 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).

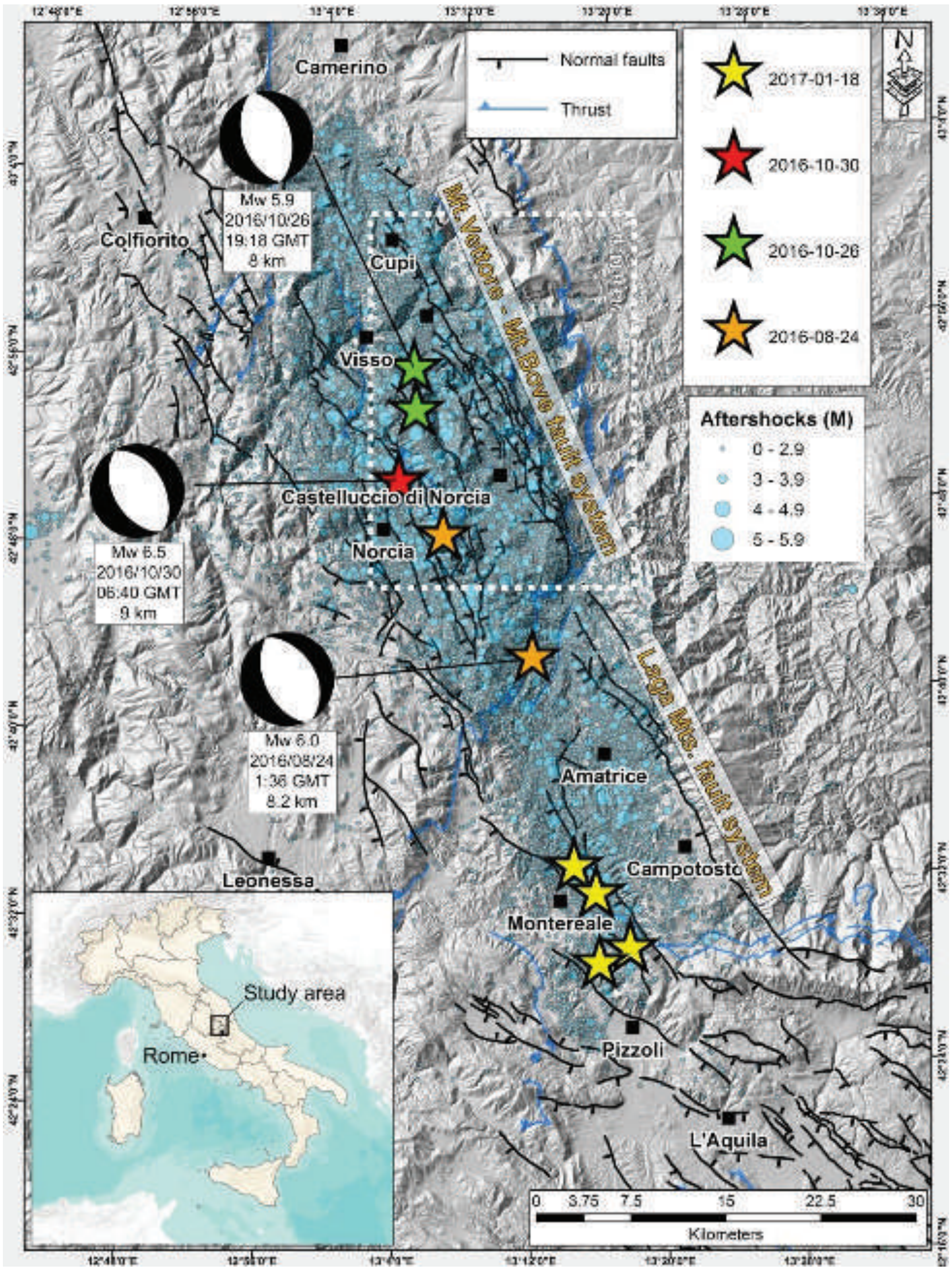


Fig 3.1. The 2016-2017 central Italy seismic sequence as recorded by the INGV Italian National Seismic Network (data from ISIDe - Italian Seismological Instrumental and Parametric Data-Base - http://iside.rm.ingv.it) for the time period of 24 August 2016 through 23 January 2017. Time Domain Moment Tensor 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. 3.1):

~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. 3.1). This seismic event produced coseismic effects on an area of nearly 450 km^2 mainly consisting of primary surface ruptures (Fig. 3.2), 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.3.2). 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 (OpenEMERGEO_WG 2017).

The ruptures involved mapped and (subordinately) unknown fault strands for a total cumulative surface rupture length of about 43 km (OpenEMERGEO_WG_MainMap2017).

Fig. 3.2. 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.

Furthermore, Aringoli et al. (2016) pointed out the presence of several trenches and double ridges, E-W oriented, along the alignment Punta di Prato-Monte Vettore (Fig. 3.4). All these features, showing lengths of more than 100m, width up to 4m and depth over than 1m and favored by dip-slope attitude, were partially filled with debris and vegetated at the bottom. Inside, crack and fractures around 20 cm deep and 5 cm wide, and free-faces on bedrock, as a consequence of the compaction of the filling material during the earthquake, have been evidenced. Also the south-western slope is strongly deformed and shows a convex morphology with presence of small dips and rounded counterslopes, filled by debris and soil material; despite the lithology is the same, the strata attitude changes along the slope with respect the top of the relief (Aringoli et al. 2016).

Fig. 3.3. Map of surface ruptures following the 30 October 2016 Mw = 6.5 Norcia earthquake, central Italy (Civico et al., 2017).

Fig. 3.4. Trench at the top of the Mount Vettore.

The above mentioned morphological elements confirm the presence of a deep-seated gravitational slope deformation (DSGSD), already recognized by Aringoli et al. (2010a, 2014 and references therein), that would affect the highest portion of the slope with a depth of hundreds of meters and partially covered by debris material (Fig. 3.5a and b). The genesis of this phenomenon that can be defined as a deep rock creep can be associated to the high relief, generated by the quaternary tectonic uplift, and to the interaction between the fault system of Monte Vettore and the portion of the Monti Sibillini thrust. The triggering factors can be related to seismic events (as in this case) or the effects following extreme weather events.

However, according to Wilkinson et al. 2017, such mechanisms are very unlikely to be the cause of the displacements observed in the Vettore fault system, as landslides and large-scale slope deformation are known to occur progressively over typical time periods of 45–220 seconds, whereas the finite coseismic displacement in the near-field occurred rapidly, within six to eight seconds of the hypocentre origin time (Wilkinson et al. 2017).

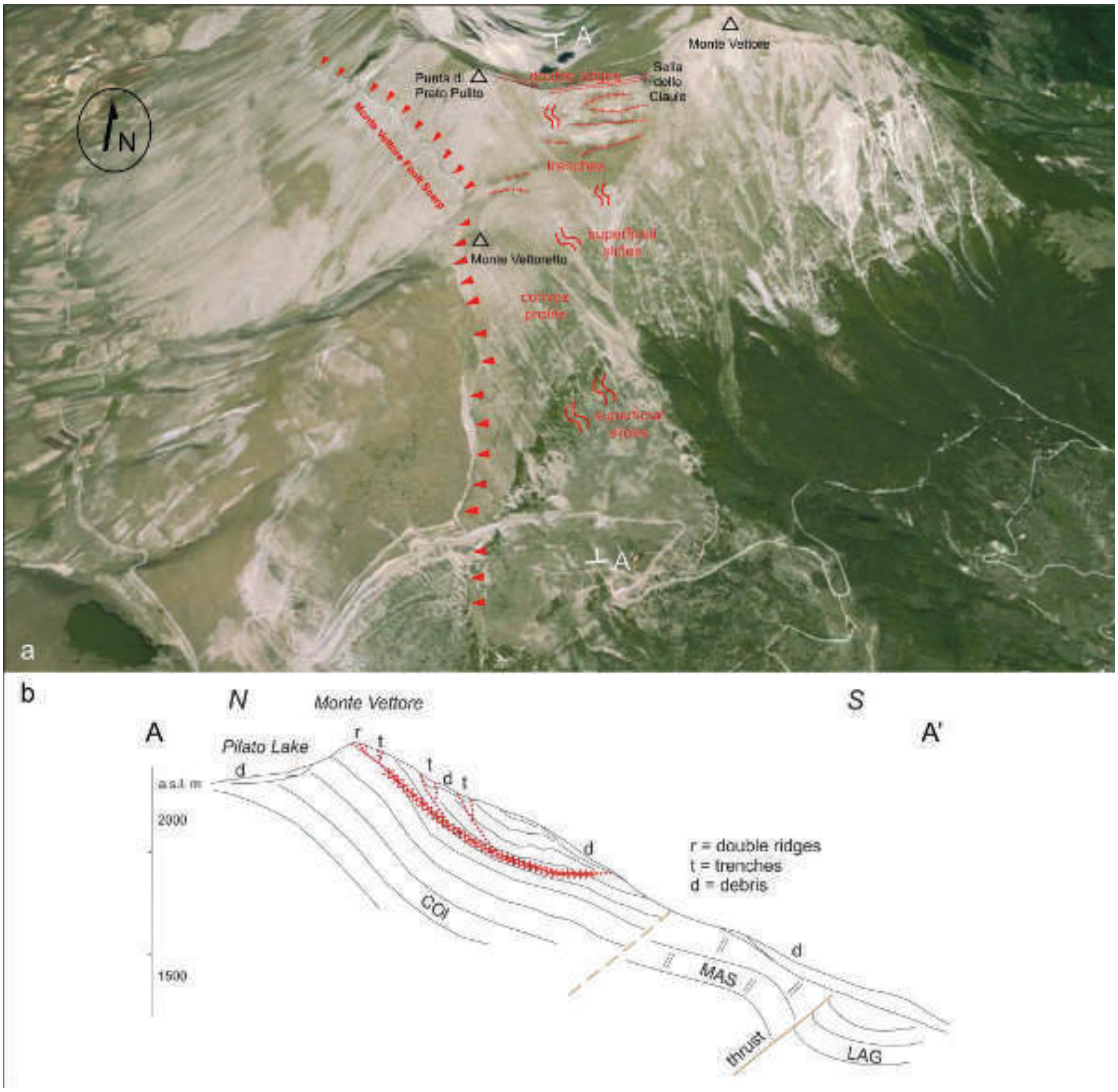


Fig. 3.5. a) Panoramic view of the southern slope of Monte Vettore, with indication of the main geomorphological elements (source Google earth): b) schematic cross section evidencing the geomorphological model of the DSGSD of Monte Vettore (Aringoli et al. 2016)

3.2 Field Trip

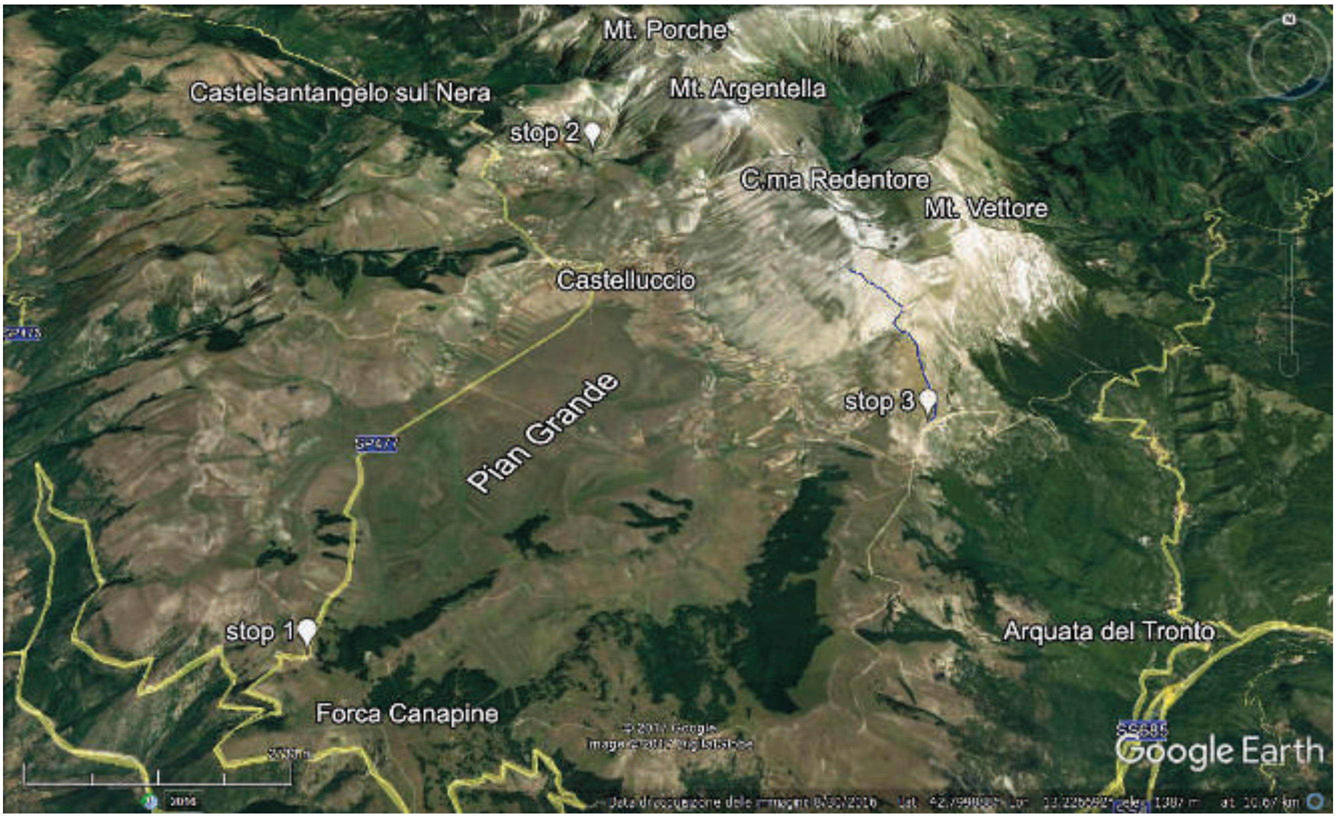


Fig. 3.6. Oblique view from satellite of the Southern part of the Sibillini Mountains where the stop locations are displayed.

From the satellite image in Fig. 3.6, 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 3 main villages visible in this area from NW to SE are Castel Sant'Angelo sul Nera, Castelluccio di Norcia and Arquata del Tronto. These villages 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 the southern part of the Pian Grande di Castelluccio, at the Forca Canapine promontory. Here, 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.

The second stop is located in Pian Perduto (municipality of Castel Sant'Angelo sul

Nera), about 3km north from Castelluccio di Norcia. In this location, the INGV leads the seismological investigation of two antithetic faults through trench sites cutting Holocene deposits.

In the third stop, there will be a hike along the "Cordone del Vettore" fault scarp, starting from Forca di Presta locality to "Scoglio dell'Aquila", the trail is highlighted by the blue line on Fig. 3.6.

STOP 1. Forca Canapine: panoramic view and 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. 3.9a) 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. 3.7). 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 (Fig 3.8) is produced by extensional tectonics with slight left lateral component.

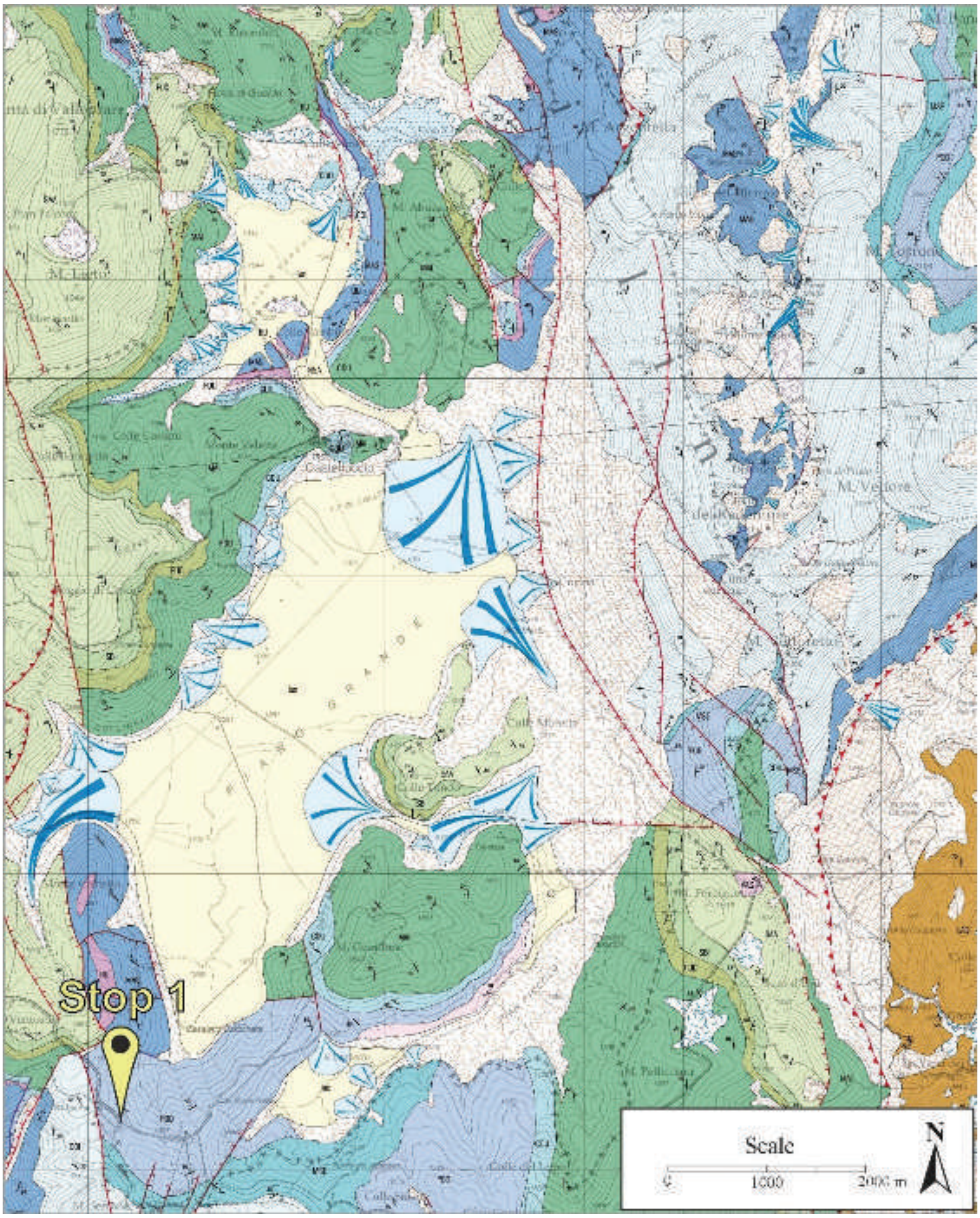


Fig. 3.7. Geological map of the western slope of Mt. Vettore (from: Pierantoni et al., 2013). Stop 1 shows your position.

Fig. 3.8. Geomorphological map of the Castelluccio di Norcia basin (source: Coltorti and Farabollini, 1995).

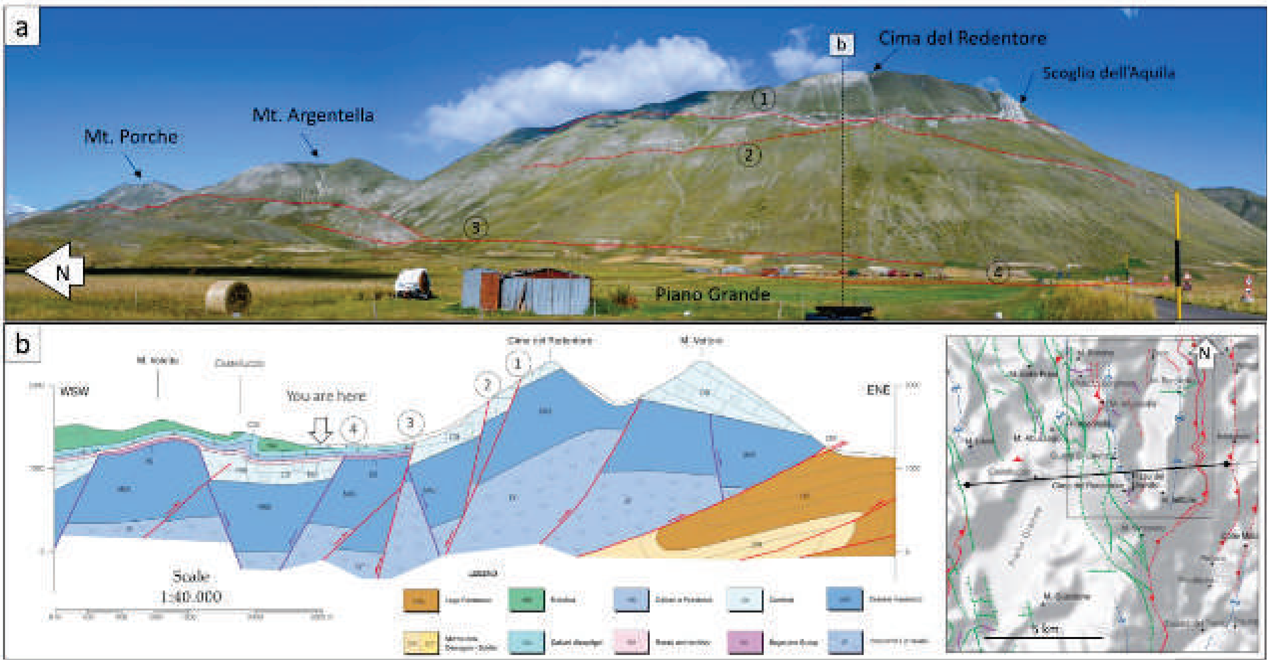


Fig. 3.9. Outline of the fault scarps related to the main normal faults of the Mt. Vettore-Mt. Bove system. a) Panoramic view of the Sibillini Mountains indicating the surface expression of major faults activated during the last earthquake sequence of 2016. b) Cross-section orthogonal to the panoramic 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.

STOP 2. Pian Perduto: visit to the paleoseismological trench sites at Fonte San Lorenzo

Previous paleoseismological investigations in the Castelluccio Basin (Galadini and Galli, 2003) provided stratigraphic evidence for three paleoearthquakes in the last 18 ka years.

This stop gives us the possibility to observe the paleoseismological investigations conducted by the INGV on two antithetic faults (Fig. 3.10) located on the Pian Perduto basin, eastward from Mt. Argentella. The Pian Perduto basin, as well as the Pian Grande di Castelluccio basin, is a depression of tectonic-karst origin, linked to the Quaternary activity of normal faults that have disrupted the landscape.

Inside the study area there are holocenic deposits overlaying pleistocenic detritic sediments, sometimes covered by a cemented horizon, developed in Mediterranean climate during the last Interglacial stage. In some cases, at the top of these deposits it is possible to observe a Bt horizon, decarbonate, rich in silica clasts.

Two trenches, about 2.5 m deep and 10 m long, have been excavated in order to study the seismic event that occurred in the past and which have permanently deformed the soil in proximity of the fault. The temporary trenches, in fact, have the purpose of highlighting the latest stratigraphy affected by structures or sediments that are the evidence of relevant earthquakes in the past.

Fig. 3.10. a) Panoramic view of the antithetic faults in Pian Perduto (highlighted by red triangles) subjected to paleoseismological investigation; b, c) close up of the fault plane showing ≈50cm throw.

The stratigraphic horizon to which the anomaly occurs is called "event horizon" and the next step is to date it and then date the earthquake that produced it. The dating is generally based on geochronological and archaeological methods. The radiocarbon method is certainly the most common and generally applies to the last 40-50 kyr.

STOP 3. Forca di Presta: visit to the paleoseismological trench site and walk along the "Cordone del Vettore" fault scarp

This stop consists of two parts, first we have an overview of a trench site in Forca di Presta for paleoseismological investigation; then 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.3.11b). Going a few meters to uphill, even more evidence of coseismic ruptures are found and the offset increases to 50-60 cm (Fig. 3.11c). Continuing up to the end of Mt. Vettoretto the observable offset gradually increases up to 60-80 cm (Fig. 3.11d). 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. 3.11e).

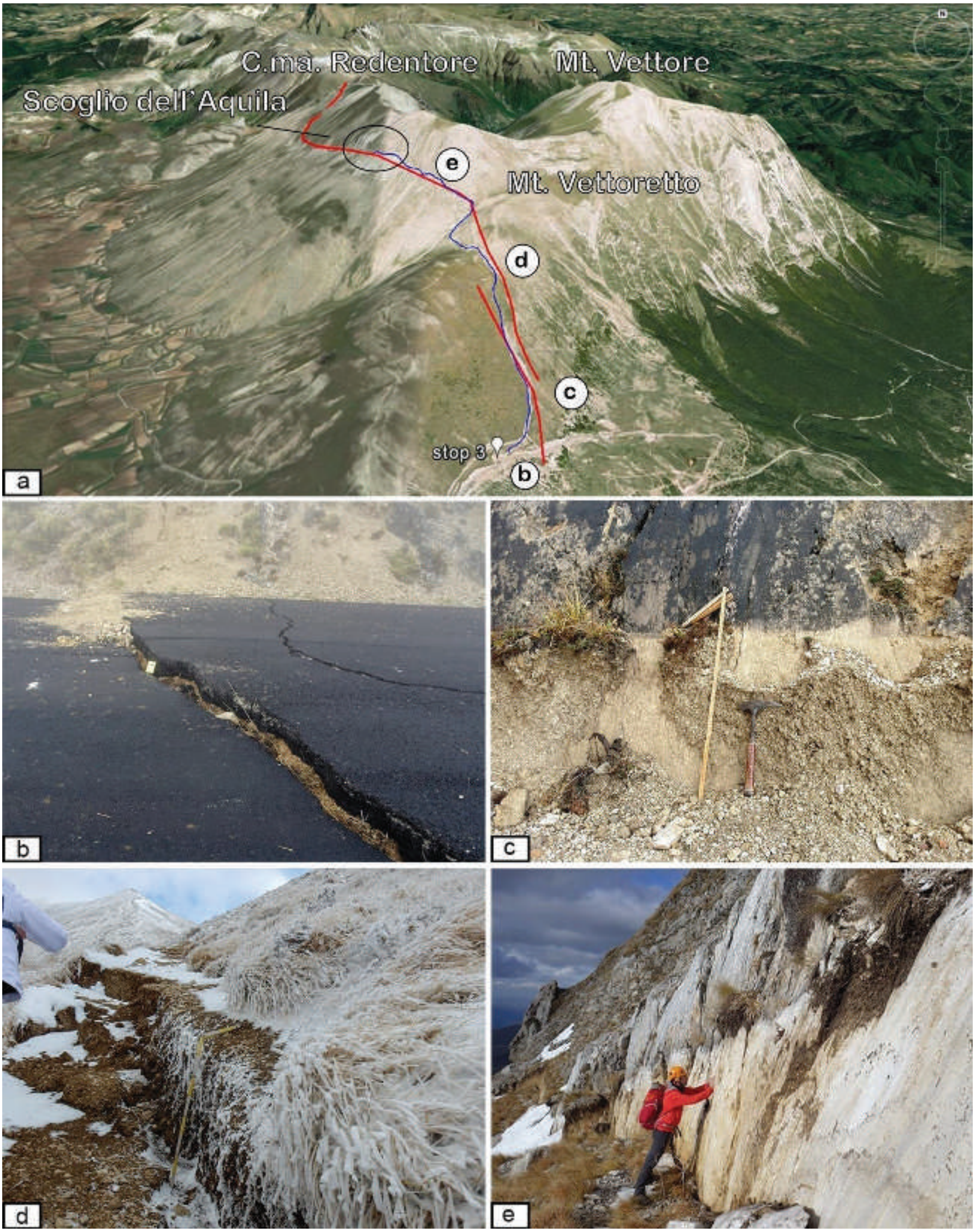
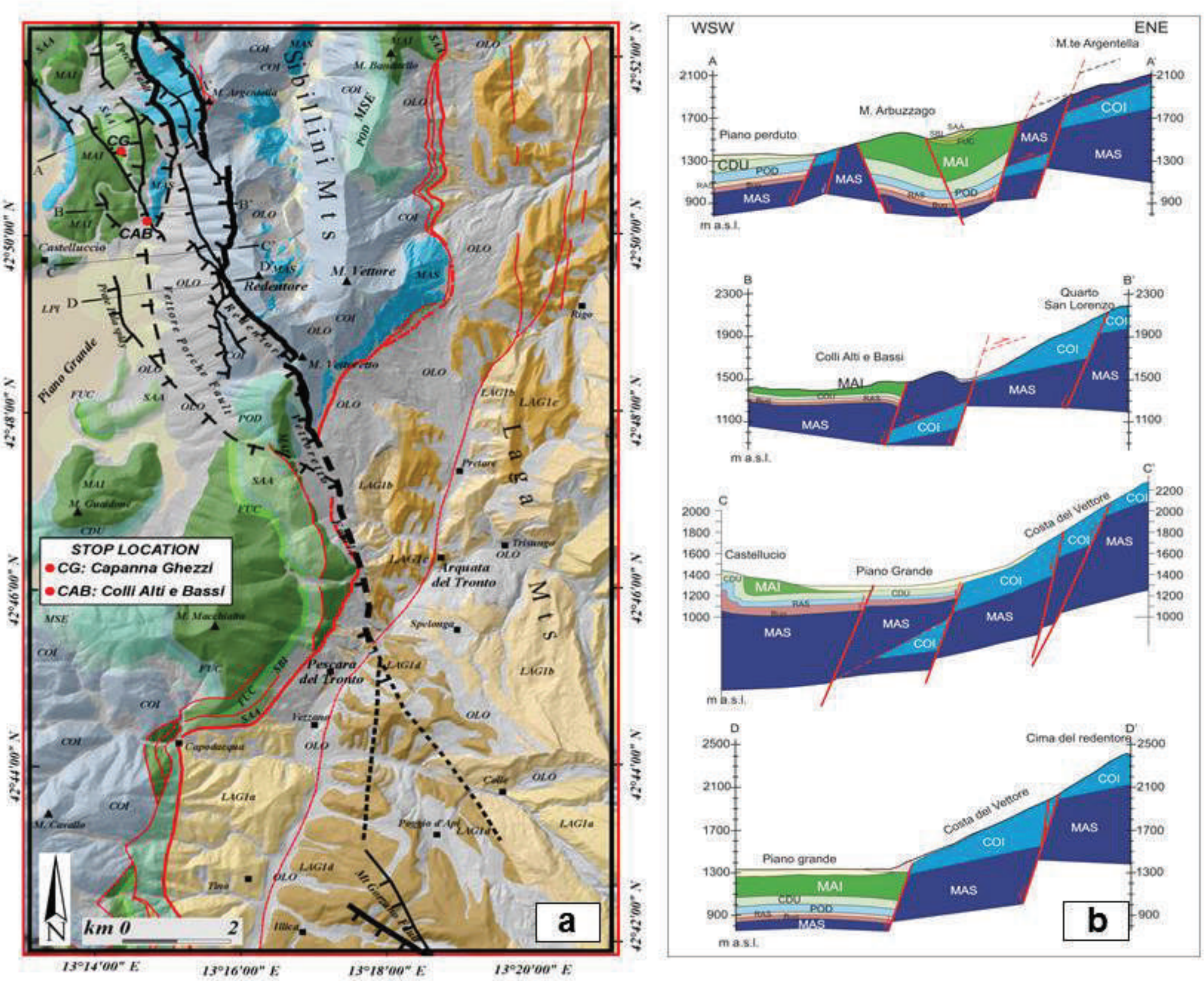


Fig. 3.8. a) Satellite view of the location, blue line: hike route, red lines: faults extracted by Pierantoni et al. 2013; b, c, d, e) coseismic structures encountered along the walk.

STOP 4. Colli Alti e Bassi (optional): 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. 3.9a).

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. 3.9b, 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).



3.9. 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 refers 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 (color code as in the previous Fig.1a)

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.3.10). 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.3.10).

Fig. 3.10: **STOP CAB**: Spectacular outcrop of the Colli Alti e Bassi normal fault showing the free face due to coseismic slip of the October 30 Mw 6.6 earthquake.

After leaving Colli Alti e Bassi, the group head 1,5 km northward along a NS-oriented valley, towards Capanna Ghezzi. 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. 3.9a).

STOP 5. Capanna Ghezzi (optional): coseismic rupture on soil

Fig.3.11: a) panoramic view of the coseismic ruptures originated during the 30 October Mw 6.6 event along the trace of the Mt. Arbuzzago east-dipping antithetic normal fault; b) detail of a minor diverging splay dissecting a rural hut.

In this site, we can observe a continuous rupture that rips the grassy slope of Mt Arbuzzago, with associated coseismic displacements of 20 to 40 cm. The rupture runs along the tectonic contact which downthrows the Aptian-Albian Marne a Fucoidi Fm against the Titonian-Berriasian Maiolica, with a minimum offset of ~75 m. It corresponds to a NW-SE-striking, east-dipping, normal fault antithetical, to the CAB and, in general to the Mt Vettore fault set.

The Mt. Arbuzzago fault is in left-lateral en-echelon arrangment with the northernmost S.Lorenzo-Portella del Vao fault, crossed by the trench visited in the morning.

A minor diverging splay, which branches for the major rupture in nearly E-W direction, dissects abruptly a rural hut, built along its trace. This latter splay bounds southward a small depression filled with eluvial colluvial Holocene sediments. Also in this area, characterized by smooth and rounded reliefs, the strong control of the active tectonic structures on the present morphology appears evident.

4. DAY 3: The 2009 April 6th L’Aquila earthquake (Mw=6.3)

Fig. 4.1. Stop locations for July 22, 2017: the epicentral area of 2009 L'Aquila earthquake

STOP 1. Geological setting of the L’Aquila – Middle Aterno valley and the 2009 April 6th L’Aquila earthquake

The L’Aquila area is located in the hanging wall of the Gran Sasso thrust, the structural unit which coincides with the highest elevations in the Apennines. This block of the Neogene Apennine chain is dissected by a set of WNW-ESE trending normal faults including the Assergi Fault and Paganica-San Demetrio Fault showing a staircase geometry toward the Middle Aterno valley (Figs. 4.2, 4.3).

The Paganica-San Demetrio Fault and the Aterno valley

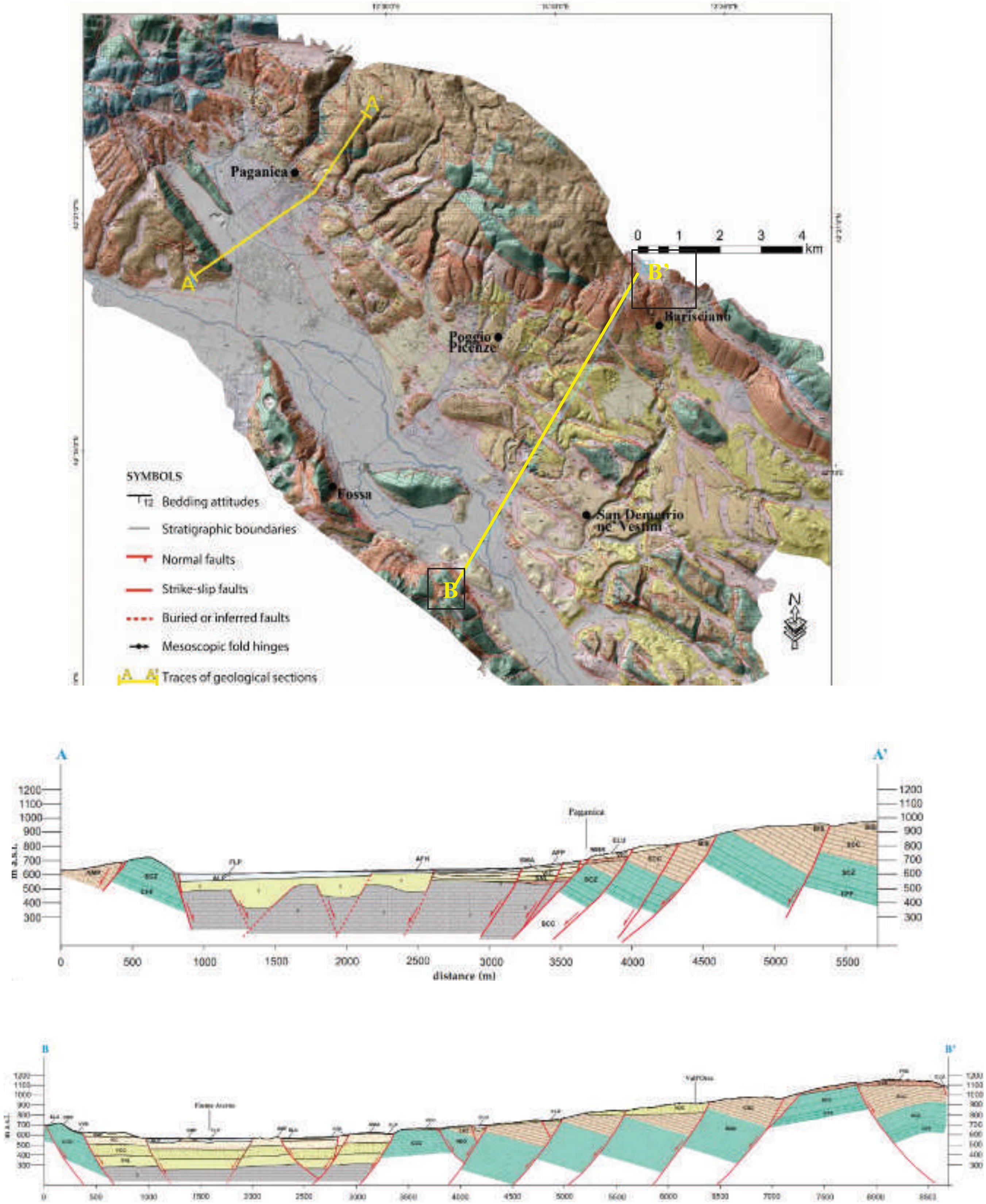


Fig. 4.2. Geological map and profiles of the Middle Aterno Valley (modified after Pucci et al., 2014).

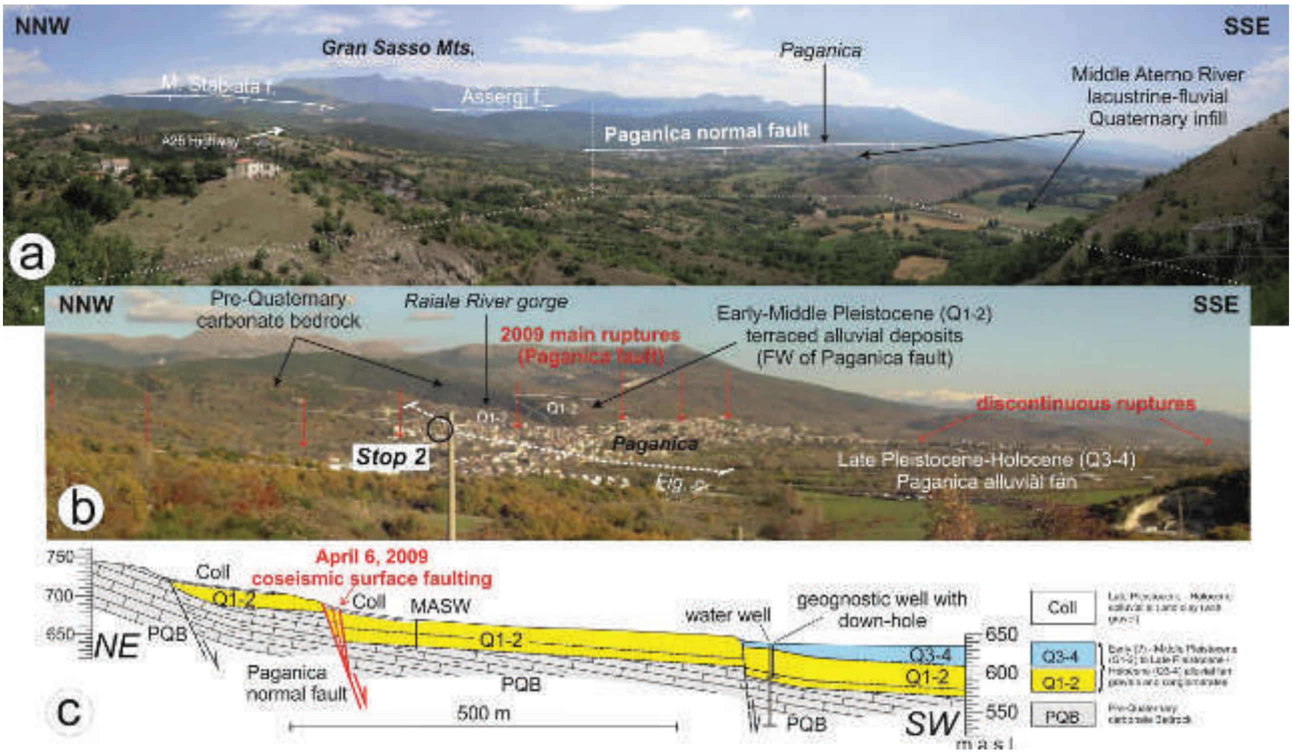


Fig. 4.3. a, b) Stop 1: view to the ENE of the northern termination of the Middle Aterno Quaternary basin and the Pagnaica normal fault (downthrown side toward the observer). The Paganica fault was reactivated by the 2009 L'Aquila earthquake. At the Paganica village, the footwall of the fault is formed by Early (?) - Middle Pleistocene fan gravels (Q1-2), unconformably covering the carbonate bedrock. In the hanging wall, Middle to Late Pleistocene fan gravels (Q2 and Q3) and scarp-derived Late Pleistocene - Holocene Colluvial deposits crop out. c) Simplified geologic section across the Paganica fault (modified from Boncio et al., 2011).

Quaternary Stratigraphy of the Middle Aterno Valley

The Middle Aterno Valley is a 18 km-long, 3 to 6 km-wide Quaternary intramontane basin located south-east of the town of L'Aquila. The basin is characterized by the presence of an extensive cover of lacustrine and fluvial/alluvial Quaternary deposits accumulated upon a Meso-Cenozoic mainly carbonate bedrock and generally separated by unconformities and/or juxtaposed by the several fault splays detectable in the area (Figs. 4.4).

Continental deposits overlying the bedrock sequence have been investigated by several authors (Bertini and Bosi, 1993; Giaccio et al., 2012; Pucci et al., 2015; Cosentino et al., 2017) and can be referred to six main depositional cycles: (1) Early

Pleistocene slope-derived carbonatic breccias (*L'Aquila Megabreccias* and *Valle Valiano Fms.* – MBR, VVB, VVC); (2) Early Pleistocene lacustrine and fluvio-lacustrine sequence (*Limi di San Nicandro Fm.* - SNL), composed of whitish silts and clayey silts with gravel lenses, up to 100 m thick; (3) Early Pleistocene alluvial sequence (*Vall'Orsa Fm*. - VOC), partially heteropic with the *Limi di San Nicandro Fm.*, and consisting of deltaic carbonatic conglomerates showing foreset and bottomset beds (100 m thick); (4) Early-Middle Pleistocene alluvial fan sequence (*Valle Inferno Fm.* - VIC), consisting of well-bedded carbonatic conglomerates showing topset beds, with sparse silty layers and palaeosoils and (5) Middle-Late Pleistocene fluvial and alluvial sequence, made of silts, sands and gravels, interbedded with volcanoclastic layers (*San Mauro Fm.* – SMF, SMA). All these deposits are covered by (6) Late Pleistocene-Holocene fluvial/alluvial sediments, mainly related to the Aterno River, and by slope debris and colluvial deposits.

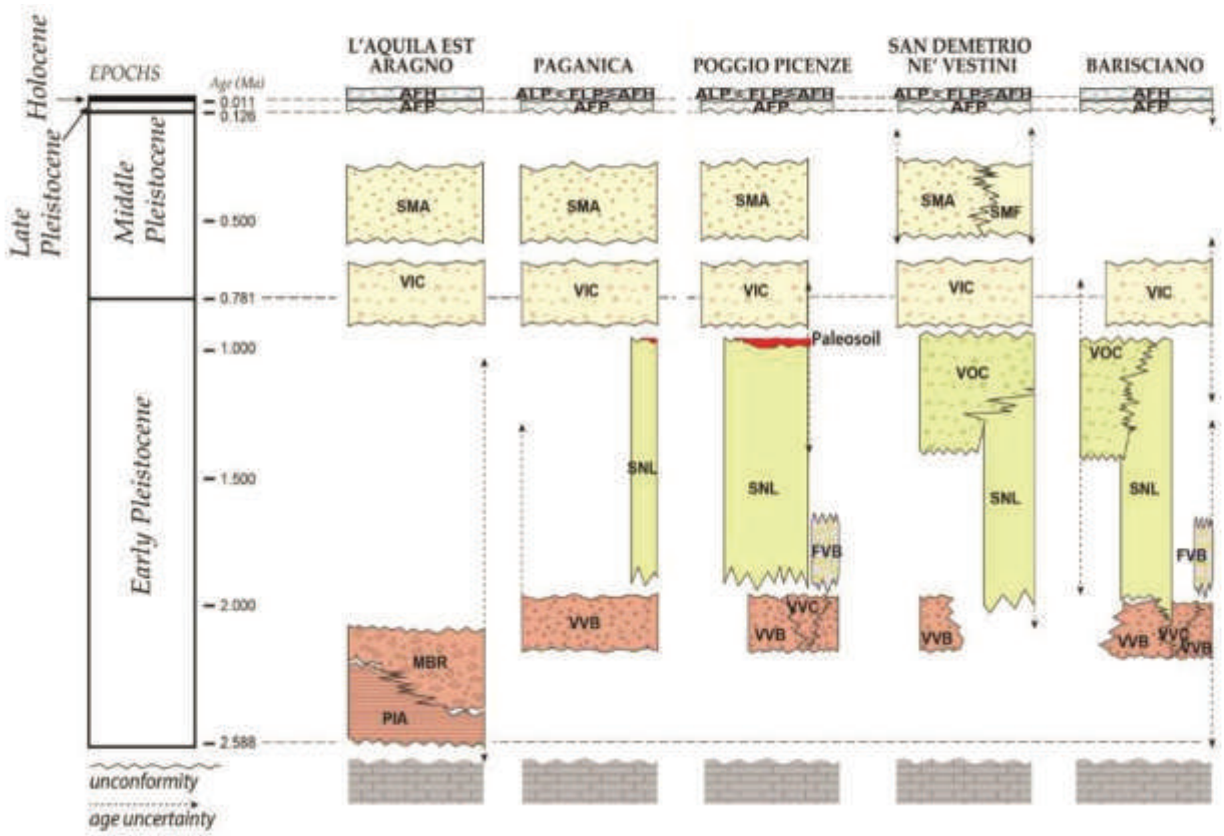


Fig. 4.4. Scheme of the stratigraphic relationship of the Quaternary deposits (modified after Pucci et al., 2014).

The 2009 April 6th L'Aquila earthquake (Mw=6.3)

On April 6, 2009, a Mw 6.3/6.1 earthquake (Chiarabba et al. 2009; Herrmann et al., 2011) struck a densely populated region in the Abruzzi Apennines and was felt in a wide area of central Italy. Due to its location and relatively shallow hypo-central depth (~10 km), the earthquake caused heavy damage in the town of L'Aquila and surrounding villages (Fig. 4.5).

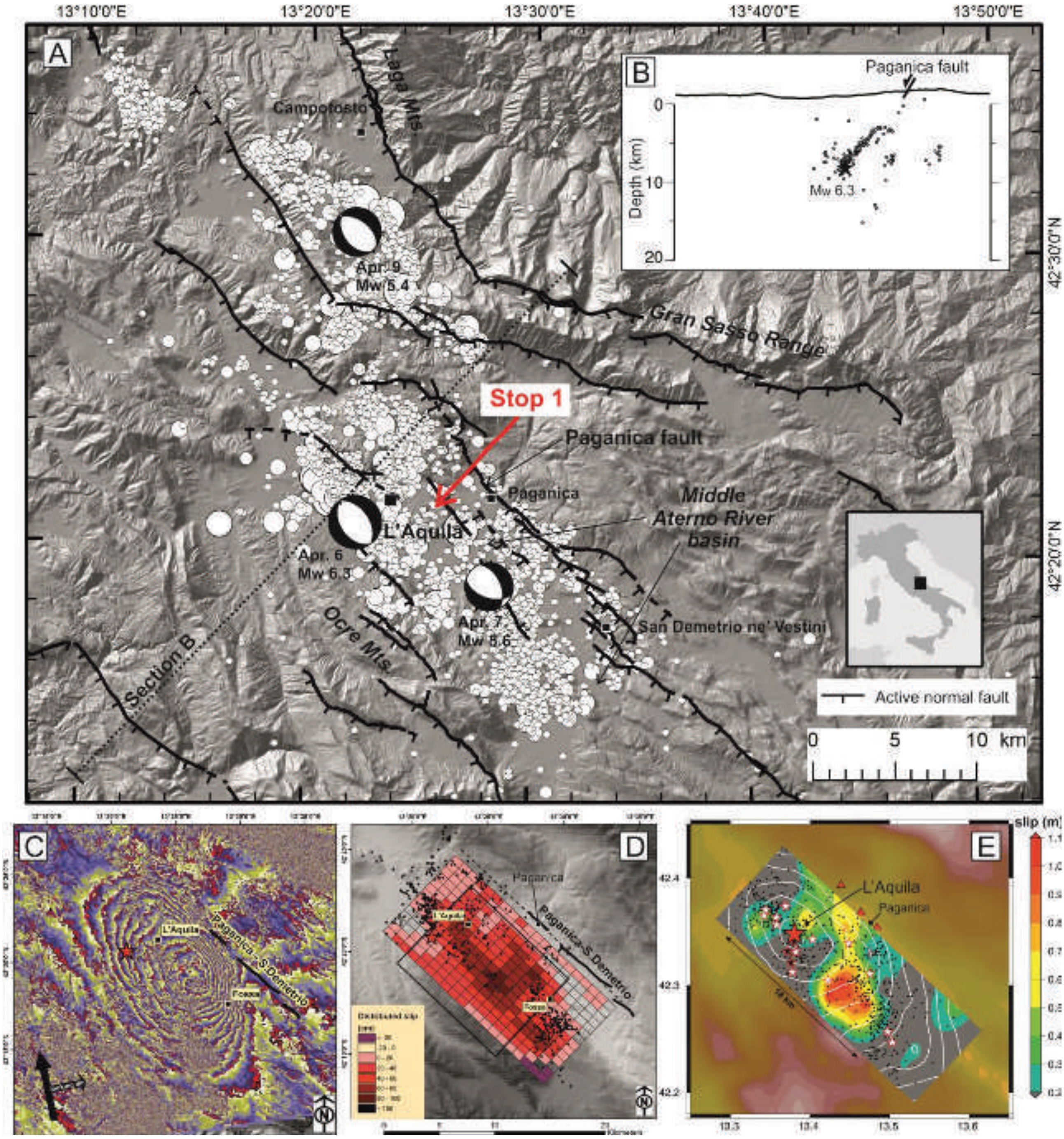


Fig. 4.5. A) Aftershocks of the 2009 L'Aquila seismic sequence and focal mechanisms of the largest shocks; B) Hypocentral section across the April 6th mainshock (Chiarabba et al.,

2009); C) DInSAR from COSMO-SkyMed images and D) variable-slip fault model from DInSAR and GPS data (Atzori et al., 2009); E) Variable slip fault model from strong motion and GPS data (Cirella et al., 2009).

The Paganica - San Demetrio Fault System (PSDFS), bounding the Middle Aterno Valley to the east, was interpreted as the surface expression of the 6 April 2009 earthquake causative fault, and along its NW sector >3 km of primary coseismic ruptures were observed (Fig. 6) (Falcucci et al., 2009; Boncio et al., 2010; EMERGEO Working Group, 2010; Galli et al., 2010; Lavecchia et al., 2010; Vittori et al., 2011).

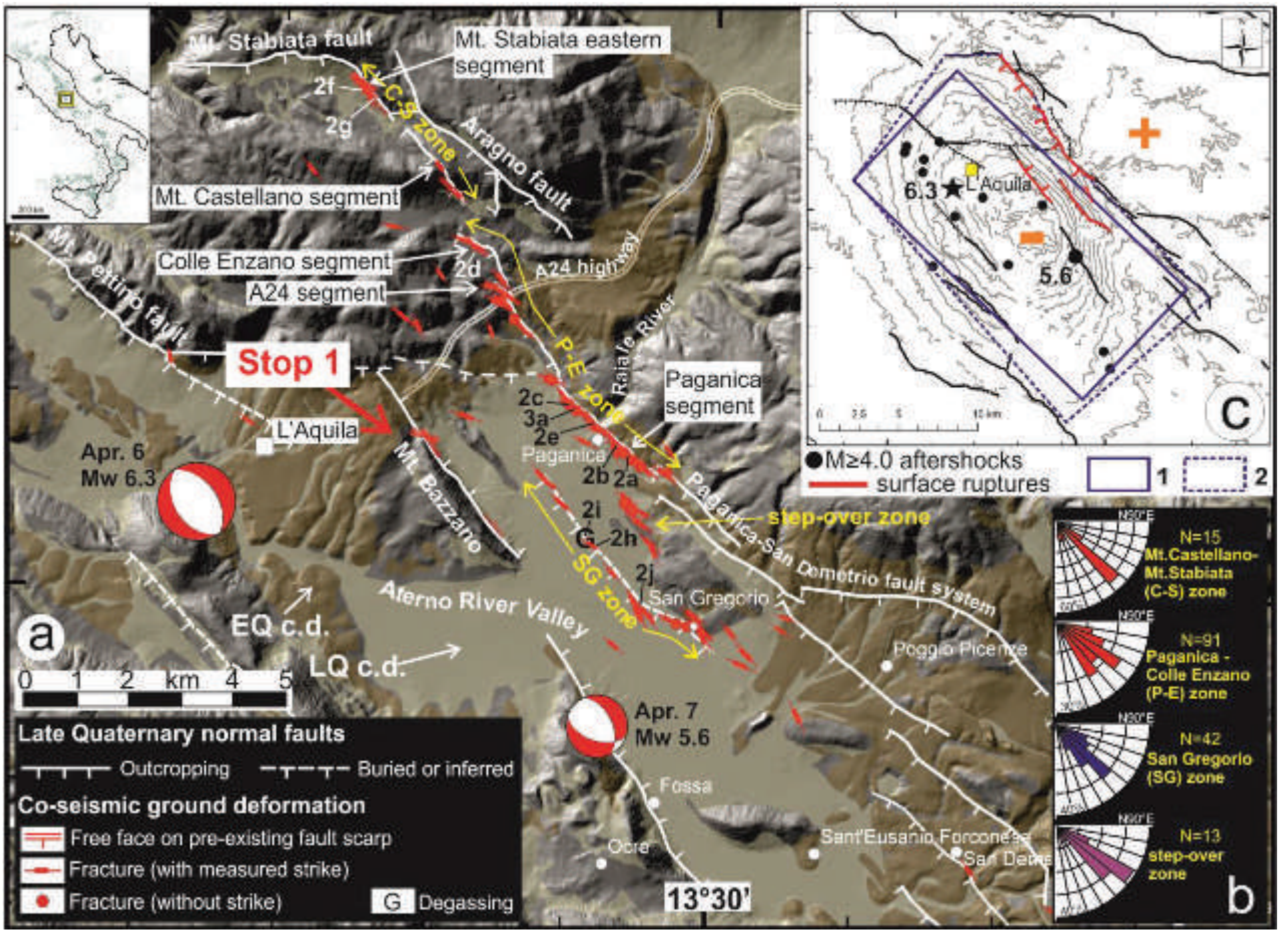


Figure 4.6. (a) Map of the L'Aquila 2009 epicentral area with active (late Quaternary) normal faults (modified from Pizzi et al., 2002 and Boncio et al., 2004) and point measurements of coseismic ground deformation; EQ c.d. (brown color) and LQ c.d. (light brown) are early and late Quaternary continental deposits, respectively; (b) strike rose-diagrams of structures in the main zones of coseismic deformation; (c) comparison among COSMO-SkyMed DInSAR fringes (from Atzori et al., 2009), surface ruptures (red), surface projections of model faults (1 = variable-slip source model from Atzori et al. 2009, 2 = geological fault from this paper) and, epicenters (star and dots) (modified from Boncio et al., 2010).

STOP 2. Surface faulting evidence along the Paganica-San Demetrio Fault

Evidence of surface faulting along the Paganica fault has been documented by a set of irregular but very well aligned ruptures, trending N120 to N140 along the Paganica fault zone, along the NE margin of the Paganica village. More precisely, the ruptures appear in the hanging wall, at a distance ranging from some meters up to a few tens of meters away from the known main fault scarp. The ruptures were mapped from NW of Tempera to the Paganica – Pescomaggiore Road to SE, and affected the natural ground as well as artificial surfaces (paved/concrete roads, parking lots, private gardens) and buildings (floors, walls and concrete frames). The fault ruptures have been mapped almost continuously for a measured length of 2.6 km (Fig. 4.7).

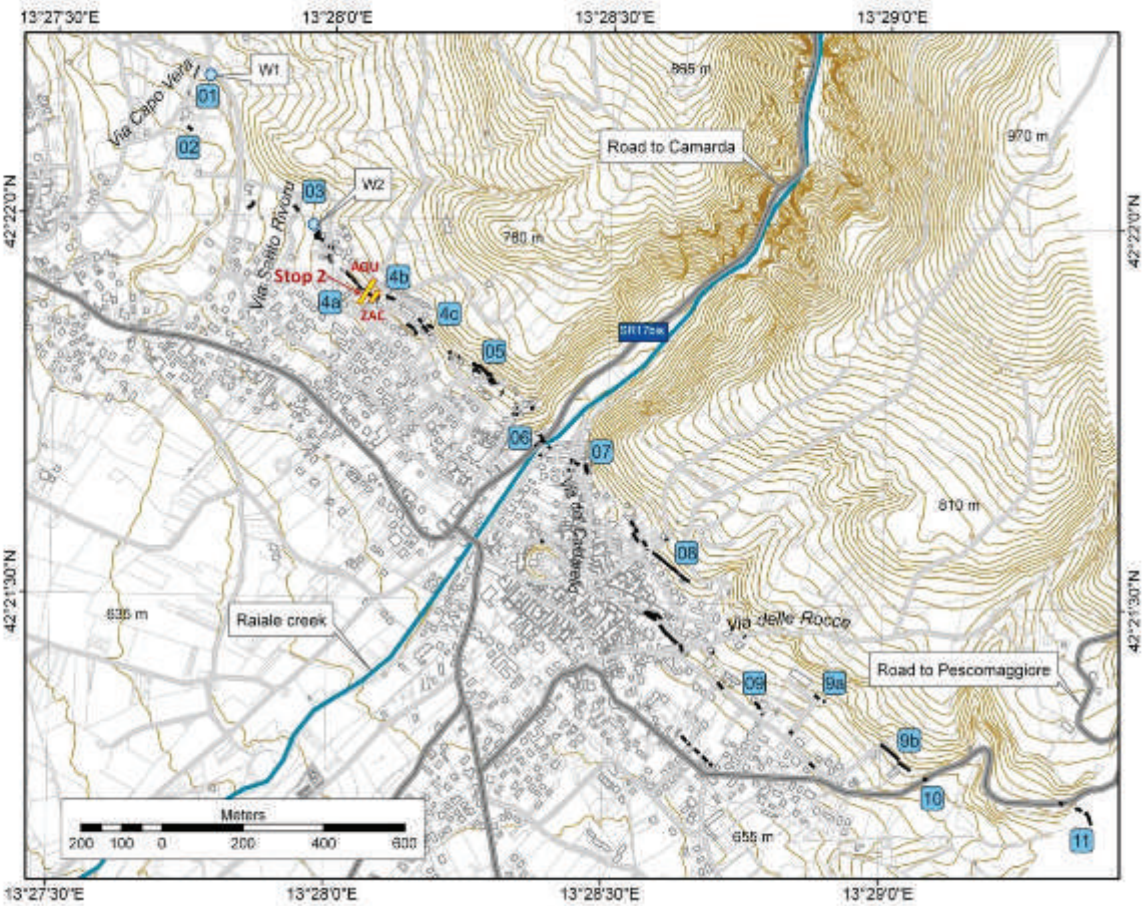


Fig. 4.7. The two yellow lines locate the Zaccagnini and the Aqueduct trench sites; this last site is the place where the coseismic surface faulting produced the rupture of Gran Sasso Aqueduct (after Vittori et al., 2011). INGV - ISPRA joint Surface Faulting Database - Mw 6.3, 2009, April 6th L'Aquila earthquake (Central Italy) http://ingv.maps.arcgis.com/apps/webappviewer/index.html?id=05901efc172e489f8db4198bc43bf507

It is noteworthy that many fractures did not display appreciable vertical offsets while others showed throws higher than 10 cm. Considering the post-seismic offset of about 2-3 cm (e.g. McCaffrey et al., 2009) within the first days after the mainshock, the true maximum coseismic vertical offset can be evaluated in the order of 7-8 cm.

Just west-northwest of Santa Croce street (San Gregorio locality, site 04 in Fig. 4.7; see photos in Fig. 4.8) the water main (diameter 70 cm) of the Gran Sasso aqueduct (mean flow rate 0.5 cubic m/s, pressure reaching 40 bars), which feeds L'Aquila, was severely damaged. The pipe failed and the high pressure water outflow produced gully erosion and a mud flow that invaded the streets and houses down-slope. The deep trench and following excavation to repair the rupture provided an extraordinary exposure of sediments displaced by a system of fault splays, and unequivocal paleoseismological evidence of Holocene coseismic offset significantly larger than that of the last event.

Fig. 4.8. Coseismic faulting at Paganica in the area of the Gran Sasso aqueduct. (a) Fault scarp across the broken aqueduct (center); arrows mark the trace of the coseismic rupture. (b) Oblique aerial view taken in 2008 of the Gran Sasso aqueduct area and (c) same area of (b) just after the earthquake. The erosion determined by the water main rupture and consequent downslope debris flow are evident in the center of the photograph in (c). (d) Detail of the aqueduct trench (southeastern wall), showing a displaced dark brown paleosol. (After Vittori et al., 2011).

Paleoseismological investigations (Aqueduct and Zaccagnini sites)

Four paleoseismic trenches were excavated by INGV along the Paganica Fault (Cinti et al., 2011). The detailed stratigraphic logs of Aqueduct and Zaccagnini sites are shown respectively in Fig. 4.9 and 4.10 (see location in Fig. 4.7).

According to these investigations i) the 2009 Paganica rupture traces at surface coincide to mainly normal, high-angle dipping, fault planes at depth; ii) the repetition of five distinct paleoevents of faulting was recognized on the same fault zones; ii) contemporary rupture of multiple strands recurred also in the past four earthquakes, like in 2009; iii) the vertical displacement for each paleoevent along the investigated part of the fault has a low variability; iii) the penultimate event that ruptured the Paganica fault is the 1461 earthquake; iv) the measured throws associated to each of the five events vary from small (<0.3 m) to larger (>0.3 m); older events seem consistently larger in slip; v) the overall average recurrence of surface faulting along the northern portion of the Paganica fault is of ~1250 yr (5 events since BC 2900), but the seismic history is punctuated by small earthquakes separated by ~500 yr and large ones separated by longer intervals; v) Holocene and Late Pleistocene dip-slip rates for the investigated portion of the fault are consistent, and range between 0.2 and 0.5 mm/yr.

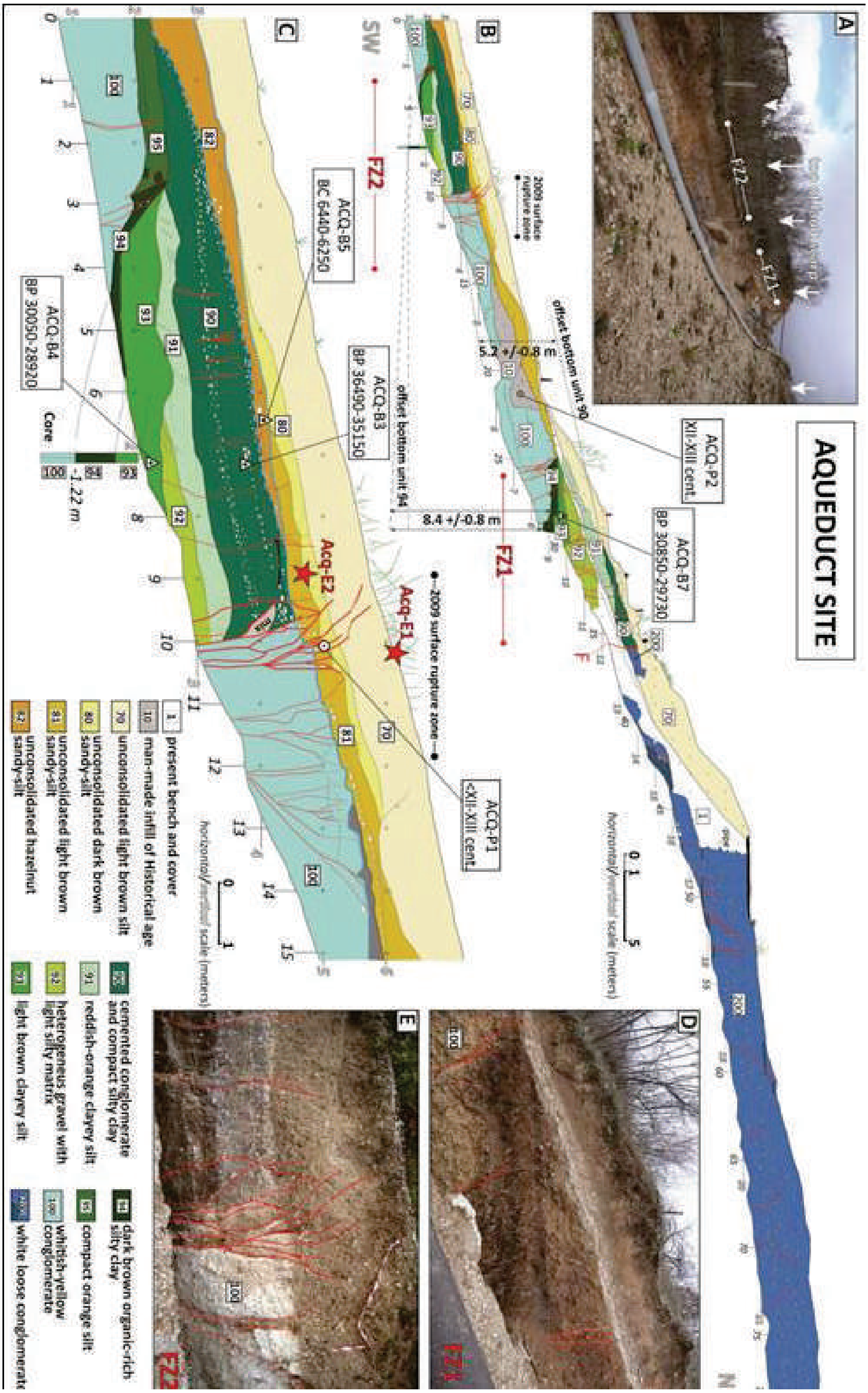


Fig. 4.9. Aqueduct site trench (after Cinti et al., 2011). (a) excavation along the PSDFS where it crosses the 20 m-high cumulative scarp. (b and c) detailed log of the NW wall of the trench; (d and e) view of the main fault zones. At this site, the 2009 ruptures occurred at the base of the scarp on the fields and tarmac road adjacent to the pipeline. In coincidence of FZ2 the 2009 ruptures produced diffuse deformation accompanied both by cracking and warping.

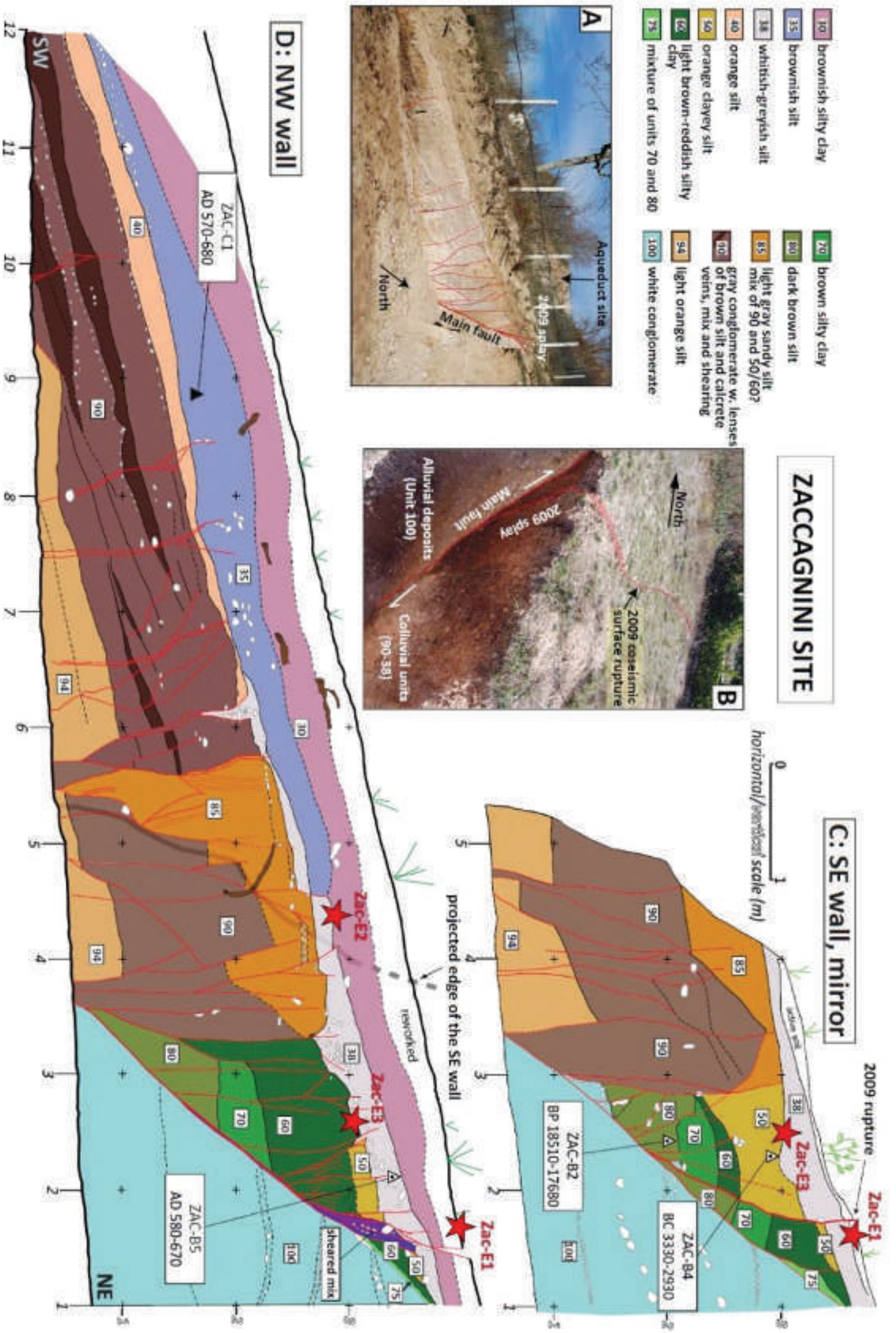


Fig. 4.10. Zaccagnini site. (A) View of the NW, long trench wall. (B) View of the SE, short trench wall. (C) Simplified log of the SE wall (average orientation N40°E) from a 1:20 scale survey. Triangles indicate dated radiocarbon samples (Table 1), red stars indicate location of event horizons. (D) Simplified log of the NW wall, symbols are the same as in C.

STOP 3. L'Aquila city centre (Piazza Duomo)

L'Aquila is a moderate-sized city (about 70,000 inhabitants). It was founded in the half of the XIII century, becoming soon the most important center of the area. *Piazza Duomo*, is the biggest square of the city and the market place since 1303. The square has always represented the cultural centre of the city. There are two main churches in *Piazza Duomo*: *S. Maria del Suffragio church* (southern side) and the *Cathedral of Santi Massimo e Giorgio* (western side), see Fig. 4.11. The geology of the city and the stratigraphy beneath *Piazza Duomo* are schematized in Fig. 4.12.

Fig. 4.11. a) L'Aquila city centre; b) S. Maria del Suffragio church after the 2009 earthquake.

The *Cathedral of Santi Massimo e Giorgio* was built in 1257 and repeatedly restored during times for damage caused by earthquakes. Historical chronicles report that this church, reconstructed after the 1315 earthquake, totally collapsed during the destructive 1703 event. Also the 1915 earthquake (Fucino earthquake, about 40 km to the SSE) damaged this church. During the 2009 earthquake the cathedral was severely damaged, in particular the dome, the transept and the triumphal arch collapsed. Also the vaulted ceiling was severely damaged.

The *S. Maria del Suffragio church* (better known as *Anime Sante Church*, Fig. 4.11b) was starting to be built soon after the 1703 earthquake in place of a small church that was destroyed by the earthquake. The church was severely damaged by the 2009 earthquake, in particular the superb dome (attributed to G. Valadier), and the lantern and the spires collapsed. The triumphal arch and roofing were in danger of collapse.

Geology of L'Aquila city

L'Aquila is a moderate-sized city (about 70,000 inhabitants). It was founded in the half of the XIII century, becoming soon the most important centre of the area.

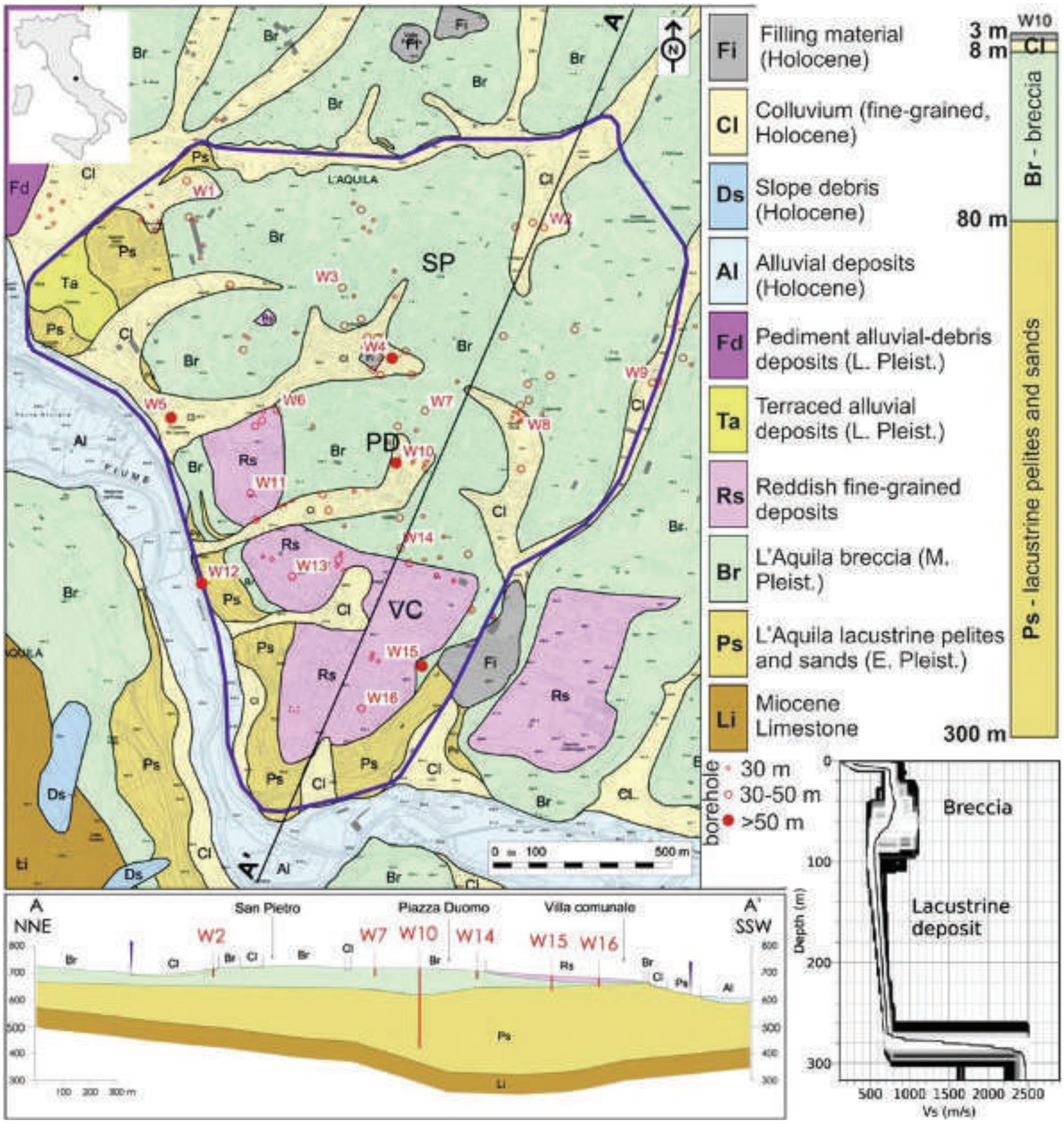


Fig. 4.12. Geology of L'Aquila city - The city center is placed on a flat terraced hill whose schematic stratigraphy consists of, from the top to bottom, Middle Pleistocene 80-100 m-thick calcareous breccias ("Brecce dell'Aquila" - Br), which lay on a 250-270 m-thick unit formed by Early Pleistocene fluvial-lacustrine pelites and sands (Figs. 13). In particular, the "Brecce dell'Aquila" are highly heterometric (breccias and megabreccias), poorly sorted, with angular to sub-angular carbonate clasts in a whitish-yellowish calcareous sandy-silty matrix. The fluvial-lacustrine deposits consist of fine- to medium-grained silts. The latter ones are placed onto the Meso-Cenozoic carbonate bedrock, whose depth decreases toward the NE, as testified

by deep boreholes, gravimetric and seismic reflection investigations. The "Brecce dell'Aquila" thickness decreases from about 100 m in the central sector of the historical centre (i.e. Piazza Duomo) to 0-10 m in the southern slope of L'Aquila hill, where they are laterally replaced by sands, pelites and calcareous gravels and breccia layers (Del Monaco et al., 2013). Further, at places, some underground caves (empty or filled with 1-10 m thick epikarst fine-grained residual soils named "Terre Rosse" - Rs) are present in the "Brecce dell'Aquila" (Amoroso et al., 2010; Del Monaco et al., 2013; Di Giulio et al., 2014; MS–AQ Working Group, 2010; Tallini et al., 2011)

The seismic history of L'Aquila and the effects of the 2009 earthquake

The first event that was reported to cause damage in L'Aquila occurred on 1315. Since then, L'Aquila has experienced several strong earthquakes (Fig. 4.13). The city, which was heavily destroyed after all these events, has been restored each time.

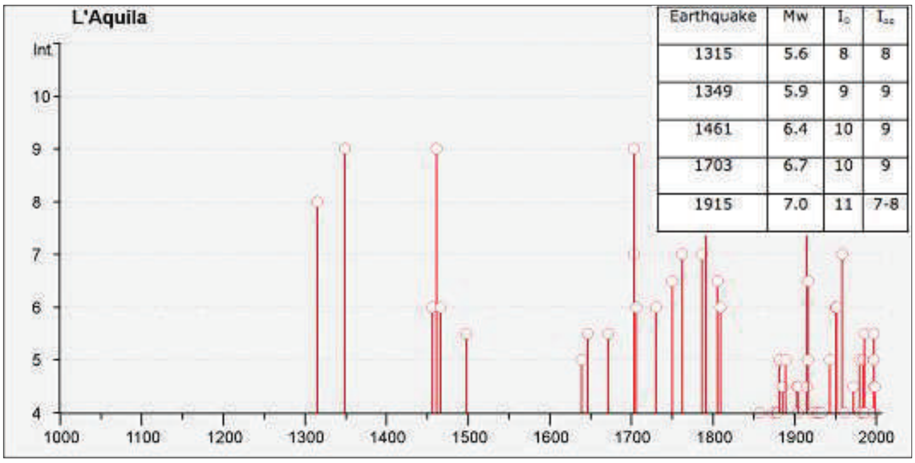


Fig. 4.13 Seismic history of L'Aquila, before 2009. (Locati et al., 2011). Table lists the earthquakes that produced the most severe damage.

In particular, the 1461 event is considered, by historians and city planners, responsible for the disappearing of the medieval housing in L'Aquila (Clementi and Piroddi, 1986), while the 1703 earthquake marked the birth of the present urban plan. This event was a major disaster in the history of L'Aquila and occurred during a long period of political and economic decline, in which further minor earthquakes (occurred in 1639, 1646, and 1672) damaged the city. After the 1703 earthquake a new building planning was established, in search of "antiseismic" techniques such as wooden beams to improve the connection of the walls and connections between roofs and walls, buttresses and reduction of floor height. However, the reconstruction of the city was very difficult and took many years: almost ten years after the earthquake, less than 15% of buildings had been rebuilt (De Matteis, 1973).

After the 1915 Avezzano earthquake and in the period between the two World Wars, the area inside the ancient walls was further urbanized, expanding into the open spaces that during ancient times had been reserved for vegetable gardens, pastures and cattle fairs.

The present building stock is very variable: buildings located downtown are mainly two to four storeys, built in simple stone masonry (vulnerability class A), often with tie-rod connections among walls (vulnerability class B). Massive stones or bricks were used only for some strategic and important edifices: among them there are more recent buildings, built during the last century, in brick masonry and reinforced concrete (RC) (vulnerability class C). In the suburban area, recently developed, most buildings are relatively modern reinforced concrete frame structures with masonry infill (vulnerability class C and D) (see for details: Tertulliani et al., 2011; 2012).

The 6 April 2009 earthquake had devastating effects in L'Aquila, and caused very severe damage also in tens of villages nearby with a heavy social impact: 309 casualties (2/3 of them in L'Aquila city), 47% of the housing partially damaged, 20% of the housing heavily damaged and more than 40,000 people left homeless. The impact on religious and monumental heritage was disastrous. The assessed macroseismic intensity for L'Aquila was 8-9 EMS98. The damage in L'Aquila downtown has been subject of many studies after the earthquake, because it was the first time in Italy that, after the 1908 Messina-Reggio Calabria earthquake, a city was severely struck by a seismic event. The macroseismic survey performed soon after the earthquake (Fig. 4.14) highlighted that about 70% of the buildings mainly represented in classes B and C, suffered substantial to very heavy damage. The heaviest damage was mainly concentrated in the western sector of the city (red circle in Fig. 4.14). About 80% of collapses in RC buildings occurred along the south-western border of the historical center.

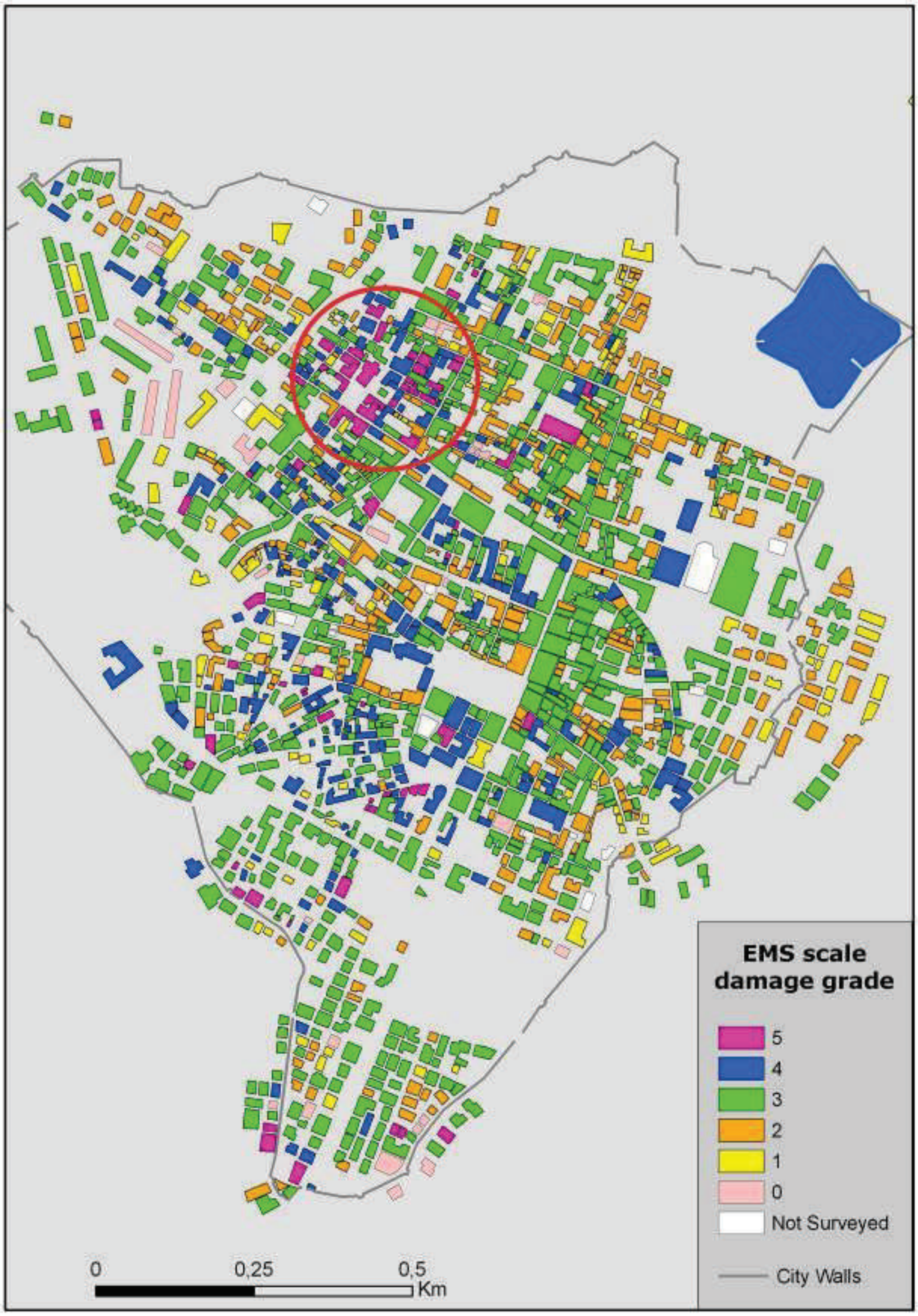


Fig. 4.14. Distribution of the damage grades in L'Aquila downtown, after the 6 April 2009 earthquake (Tertulliani et al., 2011).

Seismic microzonation of the L'Aquila area after the 2009 earthquake

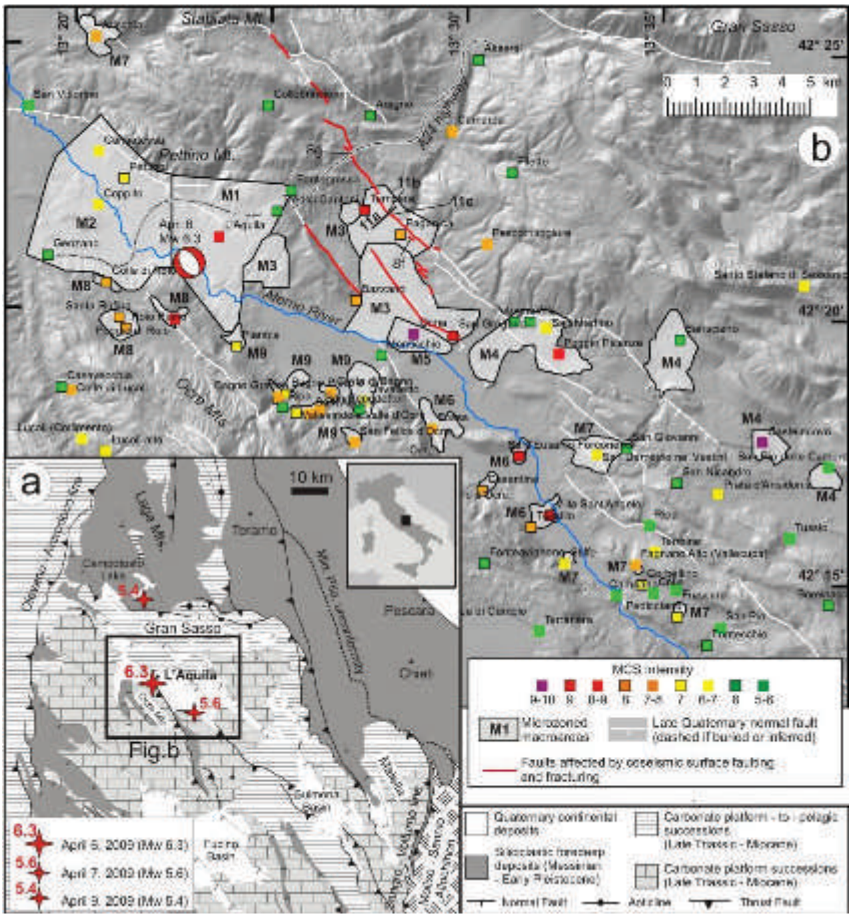


Fig. 4.15. a) Location of the April 6, 2009 L'Aquila earthquake and the two largest aftershocks; b) Distribution of Intensity (MCS scale) data points and location of the microzoning Macroareas (Martelli et al., 2011).

To assist reconstruction and future urban planning of the most damaged areas, a seismic microzoning plan started in the municipal areas, coordinated by the National Civil Protection Department. The study focused on the municipalities suffering MCS intensity ≥ 7 (Fig. 4.15; SM-AQ Working Group, 2010). The area was subdivided into macroareas, each being studied by an interdisciplinary working group. In-depth studies were carried out in macroareas 1-9, where quantitative estimates of local seismic response were made (Level 3 SM according to Working Group SM, 2008).

Fig. 4.16. Cave collapse in weathered Quaternary L'Aquila Breccia at Via Campo di Fossa (Martelli et al., 2011).

Several local effects have been observed and analysed during the seismic microzonation project, such as classical 1D stratigraphic amplifications within basins filled by Quaternary continental deposits, 2D amplifications within basins with horst-and-graben geometry of the bedrock, jointed rock-mass amplification and topographic amplification, though the latter was rarely observed (Martelli et al., 2012). A certain number of slope and ground failure cases were also reported, prevailingly falls/topples with rolling and bouncing blocks and cave collapses (including collapses within the L'Aquila city centre; Fig. 4.16), as well as co-seismic surface faulting (see Stop 2).

Concerning the L'Aquila city, one of the main features evidenced by seismic data is the presence of a strong low-frequency resonance (fundamental resonance f0 of 0.5–0.6 Hz), related to the deep impedance contrast between Quaternary infill and stiff carbonate bedrock (Di Giulio et al., 2014, MS-AQ Working Group 2010). Del Monaco et al. (2013) have also observed a secondary resonance frequency (f1) ranging from 3 up to 15 Hz, suggested to be spatially correlated with the most severe damages (Fig. 4.17).

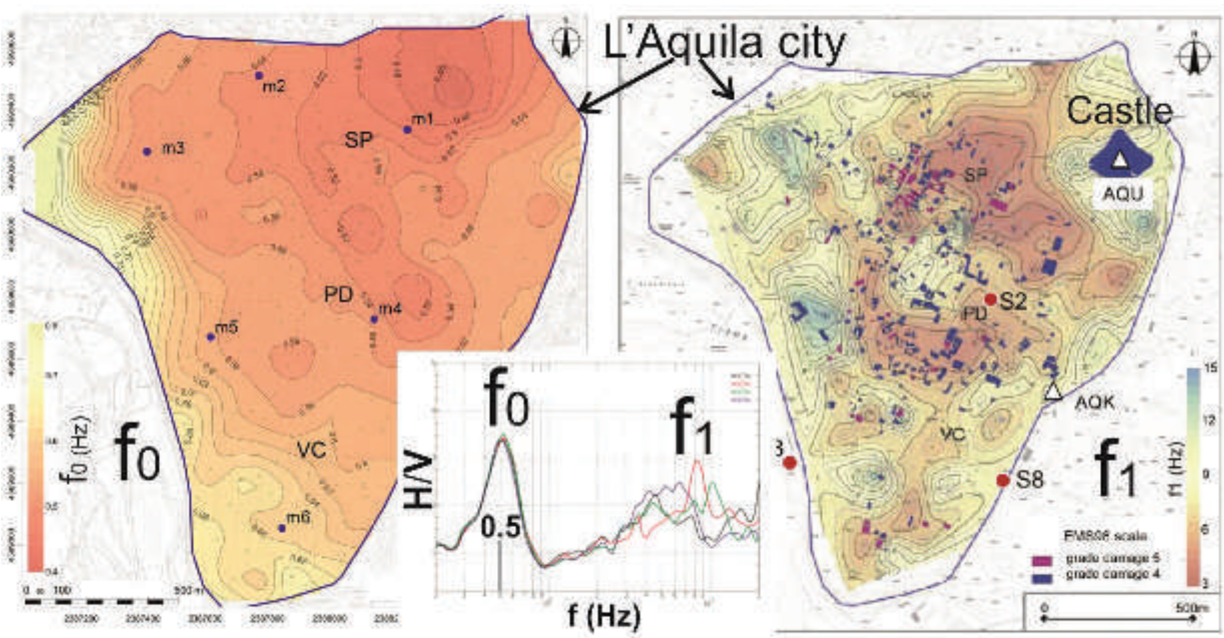


Fig. 4.17. Contour maps of fundamental resonance frequency (f0) and high-frequency peak (f1), and mean Horizontal-to-Vertical spectral ratios (H/V) from ambient seismic noise. The f1 peak is plotted together with the most severe damage on residential buildings (modified from Del Monaco et al. 2013).

STOP 4. The Assergi normal fault (optional, depending on the available time..)

The ca. 17 km-long WNW-ESE-trending Assergi normal fault runs about 8-10 km northeast (uphill) of the Paganica – San Demetrio fault representing one of the longer active faults in the Central Apennines (e.g., D'Agostino et al., 1998; Pizzi et al., 2002) and shows very fresh bedrock fault scarp (Figs. 4.18 and 4.19). Nevertheless, no conclusive paleoseismological data are available and no historical earthquakes have been associated to this "silent" seismogenic source. It belongs to the outermost alignment of the Umbria-Marche and Lazio-Abruzzi fault systems and represents the southeast continuation of the Mt. Vettore – Mt Bove and Laga fault systems.

Fig. 4.18. Stop 4: very fresh bedrock fault scarp along the Assergi normal fault.

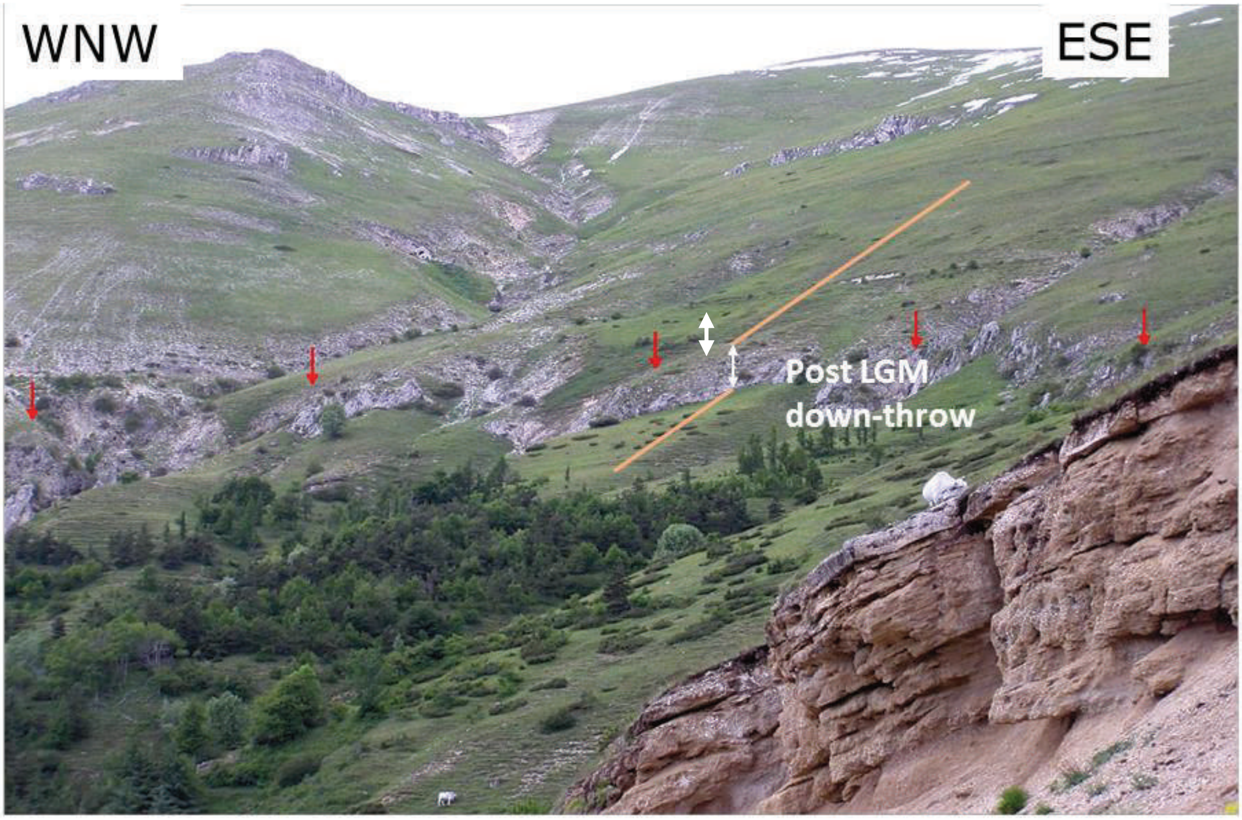


Fig. 4.19. Red arrows highlight the Assergi fault scarp displacing the "regularized" slope probably formed during the Last Glacial Maximum (LGM), at ~18 kyr. Upper Pleistocene stratified slope breccias are largely exposed in the hanging wall block of the fault.

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