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XXII CICLO

DEFINITION OF SEISMOGENIC SOURCES IN POORLY KNOWN TECTONICALLY ACTIVE REGIONS OF THE ITALIAN PENINSULA

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….Al mio Papà, alla mia Mamma e alla mia Emanuela….

….And all this time the river flowed endlessly to the sea….

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1. INTRODUCTION

The Italian seismic history is studded with small-to-large magnitude earthquakes occurred through the centuries. Information about strong seismic events of the past have been derived from historical sources the study of which brought to light the occurrence of earthquakes during a chronological interval spanning about the past two millennia and that, in many cases, have been responsible for widespread destruction of towns and villages and of thousands of casualties.

Many efforts have been therefore produced in the past decades in order to understand the seismotectonic characteristics of the Italian territory and to identify tectonic structures 1) responsible for these historical destructive seismic events and 2) potentially responsible for future earthquakes. Geological studies aiming at the identification of these faults began during the 1970s, when some "pioneering" studies (Bosi, 1975) identified "probable active faults" along several slopes of the Apennines.

A strong improvement to the knowledge about the active tectonics in Italy has been obtained during the 1980s with the "Progetto Finalizzato Geodinamica", sponsored by the National Research Council, which resulted in the Neotectonic Map of Italy (CNR-PFG, 1987). The map collected all the most updated information gathered by a large number of researchers involved in the project on tectonic structures that, by means of geological and geomorphological observations, were identified and classified on the basis of their geometry, kinematics and chronology of activity.

At the end of the 1990s, a huge amount of work has been made by researchers involved in the CNR-GNDT (National Group for the Defence against Earthquakes) to gather information (by the available literature an by means of "brand new" studies of GNDT and PALEOSIS projects) on the surficial evidence of primary active faults in peninsular Italy, aiming at the production of an inventory of the traces at the surface of the active faults (Galadini et al., 2001).

After many decades of studies, however, there are still some critical elements in terms of the definition of the seismotectonic characteristics of Italy, summarised below, that still need accurate analyses and efforts to be "enlightened" and more deeply understood in order to be properly managed in a seismic hazard assessment perspective:

- the presence of tectonic structures, active during the Late Pleistocene-Holocene and considered as potentially responsible for destructive earthquakes, to which no historical seismic events can be attributed. These faults, commonly defined as "silent seismogenic source", represent probable seismic gaps;

- the presence of faults the current activity of which is presently debated;
- the occurrence of strong earthquakes in historical times the causative faults of which have not been conclusively defined to date.

On this basis, the present study aims at providing new information, gathered by means of new geological, geomorphological and structural investigations, useful for improving the knowledge about the seismotectonic features of some sectors of the central Apennines (described below at points 1, 2 and 3) and of the north-eastern part of the Calabrian region (point 4)
In detail, we will analyse:

1) the fault system affecting the SW slopes of Mt. Morrone, a mountain ridge that delimits the eastern border of the Sulmona depression, in the Abruzzi Apennines. This fault system shows evidence of Late Pleistocene-Holocene activity (e.g. Vittori et al. 1995; Miccadei et al. 1998; Galadini and Galli 2000) and is considered as potentially responsible for M=6.5-7 earthquake. According to the available literature (e.g. Galadini and Galli; 2001; Ceccaroni et al., 2009), the last episode of activation of this fault system probably occurred about 1,800 years ago (i.e. during the 2^{nd} century A.D.). Therefore, the time that has elapsed since the last activation is in the order of the mean recurrence interval for central Apennine faults, i.e. 1500-2500 years. For this reason, the Mt. Morrone fault is considered as one of the most problematic Italian tectonic cases in seismic hazard perspective;
2) the sector of the central Apennines comprised between the Maiella Massif, Mt. Morrone and Mt. Porrara. This area has been the epicentre of the 1706 earthquake (Maw=6.6; Working Group CPTI 2004), one of the strongest historical seismic event of the central Italy, the source of which is still under debate. Within this light, studies have made in the past to define the geometry and kinematics of the probable active faults in this sector. Two opposite hypotheses assume: i) the present activity of the normal fault located along the western Maiella Massif slopes, i.e. the Caramanico fault of Ghisetti and Vezzani (2002), and ii) the out-of sequence thrusting at the frontal zone of the Maiella

anticline, proposed by Sauro and Zampieri (2004) and Lavecchia and de Nardis (2009). These two hypotheses indicate that the location and geometry of the active faults in this area represents the main seismotectonic open problem of this sector;

3) the epicentral area of the April 6, 2009 earthquake (Mw 6.3) that severely struck the city of L'Aquila and surrounding sectors, aiming at i) analysing the Quaternary activity of the Paganica fault, presently considered as the causative fault of the seismic event (e.g. Emergeo Working Group, 2009), and ii) describing the evidence of coseismic surface rupturing along this tectonic structure. This fault was already analysed by different researchers in the past (Bagnaia et al., 1992; Boncio et al., 2004) but its Late Quaternary activity was never investigated in detail. Moreover, other strong earthquakes have affected the L'Aquila region in historical times (i.e., 1461, Mw 6.4; 1762, Mw 5.9; 1916, Mw 5.2; 1958, Mw 5.2; Working Group CPTI, 2004; see also Rossi et al., 2005) but the source of these events has never been conclusively defined;
4) the NE portion of the Calabrian Arc, in the area of Rossano Calabro, where the main known tectonic feature of the area is the Rossano Fault, a normal fault bounding to N and NE the Sila Massif. This fault shows evidence of activity through the whole Quaternary (Corbi et al. 2009; Galli et al., 2006). For this reason, some authors propose the Rossano fault as the possible causative tectonic structure of the earthquake that struck this region in 1836 (Maw 6.2; Working Group CPTI, 2004). Nevertheless, thorough geological data supporting this hypothesis have not been provided to date and, therefore, the causative fault of this seismic event is still a matter of debate.

Following sections providing basic information on the recent evolution of the central Apennines and of the Calabrian Arc, and on the seismotectonic framework of the areas under investigation, the collected data will be exposed and discussed. The information gathered provides the basis for the defining, or reappraising, of the kinematics, slip rates and maximum expected magnitude of the analysed – newly found, in some cases – fault systems. These represent the fundamental ingredients for the estimation of the seismogenic behaviour and seismic potential of the investigated areas.

2. GEOLOGICAL SETTING AND SEISMOTECTONIC FRAMEWORK OF THE CENTRAL APENNINES AND OF THE CALABRIAN ARC

2.1 The central Apennines

The genesis of the Apennine chain is the result of the complex geodynamic process that has characterised – and that is still characterising – the central Mediterranean area, related to the interaction between the African and European plates and the Adria and Sardinia-Corsica microplates.

The chain consists of thrust and fold systems, that migrated towards E and NE in response to the westward subduction of the Adriatic lithosphere and its progressive eastward flexural retreat (e.g. Parotto and Praturlon 1975; Mostardini and Merlini 1988; Bally et al. 1989; Patacca et al. 1990; Cipollari et al. 1999; Meletti et al. 2000; Patacca and Scandone 2001; Patacca et al. 2008).

In the central Apennines, the compressive deformation determined the juxtaposition of terrains pertaining to different Meso-Cenozoic paleo-geographic domains:

- carbonate platform, known as "Piattaforma Laziale-Abruzzese" which, although strongly dissected by tectonic deformations, maintains a structural continuity (Parotto and Praturlon, 1975) through the chain;
- carbonate basins, located at the margins of the platform, as the "Bacino Umbro-Marchigiano-Sabino" and the "Bacino Molisano". The sequences are outcropping in the northern and southern sectors of the central Apennines (Parotto and Praturlon, 1975);
- transitional zones, located between the platform and the basins (Parotto and Praturlon, 1975).

During the formation of the central Apennines, these paleo-geographic units have been displaced by the compressive fronts that, since Oligocene, progressively migrated from the Tyrrhenian sectors towards the Adriatic, as witnessed by the formation of different silici-clastic wedges, related to foredeep domains, and of *piggy-back* basins progressively younger towards E-NE (Patacca et al., 1990; Cipollari and Cosentino, 1997; Cosentino et al., 2003).

During Pliocene, while the compressive fronts were located in the Adriatic sectors, the western part of the chain was affected by an extensional tectonics linked to the opening of the Tyrrhenian basin. This led to a drastic change of the tectonic setting inherited by the compressive deformation, with the formation of normal fault systems. This new process led to a crustal thinning – and the reduction of the lithosphere width – that favoured the arising of magmas during the Pleistocene and the formation of the volcanic districts located along the Tyrrhenian margin of the chain (Cosentino and Parotto, 1986; Cavinato et al., 1994).

The extensional deformation has partitioned along newly formed, NW-SE trending, normal faults and along the extensional structures that re-used fault planes inherited from the compressive phase (Cavinato et al. 1994; Bosi et al., 1994).

Contemporaneously to the extension, the central Apennines experienced uplift (up to 1,500 m) (e.g. Galadini et al., 2003a; Ascione et al., 2008), with an increase of the uplift rate probably occurred since the end of the Early Pleistocene and the beginning of the Middle Pleistocene (D'Agostino et al., 2001). A strict relationship between the extensional tectonic phase and the uplift of the chain has been proposed by different authors (Doglioni, 1995; D'Agostino et al. 2001; Galadini et al. 2003).

The activity of these NW-SE trending normal fault systems determined the formation of wide intermontane tectonic depressions, such as the Fucino, Norcia, Rieti, L'Aquila, Sulmona and Leonessa basins, and of minor depressions located in the mountainous areas (e.g. the Campo Imperatore, Campo Felice and Castelluccio plains, and the Salto and Turano valleys). These depressions, bounded by normal fault systems along the eastern sides, hosted sequences of continental deposits of Plio-Quaternary age, hundreds of metres-thick. The onset of the continental deposition occurred during Pliocene, thus indicating the emersion of the central Apennine chain since this period (e.g. Bosi et al., 2003, Galadini et al., 2003a).

Many works have analysed the continental sedimentary sequences contained within the intermontane depressions and some attempts of correlation between the stratigraphic units among the different basins, based on the detection of comparable morpho-litho-stratigraphic features, have been produced (e.g. Bosi and Messina, 1992; Cavinato et al., 1994; Bosi et al. 2003; Centamore et al. 2003; Fubelli, 2004). An example of this is shown in Figures 2.1.1 and 2.1.2.

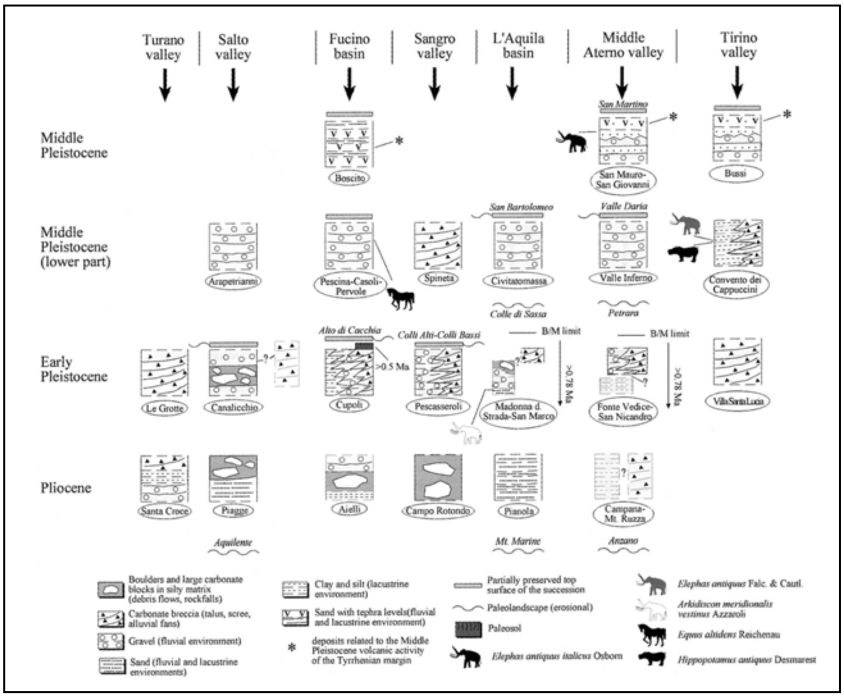


Fig. 2.1.1 – Stratigraphic scheme (and morphological features related to the main erosional landscapes and top depositional surfaces) of the Latium-Abruzzi Apennines (from Bosi et al., 2003).

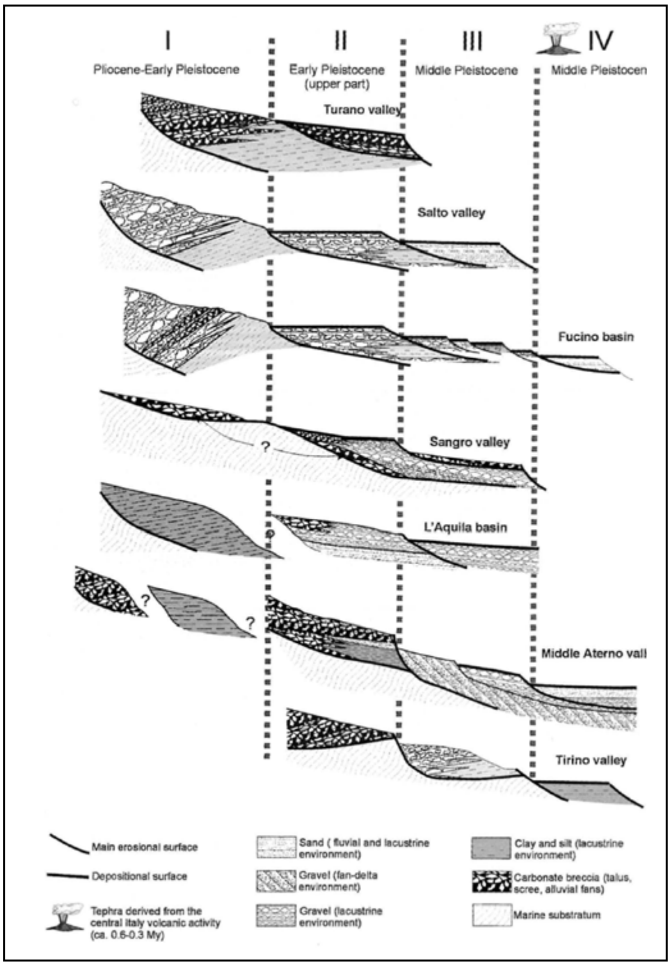


Fig. 2.1.2 – Morpho-stratigraphic schemes of some basins in the Latium-Abruzzi Apennines (from Bosi et al., 2003).

By means of the analysis of the continental stratigraphic sequences, information about the evolution of the extensional deformation in the central Apennines has been obtained. Indeed, according to the available literature (e.g. Lavecchia et al.,1994; Martini and Sagri, 1994; Bartole, 1995; Calamita et al., 1999; Galadini and Messina, 2004), comparably to the compressive front, the extensional deformation underwent a progressive migration towards E and NE. This process, related to the flexural retreat of the westward subducting Adriatic lithosphere (Patacca et al.,1990;Ghisetti and Vezzani,1999; Cavinato and De Celles, 1999), determined the formation of extensional tectonic structures that are progressively younger heading eastwards.
Galadini and Messina (2004) and Fubelli et al. (2009) issued that the migration of the extensional deformation resulted in the onset, during the Early Pleistocene, of the activity of the normal fault systems located in the easternmost sectors of the central Apennines (e.g. the Campo Imperatore, Mt. Morrone, Mt. Vettore fault systems). On the contrary, since the Early or the Middle Pleistocene, the activity of the extensional tectonic structures responsible for the formation of the westernmost depressions (e.g. the Salto valley, Turano valley, Liri basin and Leonessa basin fault systems) ceased (or strongly reduced), as they are sealed by deposits and landforms related to this period. As for the fault located in the intermediate sectors of the chain, instead, the mentioned authors defined a persistence of the activity since the Late Pliocene, through the whole Quaternary.
Many of these central Apennine normal and normal oblique faults show evidence of Late Pleistocene-Holocene activity (Fig. 2.1.3) and are therefore considered as active (Barchi et al., 2000; Galadini and Galli, 2000; Galadini et al., 2001; Valensise and Pantosti, 2001).
The active tectonic structures are made of segments, usually dipping towards W and SW, the length of which ranges between 5 and 20 km. Shorter segments are organised in fault systems made of 3-to-5 minor faults showing en-echelon relationship (often dextral step over). The length of the fault systems do not exceed 33 km (i.e. the cases of the Fucino basin and the Gran Sasso Range).

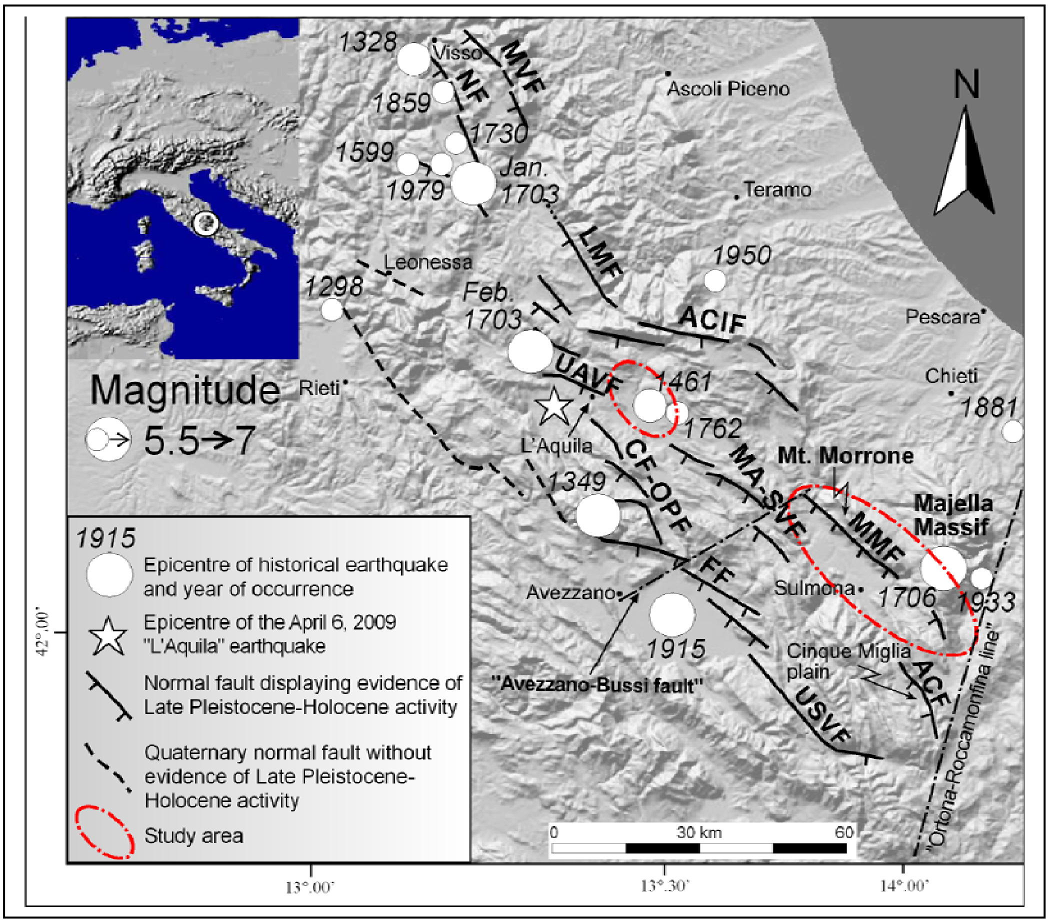


Fig. 2.1.3 – Seismotectonic framework of the central Apennines (modified after Galadini and Galli, 2000). MVF - Mt. Vettore fault; NF – Norcia fault system; LMF - Laga Mts. fault; UAVF - Upper Aterno Valley fault system; ACIF – Assergi-Campo Imperatore fault system; CF-OPF - Campo Felice-Ovindoli-Pezza fault system; MA-SVS - Middle Aterno-Subequana Valley fault system; MMF - Mt. Morrone fault; FF - Fucino fault; ACF - Aremogna-Cinquemiglia fault; USVS - Upper Sangro Valley fault system.

These active faults and fault systems are considered as the surficial expression of seismogenic sources potentially responsible for earthquakes characterised by moderate-to-large magnitudes (generally 5.8<M<7.0) (e.g. Galadini and Galli, 2000; Valensise and Pantosti, 2001). The fault-seismogenic sources dip is generally ranging between 40° and 60°, based on structural surficial and sub-surficial data (e.g. Barchi et al., 2000 and references therein).

The available literature generally agrees in considering the active faults of the central Apennines as arranged into NW-SE trending sets, paralleling the axis of the chain. The number of the sets is still debated. Indeed, Boncio et al. (2004) indicate that three active fault sets can be detected. On the contrary, no more than two sets are identified in other regional inventories of central Apennine active faults (e.g. Galadini and Galli, 2000; Valensise and Pantosti, 2001). The open question derives from different interpretation of the recent fault activity in the western Apennine domain.

Many studies, both geological and paleoseismological (e.g. Galadini and Galli, 2000; Galli et al., 2008 and references therein) permitted the definition of those features, as the slip rate, the mean recurrence interval, the time elapsed since the last activation, that are fundamental for the parameterisation of the activity of these tectonic structures (Fig. 2.1.4).

As for the slip rate, the data indicate that the mean slip rate for the central Apennines fault is comprised between 0.4 and 1.2 mm/yr (with a preference for intermediate values, i.e. 0.6-0.8 mm/yr). The mean recurrence interval per fault is in the order of 1500-2500 years.

Fault	Length of the fault system (km)	Vertical slip rate (mm/yr)	Min. vertical slip rate (mm/yr)	Max. vertical slip rate (mm/yr)	Chronological interval (reported age-Present)	Recurrence interval for surface faulting events (years)	Elapsed time since since the last earthquake of M = 6.5–7.0 (years)
Upper Sangro Valley	20		0.17–0.21		0.8–1 Ma		⩾1,000
Fucino	33	0.7–0.8[1]	0.4–0.5[2] 0.37–0.43[3]		[1]0.8–1 Ma [2]19100 ± 650 BP [3]0.4 Ma	1,400–2,600	84 (at 1999)
Ovindoli-Pezza	12–20	0.8–1.2[1] 1.2–2.3[2] (lower value pref.)			[1]7000 BP [2]7000–10000 BP	2,760–3,200	700–1130
Campo Felice–Colle Cerasitto	16	1.1[1]		0.8–1.3[2]	[1]18000 BP [2]0.25 Ma		650 (at 1999) if it was responsible for the 1349 earthquake
Upper Aterno Valley	25	0.47–0.86	0.25–0.43		31710 ± 760 BP 23330 ± 300 BP		296 (at 1999)
Norcia	27		0.2		0.1 Ma		296 (at 1999)
Aremogna-Cinquemiglia	16		0.3–0.5		[1]12000–6500 BP	1,000–4,000	2800-970
Mt. Morrone	20		0.5–0.66		0.9–1.0 Ma		1800? based on archaeo-seismological data
Middle Aterno Valley	21	0.33–0.43			1.5 Ma		>1,000
Mt. Cappucciata-Mt. S. Vito, Campo Imperatore	30	0.67–1			18000–13000 BP	2,500–7,000	>1,000
Assergi	21						>1,000?
Laga	18	0.7–0.9[1]	0.3–0.36[2]		[1]20000–30000 BP [2]6395–6175 BC		>1,000
Mt. Vettore	18		0.25–0.3		12000 BP		⩾1,650

Fig. 2.1.4 – Summary of available data on the geometric characteristics and kinematic parameters related to the active faults of central Apennines (from Galadini and Galli, 2000).

On this basis, the active faults to which no historical earthquake can be attributed – taking into consideration that the available historical seismic catalogues are complete at least in the past 800 years for high-magnitude earthquakes (Stucchi et al. 2004) – are commonly defined “silent seismogenic source” and the probability of activation of these *silent* faults in a future time span of social interest is considered as high.

Episodes of activation of some of the described active normal tectonic structures determined the occurrence of destructive seismic events in historical times (Working group CPTI; 2004; 2008), the main of which are: the 1461 (Maw=6.4), 1703 (January, 14) (Maw=6.81), 1703 (February 2) (Maw=6.65), 1706 (Maw=6.6), 1762 (Maw 5.9), 1915, (Maw=6.99), 1933 (Maw=5.7) and 1950 (Maw=5.7) earthquakes as well as the shocks of the 1349 and 1456 seismic sequences (Maw=6.6 and 7.0, respectively).

A comparison between the central Apennines active faults array and the damage distribution, plus paleoseismologically-inferred data, has allowed the attribution of the 1703 (January 14), 1703 (February 2) and 1915 earthquakes to activation events of the Norcia, Upper Aterno and Fucino fault systems, respectively (Galadini and Galli, 1999; Moro et al., 2002; Galli et al., 2005).

As for the origin of the 1461 seismic event (Fig. 2.1.5), Galadini and Galli (2000) hypothesised a possible activation of one segment of the Assergi-Campo Imperatore fault system (namely the Assergi fault) during this earthquake, although the authors issued that sufficient data are lacking to concretely relate this earthquake to this tectonic structure.

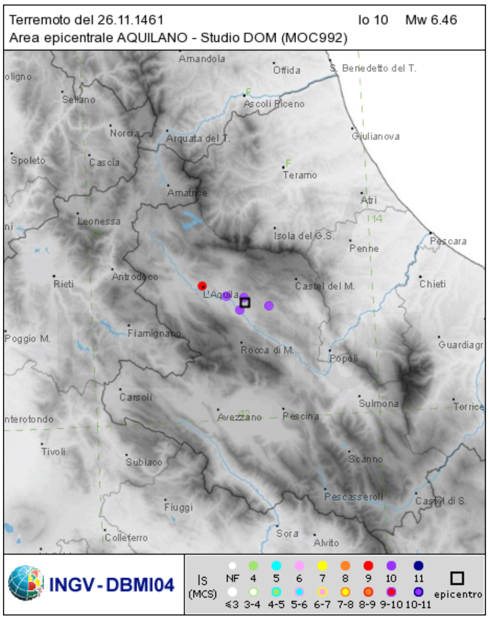


Fig. 2.1.5 – Damage distribution related to the 1461 earthquake (http://emidius.mi.ingv.it/DBMI08/).

On the other hand, Boncio et al. (2004) hypothesised an activation of a seismogenic fault named as “Aquilano *s.l.*” (the geometry of this fault, as described by these authors, is depicted in the next sections), during the 1461 and the 1762 seismic events.

As far as the causative fault of the 1706 and 1933 earthquake is concerned, Meletti et al. (1988) proposed the so-called “Ortona-Roccamonfina line” (see Fig. 2.1.3) as the possible source for the former seismic event. This structural feature is a NNE-SSW to N-S trending major regional shear zone that separates the Abruzzi Apennine fronts from the Molise domain thrust sheets (Patacca et al., 1991). By considering recent studies on the active thrusting at the frontal zone of the Maiella anticline (Sauro and Zampieri, 2004; Lavecchia and de Nardis, 2009), and on the activity of the Caramanico fault, an about 40 km long normal fault that bounds the Maiella massif to the west (Ghisetti and Vezzani, 2002), the activation of one of these tectonic structures during the 1706 earthquake cannot be excluded.

However, there is no clear and commonly accepted geological evidence that directly supports these hypotheses. Moreover, a discussion on the activity of the Caramanico fault is reported in the present work.

Although the seismic energy associated with the 1706 and 1933 earthquakes was different, the damage distribution of the two seismic events was comparable, in terms of damaged localities (Figs. 2.1.6 and 2.1.7, respectively).

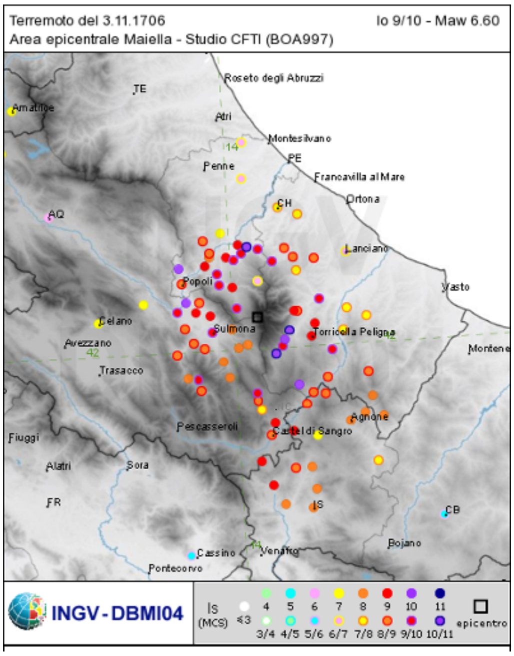


Fig. 2.1.6 – Damage distribution related to the 1706 earthquake (http://emidius.mi.ingv.it/DBMI08/)

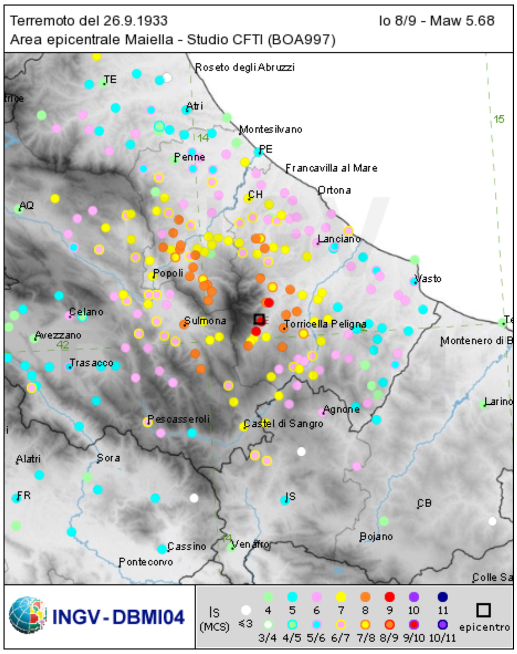


Fig. 2.1.7 – Damage distribution related to the 1933 earthquake (http://emidius.mi.ingv.it/DBMI08/)

For this reason, Galadini and Galli (2007) hypothesised that the same seismogenic process might have been responsible for both of these seismic events, and they related these to either (i) the activation of a single, but still undefined, seismogenic fault segment during both of these events or (ii) the activation of two different segments (with similar trends) of the same, again undefined, fault system. The magnitude of an earthquake expected from activation of the Mt. Morrone fault system (one of the objects of the present study) would be in the order of 6.5 to 7.0, and would be comparable, therefore, to that of the 1706 seismic event (Galadini and Galli 2000). However, the geometry of the Mt. Morrone fault does not appear to be consistent with the damage distribution of the 1706 earthquake, since the highest intensities are mainly located in the footwall and centred in a sector located ESE of the fault (Galadini and Galli 2007).

A new hypothesis about the origin of the 1706 is proposed in this thesis.

Lastly, archaeoseismological data have indicated an episode of widespread destruction in the Sulmona area during the 2nd century AD, which was related to the occurrence of a large-magnitude earthquake of local origin (Galadini and Galli 2001). This seismic event may be related to the activation (probably the last episode of activation) of the Mt. Morrone normal fault system (Ceccaroni et al., 2009).

2.2 The Calabrian arc

The Calabrian arc is an accretionary wedge lying above a narrow and steeply dipping slab subducting towards NW, beneath the back-arc Tyrrhenian basin.

Tomographic images show a northwestward dipping slab beneath the Calabrian subduction zone, which is interrupted by a 150 km-wide window beneath the southern Apennines (Selvaggi and Chiarabba, 1995; Lucente et al., 1999; Piromallo and Morelli, 2003; Wortel and Spakman, 2000; Montuori et al., 2007). This window opened after tearing occurring within a composite subduction system, formed by the Apulian continental lithosphere and the Ionian oceanic slab (Chiarabba et al., 2008; Rosenbaum et al., 2008).

The related Wadati-Benioff zone is “enlightened” by the hypocenters of hundreds of deep earthquakes recorded in the last decades (Faccenna et al., 2001; Vannucci et al., 2004; Chiarabba et al., 2008).

The “backbone” of the Arc is mainly represented by metamorphic and igneous rocks pertaining to the European geological domain the present position of which is due to the SE-drifting of this block of European continental crust that occurred since the Miocene (e.g. Gueguen et al., 1998; Rosenbaum and Lister, 2004; 2008; Cifelli et al., 2007). Since the Early Miocene, overthrusting of the Palaeozoic basement nappes on the Meso-Cenozoic basinal sequences occurred through compressive structures progressively younger eastwards. This led to the formation of the Calabria orogenic belt (e.g. Parotto and Praturlon, 2004) (Fig. 2.2.1).

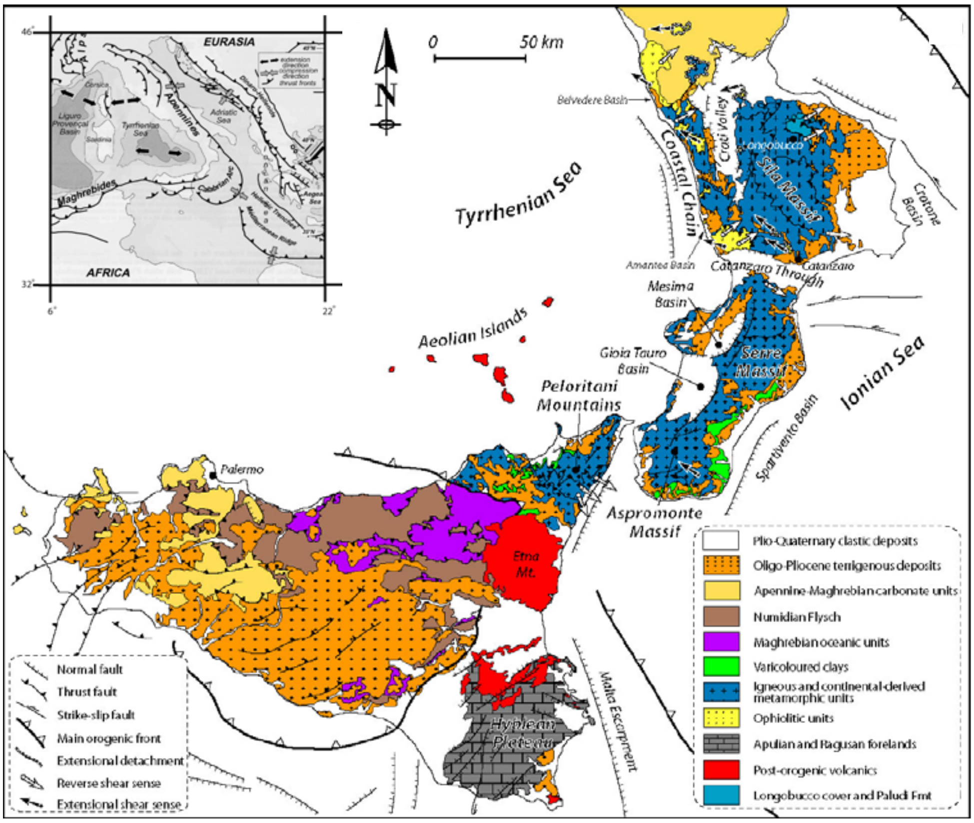


Fig. 2.2.1 – Geological map of the Calabria-Peloritani Arc (modified from Bigi et al., 1990; Cifelli et al., 2004; Minelli et al. 2009)

An extensive and detailed analysis of the tectonic evolution of the Calabrian Arc has been recently performed by Minelli (2009) who investigated the present structural setting of the Arc and of the accretionary prism, by means of geological interpretation of industrial seismic reflection profiles, corroborated by stratigraphic data.

In detail, the author distinguished four major structural domains with different evolution stages and styles: the Crotone-Spartivento foreland basin, the inner accretionary prism, the outer accretionary prism, and the foreland basin. Moreover, Minelli (2009) proposed a model of space-time evolution of Calabrian accretionary prism in the last 15 Ma. This model defines the growth of the prism, comprising the forward propagation stages, with frontal accretion, and out-of-sequence internal thrusting (of Pliocene age, at least).

During the eastward migration of the compressive domain – progressively affecting the Ionian sectors – extensional tectonics occurred in the inner portions of the Calabrian arc since the Miocene-Pliocene (e.g. Ghisetti, 1979; 1980; Tortorici et al., 1995; Monaco et al., 1996; Mattei et al., 2002; Cifelli et al. 2007). The extensional tectonics determined the formation of normal-to-transtensive fault systems, mainly parallel to the axis of the Arc, which displaced the structural edifice inherited by the compressive deformation (Monaco et al., 1996). The activity of these extensional structures determined the formation of N-S and NE-SW elongated tectonic depressions, e.g. the Crati and Mesima valleys and the Sant'Eufemia, Gioia Tauro (the area investigated in the present study) and Messina Strait basins, that hosted marine and continental sedimentary sequences (e.g. Ghisetti, 1981).

Most of these N-S and NE-SW faults often interrupt against other faults trending almost perpendicularly to the Calabrian Arc, i.e. E-W and WNW-ESE, as the Rossano, Catanzaro Strait and Nicotera-Coccorino fault systems (e.g. Moretti, 2000; Galadini et al., 2001; Galli and Bosi, 2003; Galli et al., 2006; Tortorici et al. 2003; Guarnieri, 2006; Rosenbaum et al., 2008). These structural features have probably had a complex kinematic and structural history, as they may have played – and still play – the role of 1) tear faults, accommodating differential motions of the Calabrian accretionary prism, and/or 2) transfer faults, kinematically linking different, en-echelon arranged N-S and NE-SW normal fault systems.

In particular, two regional structural features, trending perpendicular to the axis of the Calabrian belt and known as "San Gineto Line" and "Taormina Line" (Fig. 2.2.2) permitted the juxtaposition of the metamorphic terrains of the Calabrian Units, pertaining to the European domain (e.g. Amodio Morelli et al., 1976) with the carbonate sequences of the southern Apennines and of the Maghrebian Chain, respectively (e.g. Van Dijk et al., 2000; Tansi et al., 2007).

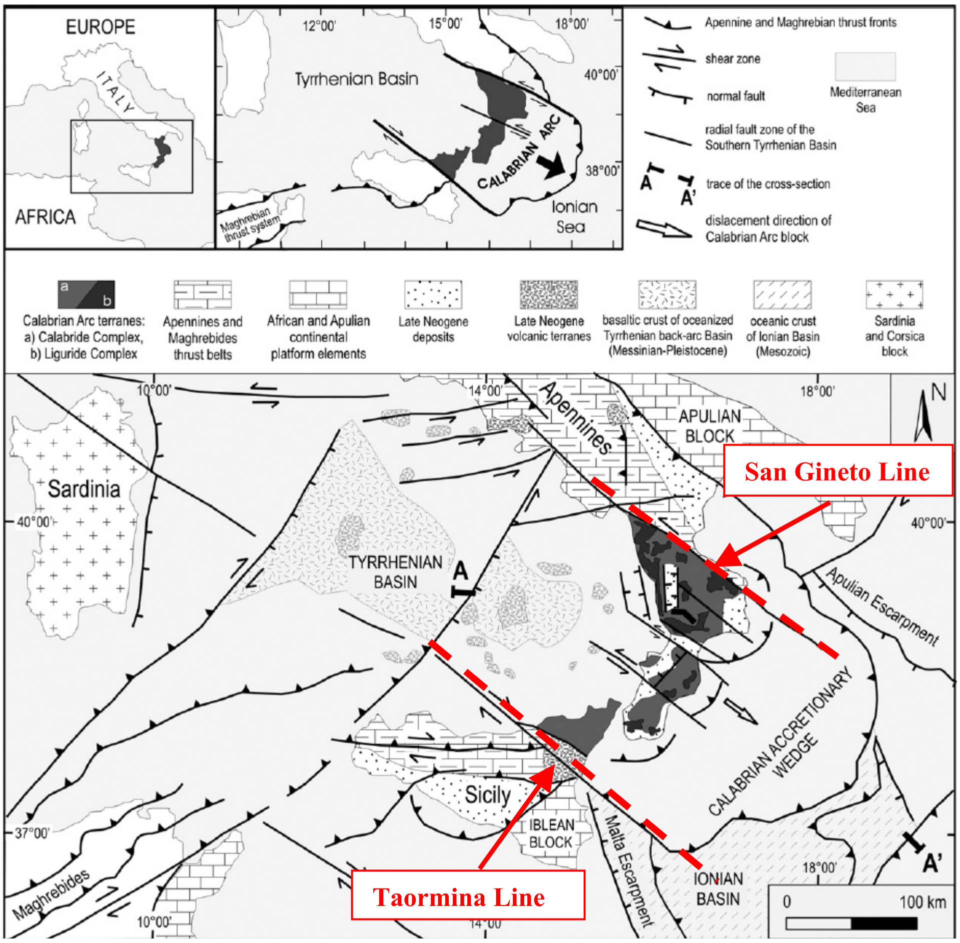


Fig. 2.2.2 – Geological map of the central Mediterranean area (from Tansi et al., 2007)

Of course, the structural setting and evolution at the junction between the Calabrian Arc and the southern Apennines, to the north, and the Maghrebides, to the south-west, is still a matter of debate. Indeed, as for the northern boundary (which is partly investigated by the present study), the southern Apennines and the Calabrian arc fold-and-thrust belts are presently not linked (Minelli, 2009).

Comparably to the Apennine chain, the Calabrian Arc experienced rapid uplift during the Quaternary, contemporaneous to the extensional deformation. Different mechanisms have been invoked as having caused the uplift. Some authors argued that it is due to an isostatic rebound related to either slab break-off (Westaway, 1993; Wortel and Spakman, 2000) or decoupling of the upper crust from the underlying slab and convective flow in the mantle wedge. According to other authors, instead, uplift may have been determined by stalling in the roll-back process and trapping of the Calabrian Arc between the continental crusts of the Adria microplate and Africa plate (Goes et al., 2004). Other views proposed the uplift to be the result of lithosphere bulging due to subduction slackening (Moretti and Guerra, 1997).

The occurrence of uplift in Calabria is testified by the presence of flights of marine terraces, dated back to more than 1 Ma, detected by several researchers (e.g. Cosentino and Gliozzi, 1988; Dumas et al., 1988; Miyauchi et al., 1994; Bordoni and Valensise, 1998; Carobene, 2003; Tortorici et al., 2003; Cucci, 2004; Cucci and Tertulliani, 2006) along both the western and the eastern coasts of the arc and occurring at elevations of more than 1,000 m above the present sea level. An uplift rate of 0.6-1.3 mm/yr (respectively, from north Calabria to south Calabria; e.g. Dumas and Raffy, 2004; Molin et al., 2004) has been defined.

In particular, in the north-eastern portion of Calabria (i.e. the area under investigation) flights of Middle-Late Pleistocene marine terraces – five to seven orders – have been recognised by different authors (Cucci and Cinti, 1998; Molin et al, 2002; Carobene, 2003; Corbi et al., 2009). On the basis of the analysis of the terraces, Carobene (2003) defined an uplift rate of 0.46-0.69 mm/yr for this part of the Calabrian region. On the other hand, Corbi et al. (2009) proposed an uplift rate for this area that increased during time, i.e. from a rate of 0.57-0.52 mm/yr, evaluated basing on the elevation of the "First Order" of terrace (the earliest one, related to the MIS 9 or 11), to a rate of 0.79-0.88 mm/yr, related to the "Fifth Order" of terrace (the latest order, related to the MIS 5a).

Many studies have been performed in the past decades to collect data on the active tectonics of the Calabrian Arc (e.g. Ghisetti, 1980; Valensise and Pantosti, 1992; Tortorici et al., 1995; Galli and Bosi, 2002; Galli et al., 2006; 2008; Catalano et al., 2008; Ferranti et al., 2008), aimed at defining the seismotectonic characteristics of this part of the Italian Peninsula.

This portion of the Italian territory has been hit, in fact, by some of the strongest seismic events of the Italian seismic history (Working Group CPTI 2004; 2008): i.e. the 1638 and 1783 seismic sequences – the main shocks of which had Mw 7 and 6.9, respectively – and the 1744 (Maw=6.2; see Galli and Scionti, 2006), 1832 (Maw=6.5), 1836 (Maw=6.2), 1905 (Maw=6.7) and 1908 (Maw=7.1) earthquakes. More in general, at least 19 earthquakes with M>6 occurred since the 91 B.C. in this region (Fig. 2.2.3).

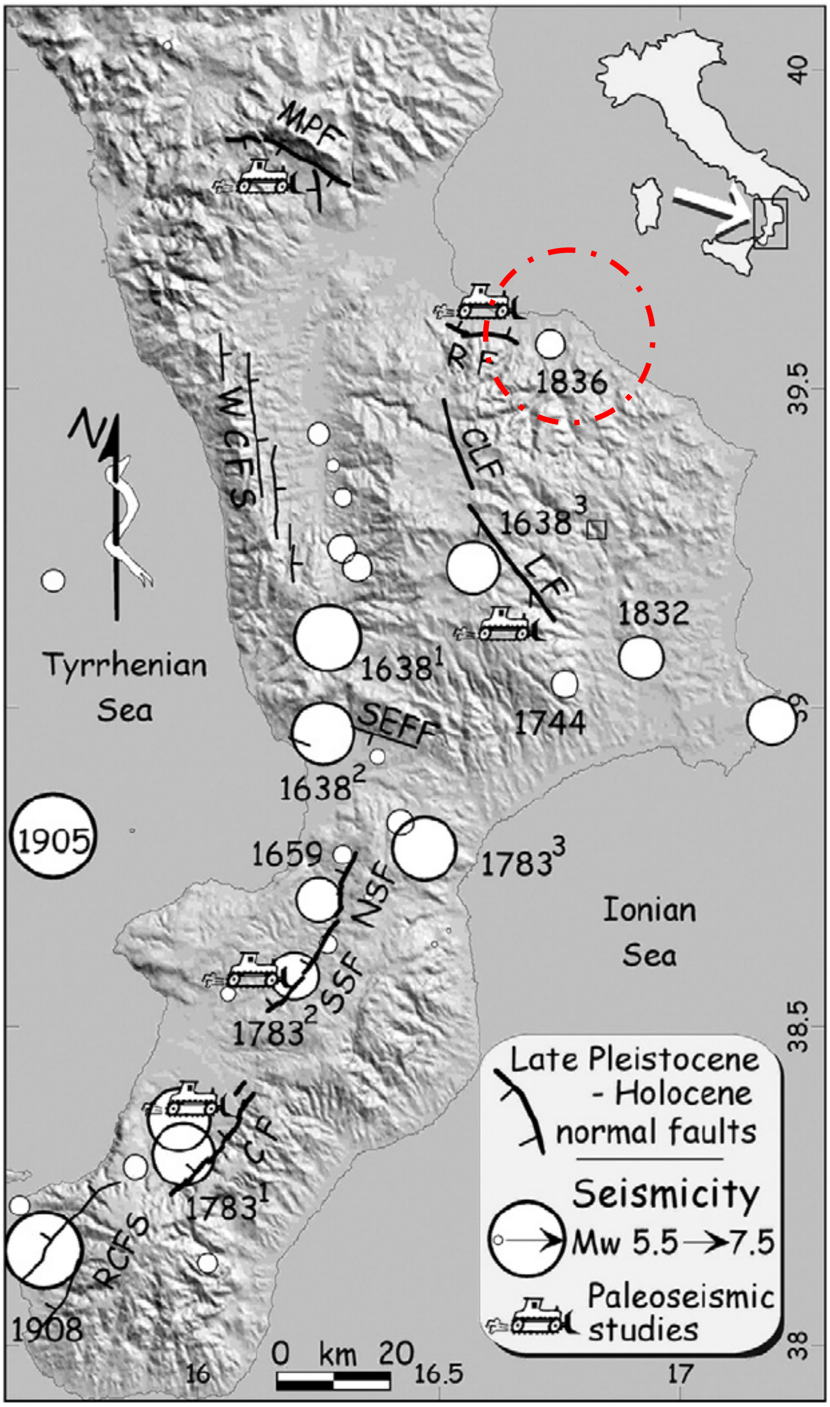


Fig. 2.2.3 – Seismotectonic framework of the Calabria region (from Galli et al., 2008). The red circle indicates the area investigated in this thesis. MPF, Mount Pollino and Frascineto faults; RF, Rossano fault; WCFS, western Crati basin fault system; CLF, Cecita lake fault; LF, Lakes fault; SEFF, Sant'Eufemia-Feroleto fault (part of Lamezia-Catanzaro fault Auctorum); NSF, North-Serre fault; SSF, South-Serre fault (Eastern Mesima graben faults); CF, Cittanova (Aspromonte) fault; RCFS, Reggio Calabria fault system (Delianova-Sant'Eufemia-Reggio Calabria and Armo faults).

Geological and paleoseismological information – the latter being summarised in Galli et al. (2008) – corroborated by the comparison between the active faults pattern and the damage distribution related to these earthquakes, permitted the attribution of some of these seismic events to episodes of activation of known active tectonic structures. This is the case of: the southernmost shock of the 1783 seismic sequence (Maw=6.7), attributed by Monaco and Tortorici (2000) and Galli and Bosi (2002) to the activation of the Cittanova fault, located east of the Gioia Tauro plain. One of the main shocks of the 1638 seismic sequence, i.e. the northernmost one (Maw 6.7), has been related by Galli and Bosi (2004) to the Lakes fault, along the Sila Massif.

Conversely, the sources of the 1905 and 1908 seismic events are still debated. As for the former, some hypotheses have been made. Monaco and Tortorici (2000) suggested a possible activation of a tectonic structure located W and NW of the Capo Vaticano High during the 1905 earthquake, while Galli and Bosi (2002) tentatively attributed this seismic event to the activation of the tectonic structure bounding to S the Capo Vaticano High, i.e. the Coccorino-Nicotera fault system. As for the source of the 1908 earthquake, some authors proposed an activation of the NE trending, west-facing Armo, S. Eufemia and Reggio Calabria fault system, including the offshore prolongation of the Reggio Calabria fault (Catalano et al., 2008 and references therein). On the other hand, other authors (e.g. Valensise and Pantosti, 1992; Amoruso et al., 2002) proposed an activation of a low angle, N-S trending and east-dipping fault merging at the surface on the Sicilian coastline.

As for the 1832 seismic event, Galli et al., (2006a) hypothesised the activation of a still unknown tectonic structure located between the Sila Massif and Capo Colonna.

Hypotheses about the causative fault of the 1836 earthquake (Fig. 2.2.4), that struck the NE sector of the Calabria territory, have been made by Moretti (2000) and Galli et al. (2006b). The former author proposed the activation of the "Corigliano-Rossano Line" – affecting the area investigated in this work – during this seismic event, although no evidence supporting this hypothesis has been provided by the author. The same hypothesis has been proposed by Galli et al., (2006b) who suggested the Rossano fault as the causative fault of the 1836 seismic event (Fig. 2.2.3).

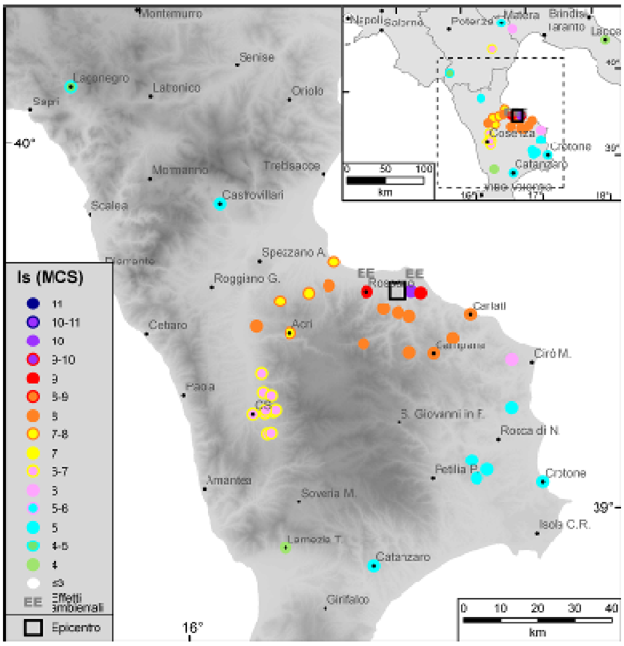


Fig. 2.2.4 – Damage distribution related to the 1836 earthquake (http://emidius.mi.ingv.it/DBMI08/).

3. METHODS

In order to achieve data useful for the goals of this thesis, we adopted a multi-methodological approach that is here exposed.

We performed an extensive aerial photograph analysis of the areas under investigation, by utilising the 1954 IGM (Istituto Geografico Militare) and 1985 "Regione Abruzzo" aerial photographs series, provided by the "Geomorphology Lab" at Dipartimento di Scienze Geologiche, Università degli Studi Roma Tre (Roma) and by Istituto Nazionale di Geofisica and Vulcanologia (Roma). This permitted us:

1) to map in detail the surficial geometry of the tectonic structures detected.

2) to identify and map geomorphological features, such as alluvial fans, terraces and landsurfaces which provided fundamental elements for the aim of this work.

3) to identify and map Quaternary depositional sequences outcropping in the analysed sectors.

An extensive and detailed geological survey has been carried out by utilising topographic maps with 1:25.000 scale, aimed at identifying and mapping the Quaternary deposits, both continental and marine, and to correlate them with the geomorphic features detected by means of aerial photograph analysis. These investigations permitted us to define the relationship between the Quaternary sedimentary sequences and the tectonic features detected, thus allowing to achieve fundamental data to define their Quaternary activity, in particular the Late Quaternary activity. This provided fundamental information to describe the recent kinematic behaviour of the investigated fault systems.

Information about the kinematics of the investigated faults has been gathered by means of structural observations performed along the fault planes and in the fault zones, aimed at collecting kinematic indicators and structural features related to the kinematic history of the tectonic structures. Schmidt net diagrams have been utilised to plot the collected data.

Information about the chronology of the Quaternary deposits has been obtained by means of:

1) Radiocarbon age determinations of charcoals and bulks of organic-rich sediments, performed by Centre of Isotopic Research on Cultural and Environmental Heritage (CIRCE)-INNOVA, Dept. of Environmental Sciences, Caserta (Italy).

2) U-series disequilibrium methods of carbonate sediments, i.e. calcareous mud, calcareous tufa and tephra layers, perfomed by Dr. Mario Voltaggio of Istituto di Geologia Ambientale e Geoingegneria (IGAG), Consiglio Nazionale delle Ricerche (Roma).

3) Tephro-stratigraphic analyses, performer by Dr. Biagio Giaccio of Istituto di Geologia Ambientale e Geoingegneria (IGAG), Consiglio Nazionale delle Ricerche (Roma), which permitted the attribution of volcanic layers found within the continental sedimentary sequences to eruptions of some Quaternary Italian volcanoes.

4) analysis of the archaeological founding (pottery fragments, flint artefacts) detected within the sediments.

4. CASE STUDIES IN THE CENTRAL APENNINES

4.1 The Mt. Morrone fault system

The NW-SE trending fault system that affects the SW slopes of Mt. Morrone comprises two main, parallel segments. The western fault branch and the related carbonate bedrock fault scarp can be detected at the base of the slopes, between Popoli and Pacentro. The eastern fault branch and the related fault scarp is located along the intermediate-upper sector of the slopes (Fig. 4.1.1).

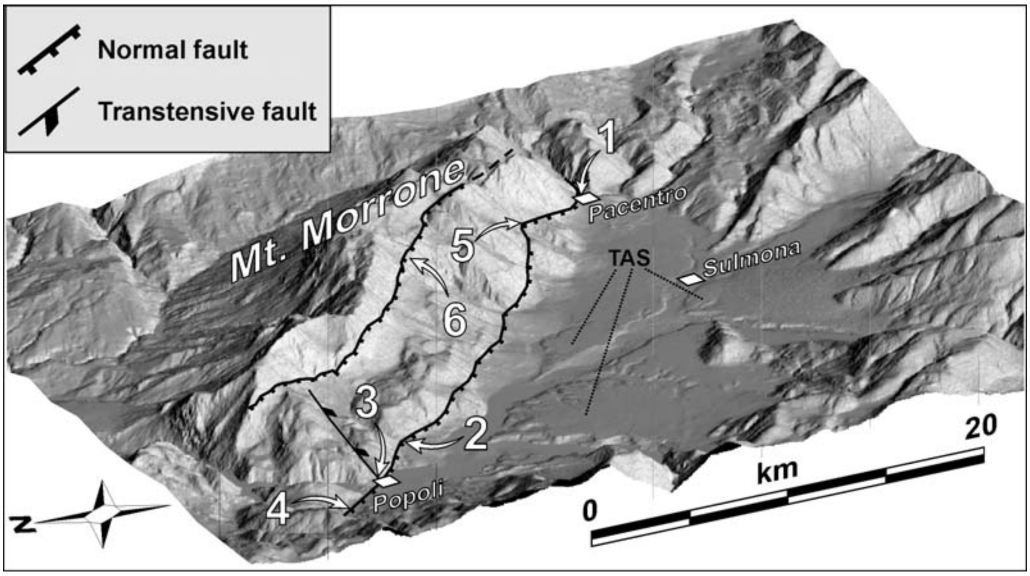


Fig. 4.1.1 – Reference map of the area under study, with the locations of the two segments of the Mt. Morrone fault system (black lines) as defined in the present study, and the sites cited in the text (numbers 1 to 6) where the slip rate has been evaluated. The wide and flat surface of the "Terrazza Alta di Sulmona" (TAS) unit is indicated by the dotted black lines.

The Quaternary activity of this normal fault system has been documented in a number of previous studies (e.g. Vittori et al., 1995; Miccadei et al., 1998; Galadini and Galli, 2000). Seismic lines (Miccadei et al., 2002) plus gravimetric analyses (Di Filippo and Miccadei, 1997) provided an "image" of the deep geometry of the basin. These data show that the present geometry of the Sulmona basin and of the continental sequences infilling the depression has been "shaped" by the long-term (Quaternary) activity of the normal fault system. Indeed, the Quaternary continental deposits of the basin (Fig. 4.1.2 a) are clearly tilted towards the normal fault system, showing evident growth strata (Fig. 4.1.2 b) the formation of which is clearly related to the activity of the Mt. Morrone normal fault system.

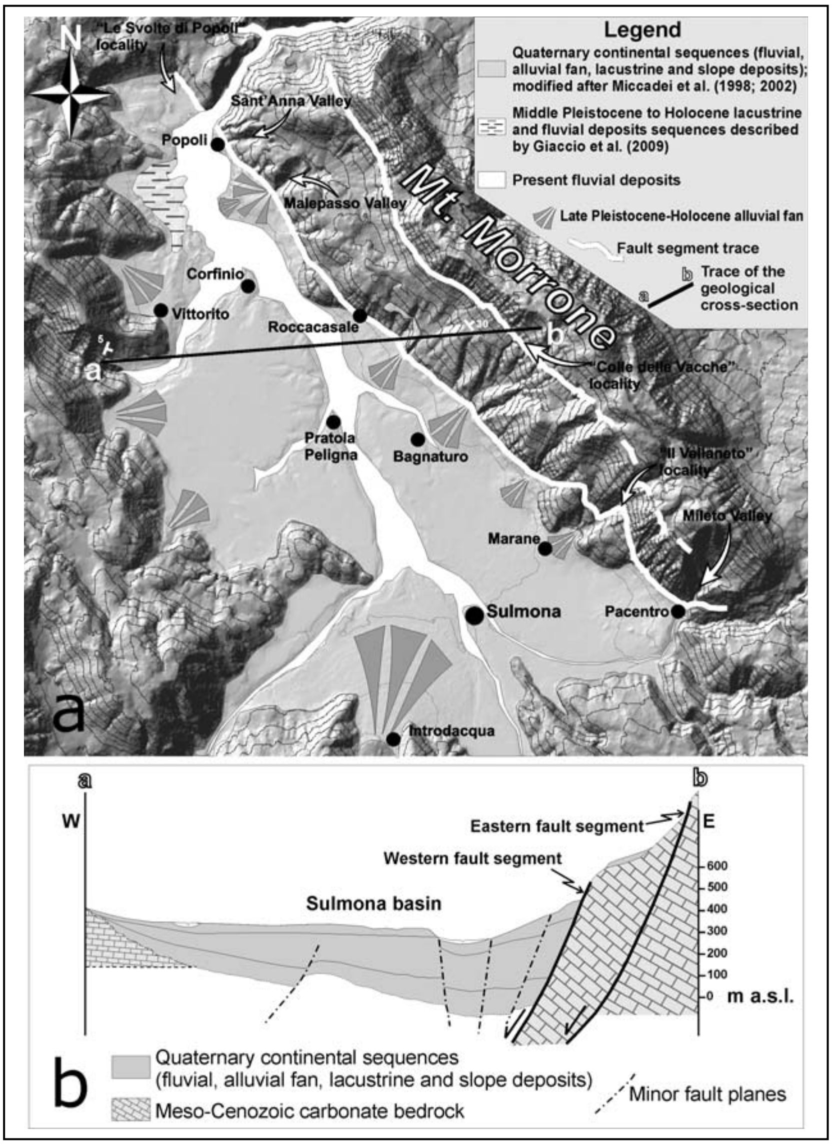


Fig. 4.1.2 – a) Shaded relief of the area under investigation (contour lines equidistance is 100m) on which a simplified geological map of the Sulmona basin (modified after Miccadei et al. (1998) and Giaccio et al. (2009)) is reported; b) schematic geological cross-section of the Sulmona basin (modified from Miccadei et al., 2002).

As for the Late Pleistocene-Holocene activity of the tectonic structure, it has been indicated by the displacement of slope-derived deposits related to this chronological interval (Galadini and Galli, 2000). The estimates of the slip rate proposed in previous studies are rather scattered, ranging from 0.1 to 1.4 mm/yr (Vittori et al., 1995; Galadini and Galli, 2000; Miccadei et al., 2002; Miccadei et al., 2004; Gori et al., 2007). This wide range is due to the different methods used (and related to the different reliabilities of these estimates) to determine this slip rate. A comparison between the slip rates proposed in previous studies and those obtained in the present study is provided below, together with a full description of the procedures adopted in the various studies.

4.1.1 Field data

Stratigraphy and chronology of the Middle Pleistocene/Holocene deposits

The continental stratigraphic sequence of the Sulmona basin includes several units of fluvio-lacustrine, alluvial and slope-derived sediments that span from between the Early Pleistocene to the Holocene (e.g. Demangeot, 1965; Cavinato and Miccadei, 1995; Miccadei et al., 1998).

Recent morphological and litho-pedostratigraphic investigations, supported by new radiocarbon, U-series and tephrochronological age determinations, have allowed an update of the Quaternary stratigraphic and chronological framework of the Sulmona basin sequence, as discussed in detail by Giaccio et al. (2009), with the designation of six informal units of lacustrine deposits. A comprehensive, simplified, schematic stratigraphic and chronological framework is shown in Figure 4.1.3.

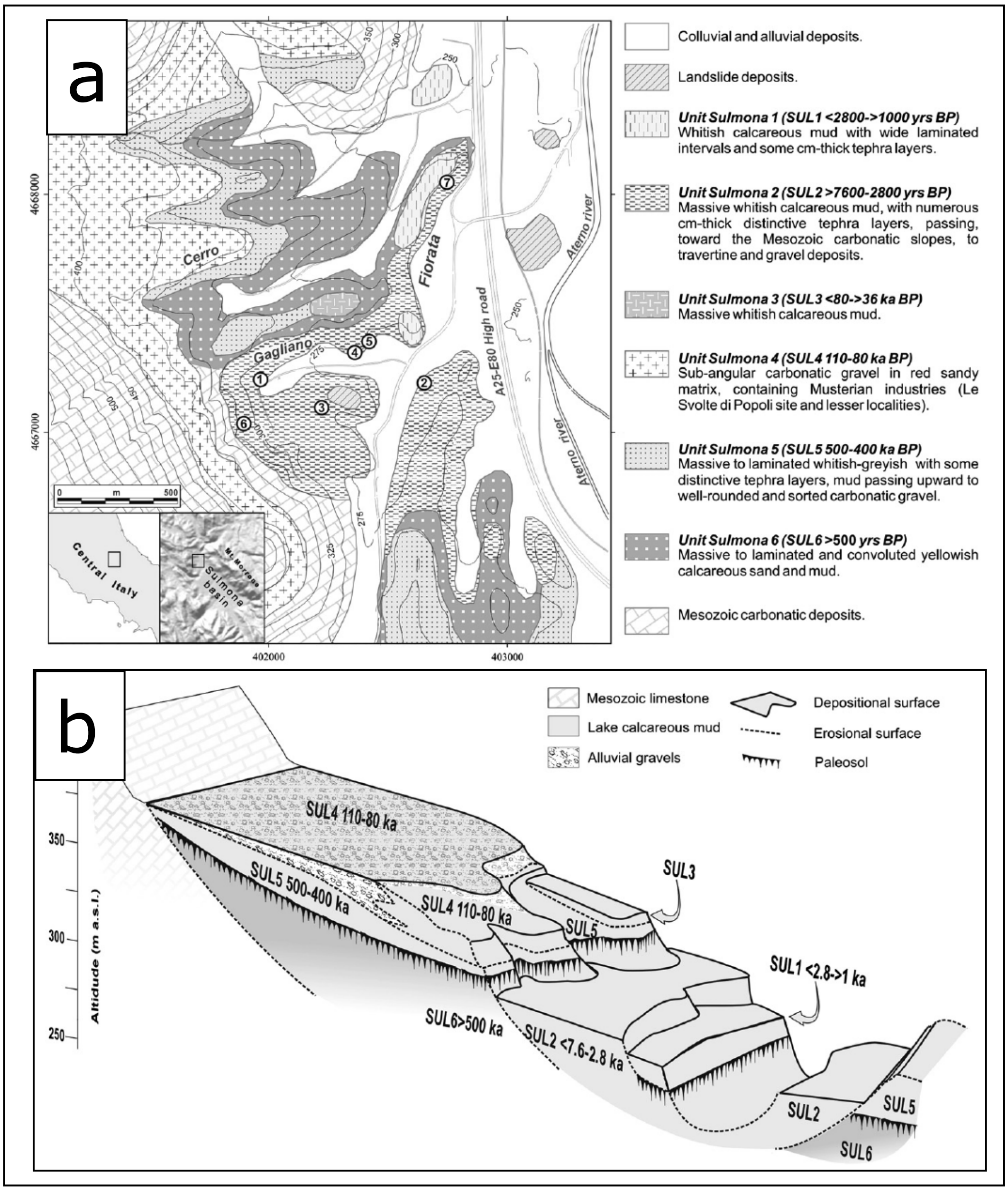


Fig. 4.1.3 – a) Geological map of the north-eastern sector of the Sulmona basin (numbers refer to the main measured sections reported in Giaccio et al., 2009); b) Scheme of the stratigraphic and geomorphological relationships between the six sedimentary units (SUL6–SUL1) recognised by Giaccio et al. (2009).

These lacustrine units, separated by erosional surfaces and/or pedogenic levels, have been detected and annotated from the earliest ("Sulmona 6") to the most recent ("Sulmona 1"). According to Giaccio et al. (2009), the six units can be chronologically attributed to the following time spans: Sulmona 6: >800 ka BP; Sulmona 5: 600 to 400 ka BP; Sulmona 4: 120 to 80 ka BP; Sulmona 3: 80 to 60 ka BP; Sulmona 2: 8 to 2.6 ka BP; Sulmona 1: 2.6 to 1.2 ka BP (Fig. 4.1.3).

The lowermost limit, i.e. >800 ka BP, that was attributed to the oldest analysed lacustrine unit derives from the presence of calcalkaline tephra layers related to the activity of the peri-Tyrrhenian volcanoes which preceded the onset of the activity of the ultra-potassic Roman Comagmatic Province, started at the beginning of the Middle Pleistocene (e.g. Peccerillo, 2005).

Besides this lacustrine sequence, at least seven units of alluvial deposits, some of which may be morphologically related to the lacustrine ones have been distinguished (Fig. 4.1.4). These are represented by different orders of telescopic and/or superposed alluvial fans, which are mainly fed by the fluvial network that cuts across the Mt. Morrone SW slopes.

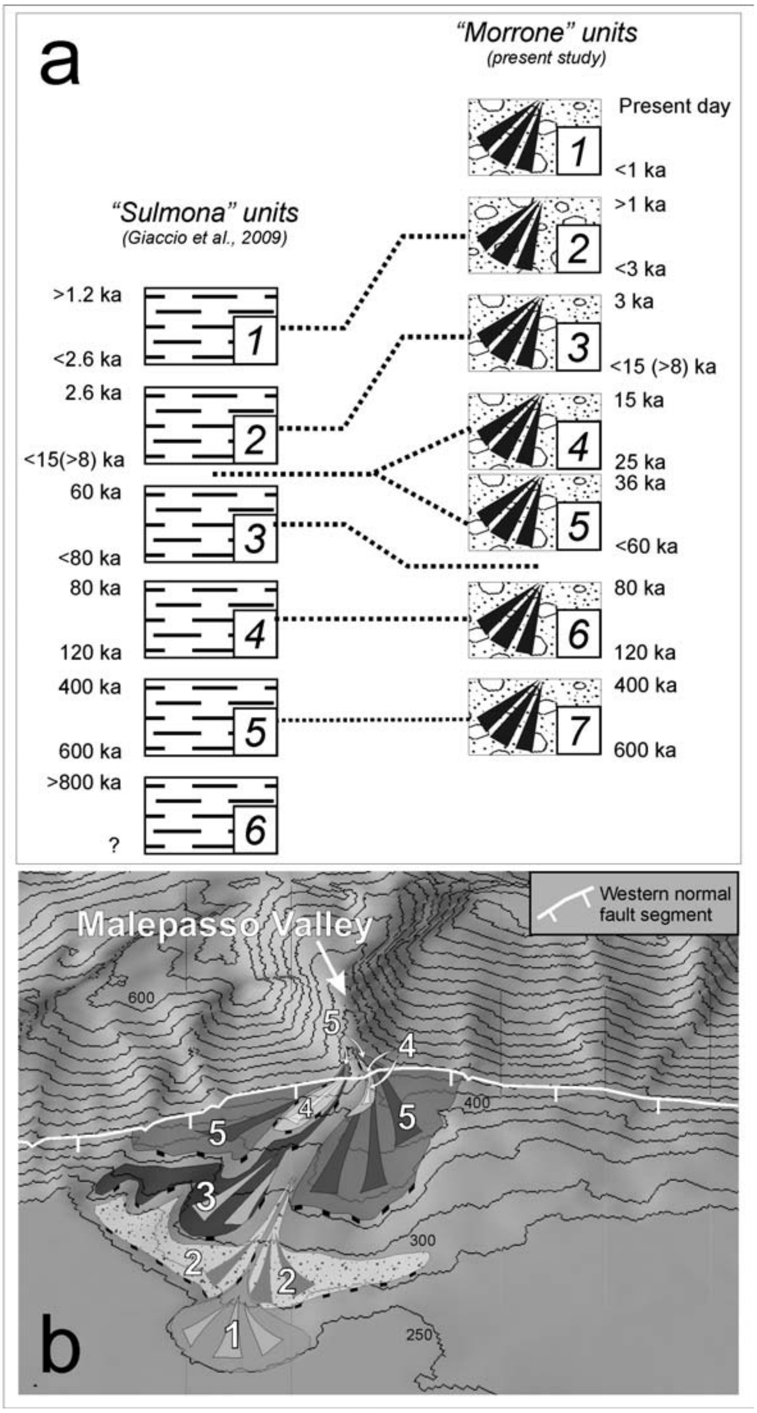


Fig. 4.1.4 – a) Scheme of the possible morpho-stratigraphic correlation between the "Sulmona" lacustrine units of Giaccio et al. (2009) and the "Morrone" alluvial units described in the present study; b) Schematic reconstruction of the five orders of alluvial fan deposits detected near Popoli village, overlying a hillshade Digital Terrain Model (DTM). Numbers indicate the "Morrone" units described in the text.

A basic description of the alluvial units (labelled from the oldest, “Morrone 7”, to the most recent, “Morrone 1”) is provided below together with the possible relationship between some of these units and the lacustrine units of Giaccio et al. (2009).

- Morrone 7 (<600 – >400 ka BP) – This is the oldest alluvial unit of the basin that contain volcanic levels (older, “pre-volcanic” alluvial deposits of the basin have been detected and described in other studies, e.g. Miccadei et al., 1998; Gori et al., 2007). This unit corresponds to the “Conoide Superiore di San Venanzio” unit of Miccadei et al. (1998), who attributed these deposits to the Middle Pleistocene. The gravels of this unit are interfingered with the lacustrine sediments of the Sulmona 5 unit.

- Morrone 6 (120 – 80 ka BP) – This unit comprises the deposits described by Radmilli (1984) and Tozzi (2003) that contain a sequence of Paleolithic layers that have been attributed to the Musterian technocomplexes. In peninsular Italy, these Paleolithic layers have been related to a chronological interval from between ca. 120 to 40 ka BP. (e.g. Tozzi, 2003, and references therein). The possible correlation between the Morrone 6 and Sulmona 4 units is supported by the detection of a particular marker, i.e. a tephra layer that is seen for both the alluvial and the lake sediments.

- Morrone 5 (<60 – 36 ka BP) – The alluvial fan that represents this unit is the equivalent of the “Terrazza Alta di Sulmona” (TAS) unit of Miccadei et al. (1998). The wide, northward inclined top depositional surface of the TAS unit is detectable over almost all of the basin and dominates the Sulmona plain landscape (from about 420 m a.s.l. in the southern part of the basin, to about 340 m a.s.l. in the northern basin sector) (Fig. 4.1.1). The correlation between the Morrone 5 and TAS units is supported by the presence of the same reworked tephra layers that have been detected at comparable depths (about 1-2 m) below the top depositional surfaces of each of the units (Fig. 4.1.5). In more detail, this volcanic level is made of sub-mm-sized to mm-sized, grey-black, poorly vesicular scoria with abundant leucite and clinopiroxene, and up to cm-sized phlogopite crystals (see Miccadei et al., 1998).

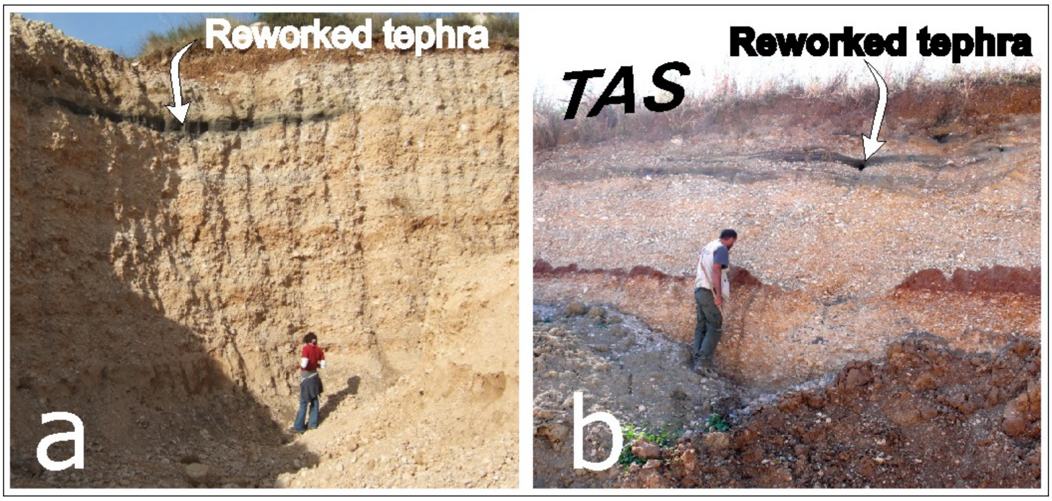


Fig. 4.1.5 – Reworked tephra layer detected within both a) Morrone 5 unit (described in the text) and b) the TAS unit of Miccadei et al. (1998).

These particular compositional features characterise a cluster of two or more crystal-rich tephra layers that have been recognised in a wide area of the central Apennines, and on the basis of chemical, isotopic and chronological data, they have been attributed to the most recent volcanic activity of the Albano Maar (Colli Albani volcanic district, near Rome) (Narcisi, 1994; Giaccio et al., 2007, and references therein) that was recently dated to between 40 and 36 ka BP (Freda et al., 2006). A radiocarbon dating of a terrestrial gasteropod shell embedded in the reworked tephra of the TAS unit yielded an age of 36610 ±209 cal years BP (estimated calibration, according to Fairbanks et al., 2005), which supports the chronological constraint defined for these deposits.

Moreover, from a morphological point of view, the correlation between the Morrone 5 and TAS units is supported by the alluvial fan of Morrone 5 that is related to a base level that corresponds to the top surface of the TAS unit.

Lastly, the deposits of the Morrone 5 unit unconformably overlie the lacustrine sediments of the Sulmona 4 unit (120-80 ka BP).

- Morrone 4 (L.G.M., i.e. 25-15 ka BP) – The deposits of this unit are morphologically comprised between those of the older Morrone 5 and the younger Morrone 3 (see below). The chronological attribution of this unit is supported by the fact that other alluvial fans, formed during the Last Glacial Maximum (LGM), have been detected in many areas of the central Apennines (i.e. Fucino plain-Valle Majelama, Giraudi, 1992; Campo Imperatore plain, Giraudi and Frezzotti, 1997;

Corvaro plain, Chiarini et al., 1997; Castelluccio di Norcia plain, Galadini and Galli, 2003). Locally, this unit is represented by slope-derived deposits that are widespread all over the Apennines (Castiglioni et al., 1979; Dramis, 1983; Coltorti and Dramis, 1988), and which result from periglacial erosional/ depositional slope processes that were active during the LGM.

- Morrone 3 (<15 (>8) – 3 ka BP) – This is represented by an alluvial fan, the top depositional surface of which defines a well preserved terrace that seems to be at the same elevation a.s.l. of the shoreline of the paleo-lake that corresponds to the Sulmona 2 unit.

- Morrone 2 (<3 – >1 ka BP) – This unit is represented by alluvial fan gravels, the top depositional surface of which morphologically correlates with the top surface of the Sulmona 1 unit.

- Morrone 1 (>1 ka – present day) – This unit is represented by small alluvial fans related to the present base level of the basin.

The whole sequence of units Morrone 5 to Morrone 1 has been clearly identified where the Malepasso valley (see Fig. 4.1.2 b) opens on the plain. Here, these units are represented by five orders of telescopic alluvial fans (see Fig. 4.1.4 b) – partly already detected by Miccadei et al. (1998) and attributed by the authors to the Late Pleistocene – the eldest of which (Morrone 5 unit) is related to the top depositional surface of the TAS unit while the younger units (Morrone 4 to 1 unit) are embedded in it. In other sectors along the base of slopes – i.e. W and N of Bagnaturo – these units are represented further superposed and/or embedded alluvial fans some of which relate to the top depositional surface of the TAS unit while younger fans overlay it. The different geomorphic setting between the alluvial fans at the Malepasso and Bagnaturo areas is due to fact that, in the former area, the regressive fluvial erosion incised the TAS unit, progressively lowering the base level and thus permitting the formation of subsequent telescopic fans. In the Bagnaturo sector, instead, the top surface of the TAS unit has not yet been significantly incised by fluvial erosion. Owing to this, at this site the alluvial fans that are younger than the TAS unit deposited on its top depositional surface.

Although this different geomorphic framework prevented a "one by one" correlation between the Malepasso and the Bagnaturo alluvial fan units, the analysis of stratigraphic sections exposed by quarries near Bagnaturo permitted us to obtain further chronological elements that corroborate the age of the deposition of the Morrone 5 to Morrone 1 units. Indeed, 1) radiocarbon dating of a paleosoil contained within the alluvial fan that is morphologically related to the TAS unit provided an age of 41830±2130 years BP (Fig. 4.1.6 a), and 2) a tephra layer occurring within an alluvial fan that deposited over the top surface of the TAS unit can be related to the "Neapolitan yellow tuff" (Fig. 4.1.6 b), dated at 14200 years BP on the basis of ^{14}C chronological constraints (Asioli et al., 2001; Siani et al., 2001).

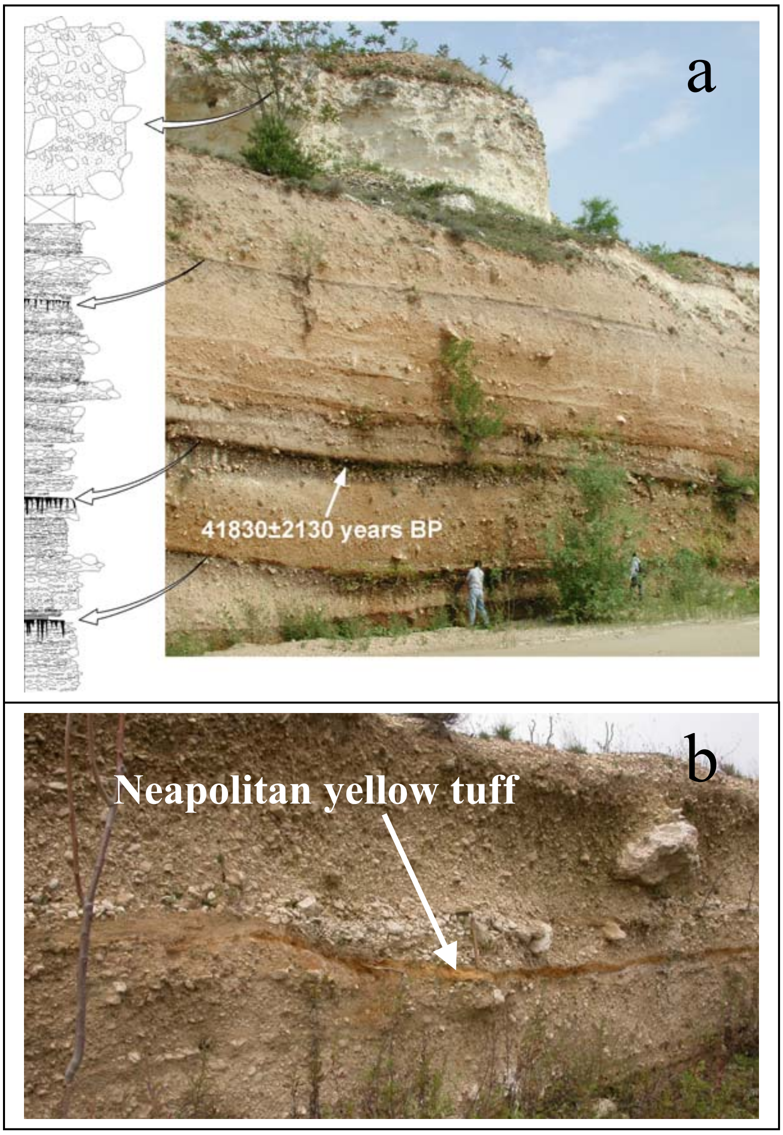


Fig. 4.1.6 – a) Alluvial fan sequence exposed by a quarry near Bagnaturo, at the base of the Mt. Morrone SW slopes; b) Tephra layer, associated to the "Neapolitan yellow tuff", occurring within alluvial fan deposits near Bagnaturo overlaying the TAS unit.

These data corroborate the attribution of the units Morrone 5 to Morrone 1 to a time span younger than 60 ka.

Evidence of Late Quaternary tectonics

- Pacentro site (Fig. 4.1.1, site 1)

In the southern sector of the SW slopes of Mt. Morrone, the fault plane of the western segment can be detected almost at the base of the slopes, close to the village of Pacentro. Kinematic indicators detected along the fault plane (Fig. 4.1.7) as slickenlines, with a pitch angle from 72° to 82°, *lunate fractures* (Petit, 1987), and the synthetic shear planes in the fault zone all indicate mainly normal kinematics of the fault segment, with a minor sinistral oblique component.

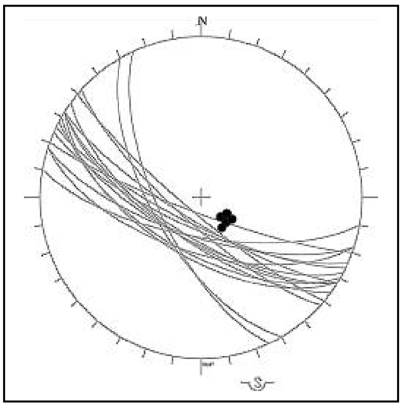


Fig. 4.1.7 – Schmidt net diagram on which the synthetic shear planes detected in the fault zone (black bows) and the pitch of the slickenlines (black dots) are plotted

Here, the alluvial fan deposits of the Morrone 7 unit are exposed about 1.5 km away from the southernmost tip of the fault branch.

The fan has been fed by the Mileto valley, a deep V-shaped fluvial incision that is perpendicular to the slope (Fig. 4.1.8).

Fig. 4.1.8 – Alluvial fan deposits of the Morrone 7 unit outcropping within the Mileto Valley, upslope of the village of Pacentro.

The deposits are displaced along the fault branch. In the footwall of the fault, the deposits lie on the bedrock. They can be detected within the Mileto Valley incision, at an elevation ranging between 1,100 m a.s.l. (i.e. the apex of the fan, where the layers show a steep angle of 25°) and 825 m a.s.l. (Fig. 4.1.9).

Fig. 4.1.9 – Alluvial fan deposits of the Morrone 7 unit detected within the Mileto Valley incision, in the western fault segment footwall. The white dashed line highlights the layer attitudes that in the distal part of the deposits become sub-horizontal.

At this elevation, the layers have a sub-horizontal attitude (about a 12° dipping) and are clearly truncated towards the plain due to the fault activity, such that they are at present suspended over the basin bottom (Fig. 4.1.10).

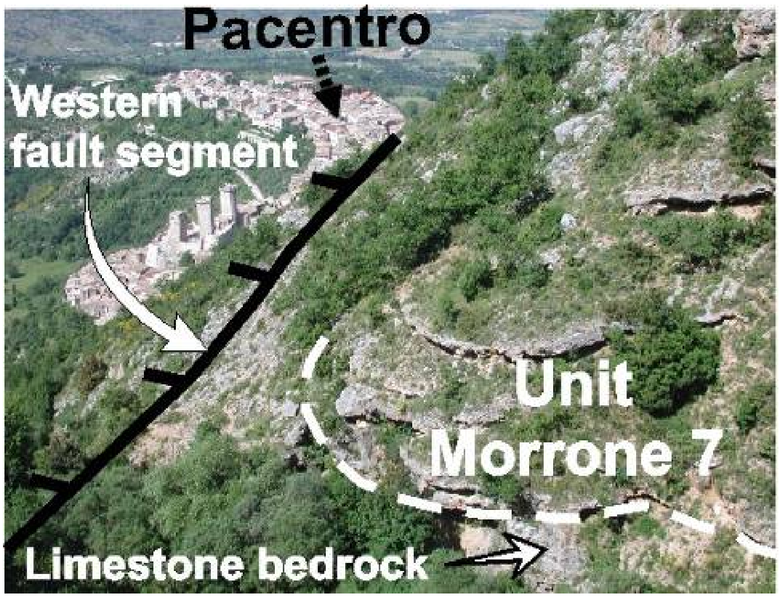


Fig. 4.1.10 – The Morrone 7 unit deposits lying on the carbonate substratum (the white dashed line marks the contact between the deposits and the bedrock) in the fault segment footwall. The layers are clearly suspended over the present basin bottom and truncated by the fault movements.

In the hanging wall sector, instead, the base of the fan can be detected between 667 m and 675 m a.s.l. (part of Pacentro village has been built on it) (Fig. 4.1.11), overlying a huge paleo-landslide accumulation known as “Pacentro paleolandslide” (Miccadei et al. 1998; 2004). The sub-horizontal attitude of the layers (about 10° SW dipping) suggests that the deposition in this area occurred close to the local base level.

Fig. 4.1.11 – Alluvial fan deposits of the Morrone 7 unit close to Pacentro, outcropping in the hanging wall sector of the western fault segment. The white dashed lines highlight the sub-horizontal attitude of the layers.

The fault segment places the alluvial fan sediments in contact with the carbonate substratum.

The vertical offset affecting the base of the Morrone 7 unit across the western fault segment (Fig. 4.1.12)can therefore be estimated at about 160 m (Fig. 4.1.13).

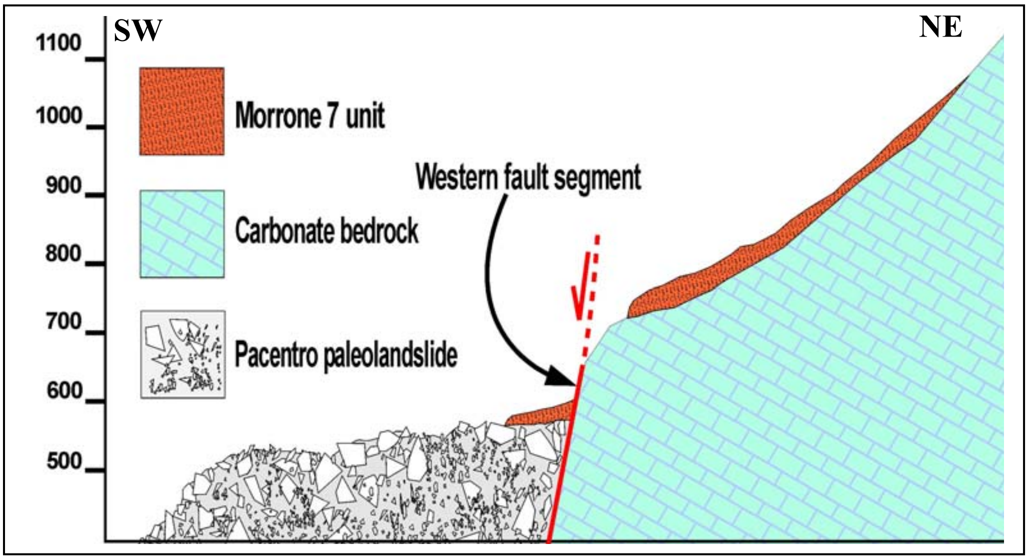


Fig. 4.1.12 – Schematic geological profile showing the offset of the Morrone 7 units due to the western fault segment activity.

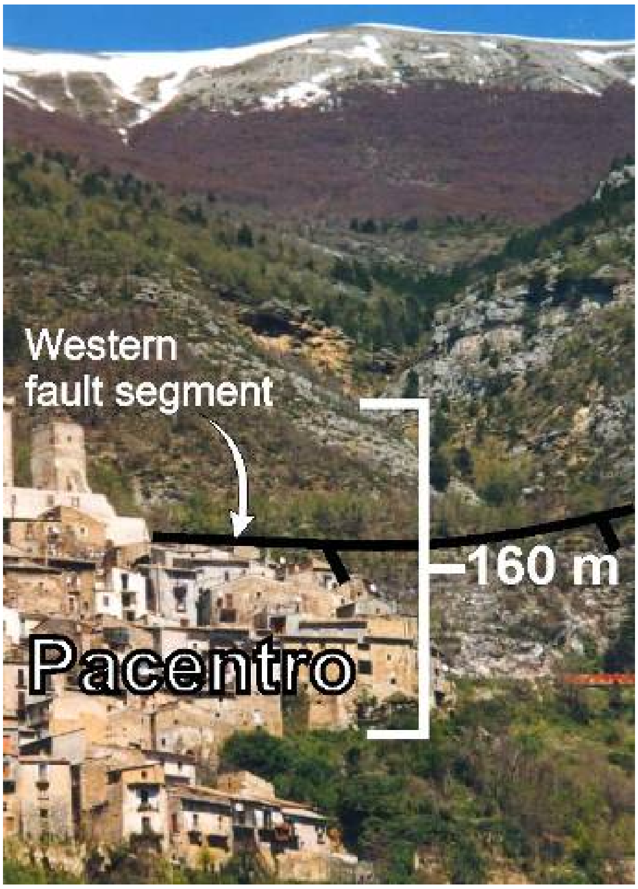


Fig. 4.1.13 – Vertical displacement of the Morrone 7 unit deposits due to the fault segment movements. The offset can be quantified in about 160 m.

- Popoli-Malepasso Valley site (Fig. 4.1.1, site 2)

The complete sequence of the units Morrone 1 to 5 has been detected at this site (Fig. 4.1.4 b), where the Malepasso Valley opens on the plain (see Fig. 4.1.2 a). Here, the westernmost fault branch is detectable at the base of the slope. The kinematic indicators collected along the fault plane in this area (Fig. 4.1.14) as slickenlines, with a pitch angle ranging from 76° to 83°, and the synthetic shear planes in the fault zone confirm mainly normal kinematics with a minor sinistral oblique component.

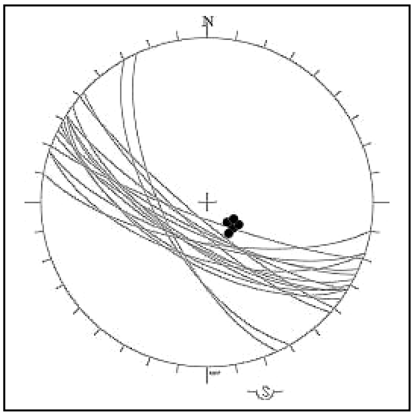


Fig. 4.1.14 – Schmidt net diagram on which the synthetic shear planes detected in the fault zone (black great circles) and the pitch of the slickenlines (black dots) are plotted.

The fault has displaced the alluvial fan deposits of the Morrone 5 and 4 units (Fig. 4.1.15, inset).

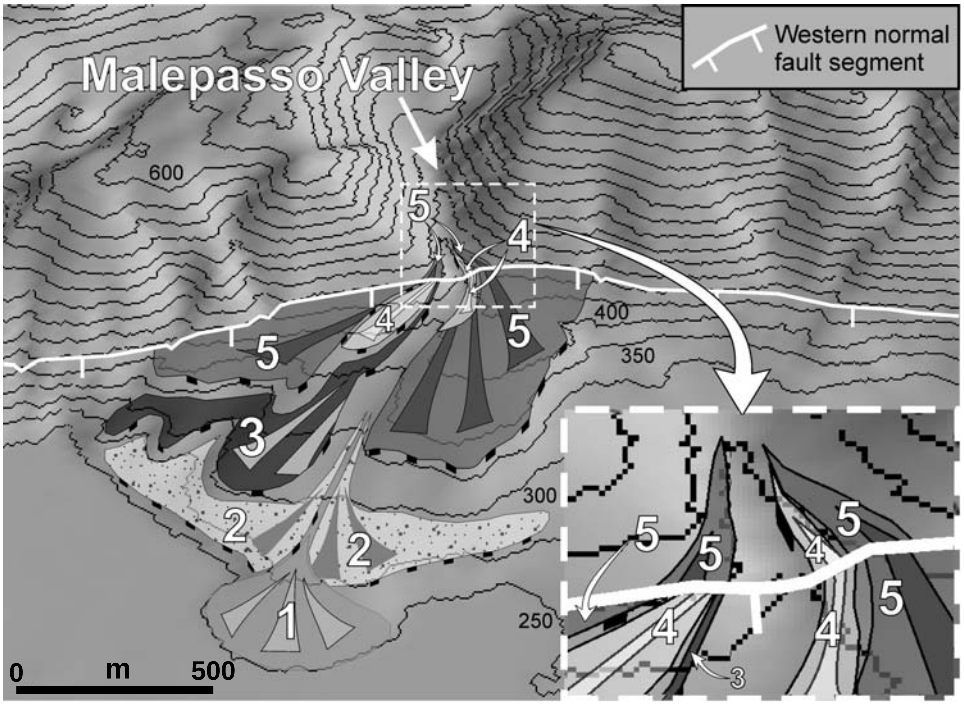


Fig. 4.1.15 – Digital Terrain Model showing the sedimentary units detected at site 2 in Fig. 4.1.1; the Morrone 4 and 5 units are clearly displaced along the western fault segment (inset).

The sediments of these units are detectable both in the hanging wall and in the footwall. The top depositional surface of the unit Morrone 5 is displaced along the fault by about 20 m (Fig. 4.1.16). Moreover, the layers of the alluvial fan are clearly truncated by several secondary fault planes.

In the proximal part, the Morrone 4 unit is represented by a flat alluvial terrace along the left flank of the Malepasso valley incision. The fault activity has displaced this terrace by about 7 m (Fig. 4.1.16).

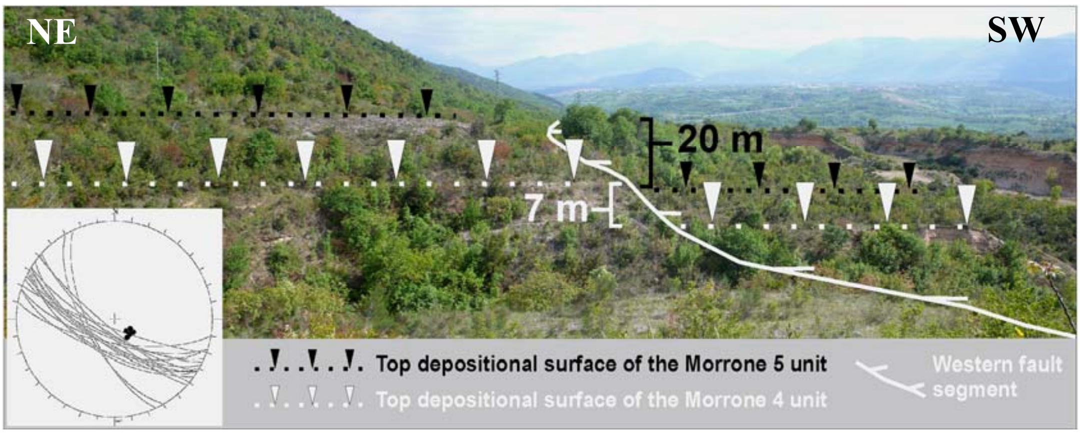


Fig. 4.1.16 – (Site 2 in Fig. 4.1.1) Vertical displacement affecting the top depositional surface (indicated by the triangles) of the Morrone 4 and 5 units, quantified in about 7 and 20 m, respectively; on the Schmidt net diagram (inset) the synthetic shear planes detected in the fault zone (black great circles) and the pitch of the slickenlines (black dots) are plotted.

- Popoli-Sant'Anna Valley site (Fig. 4.1.1, site 3)

At this site, the western fault segment affects the base of the slope. The kinematic indicators detected along the main and the secondary fault planes (Fig. 4.1.17), i.e. slickenlines, with a pitch angle ranging from 75° to 80°, and the synthetic shear planes in the fault zone confirm a mainly normal kinematics.

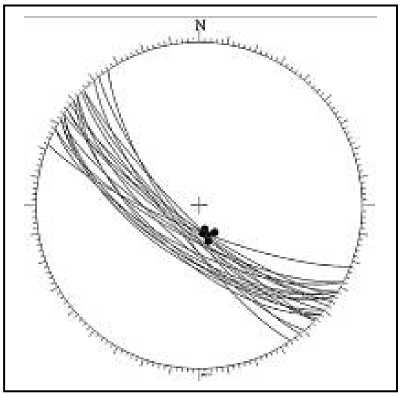


Fig. 4.1.17 – Schmidt net diagram on which the synthetic shear planes detected in the fault zone (black great circles) and the pitch of the slickenlines (black dots) are plotted.

The Sant'Anna Valley is a deep fluvial incision that is almost perpendicular to the main slope and that opens onto the plain near the village of Popoli (Fig. 4.1.2 a). This incision cuts the deposits of the Morrone 7 and 6 units, which are only detectable in the footwall of the main fault. Nevertheless, the sediments of the Morrone 7 unit are displaced by about 13 m along a secondary fault plane (linked to the main one). The offset was evaluated by correlating the erosional surface that separates the deposits and the carbonate bedrock across the fault (Fig. 4.1.18).

Fig. 4.1.18 – Left flank of the Sant'Anna Valley incision, along which the vertical offset that affects the deposits of the Morrone 7 unit, due to the western fault segment activity, is shown (Fig. 4.1.1, site 3).

Several synthetic, secondary fault planes truncate the layers of the Morrone 6 and 7 units (Fig. 4.1.19 a, b), that locally display a counter-slope tilting (Fig. 4.1.20).

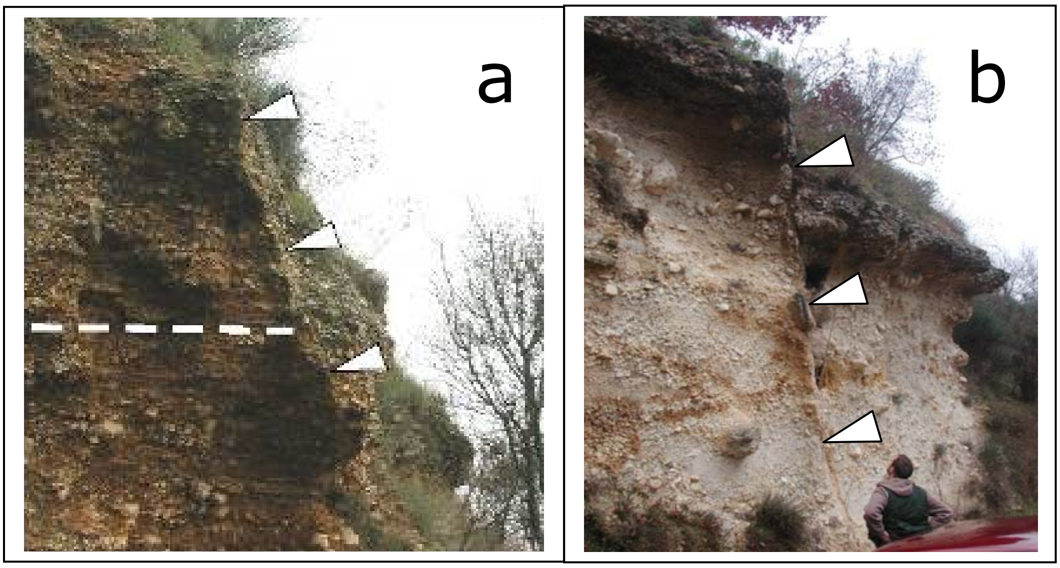


Fig. 4.1.19 – Synthetic fault planes (indicated by the white triangles) that displace the deposits of the Morrone 6 (a) and 7 (b) units.

Fig. 4.1.20 – Deposits of the Morrone 6 unit displaying a counter-slope attitude (marked by the white dashed line).

Moreover, the almost flat depositional surface at the top of the alluvial fan is affected by a fault scarp, indicating a 12-13 m vertical offset along these secondary splays (Fig. 4.1.21).

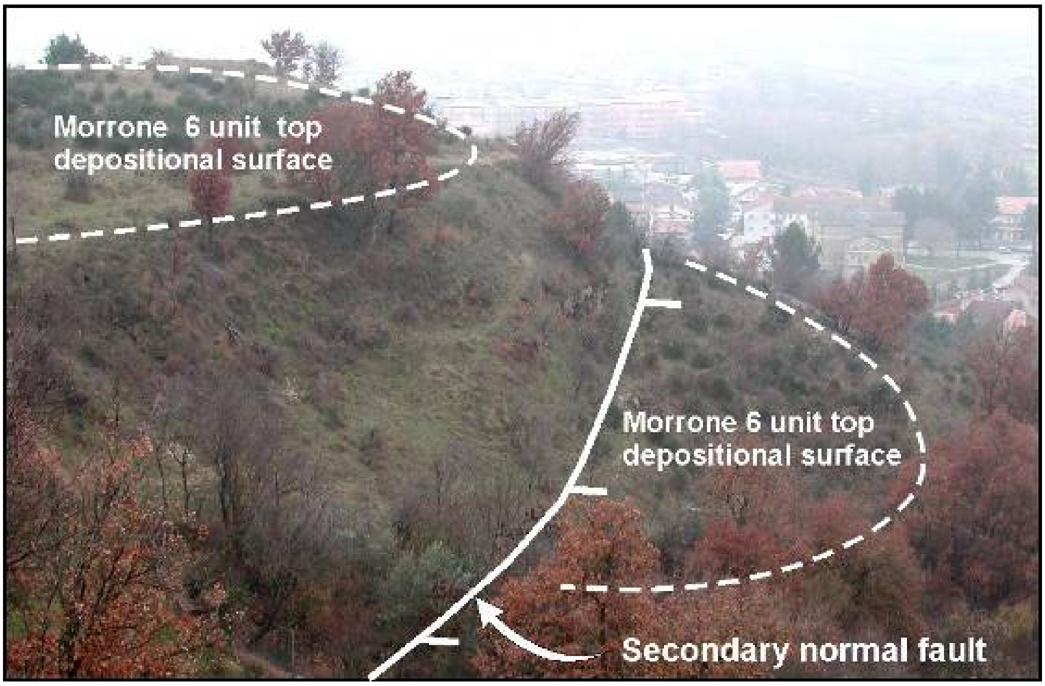


Fig. 4.1.21 – Vertical displacement of about 10-11 m that affects the top surface (delimited by the white dashed lines) of the Morrone 6 unit deposits.

Moreover, the Morrone 6 unit deposits and some sediments younger than the Morrone 6 unit (as they are embedded in it) are displaced along a fault (already reported by Miccadei et al., 1998) parallel to the Sant'Anna Valley, WSW-ENE trending and almost perpendicular to the main Mt. Morrone normal fault segments (Fig. 4.1.22 a, b).

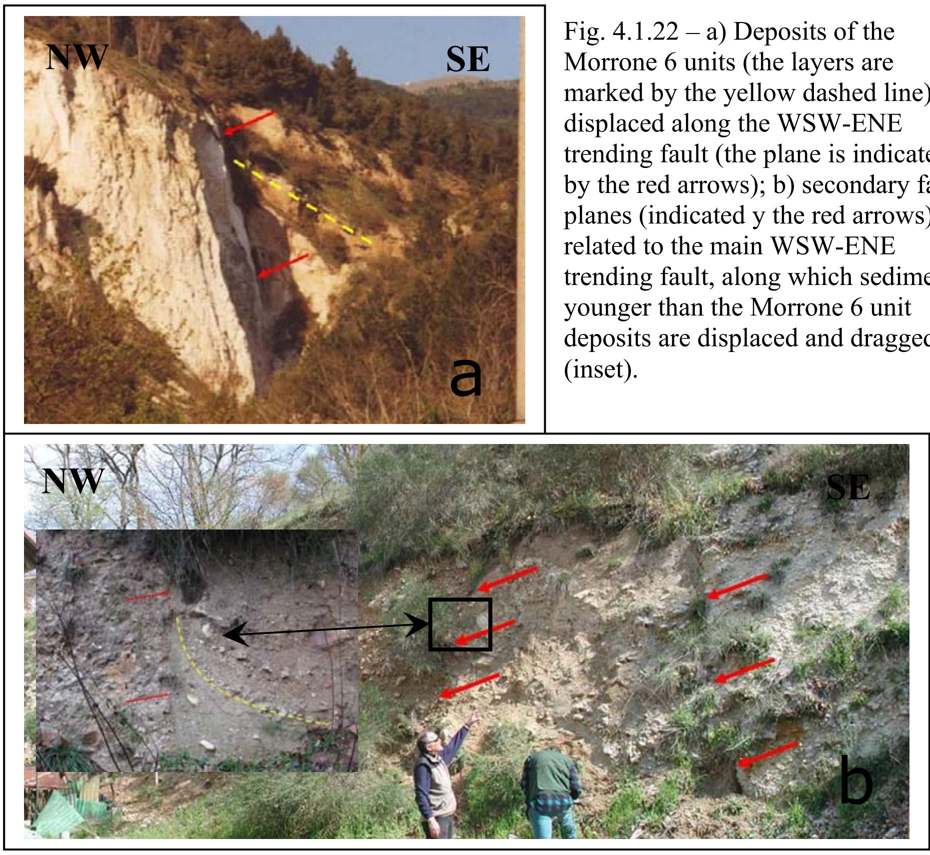


Fig. 4.1.22 – a) Deposits of the Morrone 6 units (the layers are marked by the yellow dashed line) displaced along the WSW-ENE trending fault (the plane is indicated by the red arrows); b) secondary fault planes (indicated y the red arrows), related to the main WSW-ENE trending fault, along which sediments younger than the Morrone 6 unit deposits are displaced and dragged (inset).

The kinematic indicators collected along the fault plane indicate a prevailing dextral strike-slip motion of the tectonic structure, with a minor normal component. The structural setting suggests that it represents a transfer fault – probably a breached relay ramp (e.g. Peacock and Sanderson, 1994; Childs et al., 1995; Peacock, 2002; Walsh et al., 2003) – that connects the main Mt. Morrone fault branches, and that was at least active after the deposition of the Morrone 6 unit. The lack of synchronous deposits that can be correlated across the fault prevented the possibility of estimating the offset. Moreover, according to Gori et al. (2006; 2008), a certain amount of gravitational displacement along this transfer fault can be hypothesised, since this tectonic structure represents the lateral boundary of a large-scale mass movement that affects the slopes.

- Le Svolte di Popoli "archaeological" site (Fig. 4.1.1, site 4)

Here, the Morrone 6 unit is displaced by about 5 m along the main western fault branch (Fig. 4.1.23). This offset can be estimated on the basis of the displacement affecting a reworked volcanoclastic level, present both in the footwall and in the hanging wall.

Fig. 4.1.23 – (Fig. 4.1.1, site 4) Deposits of the Morrone 6 unit displaced along the northern tip of the western fault segment (indicated by the white triangles).

The outcrop investigated is located very close (a few tens of metres) to the northern tip of the fault, where the segment ends against a structural feature known as the "Avezzano-Bussi fault system" (see Fig. 2.1.3), which is perpendicular to the Mt. Morrone fault system (i.e. ENE-WSW trending) (Galadini and Messina, 2001; Cavinato et al., 2002) (Fig. 4.1.24).

Fig. 4.1.24 – Fault plane (indicated by the red arrows) related to the "Avezzano-Bussi fault system" of Galadini and Messina (2001).

This fault was active in this sector between the Pliocene and the Early Pleistocene, and its exhumed plane is exposed here. This framework has implications in terms of estimating the slip rate, as discussed in the next section.

- Il Vellaneto and Bagnaturo-Colle delle Vacche sites (Fig. 4.1.1, sites 5 and 6, respectively)

Both the western and the eastern fault segments place the carbonate substratum rocks in contact with LGM slope-derived deposits, which are ascribed to the Morrone 4 unit. Along the western fault segment, contact between the carbonate bedrock and these deposits has been seen at the Il Vellaneto site (Fig. 4.1.25), along the middle part of the slopes, northeast of Marane (see Fig. 4.1.2 a).

Fig. 4.1.25 – Last Glacial Maximum deposits (the layers are marked by the white dashed line) placed in contact with the carbonate substratum by the westernmost fault segment (site 5 in Fig. 4.1.1).

For the eastern fault branch, instead, tectonic contact has been detected at the Colle delle Vacche site, (Fig. 4.1.26) along the higher part of the slopes, east of the village of Bagnaturo (see Fig. 4.1.2 a).

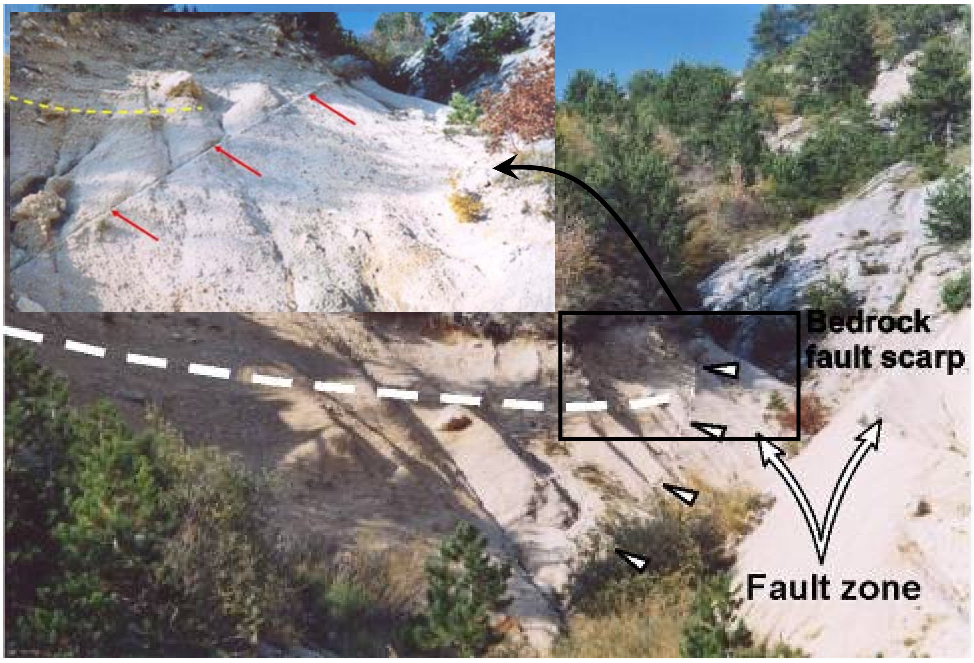


Fig. 4.1.26 – Last Glacial Maximum deposits placed in contact with the carbonate substratum by the eastern fault segment (site 6 in Fig. 4.1.1). The layers of the deposits (highlighted by the white dashed lines) are clearly truncated by the fault branches activity. A close up image of the fault zone is shown in inset, where the fault plane is marked by red arrows and the layers of the deposits are highlighted by the yellow dashed line.

In some places, the layers of the LGM deposits show evidence of dragging due to the fault movement.
The kinematic indicators collected along the plane of the eastern branch (Fig. 4.1.27), i.e. slickenlines, with a pitch angle ranging from 78° to 85°, *lunate fractures* (Petit 1987) (Fig. 4.1.28) and the synthetic shear planes in the fault zone, suggest that this segment is also characterised by mainly normal kinematics, with a minor oblique left-lateral component.

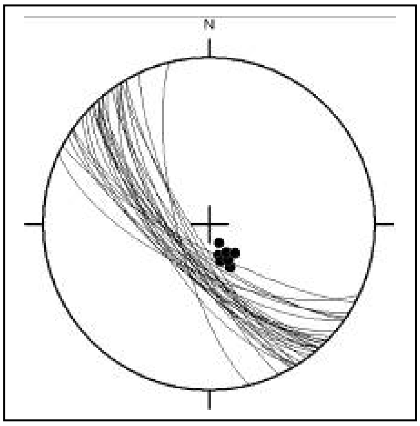


Fig. 4.1.27 – Schmidt net diagram on which the synthetic shear planes detected in the fault zone (black great circles) and the pitch of the slickenlines (black dots) are plotted.

Fig. 4.1.28 – *Lunate fracture* detected along the plane of the eastern fault segment.

The lack of synchronous landforms and/or deposits that can be correlated across the eastern fault has hindered the definition of the vertical offset. However, it should be noted that the estimate of the offset across this segment of displaced geologic/ geomorphic features has to be considered with caution, in order to define a tectonic slip rate. Indeed, the sector of the SW slopes of Mt. Morrone between the main fault branches has been affected by large-scale gravitational movements, which have already been detected by Ciccacci et al. (1999) and Miccadei et al. (2004), and described by Gori et al. (2006; 2008).

4.2 The Maiella-Porrara normal fault system

As reported in section 2.1, the sector comprised between the Maiella Massif, Mt. Morrone and Mt. Porrara was the origin of high-magnitude historical earthquakes that occurred in 1706 (Maw = 6.6) and in 1933 (Maw = 5.7) the causative faults of which is still under debate.
Geological and geomorphological surveys carried out in this area permitted us the

identification of Late Quaternary normal faulting in this area.

We have detected normal fault segments 1) in the southern sector of the Maiella Massif, here the Palena Fault, and 2) along the western slope of Mt. Porrara, here the western Porrara Fault, a relief located south of the Maiella relief. Although these faults have already been mapped in the past (Donzelli, 1969; Vezzani et al., 1993; Vezzani and Ghisetti, 1998), their Late Pleistocene-Holocene activity has not been described before.

4.2.1 Field data

These tectonic structures appear to branch from a northern fault segment that propagates towards the SW from the Mt. Morrone normal fault system (Fig. 4.2.1, 4.2.2).

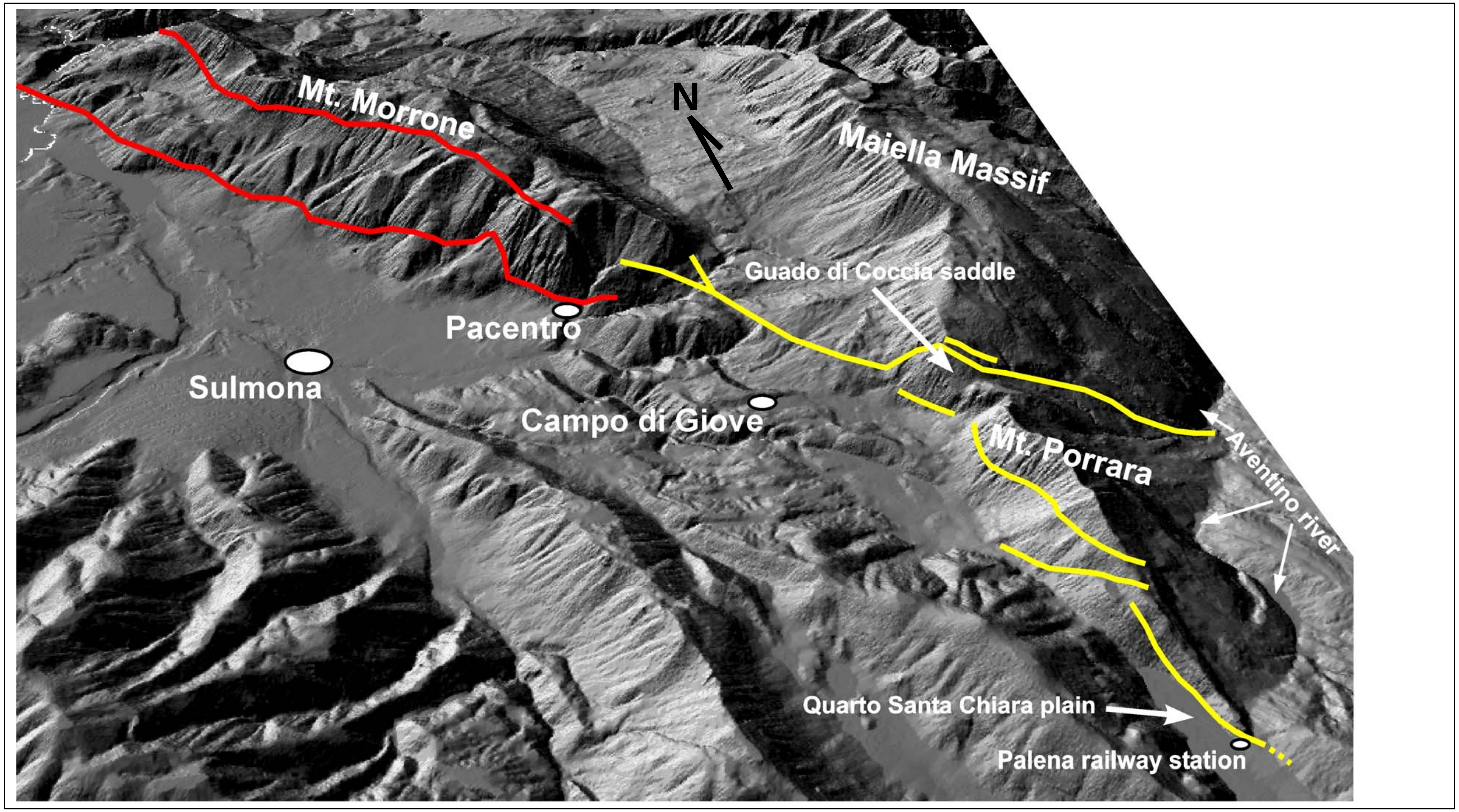


Fig. 4.2.1 - Digital Terrain Model on which red lines mark the segments of the Mt. Morrone normal fault system as described in the present work; the yellow lines, instead, mark the fault segments detected in the area comprised between Mt. Morrone, Maiella Massif and Mt. Porrara.

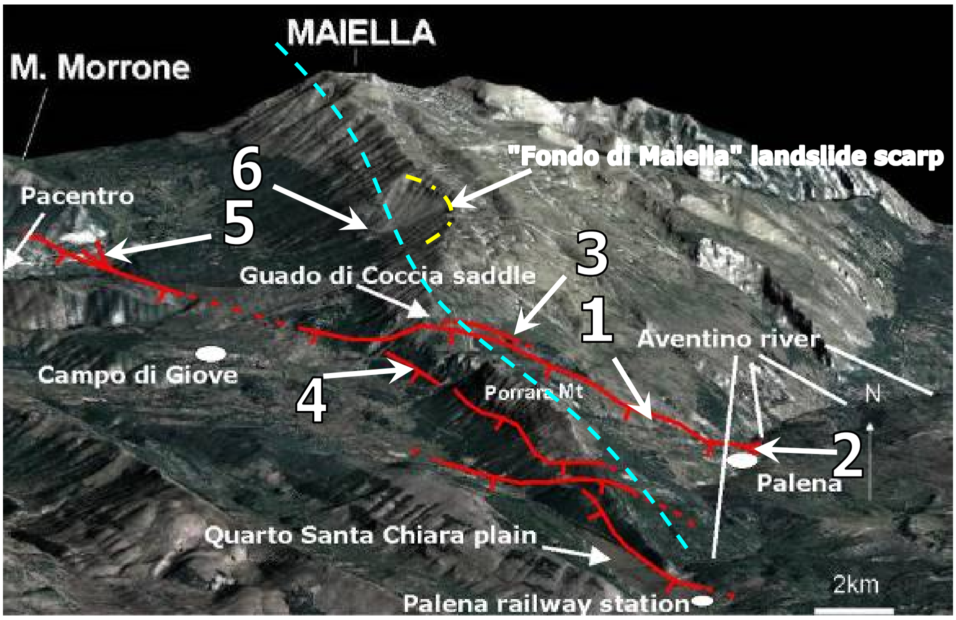


Fig. 4.2.2 – Three-dimensional images of the southern Maiella Massif and Mt. Porrara area created by draping aerial orthophotos (1:10.000 Scale, from C.G.R. Parma, Italy) over digital topography (40 m pixel resolution, from Regione Abruzzo, Italy) with sun direction from the SE and sun angle = 45°. The red lines mark the fault segments of the Maiella-Porarra fault system. The blue dashed line marks the Caramanico fault-line scarp as described by Ghisetti an Vezzani (2002) while the yellow dot-dashed line marks the "Fondo di Maiella" landslide scarp (see the text). The numbers (1-4) indicate the site described in the text.

The Palena fault

The Palena Fault is formed by a major N110°-120° trending fault segment and by some minor synthetic sub-parallel splays. The main fault crosses the slopes in the southernmost sector of the Maiella ridge at right angles (Fig. 4.2.3).

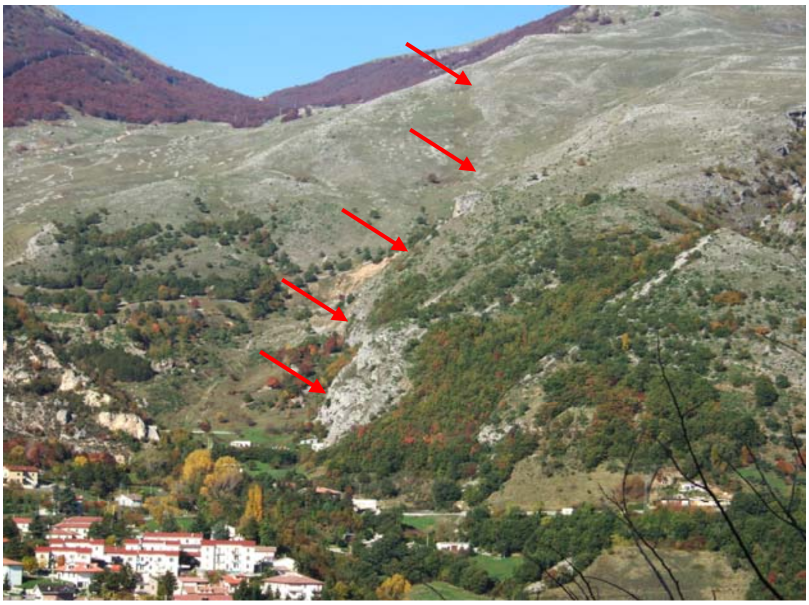


Fig. 4.2.3 – Palena Fault scarplet (indicated by red arrows) along the south-eastern slopes of the Maiella Massif, close to the of village Palena.

It is also transverse to the axial trace of the Maiella anticline close to the southern plunge.

This fault segment was observed in the field between the village of Palena (close to the Aventino river thalweg) and the Guado di Coccia saddle (see Fig. 4.2.4).

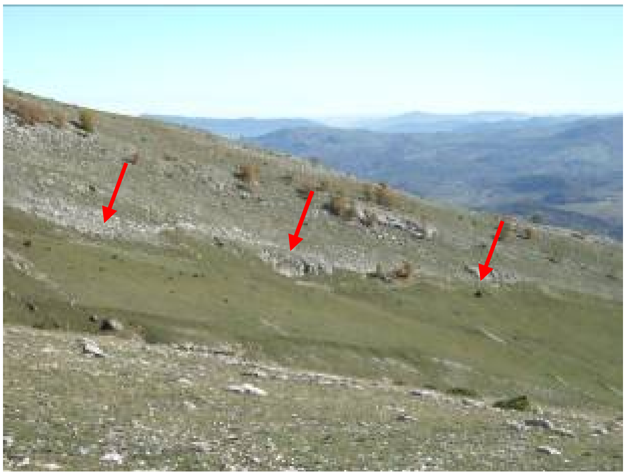


Fig. 4.2.4 – Palena Fault scarplet (indicated by red arrows) close to the Guado di Coccia saddle, along the uppermost part of the Maiella relief.

Based on geomorphic evidence, it can be extended westward along the western Maiella slope, up to ca. 1.5 km east of Campo di Giove. Hence a total length of about 7 km can be evaluated for the entire fault segment.

These SSW-dipping planes are usually associated with bedrock scarps. Along the scarps, the exposed faults are responsible for the displacement of the Mesozoic-Cenozoic carbonate bedrock that outcrops both in the footwall and in the hanging-wall blocks. This geomorphic feature suggests that erosional selective processes have had no influence on the formation of the scarps (Fig. 4.2.5).

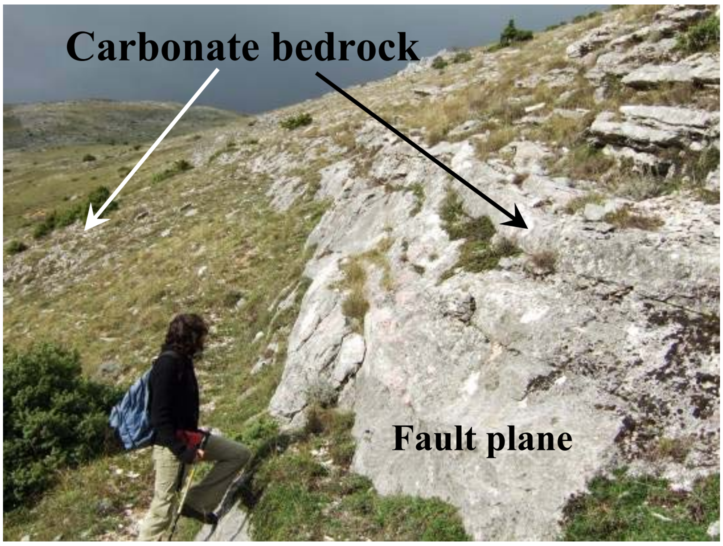


Fig. 4.2.5 – Palena fault scarplet. The carbonate substratum crops out both in the hanging wall (indicated by the white arrow) and in the footwall (indicated by the black arrow) of the fault.

Moreover, the fault scarps generally show very little degradation and interrupt the continuity of the Maiella eastern slope. Since the regular profile of Apennine slopes results from the last significant morphogenic phase, which is generally attributed to the Last Glacial Maximum, an age of post-18 kyr BP can be attributed to the scarp formation and the related fault activity (see Galadini and Galli, 2000; Roberts and Michetti, 2004, for a full discussion on this topic).

Locally, Quaternary continental deposits are juxtaposed against the bedrock fault plane (Fig. 4.2.2, site 1). Erosion of these deposits has produced exposures of the fault plane that are up to 20-30 m high (Fig. 4.2.6), and very clear kinematic indicators can be detected (Fig. 4.2.7).

Fig. 4.2.6 – The 20-30 m high exposure of the Palena Fault plane ca. 700 m NW of Palena village (Fig. 4.2.2, site 1). Here, the fault juxtaposes Messinian gypsum-arenites in the hanging wall, against Eocene-Oligocene calcarenites in the footwall.

The fault-slip data show nearly pure dip-slip normal movements (Fig. 4.2.7 a) probably superposed on slickenlines indicating sinistral oblique motions (Fig. 4.2.7b).

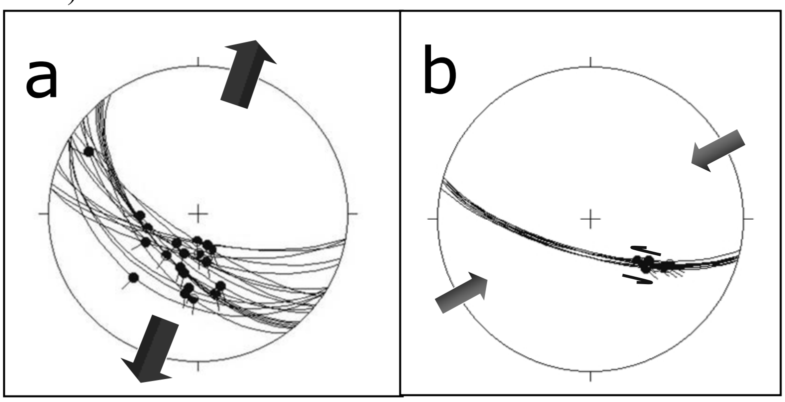


Fig. 4.2.7 – Schmidt net diagrams on which synthetic shear planes detected in the fault zone (black great circles) and the pitch of the slickenlines (black dots) are plotted, related to: a) dip-slip normal movements and b) to sinistral oblique (pre-Quaternary) kinematics.

These dip-slip movements provide the principal axis of extension, trending about. NNE-SSW.

This extension is consistent with deformation of the Late Quaternary deposits, which have been displaced and dragged by the fault activity, and it appears consistent with the extensional deformation presently acting in the chain (e.g. Galadini, 1999; Pizzi et al., 2002).

In contrast, the earlier, left-lateral, strike-slip striations probably result from the Pliocene fault motions that were related to the formation and evolution of the Maiella thrust-related anticline. The left-lateral movement of the fault is, indeed, kinematically consistent with the NE-SW-oriented main axis of compressive stress that was responsible for the formation of the Apennine thrust-belt. On the whole, the Palena Fault represents an inherited Pliocene syn-orogenic sinistral-oblique structure that was reactivated with nearly pure dip-slip normal motions during the Quaternary.

The contact between the carbonate bedrock and Quaternary slope-derived deposits can be observed ca. 1 km upslope (NW) of Palena, at an elevation ranging between 1,025 m and 1,075 m a.s.l. (Fig. 4.2.2, site 1). Here, the sediments are clearly displaced (Fig. 4.2.8) and dragged (Fig 4.2.9) along the fault plane.

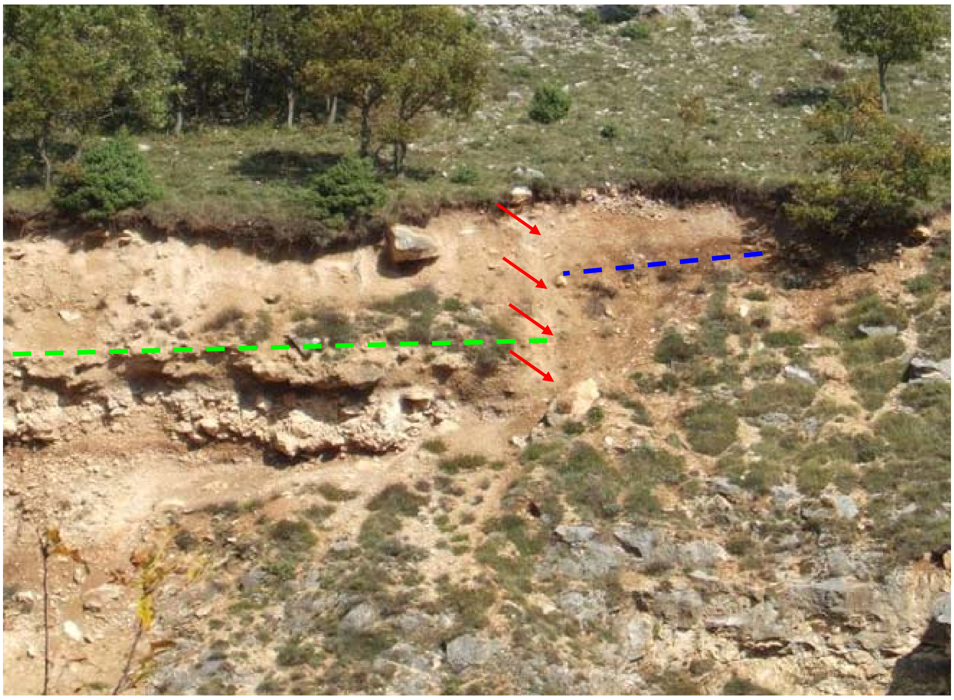


Fig. 4.2.8 – Late Pleistocene slope-derived deposits (see the text) displaced along the Palena fault. The green and blue dashed lines mark the attitude of the layers while the red arrows indicate a fault plane that affects the sediments.

Fig. 4.2.9 – Late Pleistocene slope deposits truncated by the Palena fault activity. The clasts are clearly dragged and verticalised by the fault movements.

The thickness of the exposed deposits is 18-20 m. These deposits comprise moderately well sorted, massive to well-bedded, angular-to-subangular gravels, clast-supported to matrix-supported (silty-sandy, brown-red matrix), displaying a sub-horizontal attitude. The radiocarbon dating of an interbedded organic-rich, and in places volcanic-rich, colluvium that occurs at the intermediate portion of the exposed deposits (see location in Fig. 4.2.10) and that was clearly displaced by the fault, indicated an age of 36,300 ±1,300 yr BP (analysed at Beta Analytic Radiocarbon Dating Laboratory, Florida, USA).

Fig. 4.2.10 – Slope deposits dated at the Late Pleistocene dragged along the fault plane.

It must be noted that this chronological determination actually results from the organic matter borne by the parent material of the colluvial layer, i.e. a paleosoil. This implies that the age of 36,300 1,300 yr BP represents the minimum age for the debris deposition, which therefore probably occurred in more recent times.

Furthermore, the lithological and the morphologic characteristics of the slope-derived deposits described suggest that they can be related to the debris sequences that were widespread throughout the Apennines and were deposited in the peri-glacial environment during the Last Glacial Maximum (e.g. Dramis, 1983).

Hence, an age for the deposition of the scree ranging between about 40 kyr and 15 kyr can be considered as reliable.

The continuity of the deposits towards the slope is interrupted by the fault. Their dragging and displacement along the fault plane defines the Late Pleistocene activity of the Palena Fault. Since the basal contact of the deposits with the carbonate substratum is not exposed in the hanging wall, and the layers display a sub-horizontal attitude, we can assume the measurable thickness of the sediments (18-20 m) as the fault minimum offset that occurred after about 40 kyr BP.

This estimate of the offset is supported by the displacement of the same debris sequence that outcrops in the fault footwall a few tens of metres downslope and that is suspended ca. 18 m above the present bottom of the incision (Fig. 4.2.11).

Fig. 4.2.11 – Late Pleistocene slope-derived deposits suspended above the present valley bottom of about 18 m by the Palena fault activity.

The occurrence of non-tectonic processes – such as differential compaction and/ or gravity-related phenomena (landsliding) – that might have determined the observed deformations of the deposits can be excluded, as explained in the following. Indeed, the sediments described mainly consist of clast-supported gravels. This lithological/ sedimentological characteristic suggests that compaction processes can be considered as almost negligible. Furthermore, these deposits lie on a slope characterised by a low-energy local relief, not showing morphological features suggesting the presence of slope instabilities (as visible in Fig. 4.2.6). This framework allows us to exclude that gravitational processes had a key role in determining the deformation of the sediments.

The Palena Fault is also responsible for the displacement of slope deposits a few tens of metres north of Palena (Fig. 4.2.2, site 2), detected along the wall of an abandoned small quarry (Fig. 4.2.12). These sediments are made of carbonate, angular-to-subangular gravels, ranging in size from granules to boulders, with a clayey, silty and sandy matrix. An interbedded pedogenic colluvium, warped and dragged along the fault has been dated by means of radiocarbon age determination and gave an age of 11810-11420 BC (calibrated, 2σ).

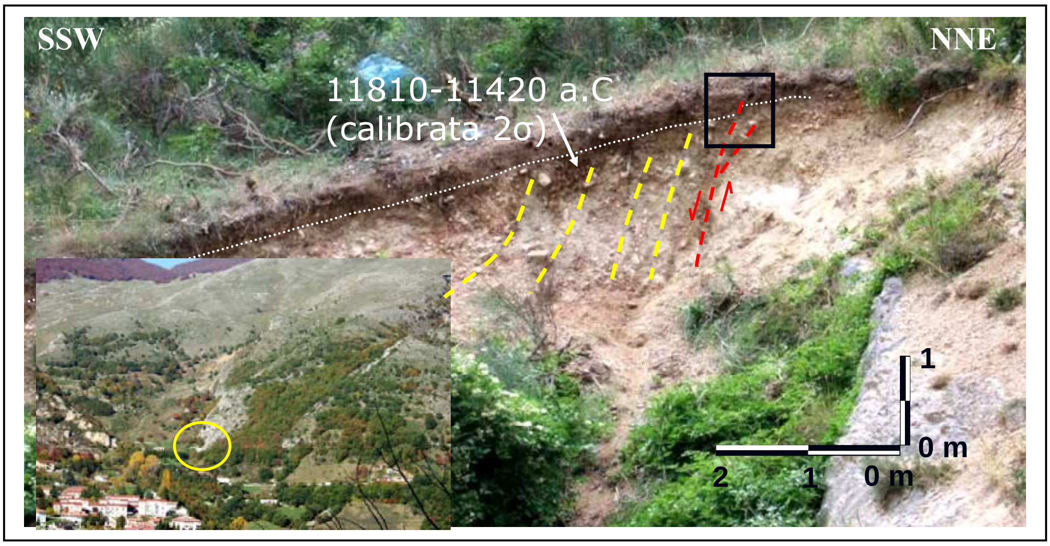


Fig. 4.2.12 – Late Pleistocene-Holocene slope debris displaced and dragged along the southern tip of the Palena fault (red dashed line). The yellow dashed lines mark the shear planes affecting the sediments.

Moreover, the present soil has also been displaced by the fault movement by about 15 cm (Fig. 4.2.13). A bronze leaf collected within the displaced soil suggests a fault activation, with consequent surface faulting, subsequent to the Bronze Age (Fig. 4.2.14).

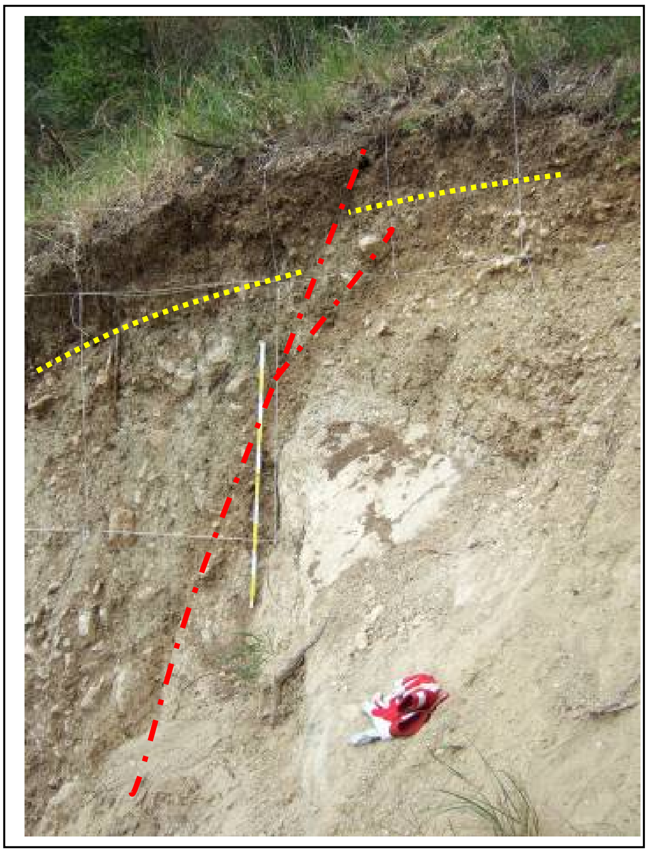
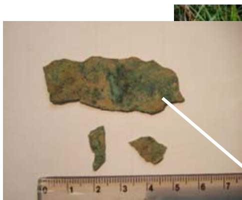


Fig. 4.2.13 – Displacement of the present soil (the base of which is marked by the yellow line) along a synthetic fault plane of the Palena fault.



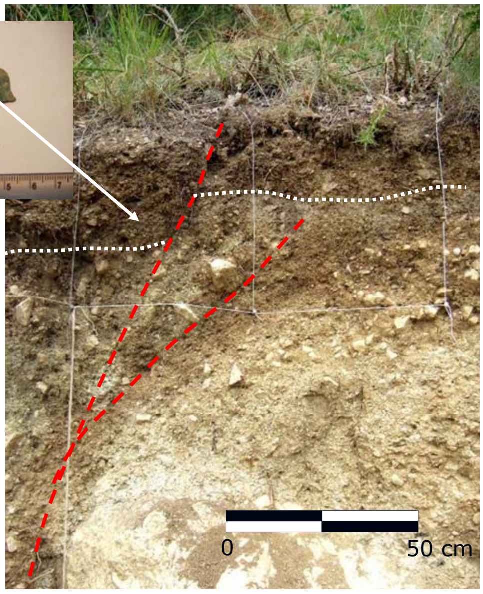


Fig. 4.2.14 – Bronze leaf found within the present soil.

Nevertheless, further studies are planned to define the age of the formation of the present displaced soil and to obtain new chronological constraints for the Holocene fault activity.

The longest northern fault segment of the Palena Fault can be detected along the middle part of the slope. Slope-derived breccias outcrop at an elevation of 1,450-1,470 m a.s.l., and they are made of layered, angular-to-sub-rounded, carbonate gravels in pink-orange cement. Their lithological characteristics suggest their possible attribution to the "Second sedimentary unit" of the regional continental stratigraphic succession referred to the Early Pleistocene by Bosi et al. (2003). These deposits have evidently been dragged along the fault plane (Fig. 4.2.2, site 3; 4.2.15).

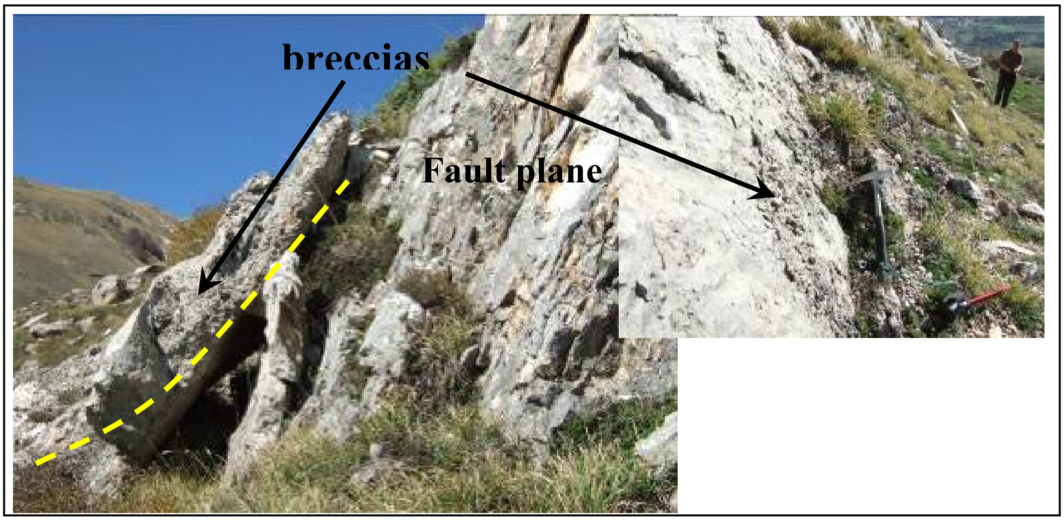


Fig. 4.2.15 – Slope-derived breccias, probably related to the Early Pleistocene, dragged along the Palena fault (the yellow dashed line indicated the attitude of the displaced

This represents further evidence of the Quaternary fault activity of the Palena Fault.

The western Porrara fault segments

Three NNW-SSE-striking fault segments (right-stepping, en-echelon pattern) were detected along the western slopes of Mt. Porrara (Fig. 4.2.2). The kinematic indicators measured along the fault planes suggest prevailing normal movements.

The central fault segment, already identified by Galadini and Galli (2000), was observed in the field for a length of about 3 km (Fig.4.2.16).

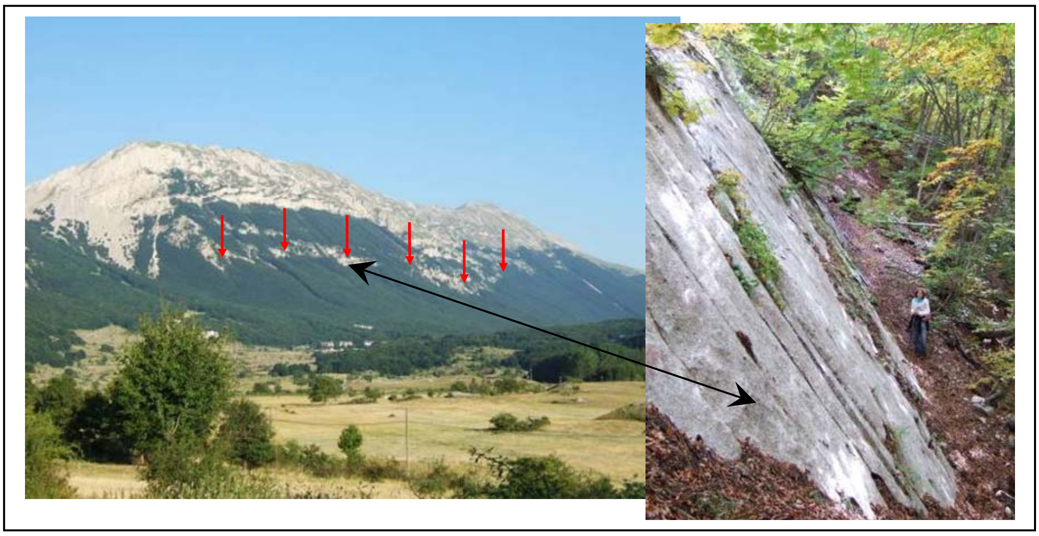


Fig. 4.2.16 – Mt. Porrara normal fault segments (red arrows indicate the central fault branch). The black arrow indicate the fault plane.

The fault places slope-derived debris in contact with the carbonate substratum (Fig. 4.2.2, site 4; Fig. 4.2.17). These slope deposits, commonly laying in the hanging wall along the whole western Porrara Fault, are made of unconsolidated, layered, clast-supported, angular-to-subangular carbonate gravels.

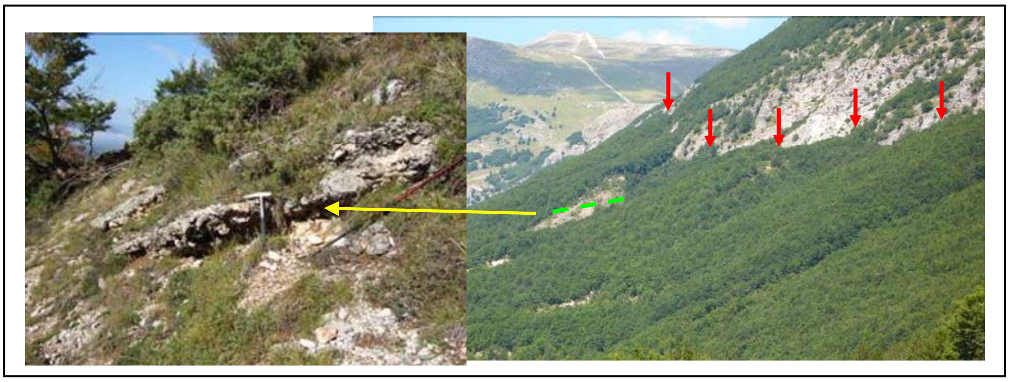


Fig. 4.2.17 – Slope-derived deposits (indicated by the yellow arrow), outcropping at the hanging wall of the Porrara fault segments. The layers (the attitude of which is marked by the green dashed line) ends abruptly against the fault (indicated by red arrows).

The thickness of the outcropping sediments is about 15 m and the slope is partially carved into them. Such lithological, stratigraphical and geomorphic characteristics suggest that these deposits can be correlated to those usually detectable along the south-facing and south-west-facing Apennine slopes, which are known as *grèzes litées* or *éboulis ordonné* (Coltorti and Dramis, 1988, and references therein), and which are typical of periglacial depositional environments of the Last Glacial Maximum.

Since the plane of the middle fault segment is not well exposed, it has been essentially mapped by its morphological evidence (as the fault activity formed a bedrock scarp) and from the available geological maps (e.g., Vezzani and Ghisetti, 1998), for a length of about 2 km. This represents the shortest segment of the western Porrara fault branches.

The southernmost segment of the Maiella-Porrara fault system is well exposed in the piedmont area of the Mt. Porrara slopes (Fig. 4.2.18), close to Palena railway station (see Fig. 4.2.2). It can be identified for a length of about 2.5 km.

Fig. 4.2.18 – Southern Porrara fault segment. The plane is indicated by the red arrow.

This segment bounds an endoreic depression, the Quarto S. Chiara plain, and it was partly responsible for the truncation of the depression threshold (Fig. 4.2.19).

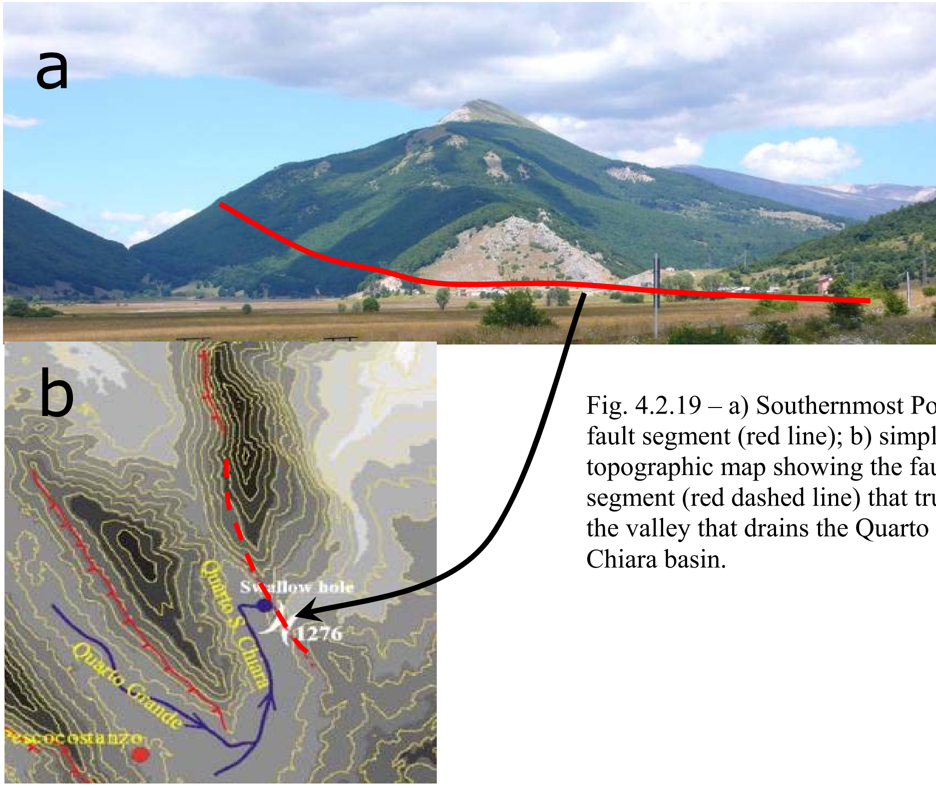


Fig. 4.2.19 – a) Southernmost Porrara fault segment (red line); b) simplified topographic map showing the fault segment (red dashed line) that truncate the valley that drains the Quarto Santa Chiara basin.

The lack of significant outcrops has prevented the determination of the amount of displacement of the deposits from the Last Glacial Maximum.

NE of the village of Campo di Giove, the northernmost segment (about 4 km in length) of the Maiella-Porrara fault system is detectable between the northern tip of the northernmost Porrara fault segment – described above – and the southern tip of the Mt. Morrone fault system (see Figs. 4.2.1 and 4.2.2).

The Quaternary activity of this fault segment is demonstrated by the displacement of the accumulation of an enormous rock avalanche, known in the literature as

"Campo di Giove rock avalanche" (Di Luzio et al., 2004) and detached from the western flank of the Maiella relief ("Fondo di Maiella" landslide scarp; see Fig. 4.2.2). The landslide accumulation, attributed to the Middle-Late Pleistocene by the mentioned authors, is displaced by about 50 m along the fault branch (Fig. 4.2.2, site 5; Fig. 4.2.20). The displacement of the landslide accumulation was already hypothesised by the mentioned authors.

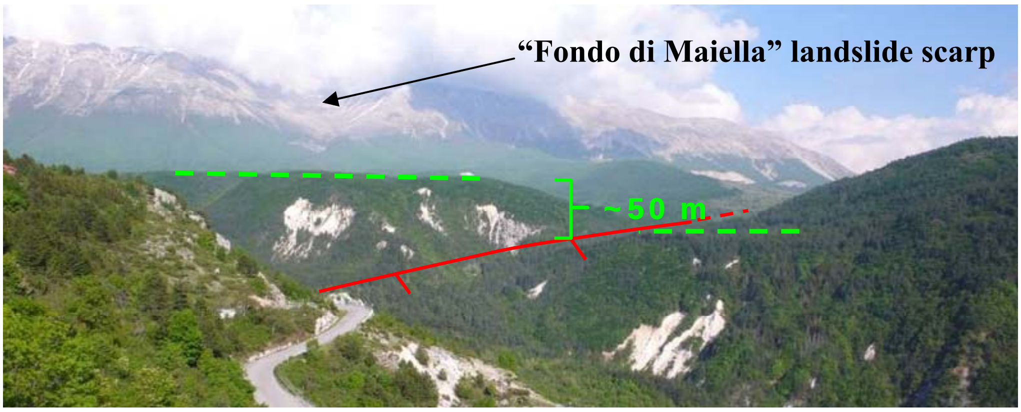


Fig. 4.2.20 – Vertical displacement, quantified in about 50 m, affecting the "Campo di Giove rock avalanche" due to the activity of the northernmost segment (marked by the red line) of the Maiella-Porrara normal fault system.

4.3 The Paganica fault and surface co-seismic ruptures caused by the April 6, 2009 earthquake

On April 6, 2009, at 01:32 GMT, a Mw 6.3 seismic event (Istituto Nazionale di Geofisica e Vulcanologia, 2009; MedNet, http://mednet.rm.ingv.it/procedure/events/QRCMT/090406_013322/qrcmt.html) hit the central Apennines, severely damaging the town of L'Aquila and dozens of neighbouring villages, resulting in almost 300 casualties. This earthquake was the strongest in central Italy since the devastating 1915 Fucino event (Mw 7.0). The INGV national seismic network located the hypocentre 5 km SW of L'Aquila, 8-9 km deep. Based on this information and on the seismotectonic framework of the region, earthquake geologists travelled to the field to identify possible surface faulting (Emergeo, Working Group, 2009; Rilievi geologici di terreno effettuati nell'area epicentrale della sequenza sismica dell'Aquilano del 6 Aprile 2009; http://www.ingv.it).

To identify the causative fault of this earthquake, we considered the structural framework of the area E and SE of L'Aquila, where different structural patterns have been depicted in the past. Indeed, since the 1970s, this sector has been repeatedly investigated regarding its neotectonic and active tectonic frameworks (Bosi and Bertini, 1970; Bosi, 1989; Bagnaia et al., 1992; Bertini and Bosi, 1993). In particular, the two most recent studies present substantially different structural frameworks regarding the Quaternary activity. Bagnaia et al. (1992) reported a normal fault in the zone of Paganica that connects it with another normal fault in the area of San Demetrio ne' Vestini, providing a simple structural image of this area (Fig. 4.3.1 a) that is affected by a ca. 20-km-long fault that partly affects Quaternary deposits. In contrast, Bertini and Bosi (1993) summarised a complicated structural framework of Quaternary faults in this area. The scheme proposed excludes a link between the Paganica fault and that in the area of San Demetrio ne' Vestini. The information on the Quaternary faults was summarised in a map by Vezzani and Ghisetti (1998), where the Paganica fault is mapped as a 9-km-long segment independent of the San Demetrio ne' Vestini fault (Fig. 4.3.1 b).

Finally, these data have been included in different ways in seismotectonic studies at a regional scale. When mapping the surficial expression of sources that could potentially be responsible for M ≥6.5 earthquakes, Galadini and Galli (2000) did not include the short Paganica fault segment at the NW end of the MAVFS. In contrast, Boncio et al. (2004) linked one segment of the UAVFS mapped by Galadini and Galli (2000), i.e. the southeastern-most one (the Mt. Pettino fault), to the Paganica fault, defining a single 13-km-long fault segment in the area of L'Aquila that is not linked to the San Demetrio ne' Vestini fault (Fig. 4.3.1 c). Roberts and Michetti (2004) and Papanikolaou et al. (2005) reported a segment of more than 30 km in this area , not including, however, the Paganica fault.

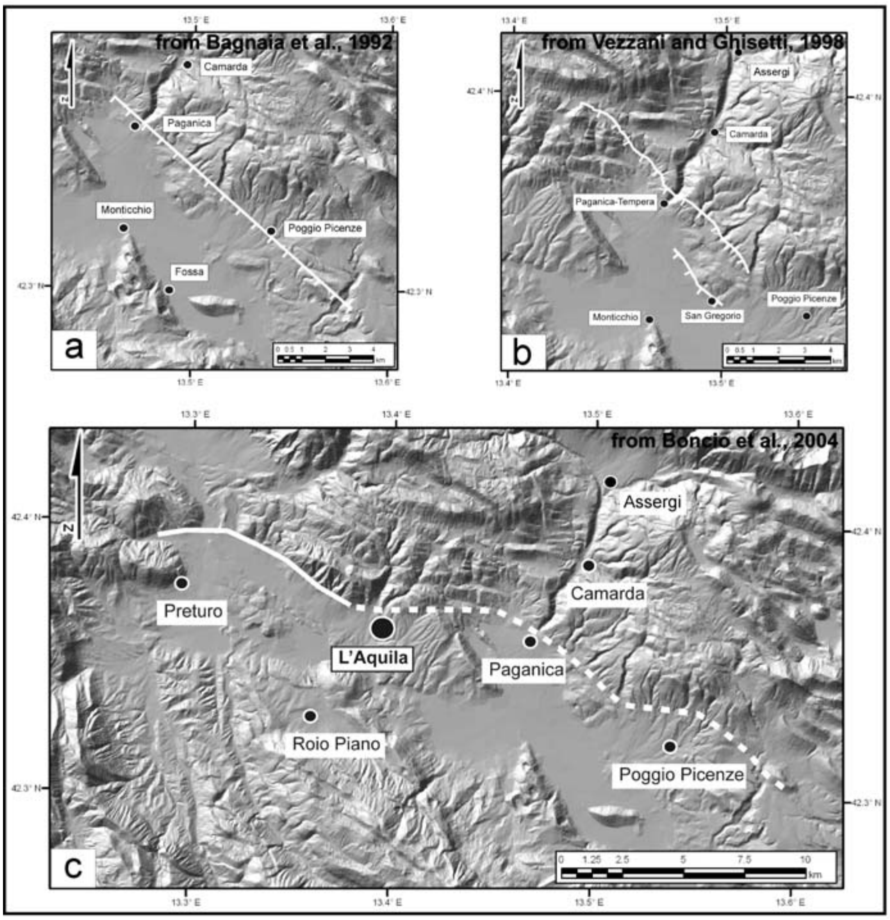


Fig. 4.3.1 – Tectonic structures (white lines) affecting the area of Paganica, as reported in a) Bagnaia et al. (1992), b) Vezzani and Ghisetti (1998) and c) Boncio et al. (2004).

The geological surveys carried out ad-hoc after the earthquake along the Paganica fault (which is presently considered the surface expression of the seismogenic source of the earthquake of April 6) provide a different picture from that in the published literature before this earthquake.

4.3.1 Field data

The Paganica fault

Our geological surveys and analyses of aerial photographs taken after the earthquake define the surficial geometry of the long-term expression of this fault. We define three NW-SE trending segments that have a dextral en-echelon relationship (Fig. 4.3.2).

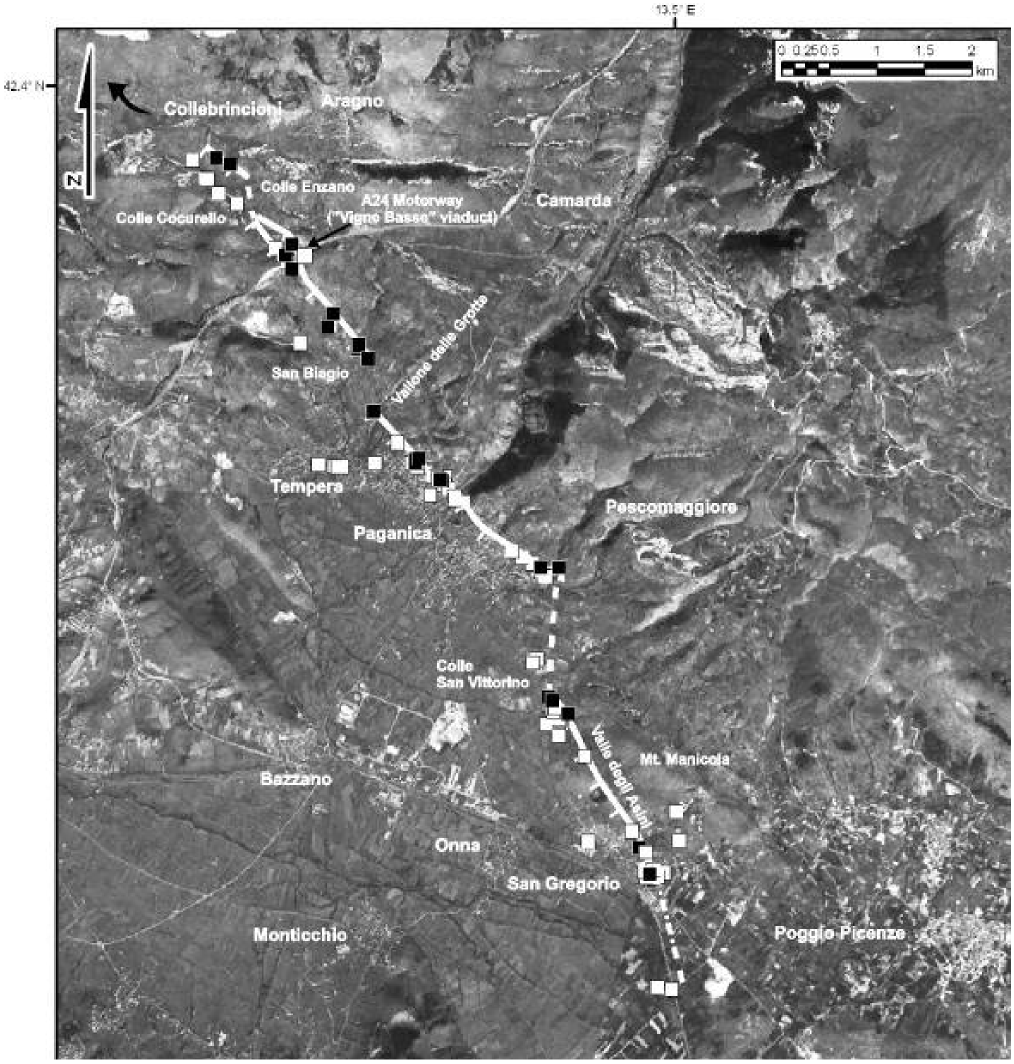


Fig. 4.3.2 – Satellite image on which the segments of the Paganica fault (as defined by the present study) are shown (white lines; white dot-dashed line mark the possible southern prolongation of the coseismic surface displacement), together with the approximately N-S trending fault plane (white dashed line) detected between the central and the southern branches of the Paganica fault; the black and the white squares mark sites where *i*) the Paganica fault and *ii*) the evidence of surface faulting/ rupturing (i.e. ground cracks and free-faces) have been observed, respectively

The northernmost segment (segment 1, 3 km long) is located between the area east of Collebrincioni and Vallone delle Grotte (NE of Tempèra). The central segment is detected in the area of Paganica (segment 2; 3 km long) and terminates towards the SE along the road that connects Paganica and Pescomaggiore. The southernmost segment (segment 3; 2 km long) extends to the NW from the village of San Gregorio.

The surficial expression of the northern fault segment is marked by a prominent fault scarp in carbonate bedrock, at the base of which the slickenside surface is exposed (Fig. 4.3.3).

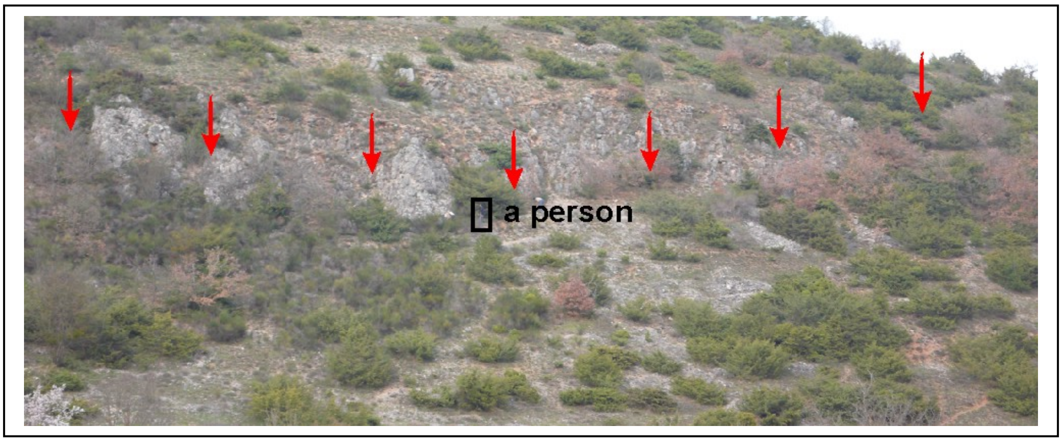


Fig. 4.3.3 – Fault scarp (indicated by the red arrows) formed on the carbonate bedrock, along the northern segment of the Paganica fault.

In the central part of the segment, next to Colle Cocurello and Colle Enzano, the fault splits into two splays (see Fig. 4.3.2). Here, unconsolidated slope deposits (i.e., not older than the Last Glacial Maximum period; see Castiglioni et al. 1979; Dramis, 1983; Coltorti and Dramis, 1988, for more on this topic) are exposed at the base of the fault scarp and are displaced along the eastern fault splay, where the "Vigne Basse" viaduct of the A24 motorway crosses the fault zone (Fig. 4.3.4).

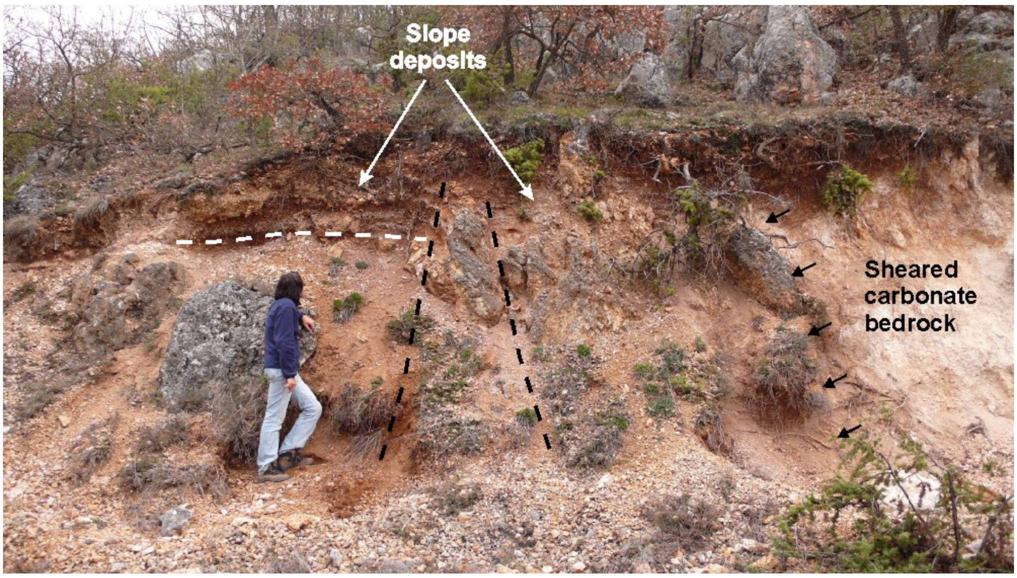


Fig. 4.3.4 – Slope deposits, the attitude of which is highlighted by the white dashed line, placed in contact (the contact is marked by the black arrows) with the carbonate bedrock by the northern fault branch. Black dashed lines mark secondary shear planes.

Moreover, a small hand-made excavation (few tens of centimetres deep) performed along the fault scarp slightly to the north exposed post-Last Glacial Maximum debris dragged along the fault scarp, due to the fault movement. Hence, overall, these findings confirm the Late Pleistocene-Holocene activity of the Paganica fault. In the southern portion of the segment, the scarp is carved on alluvial deposits (Fig. 4.3.5).

Fig. 4.3.5 – Fault scarp on the northern fault branch formed on alluvial deposits, near to the southern end of the segment. The red arrows indicate a freshly exposed (co-seismic) free-face at the base of the scarp.

The scarp on the central segment of the Paganica fault is present at the base of the slopes between Tempèra and Paganica. The fault scarp is formed both in the carbonate bedrock, in the northernmost part of the branch, and in fluvial deposits, in the central and southern portions of the segment. Here, according to Sheet 359 "L'Aquila" of the Geologic Map of Italy at 1:50,000 (Foglio CARG 1:50,000, 2009. Cartografia geologica ufficiale Foglio CARG 1:50,000 N. 359, L'Aquila), the tectonic structure places Pliocene/Middle Pleistocene continental deposits in contact with Late Pleistocene sediments.

Many outcrops in the fault zone show displaced middle Pleistocene-Holocene fluvial and slope deposits (Fig. 4.3.6) along several synthetic fault planes (about N140° trending).

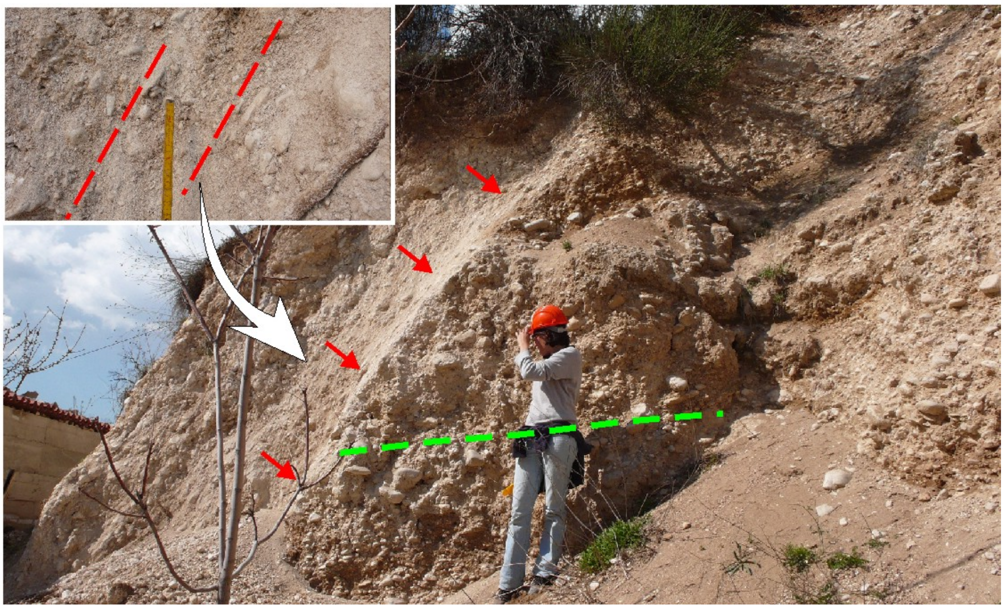


Fig. 4.3.6 – Fluvial gravels (the green dashed line marks the attitude) displaced along a synthetic fault plane (indicated by the red arrows) related to the Paganica fault, characterised by rotated clasts in the shear zone (red dashed lines inset)

The oldest fluvial sediments displaced along the fault contain partially-to-strongly reworked and/or weathered ash layers. Locally, ash deposits occur as primary air-fall deposits, as centimetre-thick, tephra layers (Fig. 4.3.7).

Fig. 4.3.7 – Fluvial and slope deposits containing Middle Pleistocene tephra layers (inset) displaced along a synthetic fault plane (indicated by the red arrows) of the Paganica fault.

Chemical, lithological and isotope analyses on three of the thickest, best-preserved ashes have allowed us to assign them to the eruptions of “Tufo Pisolitico di Trigoria”, “Pozzolane Rosse” and “Tufo Rosso a Scorie Nere” (authors’ unpublished data) from the Colli Albani and Sabatini volcanic districts (central Italy); these ashes have been dated to about 560, 456 and 450 ka, respectively (Marra et al., 2009, and references therein). These data provide the oldest chronological point-control for the dating of the activity of the Paganica fault.

More recent activity on the central segment of the Paganica fault is documented by displaced colluvial and fluvial deposits along at least three shear planes that are exposed in the walls of a deep trench (up to 5 m high) that is perpendicular to the fault. The trench, which is in north of Paganica, was dug out by a strong jet of water from a leak in an aqueduct that ruptured during the earthquake (Fig. 4.3.8). In the uppermost part of the trench, one fault plane places carbonate breccias in contact with fluvial gravel, colluvial and soil levels that are displaced by some metres.

Fig. 4.3.8 – Synthetic fault plane, detected along the walls of the trench of the aqueduct, displacing alluvial, pedogenic and colluvial deposits.

Other shear planes exposed in the trench displace fluvial and slope deposits (Fig. 4.3.9). Organic-rich material in the colluvium yielded radiocarbon ages of 5,718 BC/5,467 BC to 5,403 BC/5,387 BC (calibrated 2**σ)** (Fig. 4.3.9) and 34,970±470 BP.

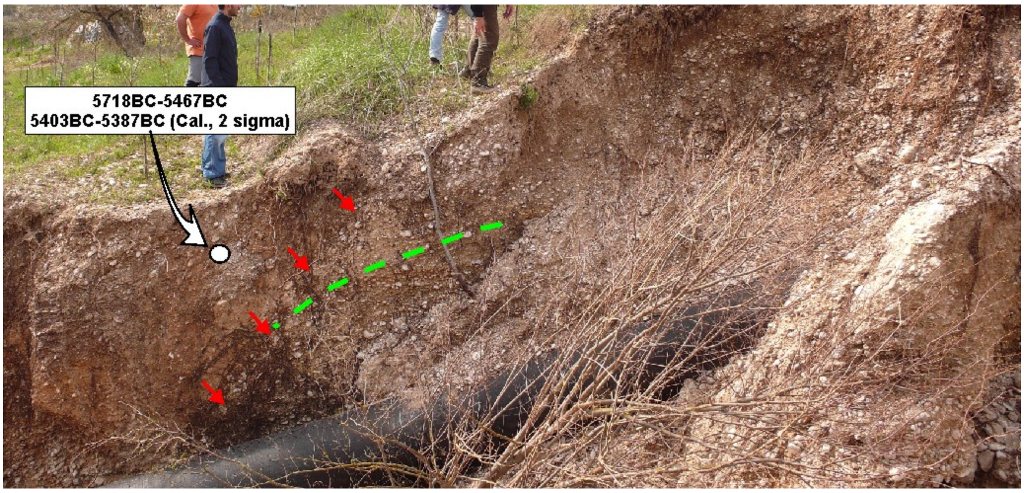


Fig. 4.3.9 – Synthetic shear plane, detected along the wall of the trench, placing fluvial gravels in contact with colluvial deposits dated to the Late Holocene.

The latter age is supported by U/Th dating of a calcareous tufa that is embedded in the dated organic-rich deposit that gave an age of 33,000 ±4100 BP. These data support the Late Pleistocene-Holocene activity of the Paganica fault.

The southern end of the central segment of the Paganica fault ends against a N-S trending tectonic structure that dips about 80° to the E. This fault is visible along the road that connects Paganica to Pescomaggiore and shows normal-to-transtensive kinematics (Fig. 4.3.10).

Fig. 4.3.10 – N-S trending fault plane (indicated by red arrows) that truncates Middle Pleistocene slope and alluvial deposits (the attitude is marked by the green dashed line).

Here, alluvial-fan and colluvial deposits are displaced on the Paganica fault and the N-S fault. The sediments contain the above-described Middle Pleistocene tephra layers, thus indicating a post-Middle Pleistocene activity of the N-S fault.

The central and the southern branches of the Paganica fault are separated by a transfer zone (e.g. Peacock, 2002) that is here marked by a wide landsurface that gently dips towards the NW.

The southern segment of the Paganica fault is located SE of Paganica from the area E of the San Vittorino to the village of San Gregorio. Its surficial expression is defined by a scarp in carbonate bedrock, at the base of which the slickenside surface is often exposed (Fig. 4.3.11 a, b).

Fig. 4.3.11 – a) Fault plane of the southern fault branch, exposed at the base of the carbonate bedrock fault scarp; b) Paganica fault plane in the area of San Gregorio.

At its northern end, the fault branch intersects a fault plane trending about N20° and dipping steeply eastward, which affects the carbonate bedrock (Fig. 4.3.12). This fault and the above-mentioned N-S trending tectonic structure are probably part of to the same fault system.

Fig. 4.3.12 – Fault plane roughly N20° trending, seen at the northern end of the southern branch of the Paganica fault.

Coseismic surface rupturing along the Paganica fault zone

The field surveys performed in the days subsequent to the main shock allowed us to identify coseismic surface deformation along the Paganica fault that produced sets of NW-SE trending ground cracks aligned along the fault zone, and parallel the fault segments, and which comprise a belt not wider than a few tens of metres. These fractures were up to a few centimetres wide and several tens of metres long (with no solution of continuity), and they commonly had an en-echelon (mainly dextral step-over) arrangement.

These ground cracks were almost continuous 1) through fields and urban areas, where roads and buildings were affected by newly formed ruptures and damage; 2) along slopes and plain areas; 3) across any morphological features of the landscape, such as small ridges, valleys and landsurfaces; and 4) affecting both natural and man-made terrain.

Moreover, most cracks along the central fault segment had vertical and horizontal offset between the sides (with the downslope side lowered) of a few centimetres; the displacement increased during the days subsequent to the April 6 shock, reaching a maximum of about 15 cm. In contrast, cracks along the northern and the southern branches did not have readily observable vertical offsets rather the ground was gently flexed, with an amplitude of less than 10 to 15 cm.

- Northern fault segment

Along the northern segment of the Paganica fault, discontinuous ground ruptures, no more than about 20 m long and 1 cm wide, were observed at the base of the fault scarp (Fig. 4.3.13).

Fig. 4.3.13 – Coseismic ground cracks (indicated by black arrows) detected along the Paganica northern fault branch.

In particular, in the central part of the segment, the cracks are located where the fault splits into two splays (i.e. between Colle Cocurello and the Vigne Basse locality, see previous section), with different sets that trend roughly 120° to 170°. We observed cracks on both splays. A crack was also present where the above-described Late Pleistocene-Holocene slope debris was perhaps displaced on the tectonic structure (Fig. 4.3.14).

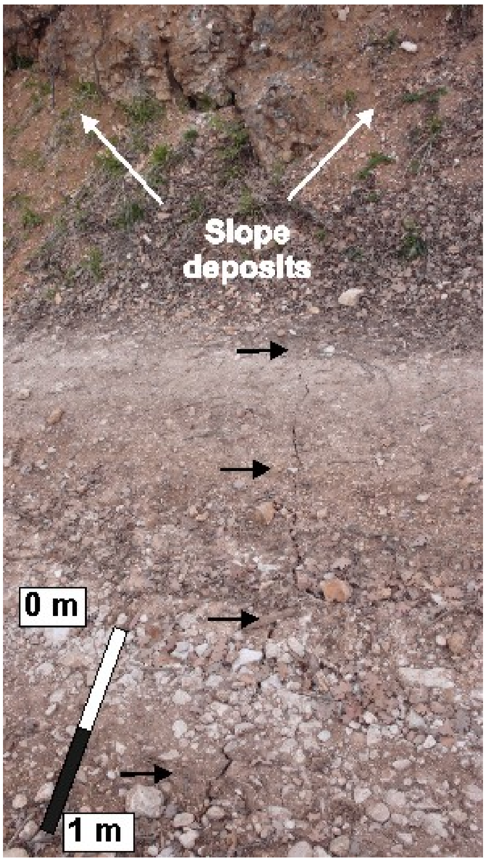


Fig. 4.3.14 – Ground cracks (indicated by black arrows) next to the slope deposits shown in Figure 4.3.4 displaced along the Paganica fault.

Here, the "Vigne Basse" viaduct of the A24 motorway that crosses the Paganica fault zone (see previous section) suffered damage during the shock of April 6. This damage to the viaduct, mainly consisting in the re-opening of pre-existing "injuries" due to aging (i.e. old cracks with traces of water percolation), occurred where it crosses the Paganica fault. Hence, the damage might have been mostly caused by the strong ground motion caused by the earthquake, combined (subordinately) with the coseismic ground deformation (which is marked by cracks) at the fault zone (where piers of the viaduct are positioned) .

Moreover, evidence of reactivation of the fault plane is visible along the northern part of the segment where a fresh-looking free-face up to 8-10 cm high is present at the base of the slickenside surface. This free-face extends continuously for several metres, and marks the contact between the carbonate bedrock and the slope scree at the base of the scarp (Fig. 4.3.15).

Fig. 4.3.15 – Fresh free-face (the width of which is marked by the red arrows) detected at the base of the fault plane at Colle Enzano.

In some places, the free-face was marked by remnants of soil that coats the base of the scarplet.

Moreover, the slope scree was separated from the bedrock scarp surface by an about 1-3-cm-wide fissure.

- Central fault segment

We found ground cracks in the area between Tempèra and Paganica that parallel the fault branch where synthetic shear planes affect the Late Pleistocene-Holocene deposits (Fig. 4.3.16).

Fig. 4.3.16 – Coseismic ground cracks (indicated by red arrows) detected along the central segment of the Paganica fault.

Cracks are present continuously along the entire segment. In the village of Paganica, these ground ruptures intersected the trench at the aqueduct (Fig. 4.3.16 c), so we can reasonably hypothesise that the damage to the aqueduct can be attributed to the coseismic surface displacement along the tectonic structure.

To the southeast, we found ground ruptures as far as the southern end of the central segment. Along the transfer zone that separates the central segment and southern of the Paganica fault, we found two intersecting sets of ground fractures, one set trending about roughly N20° and the other trending about NW-SE (about 150°) (Fig. 4.3.17).

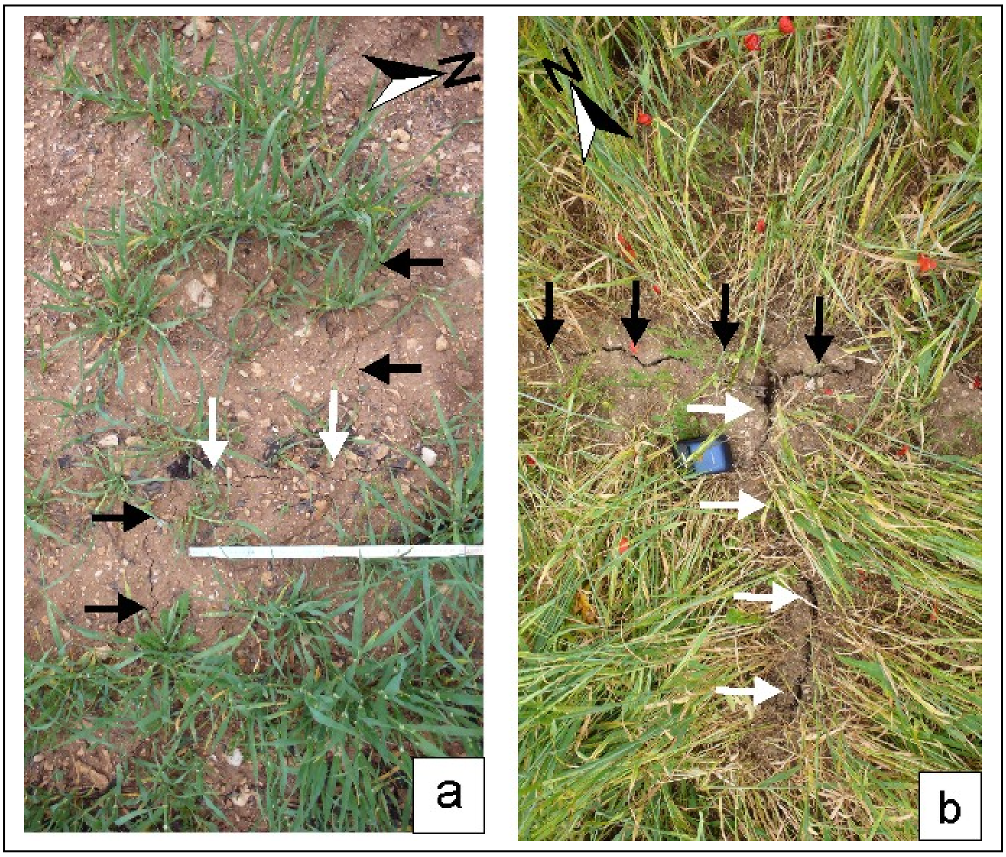


Fig. 4.3.17 – Intersecting sets of coseismic ground crack (marked by white and black arrows) detected between the central and the southern segment of the Paganica fault.

The former set was aligned with the aforementioned N-S fault, while the latter has a direction similar to the Paganica fault trend. Some of these intersecting ground cracks appeared in the days subsequent to the mainshock, probably related to the occurrence of afterslip.

Rather discontinuous E-W trending fractures extend for less than 1 km in length in the area of Tempèra. These secondary features might result from local, surficial cracking due to movements along secondary E-W striking tectonic structures, which have been mapped in this area (e.g. Bagnaia et al., 1992; Vezzani and Ghisetti, 1998; Foglio CARG 1:50,000, 2009. Cartografia geologica ufficiale Foglio CARG 1:50,000 N. 359, L'Aquila); although the Late Quaternary activity of these E-W tectonic structures has never been investigated, they may represent transfer faults between different fault branches that, in this case, can be represented by the Paganica fault and the Pettino fault, the latter being considered as an active fault segment by different authors (e.g. Galadini and Galli, 2000; Boncio et al., 2004) pertaining to the Upper Aterno Valley fault system (Galadini and Galli, 2000).

- Southern fault segment

A few tens of metres south-eastwards, we found NW-SE trending ground cracks at the northern end of the southern fault segment that extend towards the SE and parallel the carbonate bedrock fault scarp (Fig. 4.3.18).

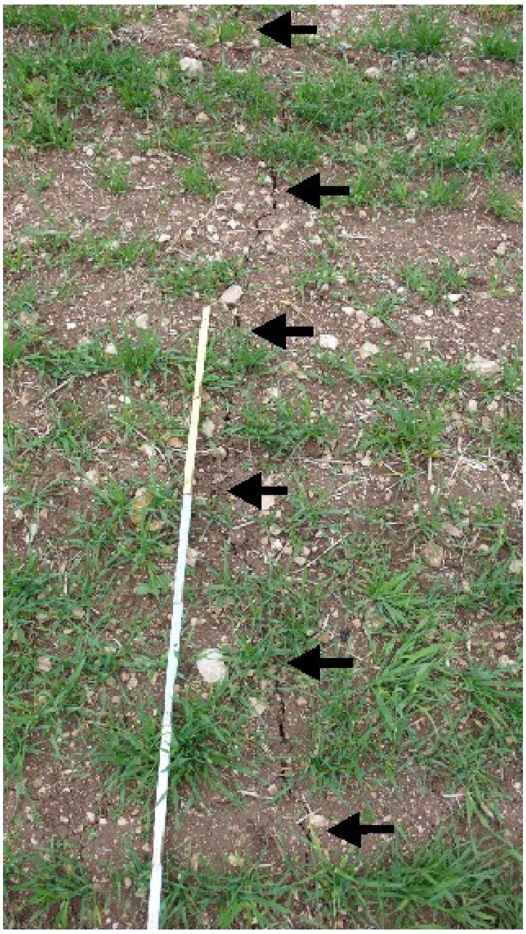


Fig. 4.3.18 – Ground fissure (indicated by black arrows) found north of San Gregorio, close to the northern tip of the Paganica southern fault segment.

The width of the fractures increased in the days subsequent to the mainshock. This confirmed the occurrence of a certain amount of afterslip.

Further south, we found several ground ruptures close to the southern end of the fault branch, in the area of San Gregorio (Fig. 4.3.19), with some cracks being tens of metres long. According to eye witnesses, some of these fracture formed during the aftershock of April 7 (Mw 5.6; Istituto Nazionale di Geofisica e Vulcanologia, 2009; MedNet, http://mednet.rm.ingv.it/procedure/events/QRCMT/090406_013322/qrcmt.html).

Fig. 4.3.19 – Ground cracks (indicated by black arrows) in the area of San Gregorio.

Here, the cracks were arranged in two sets trending between N120° and N150°. We also found, a fresh fracture with N350° trend that affected the carbonate bedrock (Fig. 4.3.20). A fresh-looking crack on the ground occurred where the fracture intersected the surface (Fig. 4.3.20, inset).

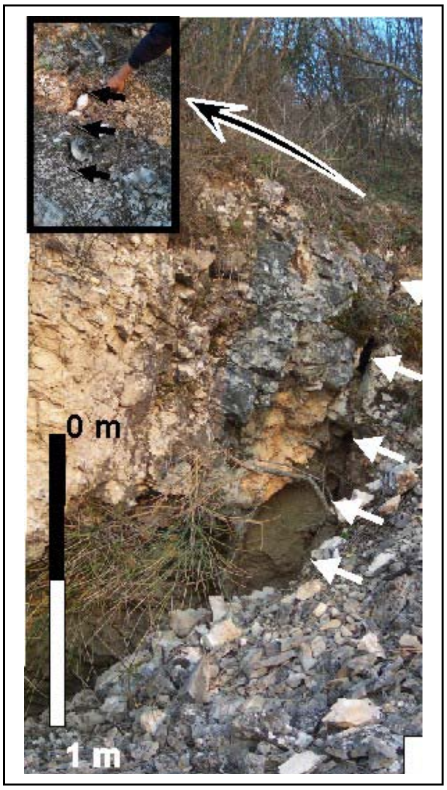


Fig. 4.3.20 – Fracture affecting the carbonate bedrock (indicated by white arrows) near the southern termination of the southern segment of the Paganica fault.

Investigation along the Mt. Bazzano antithetic normal fault

We also examined a previously mapped normal fault (e.g. Vezzani and Ghisetti, 1998) on the eastern slopes of Mt. Bazzano, and that is an antithetic fault to the Paganica fault. The surficial expression of this structure is a preminent fault scarp at the base of which the fault plane is exposed.

We identify local evidence of fault-plane reactivation that consists of a free face of up to 15 cm high, at the base of the slickenside and which, in places, had remnants of the soil coating the scree deposited at the base of the fault plane. This new free face was discontinuous as it was typically observable for no more than a few metres in length. Many sectors of the fault, indeed, showed no evidence of rejuvenation along the bedrock scarp. (Fig. 4.3.21)

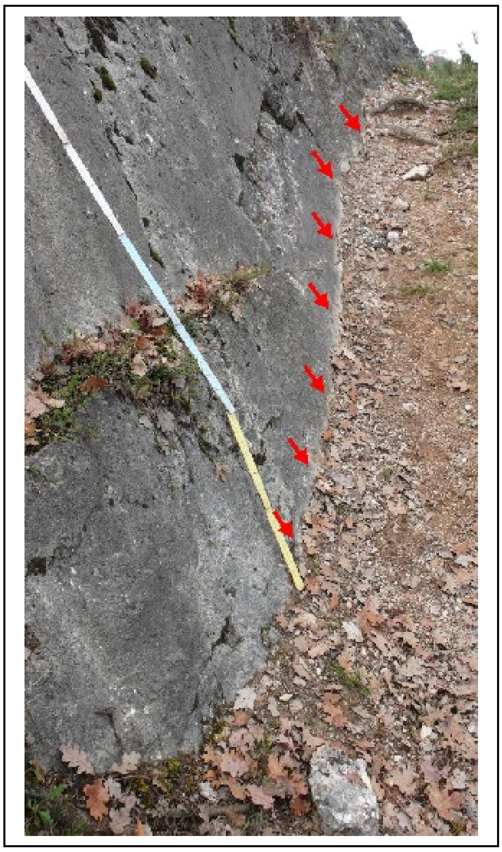


Fig. 4.3.21 – Free-face (white band at the base of the slickenside, indicated by red arrows) exposed in places at the base of the bedrock of the Bazzano fault.

Taken together with 1) the remarkable steepness of the slopes, and 2) the absence of evident ground cracks along the fault, – comparably to the Paganica fault – this suggests that the formation of the free face along the Bazzano normal faults was probably mainly due to non-tectonic gravitational processes and/or compaction of the unconsolidated scree at the base of the fault planes. Nevertheless, we cannot preclude a coseismic tectonic component to the new free face because, the fault is antithetic to the Paganica fault.

5. CASE STUDY IN THE CALABRIAN ARC

5.1 Evidence of active inverse faulting in the north-eastern sector of the Calabrian Arc

The sector of the Calabrian Arc under investigation is characterised by a complex structural evolution, as the main structural feature located in this area is part of the aforementioned “San Gineto Line”. Here, this tectonic structure, mainly E-W and NW-SE trending and bounding to N and NE the Sila Massif, is known as “Cetraro-Rossano Line” (Moretti and Guerra, 1997), or “Rossano-San Nicola fault zone”, or

“Corigliano-Rossano Line” (Moretti, 2000) or “Rossano Fault” (Galli et al., 2008) (Fig. 5.1.1).

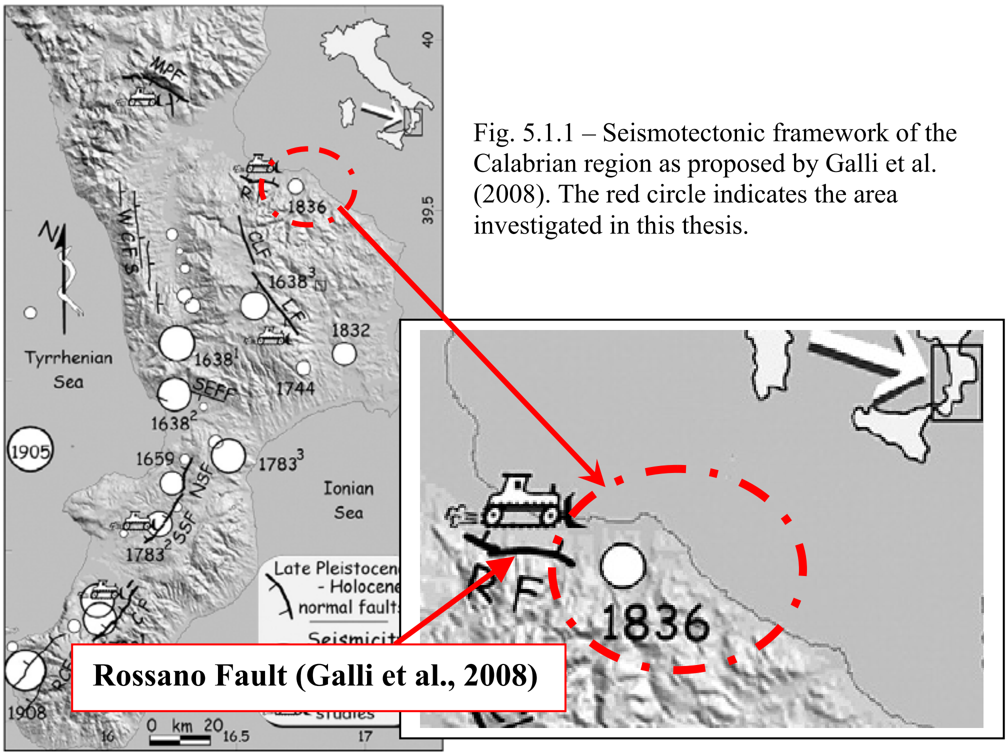


Fig. 5.1.1 – Seismotectonic framework of the Calabrian region as proposed by Galli et al. (2008). The red circle indicates the area investigated in this thesis.

This fault system experienced a complex kinematic history – that is still under debate – being characterised by a normal-to-normal oblique kinematics that probably superposed on a strike slip kinematics (Moretti and Guerra, 1997; Galli et al., 2006; Corbi et al., 2009).

As for the activity of this fault system, several minor faults – related to the Rossano Fault – displaying a mainly normal-to-strike slip kinematics, have been seen within the Quaternary marine and continental sequences outcropping in the area of the Rossano plain (e.g. Corbi et al., 2009). Hypothesis about the Late Pleistocene-Holocene activity of this tectonic structure has been discussed by Moretti (2000) who, however, did not provide geological evidence supporting the hypothesis.

More recently, Galli et al. (2006; 2008) identified evidence of displacement (related to normal movements) of Holocene slope-derived deposits along the 12 km long Rossano Fault.

5.1.1 Field data

Our preliminary field investigations in this area permitted us the identification of an excavation for a building located few tens of metres far from the coastline, SE of the village of Mirto, some kilometres E of Rossano Calabro (Fig. 5.1.2).

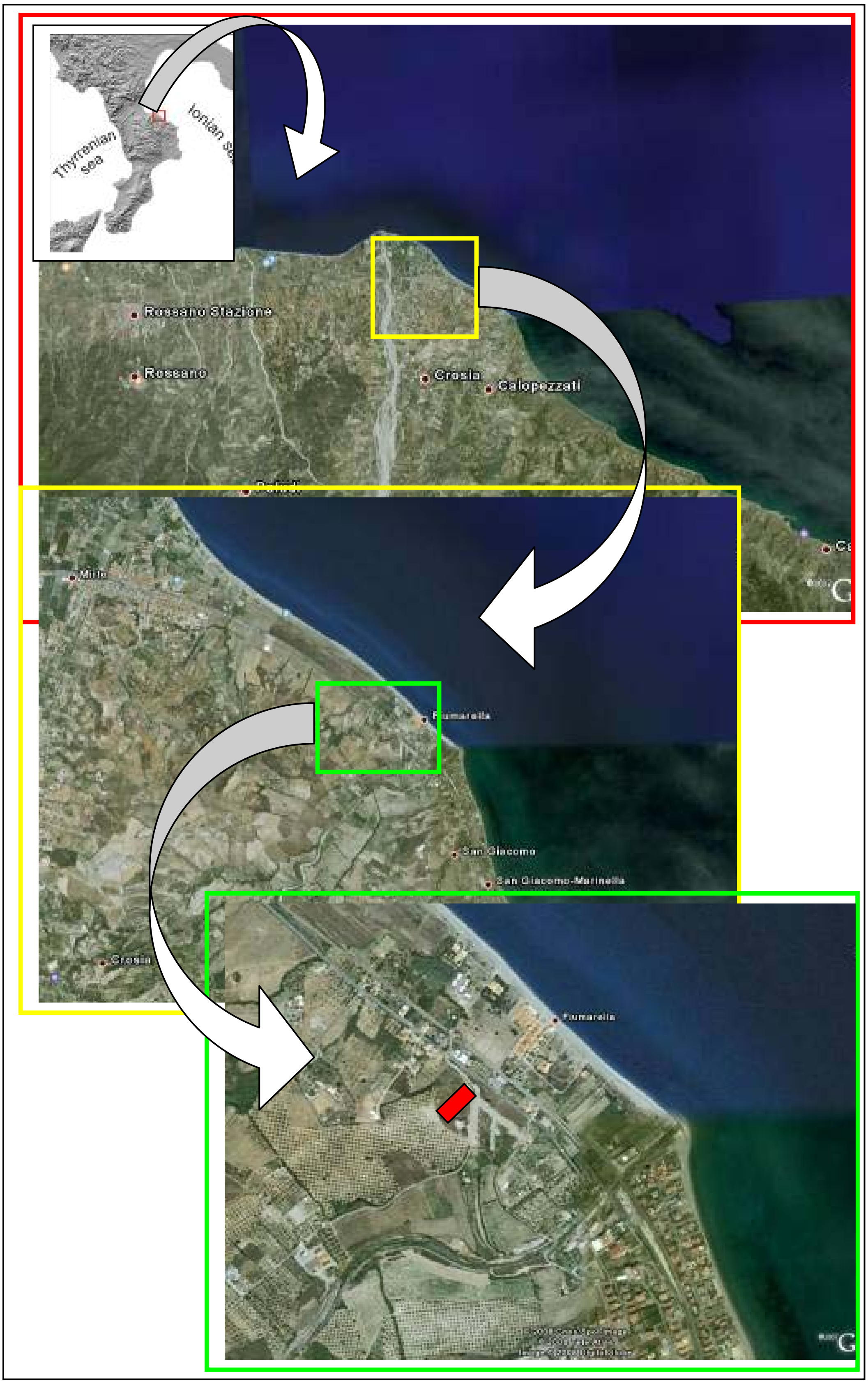


Fig. 5.1.2 – Location of the excavation (red rectangle) described in the text.

This excavation was located on the left flank of the Fiumarella river valley, at the top of a fluvial terrace suspended about 15 m over the present thalweg. This terrace is morphologically embedded in a marine terrace the outer margin of which occurs at about 25-30 m a.s.l. and that, therefore, can be attributed to either i) the fourth order of terraces of Carobene (2003), related by the author to the Marine Isotopic Stage (MIS) 5.5 (i.e. the "Tyrrhenian" terrace) or ii) to the fifth order of terraces of Corbi et al. (2009), related by the authors to the MIS 5.1.

This fluvial terrace display a gently warped profile (with a wavelength of some tens of metres), with the axis of the bend trending about NW-SE, and is truncated towards the sea by an about 15 m high scarp that separates the landform from the costal plain. The wall of this excavation, roughly NE-SW oriented, exposed a sequence of layered yellow-orange sands and clayey sands, with rare gravel levels interbedded. These sediments display a counterslope dipping attitude (Fig. 5.1.3).

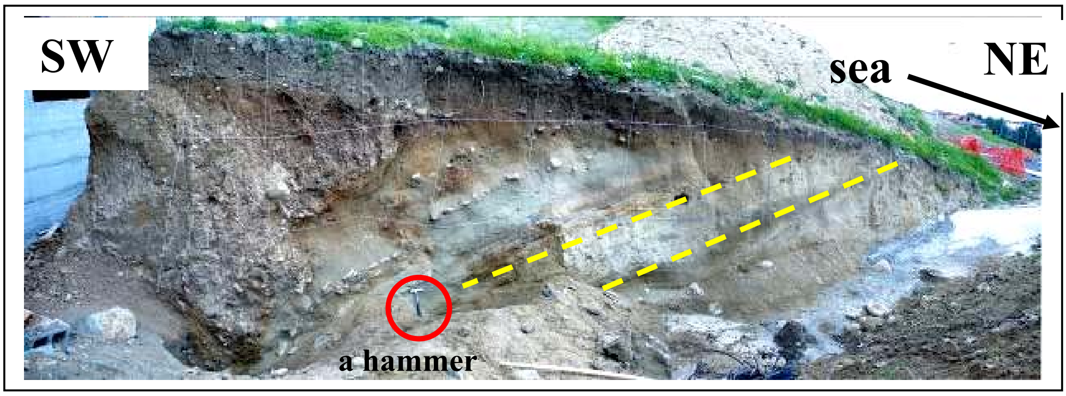


Fig. 5.1.3 – Wall of the excavation described in the text. The yellow dashed lines mark the attitude of the layers of the paleo-deltaic sediments.

The gravels are made of rounded and flattened pebbles made of limestone, granite and metamorphic rocks, pertaining to the pre-Quaternary bedrock sequences outcropping along the innermost sectors of the Fiumarella river valley.

Paleontological analyses performed on the clayey portions of the sequence provided a foraminifers fauna (both planktonic and benthic) made of:

- Planktonic foraminifers: *G.lia inflata, N. acostaensis sx, G.lia crassaformis, G.lia scitula, Globigerinoides obliquus, Globigerina bulloides, O. universa.*
- Benthic foraminifers: *Ammonia tepida, A. parkinsoniana, Elphidium crispum, E. advena, Cassidulina carinata, C. crassa, Bulimina basispinosa, B. elegans marginata, B. elongata, Cibicidoides kullenbergi, Hyalinea baltica, Melonis barleeanum, Valvulineria bradyana.*

This paleontological data provides some information as for the chronology of the exposed sequence. Indeed, *Globorotalia inflata* appears at the base of MPL6 biozone (i.e. between the Gelasian and Calabrian stages); *Hyalinea baltica* appears at the base of the Emilian substage (i.e. middle Early Pleistocene) while *Bulimina basispinosa* disappears at the top of the Emilian substage

These data, together with the sedimentological characteristics of the deposits allow us to attribute them to a deltaic environment, of infra- to circa-littoral zone, not older than the Early Pleistocene in age.

This chronological attribution is also corroborated by the fact that these paleo-deltaic deposits laterally pass to a sequence of clay sediments likely pertaining to the "Ciclo Suprapliocenico-Pleistocenico" of Vezzani (1968) and attributed by Bigazzi and Carobene (2004) to the Middle Pleistocene because of the presence of an interbedded tephra layer, related by the authors to this chronological interval.

Both the deltaic and the clay deposits were laterally in contact – through an evident erosional surface – with colluvial deposits, made of sparse rounded pebbles (mainly of sandstone, limestone, granite and gneiss) in a brownish-reddish silty-clayey matrix. These colluvial sediments were fed by a small incision located along the slope, uphill of the excavation. They probably resulted from the erosion and re-sedimentation of the deposits on which the marine terrace is carved (Fig. 5.1.4).

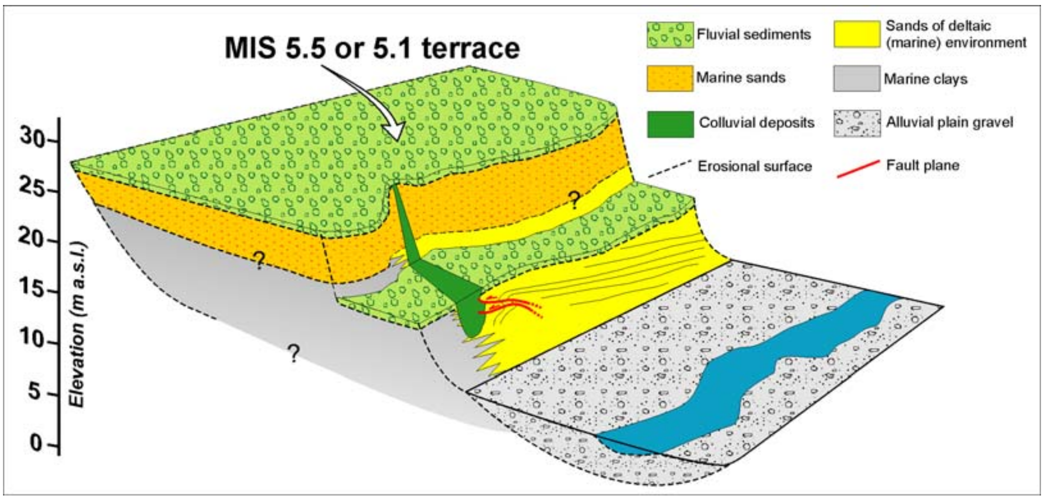


Fig. 5.1.4 – Morpho-stratigraphic scheme of the area.

Radiocarbon age determination performed on these colluvial sediments gave an age of 9800 BC-9786 BC/9771 BC-9360 BC – 7568 BC-7559 BC; 7553 BC-7351 BC (calibrated, 2**σ**)

The wall of the excavation permitted the detection of several shear planes, about NW-SE trending and dipping towards NE, that displaced the whole sedimentary sequence described. The geometry of the deformed sediments indicates an inverse kinematics of these structural features. Indeed, the sands of the paleo-deltaic sediments are warped by the shear planes, the activity of which has been also probably responsible for the landwards tilting of the layers. (Figs. 5.1.4, 5.1.5 and 5.1.6). The faults movements also determined the displacement of the Holocene colluvial sediments. The offset of the erosional surface that marks the contact between the marine sands and the continental deposits has been clearly identified along the excavation wall. This observation indicates, therefore, the Holocene activity of these structural features.

It must be noted that, as the geometry of the faults defines a counterslope, SW vergence of the deformation, a "non-tectonic" origin (i.e. gravity related processes, as landslides) of the deformations can be excluded.

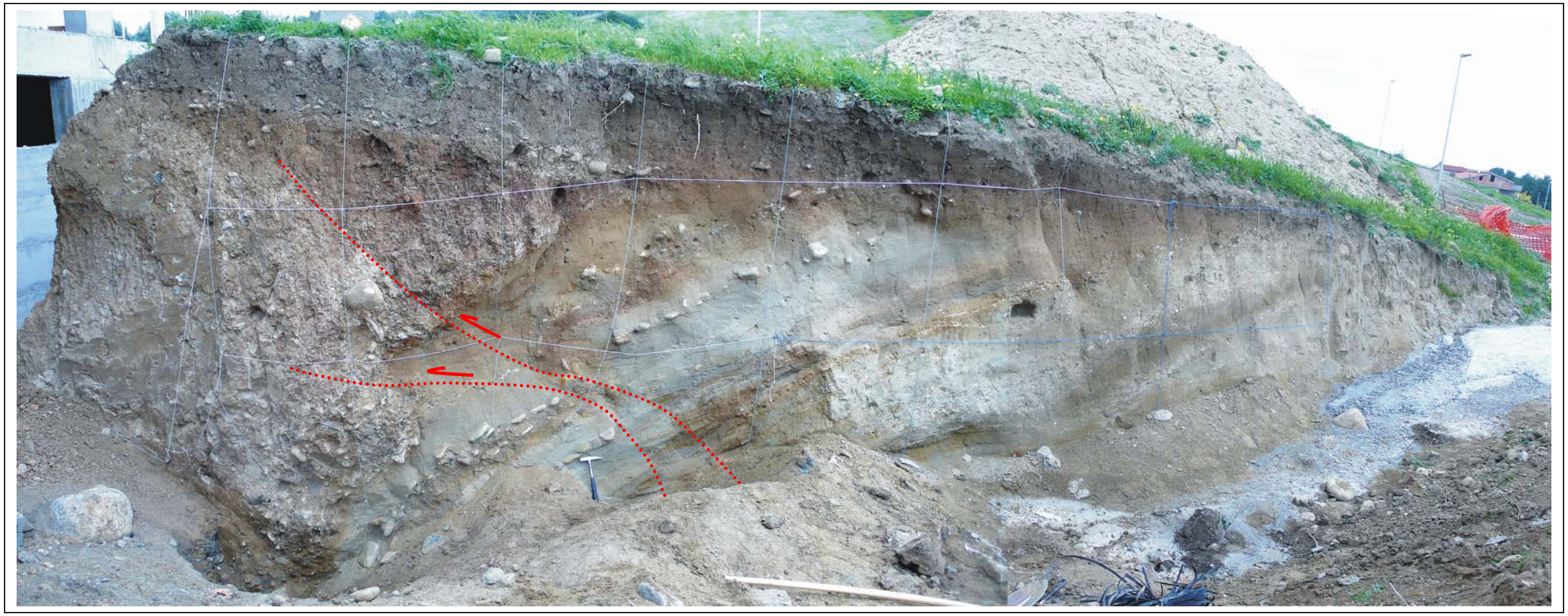


Fig. 5.1.4 – Inverse shear planes (marked by red dotted lines) affecting the sedimentary sequence exposed by the excavation.

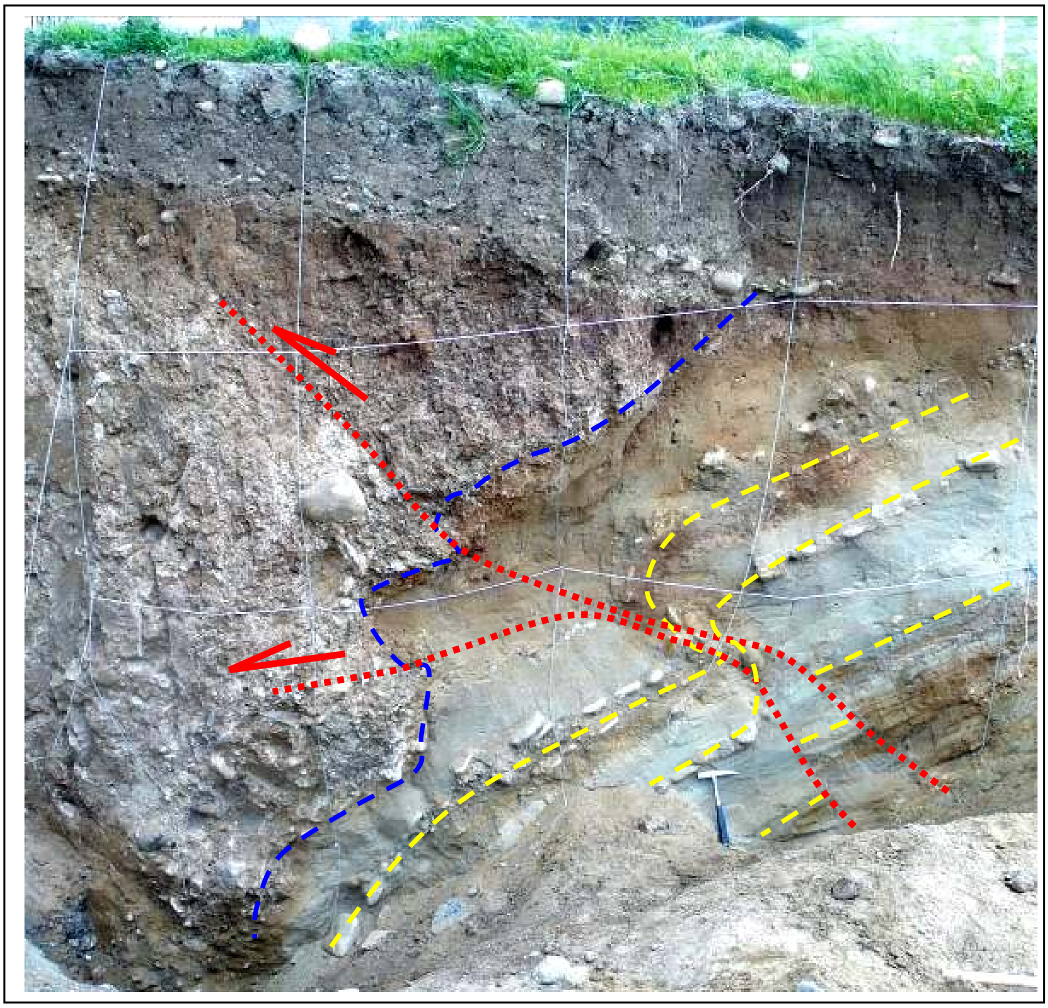


Fig. 5.1.5 – Close-up photograph showing the inverse shear planes (red dotted lines) affecting the deposited described in the text. The yellow lines marks the layers of the deposits while the blue dotted line marks the erosional surface between the deltaic sediments and the Holocene colluvial deposits.

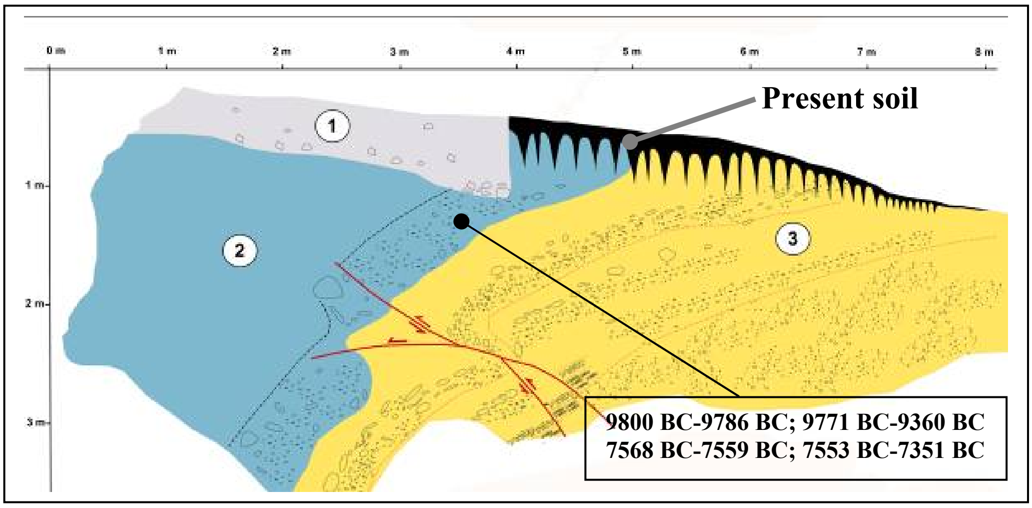


Fig. 5.1.6 – Scheme of the wall of the excavation: 1) "cultural" unit; 2) colluvial deposits, made of parse rounded pebbles (mainly of sandstone, limestone, granite and gneiss) in a brownish-reddish silty-clayey matrix; 3) paleo-deltaic sediments represented by yellow-orange sands and clayey sands.

6. DISCUSSION

6.1 Mt. Morrone fault system

The data collected through geological and geomorphological surveys confirm the Late Pleistocene-Holocene activity of both of the segments that represent the surficial expression of the Mt. Morrone fault. In this section, we discuss the data that have been gathered in terms of the kinematic implications, slip rate estimations and magnitude that can be associated with a seismic event that may originate from the activation of the fault system.

6.1.1 Kinematics of the fault system

The structural data collected along the fault planes indicate that the fault system is characterised by mainly normal kinematics, with a minor oblique left-lateral component, accommodating a NE-SW trending extension (i.e. about N20° trending). This matches the results obtained in other studies performed in the central Apennines (e.g. Calamita and Pizzi, 1994; Calamita et al., 1995; Galadini, 1999) which concluded that during the Early Quaternary the central Apennine normal faults experienced movements related to a N 45° trending extension, and in more recent times, to a N10°-20° extension. Hence, the data collected along the Mt. Morrone fault system are consistent with this regional kinematics.

6.1.2 Slip rate

The data that have been gathered have provided information on the offset that affects the chronologically constrained continental deposits. This has allowed us to define the slip rate of the western fault branch.

1) Site 1 in Fig. 4.1.1: the ca. 160-m-vertical displacement of the Morrone 7 unit (<600 – >460 ka BP) defines a vertical slip rate of 0.31 ±0.04 mm/yr. This might be slightly lower than the actual vertical slip rate, since it was calculated by considering the displaced deposits outcropping not far (about 1.5 km) from the fault tip (derived from geomorphological observations), where the vertical throw is expected to be lower than in the central sectors of the fault.

2) Site 2 in Fig. 4.1.1: the ca. 20-m vertical offset affecting the top surface of the

Morrone 5 unit (<60 – 36 ka BP) allows the evaluation of a slip rate of 0.44 ±0.12 mm/yr for the fault branch. The middle-higher values of the range have to be regarded as more reliable, because the tephra layer dated at about 36 ka occurs only 1-2 m below the top depositional surface of these deposits. This implies that ca. 36 ka is very likely to be the age of the formation of the displaced landsurface.

3) Site 2 in Fig. 4.1.1: the ca. 7-m vertical displacement detected on the top depositional surface of the Morrone 4 unit (15-25 ka BP, i.e. the LGM) defines a vertical slip rate of 0.37 ±0.09 mm/yr for the western fault.

4) Site 4 in Fig. 4.1.1: the ca. 5-m vertical offset that affects the Morrone 6 unit at the Le Svolte di Popoli site defines a slip rate for the western fault branch of 0.05 ±0.01 mm/yr. This slip rate estimation cannot be considered as representative of the fault kinematics. Indeed, as indicated in Figure 4.1.1, the Le Svolte di Popoli site is located close to the northern tip (defined by aerial photography analysis and *ad-hoc* geomorphic field surveys) of the fault, where the displacement is assumed to be lower than in the central parts of the tectonic structure. Therefore, the offset evaluated at this site cannot be included in the definition of the actual slip rate.

Although not really useful for the definition of the actual fault slip rate, further indication of Late Quaternary activity of the western fault branch derive from the Sant'Anna Valley site, where the vertical displacement along secondary splays and along the transfer fault has been detected. Here, the offset of the Morrone 7 and 6 units has been quantified at about a dozen metres (see paragraph 4.1.2).
The estimates of the slip rate listed above, which were determined by considering the displacement that affects units of different ages, i.e. ranging from the Middle Pleistocene to the LGM, are included within a narrow interval of values. However, the estimates defined at the Popoli-Malepasso site have to be considered as being more reliable than those defined at the Pacentro and Le Svolte di Popoli sites, since these latter sites are located close to the fault tips. Nevertheless, the identification of the fault tips from a structural point of view (i.e. derived from the variations in the slip rate along the fault), as well as the definition of the fault geometry by means of

geomorphologic observations (i.e. the detection and mapping of the fault planes and related scarps), allows an accurate evaluation of the length at the surface of the western fault, which is about 22-23 km. Hence, taking into account the slip rates defined at the Popoli-Malepasso site, the estimates are statistically indistinguishable from each other, and their weighted mean is 0.4 mm/yr, with a standard deviation of 0.07.

For the easternmost fault segment, although its post-LGM activity is documented in section 4.1.1, no data are available for the definition of its slip rate. Indeed, sediments that can be correlated across the fault are lacking. However, field data and a comparison with cases reported in the literature relating to normal faulting allow some hypotheses to be defined, which are discussed in the following.

As evident from Figure 4.1.1, the two main parallel fault segments are spaced at less than 2 km, and they have comparable lengths. Moreover, they were probably activated at different times – i.e. the western branch after the eastern one – testifying to a basin-wards nucleation of the fault segments (Gori et al., 2007). This structural setting is quite common in the central Apennines (e.g. the Fucino Plain; Galadini and Messina, 1994; Galadini and Galli, 1999; the Gran Sasso Range; Galadini et al., 2003b), and it is usually attributed to the shallow splaying of deeper single faults, following well known models depicting the geometry of normal faults (e.g. Stewart and Hancock, 1991; Walsh and Watterson, 1991; Childs et al., 1995; 1996; Walsh et al., 2003). Moreover, according to Stewart and Hancock (1991) and Walsh and Watterson (1991), in cases where fault systems show a migration of segment nucleation towards the hanging wall, a distribution of the deformation along the branches occurs. With this in mind, both the Mt. Morrone normal fault segments may include the displacement.

It must be considered, however, that in most of the cases reported in the literature in which such structural evolution of fault systems has been seen, the studies indicated that the older faults become less active or completely inactive (e.g. Dart et al., 1995; Messina, 1996; Horton and Schmitt, 1998; Jackson, 1999; Goldsworthy and Jackson, 2000; 2001; Goldsworthy et al., 2002; De Martini et al., 2004; Taylor et al., 2004; Lamarche et al., 2006). Hence, although the inactivity of the eastern fault segment can probably be excluded (as it shows evidence of Late Pleistocene-Holocene activity), a cautious slip rate for this branch that does not exceed that of the western branch can be hypothesised, i.e. included between >0 and <0.4 ±0.07 mm/yr.

Therefore, the slip rate of the whole Mt. Morrone fault system probably ranges from >0.4 ±0.07 to <0.8 ±0.09 mm/yr, with a preference for the average-to-higher values of this range.
This estimate we propose is comparable to the slip rates defined by Galadini and Galli (2000) for other central Apennine normal faults that show structural and geometric characteristics that are comparable to those of the Mt. Morrone fault system.
The slip rate obtained in the present study is, however, different from that estimated by Miccadei et al. (2002) and Miccadei et al. (2004). The former study reported a slip rate of about 1 mm/yr through correlation of Early Pleistocene breccias detected in the fault footwall with reflectors identified in seismic profiles crossing the Sulmona basin (i.e. in the hanging wall), which were considered as imaging the correlative deposits of the breccias. However, conclusive data supporting this correlation were not produced in that particular study.
On the other hand, Miccadei et al. (2004) estimated the slip rate for the Early (?)-Middle Pleistocene period by means of morphometric analyses (i.e. synthetic transversal and stream channel morphostructural profiles) of the Mt. Morrone south-western escarpment. This study defined different slip rates for different sectors of the slope: i) 0.3 mm/year on the eastern fault segment; ii) 0.8-1.0 mm/year on the western one, and in the northern sector of the fault system; and iii) a total slip rate of 1.2-1.4 mm/year for the southern sector of the fault system. These were based on displaced relict landforms embedded in the Early Pleistocene Monte Orsa alluvial fan. However, in our opinion, these estimates were proposed without a conclusive chronological framework defining the age of the landforms displaced. Therefore, the values obtained have to be considered with caution.
The long-term minimum slip rate for the westernmost fault segment defined by Galadini and Galli (2000) is also higher than our estimate. Indeed, in this study they indicated a slip rate of 0.50-0.66 mm/yr by considering the difference in elevation between the Early Pleistocene breccias, detected along the SW slopes, and the base of the Middle Pleistocene continental deposits lying beneath the basin surface, as reported in a geological section by Cavinato and Miccadei (1995). In this case, the estimate of the vertical offset is based on a hypothesis of a sub-surficial stratigraphic setting, and it cannot be considered, therefore, as being as reliable as an estimate derived from surficial data.

Lastly, Gori et al. (2007) proposed an estimate of the slip rate for the western fault ranging from 0.30 to 0.43 mm/yr, which is close to that defined in the present study. This was determined by considering the differences in elevation between the Early Pleistocene "Monte Orsa alluvial fan" breccias by Miccadei et al. (1998), located in the footwall, and the analogous deposits detected along the western border of the Sulmona basin, i.e. in the fault hanging wall. Since the "long period" slip rate (Early Pleistocene) produced by Gori et al. (2007) is comparable to that defined in the present study and related to the Middle Pleistocene and to the Late Pleistocene-Holocene, a persistence of the western fault segment activity since the Early Pleistocene with an unvaried slip rate can be hypothesised. This probably indicates stationary fault kinematic behaviour over a large Quaternary time interval.

6.1.3 Expected magnitude

The maximum expected magnitude of an earthquake that might originate along the Mt. Morrone fault has been evaluated by applying two of the empirical equations proposed by Wells and Coppersmith (1994), i.e. the equations that link the moment magnitude with: 1) the surface rupture length (SRL); and 2) the displacement per event.

1) We assume that the length of the surficial expression of the fault system is comparable to the SRL, as the surficial expression indicated results from the repetition of earthquakes that caused surface faulting.

With this assumption, the SRL defined for the fault system, which is derived from both geomorphic and structural observations (see previous sub-section), is about 22-23 km. This represents the total length of the surficial expression of the Mt. Morrone seismogenic fault, considering that, as indicated in the previous paragraph, the geometry of the fault branches suggests a connection at depth between the two parallel fault segments

The maximum expected magnitude of an earthquake that might originate along this fault is, therefore, 6.6 to 6.7. This is in agreement with that already available in the literature (Galadini and Galli, 2000).

Although this estimation is a mean value of the uncertainty range related to the equations proposed by Wells and Coppersmith (1994) – which yields a Mw ranging between 6.0 and 7.3 – it can be considered as reliable. Indeed, as i) the 1915 "Avezzano earthquake" (Maw 7.0) originated along the 33 km-long Fucino fault system (e.g., Galadini and Galli, 1999; Galadini and Messina, 2004) – which is evidently longer (at the surface) than the Mt. Morrone fault system, as depicted in this study – and ii) the April 6, 2009 “L’Aquila earthquake” (Mw 6.3) was caused by the about 10-11 km-long Paganica fault (see this thesis) – that is shorter than the Mt. Morrone fault system – a reliable moment magnitude of an earthquake that might originate on the 22-23 km-long Mt. Morrone fault system is in the order of that defined above, i.e. 6.6-6.7.

2) Considering that the last activation of the Mt. Morrone fault occurred during the 2nd century (Galadini and Galli, 2001; Ceccaroni et al., 2009), and assuming that the fault did not experience aseismic creep, the total maximum slip rate proposed, which is between >0.4 ±0.07 and <0.8 ±0.09 mm/yr, may provide a displacement per event of about 0.5 m to 2.0 m. This derives by considering the mean recurrence interval per central Apennines fault, that ranges from 1400 to 2600 years (Galadini and Galli, 2000).

Hence, by using the above-mentioned empirical equation of Wells and Coppersmith (1994) and the obtained possible displacement per event,, an earthquake that originates along the Mt. Morrone fault system would have a magnitude of between about 6.5 and 6.9.

It is worth noting that, this range of magnitude, that is based on some assumptions and that, therefore, must be taken with cautions, is nevertheless consistent with expected magnitude obtained by means of the SRL (i.e., 6.6–6.7). This also implies that the slip rate range defined in this work can be considered to be reliable.

6.2 The Maiella-Porrara normal fault system

The present study indicates that the active tectonics in the sector W and SW of the Maiella front can be related to normal faulting.

6.2.1 Kinematic history of the fault system

From a general point of view, basing on the structural data collected along the fault planes and the geomorphic observations performed along these mountain slopes, the faults investigated are probably at an early stage of evolution, since they are characterised by a low amount of vertical offset and very irregular patterns (short en-echelon segments and sub-parallel splays).

The evidence of Late Pleistocene-Holocene activity and the location of the faults investigated suggest that the Palena Fault and the western Porrara Fault represent the easternmost evidence of active normal faulting in the central Apennines. In short, the faults mark (or they are very close to) the easternmost boundary of the intra-Apennine extensional domain.

The absence of basins and intermontane depressions and, especially for the Palena Fault, the lack of a clear geomorphic signature of recent activity (such as a well developed and continuous fault scarp) suggest that their Quaternary activity began more recently than along other central Apennine Quaternary faults.

This evidence supports the view of an Apennine extensional domain propagating towards the outermost sector of the chain (e.g. Galadini and Messina, 2004; Fubelli et al., 2009). The recent onset of the activation might indicate that the migration of the extensional domain is a process that was still active in the Late Quaternary.

The surficial pattern of the Palena Fault and the western Porrara Fault suggests that inherited syn-orogenic tectonic structures controlled the localisation of the Quaternary extensional faults. The western Porrara Fault, in fact, strictly follows part of the southernmost traces of the Messinian-Pliocene(?) Caramanico fault.

The activity of the Caramanico fault has been analysed by Ghisetti and Vezzani (2002) who described it as an about 40 km long active normal fault with a slip rate of 2.6 mm/yr, evaluated by considering the offset (quantified in 4.2 km) of pre-Quaternary marine sequences and determined in the last 1.8 M by the fault activity during the Quaternary. In our opinion, the present activity of the Caramanico fault, issued by Ghisetti and Vezzani (2002), and their estimate of the slip rate are based on too speculative elements and it is not supported by thorough geological evidence, i.e. consisting in the observation of chronologically constrained (related to the Late Pleistocene-Holocene) sediments and/or landforms displaced along the fault. Moreover, our observations provided no evidence of Late Quaternary activity along the Caramanico fault, except for the southernmost sector (coinciding with the described western Porrara fault segments). Indeed, close to the “Fondo di Maiella” landslide scarp (Fig. 4.2.2, site 6), few kilometres north of the northern tip of the Porrara fault, the Caramanico fault scarp is almost continuously sealed by the debris deposited along the hillside and the slopes display a linear profile, being smoothed by the exogenous erosional/depositional processes. The fault plane can be exclusively detected where streams, running perpendicular to the Maiella western flank (Fig. 4.4.4, site 6), eroded the scree deposited along the slopes (Fig. 6.2.1).

Fig. 6.2.1 – Western slopes of the Maiella Massif. The so-called "Caramanico fault" described by Ghisetti and Vezzani (2002) is here exclusively exposed where streams eroded the scree deposited along the scarp (indicated by the black arrow). Where no erosional processes have occurred, the fault plane is not exposed and the hillside displays a linear profile (yellow asterisk).

Our observation is also corroborate by the stratigraphic and structural analyses performed by Scisciani et al. (2002) who attributed to the Caramanico fault exclusively a pre-orogenic activity.

Hence, the right-stepping pattern of the western Porrara Fault segments is consistent with the measured sinistral-oblique normal slip, which suggests the local reactivation of the pre-existing and no more active Caramanico fault in response to the Late Quaternary, NNE-SSW direction of the extension.

In turn, the Palena Fault results from the Late Quaternary reactivation (with normal dip-slip kinematics) of a pre-existing (Pliocene), left-lateral, oblique fault that is associated with the Maiella thrust and fold emplacement.

The major role played by reactivation of pre-existing faults is also supported by the fact that the Palena Fault is transverse to the Maiella ridge, and hence its orientation and localisation were not conditioned by the topography. Furthermore, since the south-eastern tip of the Palena Fault is located in correspondence to the NNE-SSW "Ortona-Roccamonfina Line" (Meletti et al., 1988), the propagation of the rupture towards the SE has probably been inhibited by the presence of this pre-existing crustal cross-structure, as it has determined a zone of intense deformation that hindered the southward propagation of the more recent extensional shear structure.

We suggest, therefore, that the Ortona-Roccamonfina Line may have acted as a "barrier" to the SE propagation of the Quaternary extensional faulting in this sector of the central Apennines. Fault intersection with this barrier might also explain the strike difference (about 50°) between the Palena Fault and the western Porrara Fault, suggesting that this complex fault pattern may represents the surficial expression of a deeper active and seismogenic fault.

6.2.2 Slip rate

The collected data have provided information on the minimum offset that affects the chronologically constrained slope-derived deposits displaced along the Palena Fault. This has allowed us to define the slip rate of this fault segment.

Indeed, the about 18-m-minimum vertical displacement of the slope-derived debris dated at 36,300 ±1,300 yr BP (Fig. 4.2.2, site 1) defines a minimum slip rate of the Palena Fault of roughly 0.5 mm/yr.

6.2.3 Maximum expected magnitude

Comparably to the case of Mt. Morrone normal fault system, we assume that the length of the surficial expression of the fault system is comparable to the SRL, as the surficial expression indicated results from the repetition of earthquakes that caused surface faulting.

The SRL of the Maiella-Porrara fault system, defined by means of geomorphic and structural observations, is of about 16-18 km.

The maximum expected magnitude of an earthquake that might originate along this fault is, therefore, 6.4 to 6.6 (Wells and Coppersmith, 19994).

This magnitude range is consistent with that estimated for the 1706 earthquake, i.e. 6.6, and it may therefore hypothesised that this seismic event may be related to an episode of activation of the analysed extensional fault system. Nevertheless, future studies aiming at verifying this hypothesis are planned.

Moreover, although not useful for a slip rate evaluation, the displacement of about 15 cm of the present soil containing the bronze leaf, however, permitted the identification of an episode of surface faulting along the Palena fault subsequent to the Bronze Age, i.e. about 4 ka BP.

Considering that i) the displaced soil has been detected at the tip of the fault segment, where the displacement is assumed to be lower than in the central parts of the tectonic structure and ii) the April 6 2009 Mw 6.3 seismic event resulted in a coseismic surface deformation having a maximum downthrown of about 15 cm (as described in this work), the 15 cm-offset of the soil detected at the tip of the Palena Fault suggests that a seismic event having a magnitude comparable – or larger – to that of the April 6 may originate along the Maiella-Porrara fault system.

6.3 The Paganica Fault and the April 6, 2009 "L'Aquila" seismic event

Our field surveys and studies of aerial photographs in the L'Aquila area after the April 6 seismic event (Mw 6.3) permitted us to identify evidence of coseismic surface faulting on the Paganica fault, a NW-SE striking and SW dipping Quaternary normal fault located E of L'Aquila.

This structure had been mapped by previous studies (Bagnaia et al., 1992, Vezzani and Ghisetti, 1998; Boncio et al., 2004; Foglio CARG 1:50,000, 2009) but none of the previous works had documented its latest Pleistocene and Holocene activity.

Our data define three en-echelon segments of the Paganica fault, based on its surficial expression, each one 3-4 km long. The total length of the structure is about 10 km.

Apart from the obvious association with the April 6 earthquake, recent activity of the Paganica fault is defined by the displacement of ^{14}C- and U-series-dated Late Pleistocene-Holocene deposits along the tectonic structure. In particular, a trench eroded along a ruptured aqueduct exposed several tens of centimetres of offset in Late Holocene deposits along the Paganica fault, which suggests that the fault has probably generated stronger earthquakes in the past.

We identified evidence of surface faulting along the Paganica fault due to the April 6 shock including set of continuous aligned ground cracks along the central segment of the fault; some cracks had both vertical and horizontal offset up to about 15 cm. The offset of some cracks increased as much as a few centimetres in the days subsequent to the mainshock. This is probably evidence of a certain amount of afterslip related to the aftershocks. The presence of ground cracks, although discontinuous and with no vertical offset along the northern and the southern fault segments suggest that also these branches of the Paganica fault were probably activated during the April 6 shock.

Furthermore, the presence of discontinuous ground fractures aligned along the E-W tectonic structures located between the Paganica and Mt. Pettino faults suggests the probable activation during the April 6 earthquake of these E-W structural features, that may represent transfer faults that structurally link the Paganica and Mt. Pettino faults. These structures, therefore, may be part of the same fault system. The surficial expression of this fault system may be therefore represented by the Upper Aterno Valley fault system, as defined by Moro et al. (2002), plus the Paganica fault.

6.4 Evidence of active inverse faulting in the north-eastern sector of the Calabrian Arc

The wall of the excavation found SE of the village of Mirto, exposed a sequence of paleo-deltaic sediments, probably of Middle Pleistocene age, deposited in a infra- to circa-littoral environment and presently located at an elevation of about 15 m a.s.l..
These would indicate that marine sediments deposited at more than 100 m below the sea level have been uplifted to 15 m a.s.l. onshore in a time span not larger than 780 ka (i.e. the beginning of the Middle Pleistocene). This defines a minimum uplift rate of about 0.15 mm/yr of the sediments.
Our observations suggest that the uplift of the marine sequence is probably due to two different tectonic processes: i) the "regional" uplift, affecting the whole Calabrian Arc (see paragraph 2.2), and ii) the activity of the inverse faults, observed along the excavation wall, that displaced and raised the paleo-deltaic deposits.
Taking into account that these compressive tectonic structures determined the displacements of Holocene colluvial sediments, it indicates that inverse faulting has to be considered as active in this portion of the Calabrian Arc.
Although our studies in this area are still in progress, some preliminary hypothesis about the "tectonic origin" of such deformation can be performed.
The observed compressive deformation may represent the expression at the surface of:

1) a secondary back-thrust related to a main compressive tectonic structure verging towards NE;
2) a main transpressional tectonic structure;
3) a local compressive deformation (restraining bend) related to a main strike-slip fault.

Taking into account the available literature, the hypotheses at point 2 and 3 are probably more probable. Indeed, Van Djik et al. (2000) depicted the structural setting of this portion of the Calabrian Arc by analysing a net of commercial seismic reflection profiles. The authors defined the presence of a transpressional complex structure in the offshore of this part of the Arc. This complex fault system resulted in a "positive flower structure", with some fault splays verging landwards and affecting the Rossano basin area.

The hypothesis at point 2 is also supported by a recent work by Ferranti et al. (2008). These authors found i) local-scale, but pervasive undulations in the deformation profile of marine terraces, attributed to transpressional deformations, and ii) compressive deformations, NW-SE trending, of Middle and Late Pleistocene sediments in the offshore of the Sibari plain (i.e. few tens of kilometres north of the area investigated in the present work) derived from the analysis of industrial seismic lines.

Hence, the evidence of active inverse faulting described in the present work, may be the result of this transpressional deformations.

As for the hypothesis at point 3, this might be supported by the observation performed by Corbi et al. (2009). The authors, indeed, detected kinematics indicators related to normal, normal oblique, strike slip and, more rarely, inverse sense of motion along several fault planes affecting the marine and continental sedimentary sequences of the Rossano plain area. The compressive deformations described in this thesis may therefore represent a local deformation, i.e. a restraining bend, related to a main strike slip fault.

7. CONCLUSIONS

This thesis aimed at improving the knowledge about the seismotectonic characteristics of the central Apennines and north-eastern sector of the Calabrian Arc. Indeed, we have investigated some of the most problematic sectors in terms of seismic hazard and seismic potential of the Italian territory.

1) As for the Mt. Morrone case (central Apennines), the stratigraphic, geomorphological, chronological and structural data reported in the present study improve our knowledge of the active normal fault system that affects the south-western slopes of the relief. The importance of research in this area is based on the fact that the fault is considered to be active, while no historical earthquakes can be attributed to it. For this reason, the fault is defined as "silent" in the literature. The

tectonic structure at the surface comprises two parallel, NW-SE trending fault segments, which represent the expression of a deeper fault that is potentially responsible for destructive earthquakes.
According to the structural observations reported in the present study, a mainly normal kinematics with a minor left oblique component, which fits about a N 20° trending extensional deformation, can be attributed to this fault system.
The displacement of continental units related to the Middle Pleistocene and the Late Pleistocene-Holocene allowed the definition of a slip rate for the westernmost fault segment of 0.4 ±0.07 mm/yr. Although conclusive data that can be used to define the slip rate of the eastern fault branch are lacking, the collected data and a comparison with similar cases reported in the literature, have allowed us to propose a slip rate for the eastern segment that ranges between 0 and 0.4±0.07 mm/yr. This thus allows us to hypothesise a slip rate for the total structure of >0.4 ±0.07 and <0.8 ±0.09 mm/year.
Finally, by using the empirical relationship proposed by Wells and Coppersmith (1994) that links the moment magnitude with the surface rupture length and with the average and maximum displacement per event, we have estimated the expected magnitude for the roughly 22-23 km long Mt. Morrone fault system as in the order of 6.6 to 6.7. The procedure for establishing the magnitude also supports our estimate of the slip rate (i.e. >0.4±0.07 – <0.8±0.09 mm/yr).
Considering the 2nd century AD earthquake as a result of the last activation of the Mt. Morrone fault (Galadini and Galli 2001; Ceccaroni et al., 2009), and that the recurrence interval of surface faulting for the active faults of the central Apennine is in the order of 1,000 to 2,000 years, the present elapsed time of about 1,800 years since the last earthquake defines that there is a high level of probability of an earthquake occurrence in a time span of that is of social interest.
The results obtained indicate that the activation of this fault might result in a destructive earthquake in the densely populated sector of the Sulmona plain and the surrounding areas, in which numerous villages (such as Sulmona, with about 25,000 inhabitants, Pratola Peligna, Popoli and Pacentro), important motorways, monuments and archaeological relics are located.

2) The investigations performed in the area comprised between the Maiella Massif, Mt. Morrone and Mt. Porrara (central Apennines), permitted us to identify new

geological, structural and geomorphological evidence of Late Quaternary faulting at the southern edge of the Maiella Massif (the Palena Fault) and along the Mt. Porrara western slopes (the western Porrara Fault), within the epicentral area of the 1706 and 1933 seismic events.

The N110°-120° Palena Fault cuts transversally across the southern Maiella ridge, with a length of about 7 km and a maximum vertical offset of 200-300 m. The fault-slip data show nearly pure dip-slip normal movements that are consistent with the present ca. NNE-SSW extension. Dip-slip slickenlines are superposed on sinistral oblique slickenlines, suggesting that the Palena Fault represents an inherited Pliocene syn-orogenic oblique structure that was reactivated as an extensional fault during the Quaternary. The fault plane in the bedrock generally shows very little degradation. Radiocarbon dating of colluviated soils and organic matter, interbedded in the coarse slope debris that was displaced and dragged along the fault, provided evidence for Late Pleistocene-Holocene activation.

Three right-stepping, en-echelon fault segments form the NNW-SSE oriented western Porrara Fault. The total length of this fault is ca. 7 km and the kinematic indicators suggest a prevailing normal movement. Locally, slope-derived deposits that are probably related to the Last Glacial Maximum (21-18 kyr BP) were found in tectonic contact with the carbonate bedrock.

Geomorphological evidence suggests a recent onset of activity for these investigated faults, and supports the hypothesis of an outward propagation of the Late Quaternary normal faulting. This propagation generally occurred by the reactivation of pre-existing (Miocene-Pliocene) inherited structures that were suitable to accommodate the NNE-SSW to NE-SW extension in the upper crustal levels. However, the available subsurface data indicate that no active normal faulting occurred in areas further east of that under investigation, i.e., towards the outer zones of the frontal Apennine chain. With this in mind, we suggest that the NNE-SSW "Ortona-Roccamonfina Line" represents a pre-existing crustal cross-structure that has acted as a barrier to the propagation of the Quaternary extensional faulting towards the SE.

Future investigations will be addressed to the definition of the northern prolongation of the Palena Fault and the western Porrara Fault, i.e. to define the structural relationships between the active faulting of the Maiella Massif and the already well investigated Mt. Morrone normal fault. These studies will allow further light to be casted on the complicated seismogenic matter, particularly with the perspective of defining the causative sources of the earthquakes that have struck the Maiella area (1706 and 1933). These represent major unsolved issues in studies of the earthquake potential of central Italy.

3) Field surveys were performed in the area struck by the April 6, 2009 seismic event, in the aftermath of the earthquake. This permitted the identification of surface rupturing along the Paganica fault, a Quaternary extensional tectonic structure located W of L'Aquila. The gathered data indicate that this fault is about 10 km long, made of three main fault segments having a dextral en echelon arrangement and detectable between Colle Enzano (close to the village of Collebrincioni) and San Gregorio. This fault has been responsible for the displacement of Middle Pleistocene to Holocene alluvial and slope deposits.

Overall, our observations show to relatively little coseismic surficial movements on the Paganica fault, which probably was less than a few centimetres. Further evidence that supports the occurrence of surface faulting on the Paganica fault includes the rejuvenation of the fault plane, i.e. the free-face observed at the base of the slickenside, along the northern and central segments of the tectonic structure. It is worth noting that base on empirical relationships between moment magnitude and the surface rupture length (Wells and Coppersmith, 1994), the length of the Paganica fault rupture is consistent (taking into account the uncertainty range proposed by Wells and Coppersmith) with the reported magnitude (Mw=6.3; Istituto Nazionale di Geofisica e Vulcanologica, 2009; MedNet, http://mednet.rm.ingv.it/procedure/events/QRCMT/090406_013322/qrcmt.html).

Our evidence of surface rupture combined with the location and the length of the Paganica fault is consistent with it being the source of the April 6 earthquake. This conclusion is also consistent with the results from studies of 1) interferometric SAR observations (Atzori et al., 2009); 2) the location and geometry of the fault modelled using the coseismic ground deformation patterns from GPS data (Anzidei et al., 2009); and 3) seismological data, that is the location and focal mechanism of the main shock and the aftershock distribution (Istituto Nazionale di Geofisica e Vulcanologia, 2009; Analisi dati di sismicità, http://www.ingv.it).

Lastly, a comparison between the geometry of the Paganica fault, the intensities (MCS scale) distribution (Galli and Camassi, 2009; Rapporto sugli effetti del terremoto aquilano del 6 aprile 2009, http://www.mi.ingv.it/eq/090406/quest.html) and the magnitude related i) to the April 6 2009 and ii) to the 1461 (Maw 6.4) seismic events, suggests that this tectonic structure may have activated during both the seismic events, the 1461 earthquake being the “ancient analogue” of the April 6 earthquake.

Moreover, i) the evidence found along the Paganica fault of Holocene surface displacements events larger than that caused by the April 6, 2009 earthquake (e.g. Cinti et al., 2009) and ii) the presence of coseismic ground ruptures aligned along E-W fault located between the Paganica and the Mt. Pettino faults, that may represent transfer fault linking these two tectonic structures, allow to hypothesise that these two en echelon arranged tectonic structures may represent the expression at surface, together with further fault branches pertaining to Upper Aterno Valley fault (Galadini and Galli, 2000), of the same 25-30 km long fault system that may activate during M 6.6-6.8 seismic event. Considering that Moro et al. (2002) related the February 2, 1703 earthquakes (Mw 6.6.5) to the Upper Aterno Valley fault system, we can hypothesise that the Paganica fault activated during this large magnitude seismic event.

4) The analyses performed along the north-eastern sector of the Calabrian Arc permitted the identification of sandy (paleo-deltaic) and cleyey marine deposits of probable Middle Pleistocene age that are presently located at about 15 m a.s.l. These sediments, together with colluvial deposits that overlay the sequence, are displaced and bended by fault planes having an inverse sense of motion and verging towards SW (i.e. landward).

These shear planes can be considered as active, as the latest deposits displaced by these structural features have been dated to the Holocene (9800 BC-9786 BC/9771 BC-9360 BC – 7568 BC-7559 BC; 7553 BC-7351 BC; calibrated, 2**σ**)

Further studies are planned in order to better define the tectonic significance of the observed tectonic structures. Nevertheless, by the analysis of the available literature, the most probable hypothesis is that they represent the expression at the surface of a main transpressional tectonic structure.

If this hypothesis will be verified by future investigations, the contemporaneous activity of compressive or (transpressional) deformation and the extensional (or transtensional) deformation (i.e. along the Rossano normal fault) occurs within a belt large few kilometres. Such structural framework may be related to different contemporaneous tectonic processes:

1) the active normal faulting may be related to the presently active uplift of the Arc, comparably to what has been proposed by several authors (D’Agostino et al., 2001; Galadini et al., 2003a) for the normal faulting in the central Apennines.
2) the active transpressional faulting may be related to the complex evolution of the junction zone between the southern Apennines and the Calabrian Arc.

Finally, from a seismotectonic point of view, the observed active inverse faults probably represent the expression at the surface of a tectonic structure that may be responsible for seismic events producing surface faulting and, therefore, having M>5.5-6 (Wells and Coppersmith, 1994). Furthermore, i) taking into consideration the magnitude of the 1836 seismic event and ii) by comparing the damage distribution related to this earthquake with the location of the observed inverse faults, these structural features may be related to a tectonic structure that is a possible candidate (together with the Rossano normal fault) as the causative fault of the 1836 event.

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