DOI: 10.4408/IJEGE.2017-02.O-01

GEOLOGICAL AND SEISMOLOGIC DATA REVIEW OF THE 2009 L'AQUILA SEISMIC SEQUENCE (CENTRAL APENNINES, ITALY): DEEP-SEATED SEISMOGENIC STRUCTURES AND SEISMIC HAZARD

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EXTENDED ABSTRACT

Il 6 Aprile 2009 un terremoto di M_W=6.1 ha interessato la media-alta valle dell'Aterno, danneggiando L'Aquila e dintorni. Questo settore si ubica in una stretta fascia in direzione NNW-NW lungo la zona assiale dell'Appennino Centrale, caratterizzata da frequenti crisi sismiche anche di elevata intensità. Sia prima che dopo l'evento di Aprile 2009, sono stati eseguiti numerosi studi in questo settore con lo scopo di identificare le faglie quaternarie e le sorgenti sismiche. La grandissima maggioranza degli autori, basandosi principalmente su elaborazioni e dati prevalentemente sismologici, ritiene che la sequenza sismica dell'Aquila 2009 sia stata provocata dall'attivazione delle faglie di Paganica e di Mt. Gorzano, faglie estensionali quaternarie di modesta estensione lineare, ad andamento NW-SE e immergenti a SW.

In questo lavoro è stato utilizzato un approccio differente: prima di tutto si è cercato di ricostruire un quadro omogeneo e preciso dell'assetto strutturale dell'area per individuare e caratterizzare le principali strutture quaternarie, integrando i dati di superficie con quelli del sottosuolo, ricavati dall'interpretazione delle linee sismiche a riflessione disponibili. Successivamente, è stata ricostruita, utilizzando i dati del Bollettino Sismico dell'INGV, la distribuzione spazio-temporale della sequenza sismica. La principale (per sviluppo in superficie e in profondità) struttura quaternaria dell'area è risultata la Celano-Cittareale (CCFS); essa è costituita da un complesso sistema di faglie orientato circa NW/NNW-SE/SSE, per lo più NE-immergenti; è stata identificata dalla Piana del Fucino fino oltre Cittareale, ma prosegue ancora più a sud e più a nord. CCFS si radica in profondità nella crosta con piani ad alto angolo, NE-immergenti. Nella parte più superficiale (fino a circa 10 km di profondità), CCFS è costituita strutture a fiore, talora positive e talora negative, con faglie SW e NE-immergenti; in profondità è caratterizzata da piani ad alto angolo prevalentemente NE-immergenti. Durante il Quaternario è stata attiva talora con cinematica transtensiva sinistra e talora puramente distensiva; la componente transtensiva è stata comunque predominante. Le altre numerose faglie quaternarie, per lo più SW-immergenti, presenti nell'area hanno uno sviluppo molto più limitato rispetto a CCFS sia in superficie che in profondità. I piani delle faglie di Paganica (sintetica del principale sistema di faglie di Barisciano-BFS) e Mt. Gorzano sono più superficiali e si interrompono contro CCFS a circa 9/10 km di profondità. CCFS è interrotta localmente da sistemi di faglie trasversali/oblique (NE-SW/NNE-SSW) ad attività quaternaria. La ricostruzione spazio-temporale della sequenza sismica indica che essa si è verificata per step successivi a partire da sud verso nord, formando tre distinti clusters di terremoti aftershocks. I tre clusters sono ciascuno confinati: a sud e a nord da sistemi di faglie trasversali /oblique antiappenniniche, a ovest da CCFS e a est da BFS e GF. Il primo cluster a formarsi e anche il principale come numero, Magnitudo, main shock e profondità dei terremoti è quello meridionale, confinato dalle strutture trasversali di Rocca di Mezzo a sud e S. Vittorino a nord. Gli altri due più settentrionali hanno iniziato a formarsi rispettivamente a distanza di diverse ore e di alcuni mesi dal main shock. Gli epicentri dei foreshocks, sviluppatesi da Ottobre 2008 fino al main shock, formano un addensamento che si ubica unicamente nella parte centro-occidentale dell'area del cluster meridionale.

Sono stati eseguiti quattro profili strutturali-sismologici con andamento circa NE-SW, ortogonali rispetto alle strutture quaternarie. Due nell'ambito del cluster meridionale e gli altri due nell'ambito degli altri due cluster. I due più meridionali evidenziano che gli ipocentri degli aftershocks si concentrano lungo i piani di CCFS e BFS; quelli in corrispondenza di CCFS raggiungono anche profondità notevoli (> 19/20 km), gli altri si attestano fino ad un massimo di circa 10 km di profondità. Meccanismi focali talora estensionali e talora transtensivi sono presenti lungo CCFS fino a circa 10 km di profondità; al sotto sono transtensivi. L'analisi della distribuzione spazio-temporale degli ipocentri evidenzia che i terremoti ricadenti sui piani di BFS sono avvenuti un po' più tardi rispetto a quelli presenti su CCFS. La proiezione in profondità dei foreshocks e del main shock evidenzia che questi ricadono sui piani di CCFS, senza coinvolgimento di BFS. Gli altri due profili mostrano una situazione analoga, l'unica differenza sta nel fatto che la faglia antitetica di CCFS è in questo caso GF. In base a quanto sopra risulta che la sequenza sismica dell'Aquila sia stata causata dalla progressiva attivazione di tre segmenti di CCFS mentre BFS/ GF si sono attivate successivamente per accomodamento. Il primo ad attivarsi è stato un tratto di circa 10/12 km del segmento meridionale; questo ha causato il main shock (M_W=6.1) e il maggiore (M_W=5.4) aftershock.

ABSTRACT

This study identified and characterized an important and complex Quaternary structure, the Celano-Cittareale Fault System (CCFS), crossing NNW/SSE-NW/SE through the entire area of the L'Aquila 2009 seismic sequence. The CCFS, which develops from the Fucino Plain and further north to Cittareale, is locally segmented by NE-SW/NNE-SSW transversal/oblique faults. It is a regional flower structure, deeply rooted in the crust, mainly NE-dipping and overall high-angle, characterized during the Quaternary by left transtensional kinematics. Based on the data acquired from the literature and on our reconstructions, the CCFS was the main seismogenic structure responsible for the 2009 L'Aquila seismic sequence and for other important seismic sequences, in particular those of 1703 and 1915. According to our view, the SW-dipping Paganica Fault (PGF, a splay of the main Barisciano Fault System BFS) and the Mt. Gorzano Fault (GF), considered by previous authors to be the only ones responsible for the 2009 L'Aquila seismic sequence, were instead local and more superficial faults, antithetical to the CCFS, activated at different times by accommodation.

During the 2009 seismic sequence, three CCFS segments, bounded by four transversal/oblique fault-systems, were active stepwise from the south to the north, producing three clusters of earthquakes that differed in energy and number of events. The activation of the CCFS southern segment caused the largest number of earthquakes, including the foreshocks, the main shock (M_W=6.1) and earthquakes deeper than 20 km. The earthquakes of this cluster were characterized by left transtensional and extensional kinematics. The activation of the other two CCFS segments and of the BFS and GF produced earthquakes of lower magnitude that also were shallower and characterized by predominantly extensional kinematics.

The main transversal faults played different roles: the RMF (Rocca di Mezzo Fault), MF (Marana Fault) and TFS (Torrita Fault System) passively confined the three clusters of the 2009 L'Aquila seismic sequence to the south and to the north, respectively; instead, the intermediate SFS (San Vittorino Fault System) first confined the southern cluster to the north at the onset seismic of the sequence and subsequently, by activating as a right transfer fault, it became itself seismogenic.

Key words: 2009 L'Aquila Earthquake, active fault system, seismogenic structures, Central Apennines, seismic hazard

INTRODUCTION

On April 6th, 2009 a M_W=6.1 earthquake occurred in the Upper-Middle Aterno Valley, strongly damaging the town of L'Aquila and its surroundings. This sector is located in a narrow NNW-NW striking seismogenic belt of the axial Central Apennine chain (Fig. 1), characterized both historically and recently by high seismicity.

Even before the April 2009 event, numerous studies had been conducted on the Central Apennine structural framework and its recent active tectonics, to identify the active faults and the seismogenic sources (Bosi & Bertini, 1970; Bosi, 1975; Pantosti *et alii*, 1996; Bachetti *et alii*, 1990; Bagnaia *et alii*, 1992; Bertini & Bosi, 1993; Blumetti *et alii*, 1993; Blumetti, 1995; Calamita & Pizzi, 1994; Lavecchia *et alii*, 1994; 2002; Cacciuni *et alii*, 1995; D'Addezio *et alii*, 1995; Salvi & Nardi, 1995; Calamita *et alii*,1997; Cello *et alii*, 1997, 1998; Frepoli & Amato, 1997; Vezzani & Ghisetti, 1998; Galadini, 1999; Barchi *et alii*, 2000; Galadini *et alii*, 2000; 2003a; 2003b; Galli *et alii*, 2008; Galadini & Galli, 2000; 2003; ITHACA Working Group, 2000; Morewood & Roberts, 2000; Tondi, 2000; Galadini & Messina, 2001; Valensise & Pantosti, 2001; Moro *et alii*, 2002; Pace *et alii*, 2002; Roberts *et alii*, 2004; Salvi *et alii*,2003; Boncio *et alii*, 2004a; 2004b; Cinti *et alii*, 2004, 2009, 2011; Roberts & Michetti, 2004; Working Group CPTI, 2004; APAT, 2006a; 2006b; 2006c; 2006d; Tertulliani *et alii*, 2006; Bagh *et alii*, 2007; Cenni *et alii*, 2008; Pizzi & Galadini, 2009).

Generally a great part of these authors, using high resolution earthquake distribution, reconstruct the fault-zone geometry of the activated faults, mainly NW-SE trending / SW dipping. Other authors (Deschamps *et alii*, 1984, 2000; Salvi & Nardi, 1995; Cello *et alii*, 1997, 1998; Tondi, 2000), have recognized, studied and called attention to other important active structures with remarkable seismogenic potential in the Central-Northern Apennines: these are NNW-SSE striking structures belonging to a complex Central Apennines Fault System (CAFS, *sensu* Cello *et alii*, 1997; 1998). According to these authors, they are a surface expression of a regional deep-seated left strike-slip SW-dipping system with high seismological potential.

Following the 2009 L'Aquila earthquake, a great number of studies were performed, in particular:

- Geological/structural and geophysical research: Elter *et alii*, 2009, 2011, 2012; Farabollini *et alii*, 2009; Galadini *et alii*, 2012; Kraus *et alii*, 2009; Mantovani *et alii*, 2009, 2010; Messina *et alii*, 2009a, 2009b, 2010a, 2010b), 2011;Viti *et alii*, 2009; Boncio *et alii*, 2009, 2010, 2011; Galli *et alii*, 2010, 2011, 2012; Mariucci *et alii*, 2010; Visini *et alii*, 2010; Balasco *et alii*, 2011; Di Stefano *et alii*, 2011; Finetti, 2011; Giocoli *et alii*, 2011; Improta *et alii*, 2012; Ferrarini *et alii*, 2012; Lavecchia *et alii*, 2012, 2017; Roberts *et alii*, 2010; Bigi *et alii*, 2013;
- Studies on distribution seismicity / hypocentral location: Amoruso & Crescentini, 2009, 2010, 2012; Chiarabba *et alii*, 2009, 2010; Chiaraluce *et alii*, 2009, 2011a, 2011b; Chiaraluce, 2010, 2012; Ciaccio *et alii*, 2010; Pino & Di Luccio, 2009; Sileo *et alii*, 2009; Tertulliani *et alii*, 2009; Valoroso *et alii*, 2009; Lucente *et alii*, 2010; Pondrelli *et alii*, 2010; Scognamiglio *et alii*, 2010; Ameri *et alii*, 2011; Di

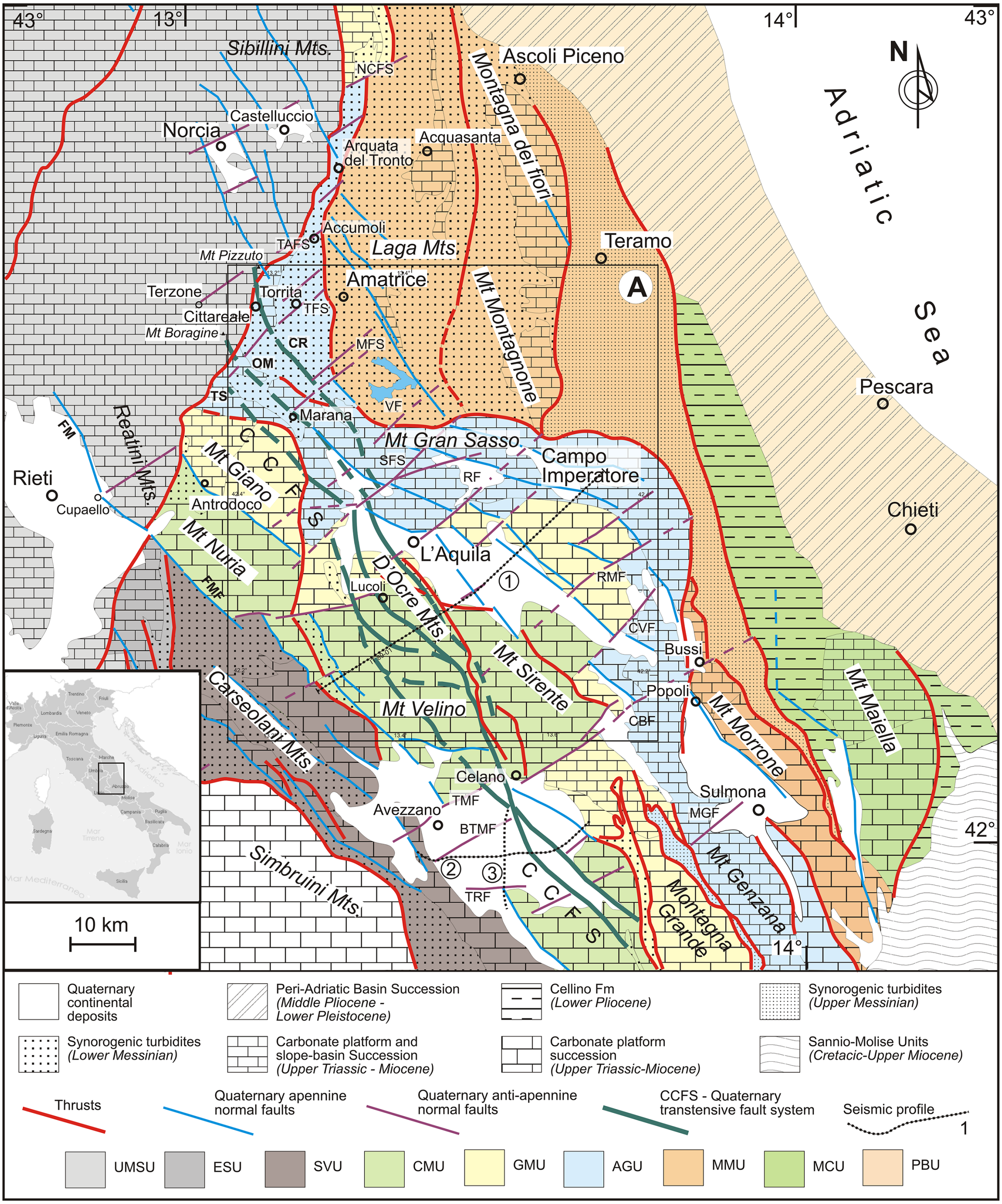

Fig. 1 - Simplified tectonic map of the Central Apennine with location of the study area (key box A). 1 - Trace of the seismic profile IT 89-01 and geological cross-section; 2, 3 - Traces of the seismic profiles 1-80-AZ-03 and 1-82-AZ-05.
UMSU, Umbria-Marche-Sabina Unit; ESU, Eastern Sabina Unit; SMU, Simbruini Mountain Unit; SVU, Salto Valley Unit; CMU, Cicolano - Western Marsica Unit; GMU, Mt. Giano - Montagna Grande Unit; AGU, Accumoli - Mt. Genzana Unit; MMU, Montagna dei Fiori - Montagna del Morrone Unit; MCU, Maiella – Cellino Unit, and the PBU, Periadriatic Basin Unit

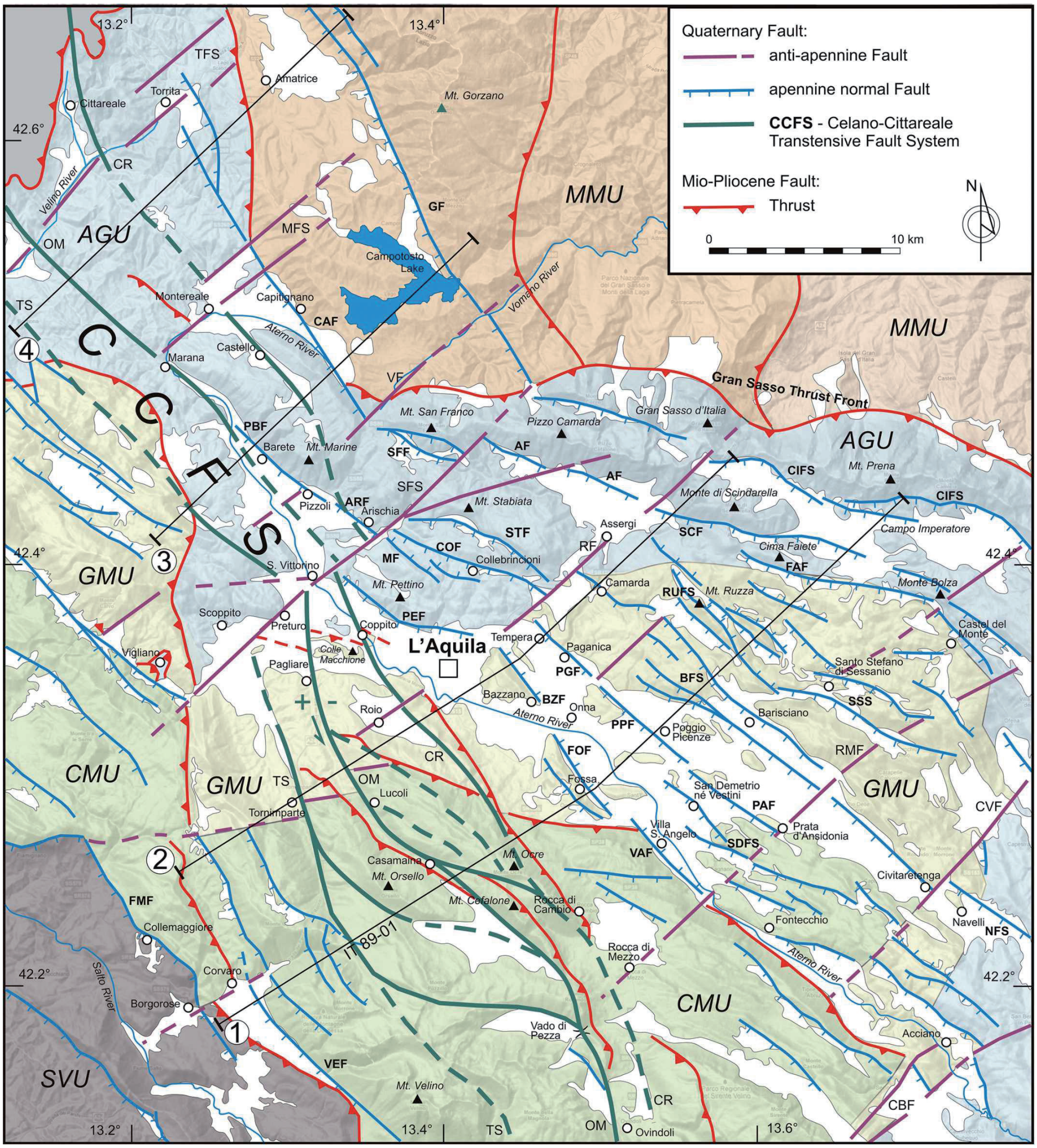

Fig. 2 - Simplified structural map of study area.
Quaternary left transtensive Fault System (green): CCFS, Celano-Cittareale (TS, Tornimparte-Scoppito branch; OM, Ovindoli-Marana branch; CR, Cittareale-Rocca di Cambio branch).
Quaternary anti-apennine structures (violet): TFS, Torrita Fault System; MFS, Marana Fault system; VF, Vomano Fault; SFS, S. Vittorino Fault System; RF, Roio-Assergi Fault; RMF, Rocca di Mezzo Fault; CVF, Civitaretenga Fault; CBF, Celano-Bussi Fault.
Quaternary normal faults (blue): GF, Mt. Gorzano Fault; CAF, Capitignano Fault; PBF, Pizzoli - Barete (or Mt. Marine) Fault; SFF, Mt. S. Franco Fault; ARF, Arischia Fault; AF, Assergi Fault; STF, Mt. Stabiata Fault; COF, Collebrincioni Fault; MF, Macchione Fault; PEF, Mt. Pettino Fault; CIFS, Campo Imperatore Fault System; SCF, Mt. Scindarella Fault; FAF, Cima Faiete Fault; RUFS, Mt. Ruzza Fault System; SSS, S. Stefano di Sessanio Fault; BFS, Barisciano Fault System; PGF, Paganica Fault; PPF, Poggio Picenze Fault; PAF, Prata d'Ansidonia Fault; BAF, Bazzano Fault; FOF, Fossa Fault; SDFS, S. Demetrio dè Vestini Fault; FNS, Fontecchio Fault System; VEF, Velino Fault.
Miocene-Pliocene, Thrust (red).
SL IT 89-01: trace of the seismic profile and geological cross-section.
1, 2, 3 and 4 structural-seismological interpretative cross-sections

Luccio & Pino, 2011; Hermann *et alii*, 2011; Margheriti *et alii*, 2011; Vannoli *et alii*, 2012; Calderoni *et alii*, 2013;
- Elaborations of GPS, RADAR and INSAR data: Antonioli *et alii*, 2009; Anzidei *et alii*, 2009; Atzori *et alii*, 2009; Avallone *et alii*, 2009, 2011, 2013; Cirella *et alii*, 2009; De Natale *et alii*, 2011; Serpelloni *et alii*, 2010, 2012; Walters *et alii*, 2009; Caporali *et alii*, 2010; Cenni *et alii*, 2012; Cheloni *et alii*, 2010; Disperati *et alii*, 2010; Guerrieri *et alii*, 2010; Papanikolaou *et alii*, 2010; Roberts *et alii*, 2010; Moro *et alii*, 2010 e 2013; Dalla Via *et alii*, 2012; Gori *et alii*, 2012; Tinti *et alii*, 2012;
- Research on coseismic surface faulting data: EMERGEO WORKING GROUP, 2009, 2010; Falcucci *et alii*, 2009; Galli *et alii*, 2009; Boncio *et alii*, 2010; Di Bucci *et alii*, 2011; Vittori *et alii*, 2011;
- Studies on fluid and ground motion: Akinci & Malagnini, 2009; Akinci *et alii*, 2010; Ameri *et alii*, 2009; Italiano *et alii*, 2009; Pacor *et alii*, 2009; Çelebi *et alii*, 2010; Di Luccio *et alii*, 2010; Chiodini *et alii*, 2011; Zambonelli *et alii*, 2011; Bonfanti *et alii*, 2012; Pastori *et alii*, 2012.

Many authors hold that the 2009 L'Aquila seismic sequence was induced by the activation of some NW-SE striking Quaternary extensional en-echelon faults, mainly SW-dipping, in particular, the Paganica (Aquila Fault, *sensu* Valoroso *et alii*, 2013) and the Mt. Gorzano Faults (PGF and GF). Several debates concerned the relationships between the fault geometries (length, down-dip, depth, width), slip-rates, recurrence time, long-term or short-time kinematics and their role in the seismic hazard, and the thickness of the seismogenic layer. By contrast, some of these authors (Chiaraluce *et alii*, 2011a, b; Valoroso *et alii*, 2013), showed that a part of the 2009 L'Aquila seismic sequence was located outside the Paganica Fault plane and was disposed along a deeper NE-dipping plane that they regarded as antithetic to the Paganica Fault (Chiaraluce *et alii*, 2011a; 2011b; Valoroso *et alii*, 2013). Furthermore, Lavecchia *et alii* (2012) believe that this seismicity is related to an indeterminate and yet-to-be located low-angle, NE-dipping "hidden Mts. D'Ocre source".

The present work tries to recognize, through a different approach, the seismogenic source of the 2009 L'Aquila seismic sequence, on the ground of many data from : a) the vast literature; b) the numerous geological, structural, and morphotectonic data acquired during detailed mapping of the Domains of Lazio-Marche-Abruzzi (CARG Project: APAT 2006a; 2006b; 2006c; 2006d; ISPRA, 2010; MURST, CNR, COFIN Programs; ENI Task Force Maiella; and CEE: Marche Sud Project); c) our identification and definition of the deep structure geometry through interpretation of some available seismic profiles (in particular IT-89-01, 1-82-AZ-05, 1-80-AZ-03, VIDEPI Project); d) our identification and definition of the space-time evolution and kinematics of part of the 2009 L'Aquila seismic sequence (1/10/2008-30/09/2009, including the 1/10/2008-5/04/2009 foreshocks (Pondrelli *et alii*, 2010) and the 6/04/2009-30/09/2009 aftershocks, Database ISIDe/Bollettino Sismico (2009)-INGV); and e) our analysis and reconstruction of the pre-Quaternary geological-structural evolution of the study area so as to identify the role and the kinematics of the Quaternary active structures.

GEOLOGICAL SETTING

The study area (Figs. 1 and 2) extends from Cittareale-Mt. Gorzano (North) to Fucino Plain (South) and from Cittareale-Borgorose (West) to Campo Imperatore-Navelli (East). This sector is a segment of the Central Apennines fold-and-thrust belt developed during Middle-Late Neogene time.

The evolution of this belt was strongly controlled by the polyphase activity of inherited structural elements, formed under different geodynamic regimes, with repeated tectonic inversion processes.

The main stages of the Apennine geodynamic evolution can be summarised as follows (according to Centamore *et alii*, 2002; 2007; 2009, a.r.t.):

a) a Triassic-Jurassic extensional stage, linked to the Tethyan rifting, where the former carbonate paleoplatform was dissected by ocean-dipping normal faults, joined with anthitetic ones, and by transtensive transversal/oblique faults. These ones present regional lengths ranging from several tens to hundreds of kilometres and somewhere they cross-cut the boundary basement/crust (Lavecchia *et alii*, 1988; Calamita & Deiana, 1996; Centamore *et alii*, 2002, 2009; Mazzoli *et alii*, 2005; Pierantoni *et alii*, 2013; Scisciani *et alii*, 2014).
b) a Late Cretaceous to Lower Paleogene stage (Alpine Orogenesis). During the Alpine Orogenesis, linked to the Africa-Europe convergence, the morphostructural pattern of the region was characterized by the development of growing anticlines at the hanging-wall of the Triassic-Jurassic ocean-dipping normal faults, reactivated in a positive inversion, joined to the accommodation normal faults forming. In this context, the transversal/oblique faults acted as tear/transfert faults, with strike-slip movements. They are arranged in transversal/oblique belts that somewhere offset the basement, favouring basic magma emissions (Centamore *et alii*, 2002, 2009). The onset of the first compressive stresses in the Apennine Domain may be referred to this stage.
c) an Oligocene-Late Pliocene stage (Apennine Orogenesis). This stage is linked to the Africa -Europe collision. An eastwards shifting of a thrust belt-foredeep system progressively incorporated the external foreland sectors into the orogenic realm (foredeep phase); the processes, such as bending of growing anticlines and the forming of new accommodation normal faults, continued to develop further.
Afterwards, in the upper part of the Lower Messinian, the

Central Apennines were involved, from the inner sector to the more eastern one, in the fold and thrust belt; this one is composed of thrusts with associated minor structures, such as folds, splays, back-thrusts, and brittle-ductile shear zones, and is dissected by transversal/oblique faults. In this phase, tectonic inversion processes affected the inherited tectonic structures. In particular, a great part of the thrust planes reactivated in positive tectonic inversion the former SW-dipping normal faults; the pre-existing E/NE dipping normal faults were rotated as W/SW dipping reverse faults or cut and passively transported by thrusts. The transversal/oblique faults were reactivated as tear/transfert faults (Bigi *et alii*, 1996, 1999); Calamita & Pizzi, 1994); Tavarnelli, 1996; Calamita *et alii*, 1994, 1997, 2000; Pierantoni, 1998; Pierantoni *et alii*, 2013; Scisciani *et alii*, 2001, 2014; Centamore *et alii*, 2002; 2006a; 2006b; 2006c; 2006d; 2009; Centamore & Dramis, 2010). The geometry of the fold and thrust belt is a set of arches, delimited by transversal/oblique ramps, along which deflections of strata strike are observed.

The main NE-SW/NNE-SSW trending structures are, from NW to SE: the Norcia-Castellucccio Fault System (NCFS), the Terzone-Accumoli Fault System (TAFS), the Torrita Fault System (TFS), the Marana Fault System (MFS), which is composed of two parallel en-echelon faults; the Vomano Fault (VF); the S. Vittorino Fault System (SFS); the Roio-Assergi Fault (RF), the Rocca di Mezzo Fault (RMF), the Civitaretenga Fault (CVF), the Celano-Bussi Fault (CBF, Centamore *et alii*, 2002; or Avezzano-Bussi line, Ghisetti & Vezzani, 1999 a.r.t.); the Tre Monti Fault (TMF) and the Mt. Morrone-Mt. Genzana Fault (MGF) (Figs. 1 and 2).

These structures had an important role during the Alpine and Appennine Orogenic Stages: they formed narrow belts of faults, often arranged en-echelon, crossing the Apennines from SW to NE with regional continuity; during the maximum compressive stage these structures delimited sectors or crustal blocks with different tectonic transport.

In the Central Apennines, several tectonic units characterized by different sedimentary successions, structural patterns and deformation chronology have been identified. They are, from the innermost/upper unit to the outermost/lower one (Figs. 1), the more external Umbria-Marche-Sabina Unit (UMSU), Eastern Sabina Unit (ESU), Simbruini Mountains Unit (SMU), Salto Valley Unit (SVU), Cicolano-Western Marsica Unit (CMU), Mt. Giano-Montagna Grande Unit (GMU), Accumoli-Mt. Genzana Unit (AGU), Montagna dei Fiori-Montagna del Morrone Unit (MMU), Teramo Unit (TU) and Maiella-Cellino Unit (MCU). The transgressive deposits of the Periadriatic Basin (PBU), cover the more eastern units (MCU, TU and MMU).

In the Late Neogene-Quaternary sedimentary successions of these units, several main depositional sequences have been recognized (Centamore & Rossi, 2009). These sequences are linked to important geodynamic processes that affected the study area during this period. Time-scanning of the stratigraphic events made it possible to reconstruct the stages of the eastward shifting of the chain-foredeep system and the deformation chronology.

The Umbria-Marche-Sabina Unit, formerly involved in the chain system since Tortonian-Lower Messinian, largely overrode, through a series of out-of-sequence pulses, the eastern ESU, SVU, CMU, GMU, AGU and MMU units.

In the Late Messinian?/Early Pliocene the UMSU, arranged in a complex thrust-sheet,overthrusted the eastern Units through the dextral oblique ramp of the Sibillini Mts. Thrust, the Ancona-Anzio Line, characterized by a high-angle, NNW dipping/NNE-SSW trending plane (Mazzoli *et alii*, 2005; Pierantoni *et alii*, 2005; 2013).This structural element represents a polyphasic structure developed along a Jurassic transversal Master Fault, separating the Tuscan-Umbrian-Marchean Pelagic Domain from the Latium-Abruzzi Neritic Domain (Scarsella, 1951; Castellarin *et alii*, 1978; Coli, 1981; Barchi *et alii*, 1988; Centamore & Nisio, 2002).

The Eastern Sabina Unit (ESU), involved in the Chain System in the Late Early Messinian, overthrusted the Salto Valley Unit (SVU) through the Navegna Thrust, while the Fiamignano-Micciani Fault (FMF, Centamore & NISIO, 1999, 2002; ISPRA, 2010) separated the SVU from the CMU. The FMF is a polyphasic structure, reactivating in negative sense part of the former thrust (APAT, 2006c; ISPRA, 2010). The Sabbie di Piagge, M4/P1a Sequences piggy-back deposits, sutured this thrust and are affected by more recent compressive pulses (Centamore & Nisio, 1999; 2002).

The CMU is a NE-wards overturned antiform, joined at the inside by other minor thrusts, back-thrusts and a set of NE-trendig tear faults. This unit came into the chain domain during the M2 Sequence. The Sabbie di Piagge, M4/P1a Sequences piggy-back deposits,sutured the former thrust and are affected by more recent compressive pulses (Centamore & Nisio, 1999, 2002). The tectonic relationships between CMU and GMU are varying:in the Corno Valley,at the NW,and along the Giovinco Valley, at the SE, GMU overrides CMU, while in the Middle Aterno Valley, the CMU is arranged in an embricated-fan thrust on GMU.

The Mt. Giano-Montagna Grande Unit (GMU) is a wide pop-up structure, with back-thrust in the extreme NW Micigliano-Valle del Corno and in the SW sector Anversa-Scanno, and widely overriding in the eastern sector on the AGU (the Antrodoco Well - Martinis & Pieri, 1962; the Vigliano tectonic-window, APAT, 2006c; ISPRA, 2010).

The fold-and-thrust system of the Accumoli-Mt. Genzana Unit (AGU) formed during the first stages of the M3 Sequence; the piggy-back deposits of M3 p.p., M4 and P1a Sequences close the local marine succession.

In the northern sector, the compressive network of the AGU is represented by a set of anticlines, with axis trending from NW-

SE to NNW-SSE to NNE-SSW and by the Accumoli Thrust, a segment of the regional Accumoli-Gran Sasso-Mt. Genzana Thrust (Centamore *et alii*, 1992). In the southern sector, where the Unit is constituted by a wide Mt. Genzana antiform delimited westwards by a back-thrust, overrode the Montagna dei Fiori-Montagna del Morrone and Teramo Units (MMU).

In the Montagna dei Fiori-Montagna del Morrone Unit, the chain building developed in the early M4 p.p. Sequence; several fan-delta deposits, formed by crystalline pebbles of the M4 p.p. Sequence, unconformably lie on former turbidites. This unit is constituted by two spaced anticlines: the Mts. Laga/Acquasanta anticlinorium and the Montagna dei Fiori-Montagnone-Montagna del Morrone anticline. The latter is arranged at the front in an embricate-fan with several splays, and delimited in the eastern side by a N-trending shear zone (the Rigopiano-Bussi Belt, Vezzani & Ghisetti, 1995).

In the Teramo Unit, the whole Messinian succession (M1, M2, M3, M4 Sequences) and piggy-back deposits of P1a Sequence are present. These latter sutured the Gran Sasso Thrust and are involved in an Upper Pliocene compressive stage (APAT 2006a; 2006b; 2006c; 2006d; ISPRA, 2010). The eastern Laga Thrust-front, arranged in a set of splays and folds, overthrusted on the Maiella-Cellino Unit.

The Cellino-Maiella Unit (CMU) is the easternmost unit exposed in the area where the fold-and-thrust system formed at the end of Lower Pliocene.

The Periadriatic Basin Deposits (PBU) are represented by Upper Pliocene-Lower Pleistocene piggy-back deposits (P2, Q1a, Q1b, Q1c, Q1d Sequences) resting unconformably on the eastern part of the Apennine chain.

In the sector delimited by the Vomano Fault (VF) on the NW, by the Celano-Bussi Fault (CBF), on the SE, and by the Middle Aterno Valley, on the SW, the Mt. Giano-Montagna Grande Unit (GMU) and the Accumoli-Mt. Genzana Unit (AGU), detached from their own substratum and roughly piled on a complex thrust-sheet, are largely overrode out-of-sequence the MMU Units through the Accumoli-Gran Sasso-Mt. Genzana Thrust. In this context, the VF and the CBF were reactivated as tear/transfert faults with remarkable offsets (APAT, 2006a, 2006b; ISPRA, 2010; Figs. 1 and 2). Left strike-slip kinematics are observed in the study area along the VF, SF, and RF, while dextral strike-slip kinematics are noted along the RMF, CVF and CBF (Figs. 1 and 2).

d) Upper Pliocene–Quaternary extensional stage.In the Late Pliocene, after the late compressional pulses stage (Lower Pliocene), in the Upper Pliocene the axial sector of Apennine Chain was affected by high uplift and by NE-SW extensional processes, while the compressional domain migrated progressively toward NE (Malinverno & Ryan, 1986; Patacca *et alii*, 1990; Lavecchia *et alii*, 1995; Frepoli & Amato, 1997; Centamore & Rossi, 2009; Mantovani *et alii*, 2009; Vezzani *et alii*, 2010, a.r.t.).

The present-day extension/compression boundary is located along the Montagna del Morrone-Gran Sasso-Sibillini Mts-Mt. Fema Range-Upper Tiber Valley alignment (from SSE to NNW), obliquely cutting the respective main thrust fronts (Fig. 1).

The Late Pliocene-Quaternary structural network is represented by some fault systems (CAFS, *sensu*): Apennine trending (NW-SE), (NNW-SSE), anti-Apennine trending, transversal (NE-SW) or oblique structures (NNE/SSW) striking (Fig. 3), and subordinately ESE-WNW (Figs. 1 and 2). Some of these structures are of new formation, while a great part reactivated pre-existing elements, inherited from the former tectonic structures characterized by polyphase activity and several tectonic inversion processes. In particular, the most important negative inversion processes occurred on the main SW-dipping thrust planes, while segments of the former NE-SW/NNE-SSW transversal/oblique tear/transfert faults reactivated as normal/transtensive faults (Figs.1 and 2).

All these faults dislocated Pleistocene, and sometimes, Holocene continental deposits and Quaternary paleosurfaces; furthermore, they controlled the evolution of the present-day hydrographic network and of the continental landscape.

A great part of them have been described by Calamita *et alii*,1997,1979, by Centamore *et alii*, (1979) and by Cello *et alii*, 1997; therefore they have been mapped on the n° 358, 359, 360, 368, 369 Geological Sheets, 1:50.000 Geological Map of Italy (CARG PROJECT) and described in Illustrative Notes (APAT, 2006a; 2006b; 2006c; 2006d; ISPRA, 2010; Centamore *et alii*, 2006a; 2006b; 2006c; 2006d; Centamore & Dramis, 2010).

The pre-existing compressional edifice is subdivided by these faults into a set of blocks, characterized by differential vertical movements; in this context, several intermountain depressions formed and were filled by continental deposits. The more ancient of these basins, arranged in a series of sub-parallel/ NNW-SSE striking belts, opened since Late –Pliocene in the more internal Apennine Sector. The opening of these basins migrated progressively NE–wards during the Early Pleistocene: the Leonessa-Cagnano Aminterno-Scoppito-Campo Felice-Fucino p.p. Belt; the Gubbio-Nocera Umbra-Cascia-Terzone-Pizzoli-Roio Plain-Fucino p.p. Belt; the Colfiorito-Norcia-Cittareale-Monterale-Middle Aterno Valley Belt. The more recent depressions (Sulmona- Campo Imperatore-Campotosto-Amatrice-Castelluccio-Gualdo Tadino Belt) are located directly to the SW of the extension/compression boundary (Fig. 1).

The development of these depressions has been strongly controlled by the activity of three main fault system: the NNW-SSE and the NE-SW/NNE-SSW Fault Systems. The NNW-SSE Main Fault System is the major regional system, arranged in several sheaves of faults, extending for about a hundred km, widening or narrowing. It presents changes in the strike,from

NNW-SSE to NW-SE to N-S and in opposite high-angle plane dipping, NNE or SSW (*sensu*, Kraus *et alii*, 2009).

For Cello *et alii* (1997,19987) this main faults system of (CAFS) represents an immature flower structure, indicative of a deep-seated shear-zone, while for Kraus *et alii* (2009) it constitutes a pop-up structure. Minor WNW-ESE trendig faults are joined to the main NNW-SSE System Faults as releasing faults.

The geometry, kinematics and deformation rates of some structures of the CAFS have been investigated in the past by Faccenna *et alii* (1993), Bosi *et alii* (1994), Salvi & Nardi (1995), Pantosti *et alii* (1996), Morewood & Roberts (2000), Tondi (2000), Tondi *et alii* (1997), and Kraus *et alii* (2009). They recognized a Quaternary polyphasic activity, evidenced by the superimposition in different times of different kinematics, from sinistral strike-slip to oblique slip to normal.

A remarkable left strike-slip event along the NNW-SSE Main Fault System occurred in the first stages of the Middle Pleistocene, when the compressive structures have been dislocated with considerable offsets ;in this stage the more eastern intramontane depressions opened as pull-a-part basins (Cello *et alii*, 1997; Faccenna *et alii*,1997; Centamore & Nisio, 2002; Centamore *et alii*, 2009), volcanic apparatus of Intramontane Alkaline Province-IUP (Lavecchia & Stoppa, 1996), Colle Fabbri, Polino, Cupaello (Lavecchia *et alii*, 2006, a.r.t.) formed at the intersection among the NW-SE / NNW-SSE and the NNE-SSW main faults and a set of sinkholes opened in S.Vittorino Plain (Faccenna *et alii*,1997; Centamore *et alii*, 2009).

In the more recent times only moderate left-oblique slip or normal kinematics developed, often superimposed each other (Cello *et alii*, 1997, 1998; Faccenna *et alii*, 1997; Kraus *et alii*, 2009).

The main Quaternary structure of the study area has been identified between Celano and Cittareale (CCFS) and extends for more than 70-75 km in a NNW-SSE trend; it is arranged in several sheaves of faults, often widening or narrowing. This structure running through the Aterno Valley (Fig. 2) divides the area into two domains characterized by different Quaternary tectonic patterns: a W-Domain and an E-Domain. The Celano-Cittareale Fault System (CCFS) is formed by three main, nearly parallel, branches: the Tornimparte-Scoppito Fault (TS), the Ovindoli-Marana Fault (OM) and the Rocca di Cambio-Cittareale Fault (RC) and by minor vicariant structures arranged in en-echelon segments (Fig. 2); other minor WNW-ESE striking structures are joined with this main fault system.

It is to be noted that in this study the CCFS has been identified for the first time as a unique structure with clearly defined role, extension, and geometric and kinematic characteristics. Formerly many faults or fault segments of the CCFS were long

Fig. 3 - Upper Pleistocene continental deposits offset by NE-SW trending SFS Fault System near San Vittorino (see Fig. 2 for location)

ago identified, mapped, described and investigated by previous authors. The OM branch fault, which includes the Ovindoli-Pezza Fault (Cinti *et alii*, 1992; D'Addezio *et alii*, 1995; Pantosti *et alii*, 1996) or the Celano–L'Aquila Fault (Salvi & Nardi, 1995; Salvi *et alii*, 2003), is the main structural element of the CCFS (Fig. 2). It crosses the study area from Ovindoli to Marana northward with a curvy trend; the fault surface is marked by a change of dip. From Ovindoli to Casamaina it exhibits a NNW-SSE trend, with a high-angle plane. Left-transtensive kinematics (pitch 50°-60°) have been recognized by Beccacini *et alii* (1992), Giraudi & Frezzotti (1995), Calamita *et alii* (1997) and by Morewood & Roberts (2000) near Ovindoli and Vado di Pezza; Cello *et alii* (1997, 1998) recognized in the same area left-lateral strike-slip motions, while Morewood & Roberts (2000) also pointed out dip-slip kinematics near Ovindoli, Vado di Pezza, and Mt. Cefalone. Along this segment, the OM offsets Quaternary deposits and former compressive structures; in Vado di Pezza-Ovindoli Salvi & Nardi (1995), and Pantosti *et alii* (1996, a.r.t.) recognized coseismic effects in recent deposits, associated with historical earthquakes; for Salvi *et alii* (2003), the OM branch is the deep seismogenic source of those earthquakes, causing coseismic effects. From Casamaina to Lucoli the OM is characterized by a high-angle fault plane. Northwest of Lucoli the fault plane changes the strike, from NW-SE to NNW-SSE, N-S, with a 70°NE dipping. The kinematics indicators show several polarity changes along the strike: sinistral strike-slip (pitch 10°), sinistral-oblique-slip (pitch 50°-60°) and dip-slip (pitch 70°-90°), but it is difficult to recognize the chronological relationships among them (Bigi *et alii*, 1995a; 1995b; Centamore *et alii*, 2006a; APAT, 2006a; ISPRA, 2010). Near Pagliare the 70°NE- dipping fault plane changes the strike, from NW-SE to NNW-SSE, N-S. From Pagliare to S. Vittorino the OM crosses the Preturo-S. Vittorino Plain deposits; this plain has been filled by Upper Pliocene-Quaternary continental deposits that hidden the OM, but its recent activity is highlighted by a remarkable N-S striking step in the Holocene deposits near Preturo airport (ISPRA, 2010). In the Upper Aterno Valley, OM is located along the Aterno River and extends northwestwards as far the Velino Valley and over (Figs. 1 and 2). The Quaternary activity of this high-angle northern segment (near Barete-Marana) of the OM is recorded by the faulting of slope deposits (Bagnaia *et alii*, 1996) and of Lower to Upper Pleistocene continental deposits (Blumetti, 1995; Galadini & Galli, 2000). Furthermore, Galadini (1999) recognized extensional kinematics with dip-slip or oblique left indicators.

The Tornimparte-Scoppito Fault (TS) and the Rocca di Cambio-Cittareale Fault (RC) are two other important faults branches of the CCFS. These two faults show the same structural characteristics of the OM, namely the same snake geometry and polyphasic activity, the same regional continuity, the offsetting of both former compressive structures and the Late Pliocene-Quaternary deposits of Scoppito-L'Aquila depressions (APAT, 2006a; ISPRA, 2010). The northern segment of the TS offsets the Lower Pleistocene deposits of the Scoppito basin (ISPRA, 2010), while the northern segment of the RC offsets the former compressive structures near Coppito and older Pleistocene conoids near S. Vittorino (APAT, 2006a; ISPRA, 2010); furthermore, along the SW side of Castello Ridge, it presents a high-angle fault plane, with change in dip from NE to SW, and it offsets the Upper Pleistocene continental deposits near Castello (Galadini & Galli, 2003) and the Lower Pleistocene paleosurfaces between Montereale and Cittareale (Cacciuni *et alii*, 1995). The RC and TS are joined to the main fault OM (Fig. 2) by secondary elements: the Mt. Orsello and the Piano di Pezza faults, between TS and OM and the Mt. d'Ocre fault, between RC and OM. These have a NW-SE to a WNW-ESE strike, a high dip angle and mainly dip-slip indicators (APAT, 2006a; ISPRA, 2010).

Summarizing, the main faults of the CCFS are set up in dextral en-echelon segments, joined by vicariant structures. The CCFS structures change the strike from NNW-SSE to NW-SE and on to N-S (snake-geometry, *sensu* Kraus *et alii*, 2009) and in opposite high-angle fault plane dipping (NNE or SSW) (Fig. 1). The geometrical, kinematics and evolutionary characteristics of the CCFS are indicative of an important polyphasic and polykinematic brittle-shear zone structure, in which left strike-slip, left transtensive and dip slip motions have been recorded in different Quaternary stages and in different parts. As discussed previously this structure divides the investigated area into two different structural domains. In the W-Domain, the post-orogenic structures, superimposed on the compressional thrust-belt edifice, are represented by a discontinuous set of NNW-SSE to NW-SE striking Quaternary normal faults, mainly SW-dipping, and by several transversal fault segments.

The E-Domain is characterized by numerous and continuous sets of NW/SE to ENE-WSW striking Quaternary normal faults, mainly SW-dipping. These faults are often organized in an en-echelon pattern and locally interrupted and/or deformed by NE-SW transversal faults. The E-Domain is split by some transversal normal/trastensive faults, reactivating the former tear/transfert structures (TFS, MFS, VF, SFS, RF and RMF) in six main sectors. From north, they are the Amatrice-Cittareale, Mt. Gorzano-Mt. Marine, Mt. S. Franco-Arischia, Gran Sasso-Mt. Pettino, Campo Imperatore-Middle Aterno Valley and Navelli-Fontecchio (Figs. 1 and 2). These faults delimit sectors characterized by different structural trends of the quaternary normal faults (NW-SE, NNW-SSE, WNW-ESE); the sectors are subdivided into minor blocks, arranged in a general SW-collapsing staircase pattern. Often these normal faults cut the upper thrusts and root in the deeper ones (Bigi *et alii*, 1995a, 1995b); they may be former thrusts, reactivated during Late Pliocene-Quaternary times in a negative sense (Bigi *et alii*, 1995a, 1995b; Centamore *et alii*, 2002, 2009). A great part of these faults, mainly SW-dipping and some kilometers long, shows an intense Late Pliocene-Quaternary activity (Fig. 2); many authors regard them as seimogenic sources (Bagnaia *et alii*, 1992; Barchi *et alii*, 2000; Bertini & Bosi, 1993; Blumetti, 1995; Boncio *et alii*, 2004a, 2004b; Bosi, 1975; Bosi & Bertini, 1970; Calamita & Pizzi, 1994; Cello *et alii*, 1997, 1998; Tondi *et alii*, 1997; Cinti *et alii*, 2004, 2011; Frepoli & Amato, 1997; Galadini *et alii*, 2000, 2003a; Galli *et alii*, 2002, 2008; ITHACA Working Group, 2000; Lavecchia *et alii*, 1994, 2002; Morewood & Roberts, 2000; Moro *et alii*, 2002; Pace *et alii*, 2002, 2006; Pantosti *et alii*, 1996; Roberts & Michetti, 2004; Tondi, 2000; Valensise & Pantosti, 2001; Vezzani & Ghisetti, 1998).

In particular, in the Amatrice-Cittareale and Mt. Gorzano-Mt. Marine Sectors, separated by the MF Fault, the NW-SE striking minor blocks are bounded by three NW-SE active normal faults: the Mt. Gorzano Fault (GF), the Capitignano Fault (CAF), and the Mt. Pizzoli-Barete Fault (PBF) (Fig. 2). The Mt. Gorzano Fault, bounding at the NE two intermountain basins, Campotosto and Amatrice (Figs. 1 and 2), is composed of a narrow belt of sub-parallel, high-angle, SSW-dipping normal faults. It presents dip-slip indicators and offset Lower to Late Pleistocene deposits (Bachetti *et alii*, 1990; Blumetti *et alii*, 1993; Cacciuni *et alii*, 1995), while evidence of Holocene activity has been recognized by Galadini & Galli (2000, 2003) and by Boncio *et alii* (2004). The Capitignano Fault bounds the NE edge of Capitignano-Montereale Plain (Figs. 1 and 2) and is composed of a narrow bundle of high-angle SSW-dipping normal faults; they present dip-slip kinematics, and offset Lower Pleistocene paleolandslide deposits, several Upper Pleistocene alluvial cones and the Lower Pleistocene paleosurface near Montereale (Cacciuni *et alii*, 1995; Galadini & Galli, 2000). The Pizzoli-Barete Fault, dissecteding Lower to Upper Pleistocene continental deposits (Blumetti *et alii*, 1993; Galadini & Galli, 2000) shows a high-angle SW-dipping plane, and extensional kinematics with dip-slip or oblique left indicators.

In the Mt. S. Franco-Arischia Sector, bounded by the VF and SF Faults, the Quaternary faults have a mainly WNW-ESE trend; it is subdivided into strongly fractured blocks that are bounded at their SW side by the Mt. S. Franco and the Arischia Faults. The Mt. S. Franco Fault has SSW-dipping fault planes with listric geometry, while the Arischia Fault presents a high-angle plane. Both these faults show intense Quaternary extensional dip-slip activity, offsetting Lower to Upper Pleistocene deposits; furthermore, effects of seismic events (29.690 B.P. and 1703) have been recognized (Bagnaia *et alii*, 1992; 1996; Blumetti, 1995).

In the Gran Sasso-Mt. Pettino sector, delimited by the transversal SFS and RF Faults, the Quaternary faults have a prevalent WNW-ESE trend. This sector is subdivided into several minor blocks delimited by SSW-dipping normal faults: the Gran Sasso (GSF), Assergi (AF), Mt. Stabiata (STF), Collebrincioni (COF) and Mt. Pettino Faults (PEF). The Mt. Pettino Fault, which bounds the SW side of Mt. Pettino, presents a change of trend from NW-SE in the northern segment to E-W in the southeastern one. All these faults show Quaternary activity with extensional dip-slip and sometimes oblique-slip kinematics; they dislocate the Lower Pleistocene paleosurfaces and the Lower to Upper Pleistocene Holocene deposits (APAT, 2006a; Bagnaia *et alii*, 1996; Blumetti, 1995; Blumetti *et alii*, 1993, 2000, 2009, 2010; Blumetti & Guerrieri, 2007; Boncio *et alii*, 2004a, 2010; EMERGEO Group, 2009, 2010; Falcucci *et alii*, 2009, 2011, 2014, 2015; Galadini *et alii*, 2003a, b; Galadini & Galli, 2000, 2003; Galli *et alii*, 2002, 2008, 2009, 2010, 2011; Giraudi & Frezzotti, 1995; Guerrieri *et alii*, 2009, 2010; Lavecchia *et alii*, 1994, 2002, 2010, 2012; Messina *et alii*, 2009a, b; Roberts *et alii*, 2010; Vezzani & Ghisetti, 1998; Vittori *et alii*, 2011).

The two southernmost sectors, Campo Imperatore-Middle Aterno Valley and Navelli-Fontecchio, are separated by the transversal RMF Fault; these two sectors are the widest and most complex structural sectors of the study area. Here the pattern of the fold-and-thrust compressional structure has been quite obliterated by the postorogenic extensional tectonics. These sectors are dislocated by numerous Late Pliocene-Quaternary normal faults that are SW and NE dipping and arranged overall in a SW-collapsing staircase pattern, forming horst-graben systems (Figs. 1 and 2). The northeastern sides of these structures are bounded by SW-dipping, high-angle normal fault systems whose segments at some point cut the eastern N-S trending lateral ramp of the Gran Sasso Thrust (Fig. 1); according to Centamore *et alii* (1992), these may reactivate former thrusts in negative inversion. In the Campo Imperatore-Middle Aterno Valley sector many normal faults, mainly SW-dipping, showing a long Quaternary activity, have been recognized (Figs. 1 and 2). The Campo Imperatore Fault System bounds the SW side of the Mt. Prena Range and presents SW dip, extensional kinematics, mainly dip-slip and dextral oblique (Calamita *et alii*, 2000b). They offset Upper Pleistocene-Holocene deposits, in which coseismic effects of prehistoric and historical earthquakes have been recognized (Giraudi & Frezzotti, 1995; Galadini & Galli, 2000; Galadini *et alii*, 2003). The Scindarella Fault System is characterized by NW-SE trending and SW/NE dipping fault planes. The main active structures of this system are the Scindarella and Mt. Bolza segments. Their SW-dipping planes show extensional kinematics, with dip-slip or left transtensive movements; they dislocated paleosurfaces and Lower and Upper Pleistocene/Holocene deposits (Bigi *et alii*, 1995a; 1995b). The Cima Faiete-Castel del Monte and S. Stefano di Sessanio Faults are arranged in a synthetic/anthitetic fault network, trending 140° to 170° with dip-slip or left oblique striae; their active segment faults (Cima Faiete, Castel del Monte, Mt. Ruzza, S. Stefano di Sessanio, Camarda, Barisciano Faults) dislocated Lower/Upper Pleistocene deposits

(Bertini *et alii*, 1989; Bigi *et alii*, 1995a, b).

The Navelli-Fontecchio sector, delimited by the RMF and CBF transversal faults, is the southern sector of the study area. Here the Navelli Fault System (NFS) is also arranged in a synthetic/anthitetic fault network, NW-SE trending with a normal or left oblique component; their Quaternary activities are well documented (Bertini *et alii*, 1989; Bigi *et alii*, 1995a, b).

The Aterno Valley is located in the lower part of the staircase of the Campo Imperatore and Navelli sectors; it is divided by the Rocca di Mezzo Fault (RMF) into two minor blocks: the Tempera-S. Demetrio and the Fontecchio-Acciano blocks. The first is filled with a thick cover of Lower Pleistocene to Holocene deposits; the second is characterized by a set of NW-SE trending carbonatic ridges, bounded on both slopes by NE and SW dipping normal faults. The Villafranchian paleosurfaces and the Upper Pleistocene deposits of the second block are affected by a gentle NE tilting (Di Bucci *et alii*, 2011) while the Aterno River course was diverted towards the present day direction. These movements are linked to the Middle-Upper Pleistocene activity of the Barisciano Fault System. The main active faults of Aterno Valley are the Paganica, Poggio Picenze, Prata d'Ansedonia, S. Demetrio de Vestini, Fontecchio, Bazzano, Fossa, and Villa S. Angelo Faults (Fig. 2). With the exception of the NW-SE trending/NE dipping Bazzano and Fossa faults, the others are SW dipping. Dip slip or sinistral oblique movements and displacements of paleosurfaces and of Lower Pleistocene to Holocene deposits have been recognized (APAT, 2006a, b; BOSI, 1975; BOSI & Bertini, 1970; Bagnaia *et alii*, 1992; Bertini & BOSI, 1993; Bertini *et alii*, 1989; Centamore *et alii*, 2006a, b; Galadini & Giuliani, 1991; Ghisetti & Vezzani, 1999). The present-day Upper-Middle Aterno Valley is superimposed on the wide Villafranchian lacustrine environment. After the Middle Pleistocene time, intense extensional tectonics dismembered the former depression, forming another set of smaller horst and graben systems.

In this Plio-Quaternary stage, transversal/oblique faults again played a remarkable role in building the morphostructural network of the study area. In fact, during the Late Pliocene-Quaternary extensional phase, they offset Late Pliocene to Pleistocene erosional/depositional surfaces and deposits (Fig. 3). Often the spatial continuity of these elements is hidden by Quaternary deposits and/or other NW-SE quaternary faults; moreover, geological and mainly morphological features evidenced their recent activity as triangular or trapezoidal facets, fresh scarp faults, anomalies of the hydographic-network, sinkholes aligments and deep-seated gravitational deformations, such as trenches and counterslope tilting of Quaternary deposits. In particular (APAT, 2006a): a) the SFS offsets the Lower-Upper Pleistocene alluvial deposits on the NW of S. Vittorino and delimits the Preturo Plain on the NW (Figs. 1 and 2); b) the RF and associated minor structures (not shown in Figs. 1 and 2), offset with remarkable throw the basal Villafranchian deposits of Coppito and L'Aquila Plain and even more the Quaternary deposits of Roio Plain; c) the RMF bounds the SW side of the Quaternary Paganica-Bazzano graben, and the sinkholes of Rocca di Mezzo Plain and associated karst apparatus of Stiffe caves formed on the Mt. d'Ocre range.

GEOLOGICAL AND SEISMIC SECTIONS

Only a few seismic sections of the study area are available (Fig. 1), mostly from the VIDEPI Project.

In Fig. 4b, 4c and 4d are shown the selected seismic profiles IT-89-01, 1-80-AZ-03 and 1-82-AZ-05. All these 2D seismic time (TWT) sections have been migrated so as to have the reflections near the real position and to facilitate comparison with the surface structures. For this pourpose we prepared a geological cross section along the same trace of the IT-89-01 seismic section (Fig. 4a) to compare the interpretation of the seismic section with the structural network derived from the surface geological data, recorded on the new maps on a scale of 1:50,000-1:10,000 of the Abruzzo-Lazio Regions (APAT, 2006a; 2006b; 2006c; 2006d; ISPRA, 2010).

In the extreme south-western side of the geological section (Fig. 4a), the Salto Valley Unit (SVU), arranged in an embricate–fan geometry, overrides on the Cicolano-WMarsica Unit (CMU, APAT, 2006c; Figs. 1 and 2). From Mt. Velino to Casamaina, the structural array of the CMU is represented by gentle folds dissected by a set of NNW-SSE trending normal faults. The most important of these are the Mt. Velino Fault (VEF), the Tornimparte-Scoppito Fault (TS), and the Ovindoli-Marana Fault (OM) (Figs. 1 and 2). The TS and OM belong to the Celano-Cittareale Fault System (CCFS). In the Casamaina-Roio Plain sectors, the CMU is also cut by another element of the CCFS, the Cittareale-Rocca di Cambio Fault (CR, Figs. 1 and 2). Further eastward of the latter structure, the CMU is arranged in a complex embricate-fan geometry (the Mts d'Ocre Thrust system) overridden on GMU (Figs. 1 and 2). Between Mt. D'Ocre and Fossa village, two high-angle NE-dipping normal faults further dislocate the Mt. Giano-Montagna Grande Unit (GMU). From Fossa to Poggio Picenze, the thick Quaternary cover does not make it possible to recognize the structural features of this sector, but one can suppose that the outcrop of Miocene carbonate rocks belonging to the GMU lies under continental cover. The GMU extends until it comes into sharp contact with the Accumoli-Mt. Genzana Unit (AGU) along the Cima Faiete–Castel del Monte Fault System, which is a former thrust reactivated as a normal fault during the more recent extensional phase. GMU and AGU are largely overridden out-of-sequence on the Montagna dei Fiori–Montagnone–Montagna del Morrone Unit (MMU, Fig. 1). The MMU is the lower unit of the study area; in this unit, as well, tectonic subunits separated by minor thrusts have been recognized.

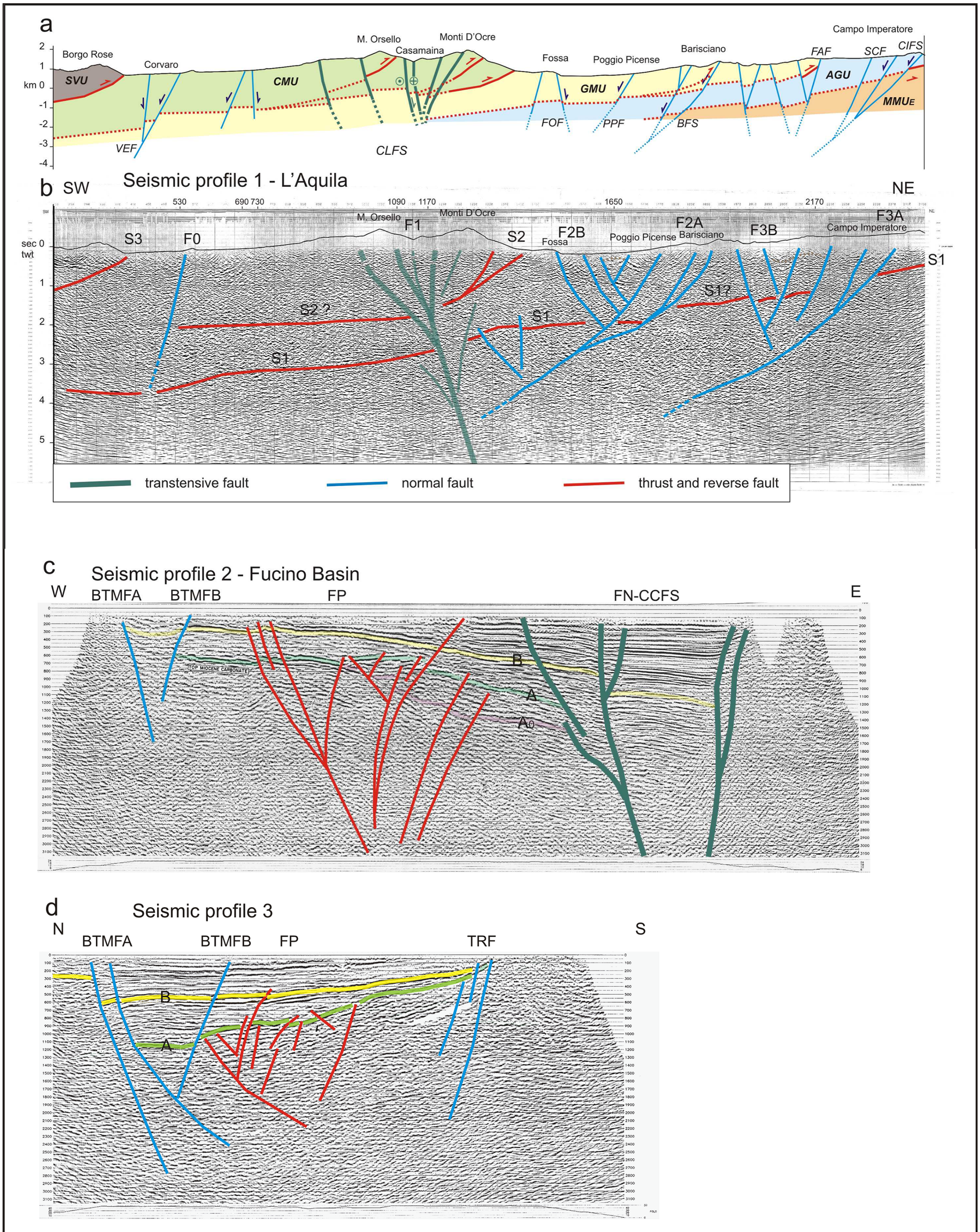

Fig. 4 - a) Geological cross-section across the study area; b) NE-SW seismic profile IT 89-01: (The geological cross-section is drawn along the same trace of the seismic profile); c) 1-80-AZ-03 E-W seismic profile in the Fucino Plain; d) 1-82-AZ-05 N-S seismic profile in the Fucino Plain. Explanations of acronyms in the text

The seismic section IT-89-01 is the key element because it crosses the whole central area affected by the 2009 L'Aquila seismic sequence (Figs.1, 2, 4b and 5). It trends NE-SW and is orthogonal to the main structural lineaments so it is possible to recognize the real subsurface structural pattern and to distinguish the structures involved in the 2009 L'Aquila seismic sequence. Low angle compressive structures (S1, S2, and S3), all NE-vergent and SW-dipping, and extensional structures (F0, F1, F2, F3) have been recognized. Among the low angle compressive structures, the most evident is the S1. This structure is characterized by well organized and continuous reflections together with evident angular unconformities (from 730 to 1090 shot points, hereafter s.p., around 3 sec TWT depths). The most continuous reflection corresponds to a thrust fault plane, while the unconformal reflections highlight different lithostratigraphic horizons inside the overridden units or minor and antithetic thrust fault planes. To the SW (from s.p. 690), the S1 plane deepens through a ramp till 3.7 sec depth. The front of the S1 structure is external to the NE boundary of the seismic section.

The S2 is an embricated-fan thrust with two main fault planes. The easternmost is low-angle while the westernmost is high-angle; they join at 1.2 sec depth. From s.p. 1090 to 530, at around 2 sec depth, there is a low angle continuous and wavy horizon with some angular unconformities, the latter being interpreted here as the SW extension of S2, although it may possibly be another thrust plane. At s.p. 530, the horizon S2 is offset by a SW-dipping high angle normal fault (F0). The S3 thrust front consists of a single low-angle fault.

The F1 structure (Fig. 4b) is a NE-dipping high angle fault system which reaches great depths (>4.5 sec) and offsets the S1 and S2 planes. The upper part of this structure consists of several branches, high and lower angle NE (mainly) and SW-dipping, joining at < 2.5/3 sec TWT; the lower part, below 3 sec, consists of one (or two sub-parallel) high angle, NE-dipping fault plane(s). In the deeper part, between F1 and F2A, there is an especially complex zone with several local faults that are NE and SW-dipping; these faults are compressive and slightly offset the S1 but not the F2A lower fault plane. F1 is a flower structure and the main structure of the seismic section, as it divides the seismic section into two very structurally different sectors: the NE sector and the SW one.

The NE sector is characterized by several NE and SW-dipping low and high angle normal faults, which in some cases can be recognized up to the surface horizons of the seismic section. Within this sector, there are two main fault systems, F2A and F3A, which are SW-dipping and reach considerable depths (about 4 sec TWT; 9/10 km b.s.l.). The dip plane of these two fault systems becomes less steep with increasing depth. Furthermore, the faults show wavy and ramp-flat geometries (in particular F3A), but overall they have a dip angle of 45°. The antithetic, NE-dipping faults (F2B, F3B) are stopped at the intersection with the F2A and F3A main fault planes. This tectonic framework is in agreement with that identified in the superficial part of the Paganica sub-basin through seismic tomography by Improta *et alii* (2012). The SW sector shows a structural setting less disjointed than the NE one. Only a normal, high-angle, SW-dipping fault (F0) is identified on the seismic section. Outside this fault, the S2 and S1 thrust planes are continuous or not significantly displaced.

The other important seismic sections are 1-80-AZ-03 and 1-82-AZ-05, which cross the Fucino Plain approximately in E-W and N-S directions (Figs. 1, 4c and 4d). These sections made it possible, inter alia, for us to verify the continuity to the south of some structures identified on the northern IT-89-01 seismic section.

A very concise representation of the Upper Pliocene-Quaternary structural framework of the Fucino Plain is shown in Fig. 1. Also, we re-interpreted the VIDEPI seismic sections 1-82-AZ-02, 1-80-AZ-04, 1-80-AZ-06, 1-80-AZ-10, AQ 319-85-V (Fucino area) and RI-315-85, RI-313-84V, CAM-3-84, CAM-2-84, CAM-5-84, and CPT-1-84 (Lake Campotosto/Cittareale areas) to examine the local details of some faults.

Seismic section 1-80-AZ-03 (Fig. 4c) which crosses the median sector of the Fucino Plain E-W, presents some well-structured and continual reflections, such as the horizons A and B (except the two ends). The N-S seismic section 1-82-AZ-05 (Fig. 4d) crosses the eastern sector of the Plain and intercepts the previous seismic section.

In the upper part of the recording of both seismic sections, there are two more evident seismic reflections that separate intervals with different characteristics. The lowest, A, an erosional surface, in agreement with Cavinato *et alii* (2002), is extensively involved in the tectonic evolution of the area and deepens considerably to E, where it ceases to be recognizable. Horizon A was identified by VIDEPI as the top Miocene carbonates. According to our study, horizon A formed as a result of an erosional process that developed in this sector in the Upper Messinian (see Geological Setting). The probable boundary between carbonates and Miocene terrigenous deposits is marked by A0.

Horizon B marks the transition between a lower depositional sequence that is somewhat irregular, discontinuous, sometimes lenticular, and coarsely structured, and an upper depositional sequence that is more regular and homogeneous. The lower sequence is strongly influenced by the faults of the FP flower structure; W and E of FP, the lower sequence tends to become a little more regular and continuous. Above horizon B there is a series of generally well structured and roughly parallel seismic horizons belonging to a sedimentary sequence of lacustrine, fluvial-lacustrine and detrital deposits (Cavinato *et alii*, 2002). In more detail in particular, two seismic reflections above the B erosion surface appear to be a discontinuous sedimentary succession (pinch out towards W and maybe towards S) whereas

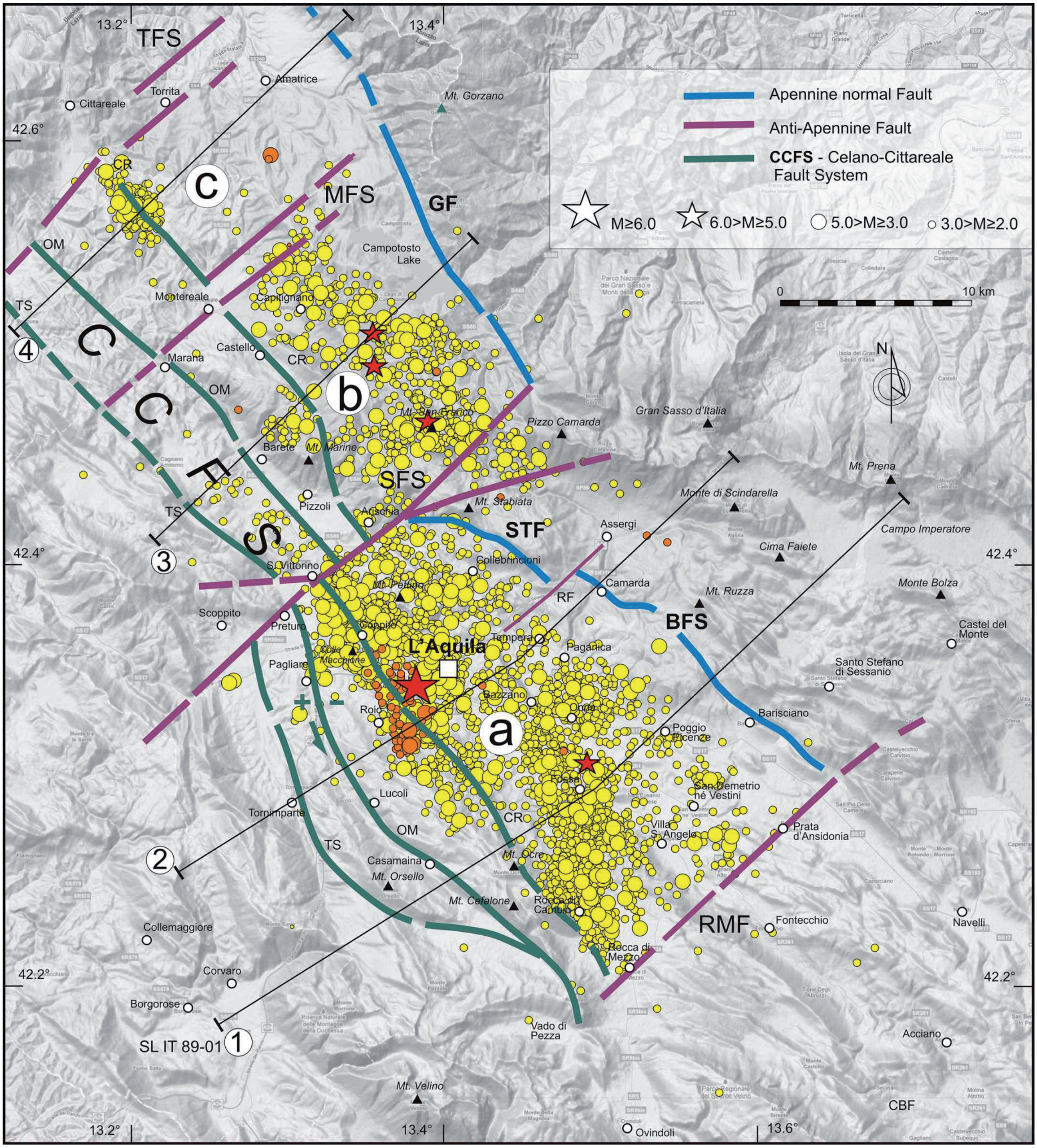

Fig. 5 - Map of M≥2 epicentres of 2009 L'Aquila seismic sequence (ISIDE Data base, INGV). Yellow: aftershocks epicentres (April 06th - September 30th, 2009); orange: foreshock epicentres October 01st, 2008 – April 05th, 2009). a, b and c seismic boxes. 1, 2, 3 and 4 traces of the structural-seismological cross-sections of Fig. 8. Main faults delimiting the seismic boxes

the reflection immediately above B is continuous and parallel to B. The whole sequence above B dips and thickens towards the E (where its bottom reaches about 1200 milliseconds/~ 1000 m depth) and N (where its bottom reaches about 600 milliseconds/~ 500 m depth). The first two seismic reflections above B, being similar and parallel, indicate a regular sedimentation in a flat basin, while the upper pinch out sedimentation shows the, progressive and consistent lowering to E and N of the same basin.

In seismic section 1-80-AZ-03, three groups of tectonic structures can be identified:

- to the west, just a small graben, whose faults displace the seismic horizons A and B;
- in the central part, a highly branched structure with mostly high-angle, W- and E-dipping reverse faults (positive flower structure, hereinafter FP) that offset widely, albeit with minimal offsets, horizon A and, only locally, horizon B (a quite similar interpretation of this structure is also found in the original VIDEPI seismic section);
- in the eastern part, a very branched structure with high-angle W- and E-dipping normal or transtensive faults (negative flower structure with the two main branches joining at just under 3 sec TWT, hereinafter FN), that cut the seismic horizons A and B with very evident offsets.

Some faults of all these structures displace or deform the most superficial reflections of the seismic recording.

Seismic section 1-82-AZ-05 crosses the Fucino Plain in an approximately N-S direction. To the north there is a system of normal or transtensive faults (hereinafter BTMF), consisting of mainly S-dipping faults (with the exception of a N-dipping antithetic fault characterized by minimal but very evident vertical displacement) that dislocated the seismic horizons A and B (displacement 300 msec, 150/200m) and virtually the entire sedimentary sequence, including the most recent horizons and shallow reflections. At the center there is a deep structure (FP) consisting of S- and N-dipping high to medium angle reverse faults that cut the seismic horizon A broadly (with offsets of a few tens of meters) and the seismic horizon B only marginally. To the south, there is a system of N-dipping normal or transtensive faults (TRF) that cuts the seismic horizons A and B, with displacement of a few tens of meters. At the FN, BTMF and TRF structures, the whole sedimentary sequence over B as well as the underlying one is strongly displaced by the main normal faults, whereas at the FP structure it is only locally affected by faults with weak vertical offsets. Between the two main E- and W-dipping faults of the FN structure (FNa and FNb), the sedimentary sequence over B is thicker; it differs from the one immediately to the west because of its alternation of very regular and thin sedimentary layers (probably fine grain size lacustrine) with other more irregular and perhaps coarse species in its medium-low part; this area corresponds to the central-east part of the so-called "Bacinetto". There is also a slight tilting toward E of this sequence part.

The FP structure is older than the FN, BTMF and TRF ones. Indeed, in FP some faults are sealed from the horizon B and just the main ones offset it with very low displacements. Instead, in FN, BTMF and TRF the fault planes can be seen up to the shallow horizons of the seismic section, also with significant vertical displacements (about 200/300 m). The vertical displacements of the FP faults, both in correspondence with the horizons A and B, are small (<25/30 m) probably because they belong to a predominantly transcurrent structure.

The comparison between the geological cross-section and the seismic sections shows the following corrispondences (Figs 1, 2 and 4): starting from the SW side of the geological cross-section (Fig. 4a), the Salto Valley Unit (SVU) overrides onto the Cicolano-Marsica Unit (CMU); the thrust plane corresponds to S3 of the seismic section (Fig. 4b); the Mt. Velino Fault (VEF) corresponds to F0. Regarding the areas between Corvaro (Mt. Velino) and Mt. Orsello, a correspondence in the seismic section has not been identified for the SW and NE-dipping normal faults and the minor Mt. Orsello thrust of the geological section (Fig. 4b), because of their limited length, depth and very low offsets. Further NE, the TS, OM and CR faults of the geological cross-section correspond to the three main branches of the CCFS. TS, OM and CR merge in the depth into a single, high-angle, NE-dipping, deep seated flower structure of Fig 4b. At the NE of the Monti d'Ocre Range, the embricate-fan Mt. d'Ocre Thrust corresponds to S2. In the Middle Aterno Valley, the NE-dipping normal fault (FOF) of the geological cross-section belongs to anthitetic faults (F2B) of the F2 Fault System. The SW-dipping main fault of the F2A system corresponds to the western structure of the Barisciano structural high (BFS)(Figs 2, 4a and 4b). The SW and NE dipping normal faults of the Campo Imperatore sector belong to the F3 Fault System; in particular, the main fault of F3A corresponds to the Campo Imperatore Fault System (CIFS). In the more eastern part of the geological cross-section, the AGU overrides the MMUE by the low-angle, SW-dipping plane of the Gran Sasso thrust, which could be in correspondence with the S1 plane of Fig. 4b.

Finally it is to be emphasized that the two structural sectors mentioned in the description of the seismic section IT-89-01 correspond to the W and E-Domains, divided by CCFS, described in the chapter "Geological setting".

The Fucino Plain, about 30 Km south of the town of L'Aquila, is filled with loose, upper Pliocene-Quaternary continental deposits (Fig. 1); therefore, the correlation with the outcropping structures is not direct as in the previous case, but requires a more detailed description. On the Fucino Plain subsurface, some important tectonic structures and two erosion surfaces, respectively referable to an event at the pre-beginning of Apennine deformation (A) and to a post-compressional phase (B), have been recognized. On the basis of geological knowledge and the evolution of the area, the

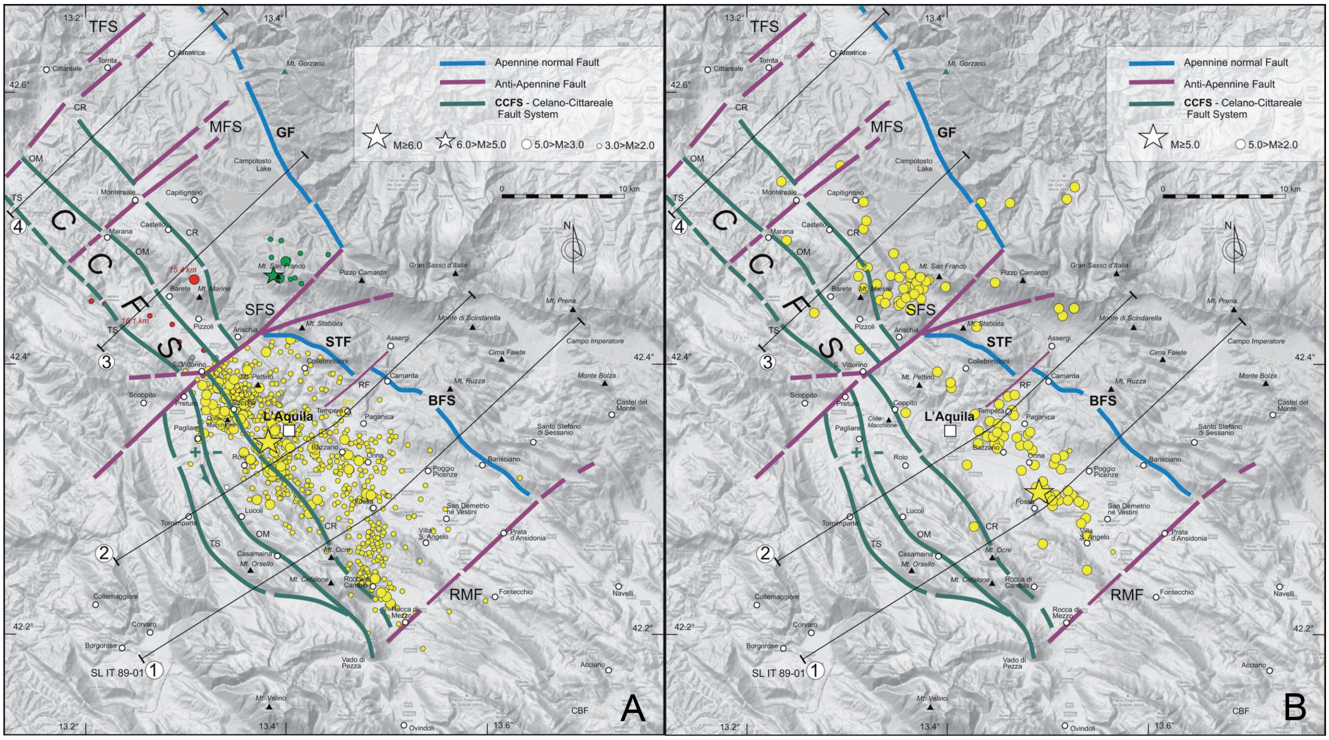

Fig. 6 - A) Map of M≥2 earthquake epicentres of the 2009 L'Aquila seismic sequence occurred in the first day (April 06th, 2009): yellow dots – Southern seismic box (a); red and green dots - Intermediate seismic box (b); grey - uncertain attribution (for more details see text).
B) map of M≥2 deep (>12 km) earthquake epicentres of 2009 L'Aquila seismic sequence occurred since September 30th

A surface is younger than the Salinity Crisis (Sequence M2, early Upper Messinian; Centamore & Rossi, 2009) and the B surface is early Upper Pliocene (Cavinato *et alii*, 2002; Centamore & Dramis, 2010, a.r.t.). Two groups of structures have also been identified: the more recent one consists of transtensive faults (FN negative flower) that widely and diffusely displace the B surface; the older one consists of compressive or strike-slip faults (FP positive flower) largely sealed from the B surface. The main faults in the first group, develop all along the eastern edge of the Plain and are the continuation of the CCFS system. They are high-angle, NE- and SW-dipping, normal or transtensive faults with remarkable Quaternary activity. Parts of these faults on the surface are known in the eastern Fucino Plain as the San Benedetto-Gioia de' Marsi Fault (Galadini *et alii*, 1997; Ciotoli *et alii*, 1998), the Parasano and Serrone faults (Piccardi *et alii*, 1999) or the Parasano-Cerchio Fault (Lavecchia & Boncio, 2006). The main buried faults have clear morphostructural evidence and are visible in the ASTER images; also at the FN main faults, on the surface, widespread and important coseismic effects occurred during the 1915 earthquake (Oddone, 1915; Giraudi, 1988; SERVA *et alii*, 1986; Galadini *et alii*, 1997; Michetti *et alii*, 1996).

Another important system of the first group consists of ENE-WSW trending buried faults (BTMF, Buried Tre Monti Fault) that cross the Plain approximately in its central-northern edge, up to where they are interrupted to the east against FN. It consists of two high-angle, SE-dipping (main) and NW-dipping (antithetic) normal or transtensive faults. Also this fault system shows remarkable Quaternary activity. BTMF represent the southernmost part of the staircase fault system known in the literature as the Tre Monti Fault (368, Avezzano Geological sheet-APAT, 2006c), which is the western prolongation of the Celano-Bussi Fault (CBF-Centamore *et alii*, 2002) or a segment of the Avezzano-Bussi Fault (Ghisetti & Vezzani, 1999). Other normal or transtensive Quaternary faults are present at the western and southern edges of the Plain, and are, respectively, E- and N-dipping (Figs. 1 and 4c-d).

In the light of these considerations, the Fucino depression began structuring in the late Upper Pliocene-early Lower Pleistocene, when the central Apennines began to be affected by extensional and regional uplift processes (Dramis, 1993; Cavinato *et alii*, 2002; Centamore & Nisio, 2003; Centamore & Rossi, 2009).

SEISMOTECTONIC

The L'Aquila seismic sequence developed from October 2008 (Pondrelli *et alii*, 2010) through all of 2009 and afterwards. This study focuses on the sequence up to September 30th, 2009 (Figs. 5 and 6), which according to the data reported by Chiaraluce *et*

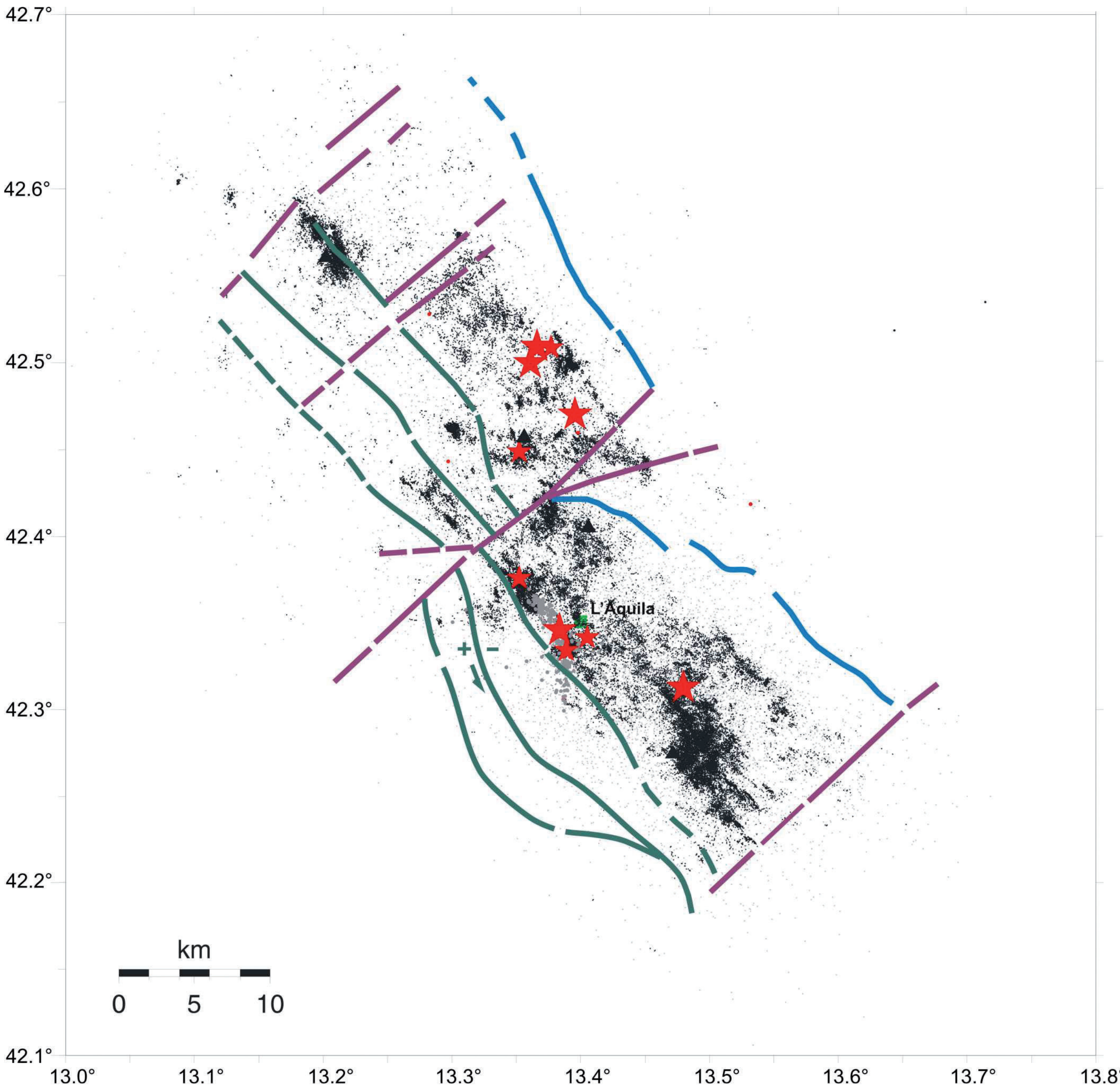

Fig. 7 - Map of the L'Aquila entire seismic sequence showing a seismological dataset of 64k moderate magnitude earthquakes (redrawn and modified after VALOROSO *et alii, 2013)*

alii (2011b) can be considered significant because of the number and energy of the seismic events. In this period, there were just over 3,200 earthquakes of M=>2, 75 of which were foreshocks (M_{max}=3.9), while the rest were aftershocks (including the 4/6/2009 main shock of M_W=6.1).

The specific seismic characteristics of this sequence have been discussed extensively by several authors, with special effort to identify the fault plane geometry of seismogenic structures (CHIARABBA *et alii*, 2009; CHIARALUCE *et alii*, 2011a; 2011b; VALOROSO *et alii*, 2013; Fig. 7); these authors have sought to identify seismogenic faults on the basis of the plot in depth of a large amount of hypocenters of earthquakes of any magnitude and time. This method can generate ambiguities in the correlations. In fact, without any tectonic reference structure, different clusters of hypocenters have been joined by creating a presumed and fictitious fault plane. In this way, in some cases not real or only partially real fracture planes have been delineated, while in other cases seismogenic fault planes, less obvious but more important, have been underestimated or unidentified. Scognamiglio *et alii* (2010); Pondrelli *et alii* (2010) and Hermann *et alii* (2011) plotted on map an amount of focal mechanisms: this representation does not provide any information on location, arrangement and geometry of seismogenic faults and gives only a generic detail on their kinematics.

This work proposes a different approach, seeking to correlate the space-time evolution of the 2009 L'Aquila seismic sequence with the Quaternary faults identified by the geological and structural surface and subsurface reconstructions. Therefore, this work focus mainly on some characteristics of the 2009 L'Aquila seismic sequence that have not been analyzed to date, but that serve for the correlation of the active tectonic structures of the area and its seismogenic evolution.

The seismic sequence epicenters were located in a well-defined and NNW-SSE/NW-SE trending area between Rocca di Mezzo (to the south) and Cittareale (to the north) (Fig. 5). The majority of the foreshocks occurred in a small elliptical area (NW-SE trending and W to L'Aquila) less than 10 km from the town of L'Aquila (Fig. 6a). There were no deep (> 11 km) earthquake hypocenters in the foreshock sequence.

Within the area of the 2009 L'Aquila seismic sequence, three main clusters of epicentres have been distinguished (a, b and c in Fig. 5). The main cluster was located between Rocca di Mezzo (to the S) and S. Vittorino (to the N), where the great majority of the foreshocks, the main shock, the major aftershocks (M_W=5.4), the deeper earthquakes and most of the 2009 seismic sequence earthquakes occurred. The second cluster was located between S. Vittorino (to the S) and Montereale (to the N), while the third cluster was located to the SSE of Cittareale. All three earthquake clusters were bounded to the W by the Celano-Cittareale Fault System (CCFS), and on the E by different fault systems. The first cluster to the E was bounded by the Barisciano/Stabiata Faults (BFS/STF), while the other two clusters (intermediate and northern) were bounded by the Mt. Gorzano Fault (GF).

Furthermore, from south to north the three clusters were separated by following anti-Apennine faults. The southern cluster was bounded to the S by the NE-SW Rocca di Mezzo Fault (RMF) and to the N by the similar S. Vittorino Fault System (SFS); the intermediate cluster was bounded to the S by the SFS and to the N by the Marana Fault System (MFS); the northern cluster was bounded to the S by the MFS and to the N by the Torrita Fault System (TFS). All these quaternary fault systems delimited three rock volumes (represented in the map by sub-rectangular areas) with peculiar seismological and structural characteristics, hereafter called seismic boxes (southern, intermediate and northern) (Figs. 5 and 7). The southern seismic box includes part of the southern CCFS segment and the western part of the Campo Imperatore-Middle Aterno Valley and Gran Sasso-Pettino structural sectors; the intermediate seismic box includes another segment of CCFS and the western part of the Mt San Franco-Arischia and Mt. Gorzano-Mt. Marine structural sectors; the northern seismic box includes the northernmost CCFS segment (in the study area) and the western part of the Amatrice-Cittareale structural sector. Subsequently, the above mentioned NE-SW transversal faults separated different areas from south to north, with seismic activity also beginning here at later times. In addition, in the intermediate seismic box there was a dextral shifting of the seismic sequence at the intersection with the SFS transversal structure (Fig. 5). The epicentre of the main shock (depth 8.3 km) and the foreshock sequence were located in the western part of the southern seismic box, just west of the town of L'Aquila. According to ISIDe database/Bollettino sismico (2009) on the day of the main shock (April 6, 2009, 30 km around L'Aquila Town), 726 earthquakes (M=>2) occurred, 708 of which were located in the southern seismic box (Fig. 6a). Most of these earthquakes fell in the depth range of 9-11 km, as was the case for almost the entire sequence of aftershocks. Of the 726 earthquakes, 12 were deeper than 12 km, and the first of these occurred about half an hour after the main shock. The 159 epicenters (6/4/2009-30/9/2009) deeper than 12 km (to 20.8 km) are shown in Fig. 6b; they were arranged in a NW-SE belt on the central part of the southern and intermediate seismic boxes. None events deeper than 12 km was present in the northern seismic box.

In the first ten minutes after the main shock five earthquakes with M between 3.6 and 4.7 and depth between 8.5 and 10 km (one event to 11 km) occurred. The epicenters of the main shock and three of these earthquakes are placed along a narrow belt aligned NW-SE between W L'Aquila and Preturo (length about 10 km and width <1 km); these earthquakes migrated progressively from SE to NW. The other two earthquakes, a little more late, occurred in an area about 6/8 km NE of this belt. Following these early events, the seismic sequence has underwent a remarkable intensification.

The three earthquake clusters started at successive times (from S to N). The first cluster (southern seismic box) of the seismic sequence began with foreshocks in October 2008 and proceeded with the main shock (4/6/2009, 1.32.40 UTC time) and most of the aftershocks. The second cluster (intermediate seismic box) began about one hour after the main shock, with a few low energy (M_W=3.1) earthquakes (15.4 and 16.1 km deep in 4/6/2009) in the western part of this seismic box (Barete-Cagnano Amiterno area, Fig. 6a). About 22 hours after the main shock, an earthquake sequence began that was focused in the southeastern part of this seismic box (Mt San Franco area, Fig. 6a) with events up to M_W=5.0. From the fourth day after the main shock (4/9/2009), there was a notable increase of earthquakes in this seismic box accompanied by events of greater energy (M_W=5.2 and M_W=5.0). The third cluster (northern seismic box) which began in June

2009, two months after the main shock, had a less important number of earthquakes and maximum magnitude (M~4).

To identify the relationships between the Quaternary faults and the seismic sequence in depth, we developed five structural-seismic cross-sections (Fig. 8), which show the main active faults identified by geological and seismic data (Figs. 2 and 4b) and the hypocenters of earthquakes of M => 2 from 1/10/2008 to 30/9/2009, falling in the range of 3 km astride the trace. These sections also show the beach balls of the hypocenters with focal mechanism. Reconstruction of the beach balls was done with "Tectonics Fp" software on focal mechanism data from Scognamiglio *et alii* (2010). All the Scognamiglio *et alii* (2010) focal mechanisms of earthquakes falling in the 3 km range of each section (see above) were selected and represented; other focal mechanisms were not represented because they were too far from the range of the section and therefore more difficult to attribute to a specific fault plane. In one case, however, (Fig. 8c, Section 3) some beach balls of earthquakes that fell just outside the section range were represented, since they were deeper than 12 km and thus their attribution to a specific fault plane was unambiguous, and also because they were compatible with the geometry and kinematics of this plane.

Sections 1-4 (Fig. 8) show the aftershock sequence, while section 2 in figure 8b-2 shows the foreshock sequence and the main shock. All the sections are NE-SW trending and are approximately orthogonal to the main outcropping tectonic structures. Sections 1-2 are located in the southern seismic box, Section 3 in the intermediate seismic box, and Section 4 in the northern seismic box (Figs. 5 and 8). Section 1 has been reconstructed exactly along the trace of the seismic section 89-01 IT and shows the main quaternary faults derived from the seismic section interpretation and the surface geology (Figs. 2 and 4b). Section 2 has the same trend of Section 1, in order to more accurately project onto it the subsurface structures present in Section 1. In fact, Sections 1 and 2 are close together, parallel and above all fall in the identical structural context and in the same seismic box (Fig. 5). Sections 3 and 4 show the main structural elements derived from surface geology, sub-surface data from other seismic sections (VIDEPI Database) and the geological/geophysical literature (Ciaccio *et alii*, 2010; Bigi *et alii*, 2013). Therefore the most important quaternary seismogenic structures of this seismic box are: CCFS to the West and BFS/STF to the East.

In Section 1, the hypocenters of the earthquakes are concentrated in two well-defined clusters: the first is located at a depth between about 7 and 11 km, while the second is located at a depth between 12 and 20 km (Fig. 8a). The cluster of 7-11 km hypocenters is bounded by the CCFS (SW) and the BFS (NE) fault planes. In this interval, the hypocenters correlate in part with the fault planes of the converging branches of the CCFS and partly with the deepest part of the flattened BFS fault plane (Fig. 4b). The 12-20 km hypocenter cluster is aligned with the continuation in depth of the high angle CCFS fault plane; this correlation seems to be unambiguous since the arrangement of the hypocenter cluster follows the trend and the position of the same fault. Indeed, the presence in this area of deep hypocenters arranged along a high-angle and NE-dipping plane was already highlighted by Chiaraluce *et alii* (2011b), Lavecchia *et alii* (2012), Valoroso *et alii* (2013) and Falcucci *et alii* (2015). The main aftershock (M_W=5,4) fell in this cluster, specifically on the deep CCFS fault plane. The hypocenters of earthquakes with focal mechanism are near the CCFS fault planes, two in the range of 8-9 km and one at about 16 km; all these earthquakes have left transtensive NNW to NW striking focal mechanisms (Fig. 8a).

In Section 2, the hypocenters are arranged into two clusters. The first, at depths between 6 and 20 km (20.8), fits the CCFS fault planes and the second, between 6 and 10 km, fits the deepest and flattened BFS fault plane. The main shock (M_W= 6.1) hypocenter lies around 8.3 km, between the OM and CR branches of the CCFS (Figs. 8b and 8e); the distribution of hypocenters along the fault plane (or planes) of the CCFS is practically continuous between 6 and approximately 19/20 km of depth, even if there is a significantly higher number in the range between 6 and 10 km. Seven hypocenters of earthquakes with focal mechanism are at the NE-dipping fault planes of the CCFS in the range of 7-10 km of depth, while two are deeper and are on the NE-dipping high angle plane of the same structure (Fig. 8b-1). All seven shallower earthquakes appear extensional (a few weakly left transtensional) with NNW-SSE strike direction. Taking into account the NE dip direction of the main CCFS fault plane, the two deeper earthquakes are left transtensive with NNW-SSE strike direction. On the surface, in this sector, the three main branches of the CCFS have on the whole a NNW-SSE strike direction. Therefore, all nine focal mechanisms of these earthquakes appear compatible with the CCFS geometry and its Quaternary kinematics (chapter 2).

The foreshock and the main shock hypocenters are arranged in the 8-10 km range and correlate unambiguously with the CCFS fault planes, in particular at the area approaching the flower branches (Fig. 8b-2). In fact, even on the surface the epicenters are located W of the town of L'Aquila. In this section, the hypocenters of earthquakes and their focal mechanisms are on 50°, NE-dipping fault planes of the CCFS (TS and OM branches) at depths ranging between 8 and 10 km. Taking into account the NE dip direction of the fault planes, three focal mechanisms are essentially normal and marked by moderately inclined plane, striking approximately NNW-SSE. The three other focal mechanisms are left transtensive along N-S planes. All the focal mechanisms are perfectly compatible with the known CCFS kinematics and geometry; on the surface, the TS and OM branches of the CCFS show NNW-SSE trend. Thus in Section 2 (Fig. 8b-2), the seismic source is located close to the planes of

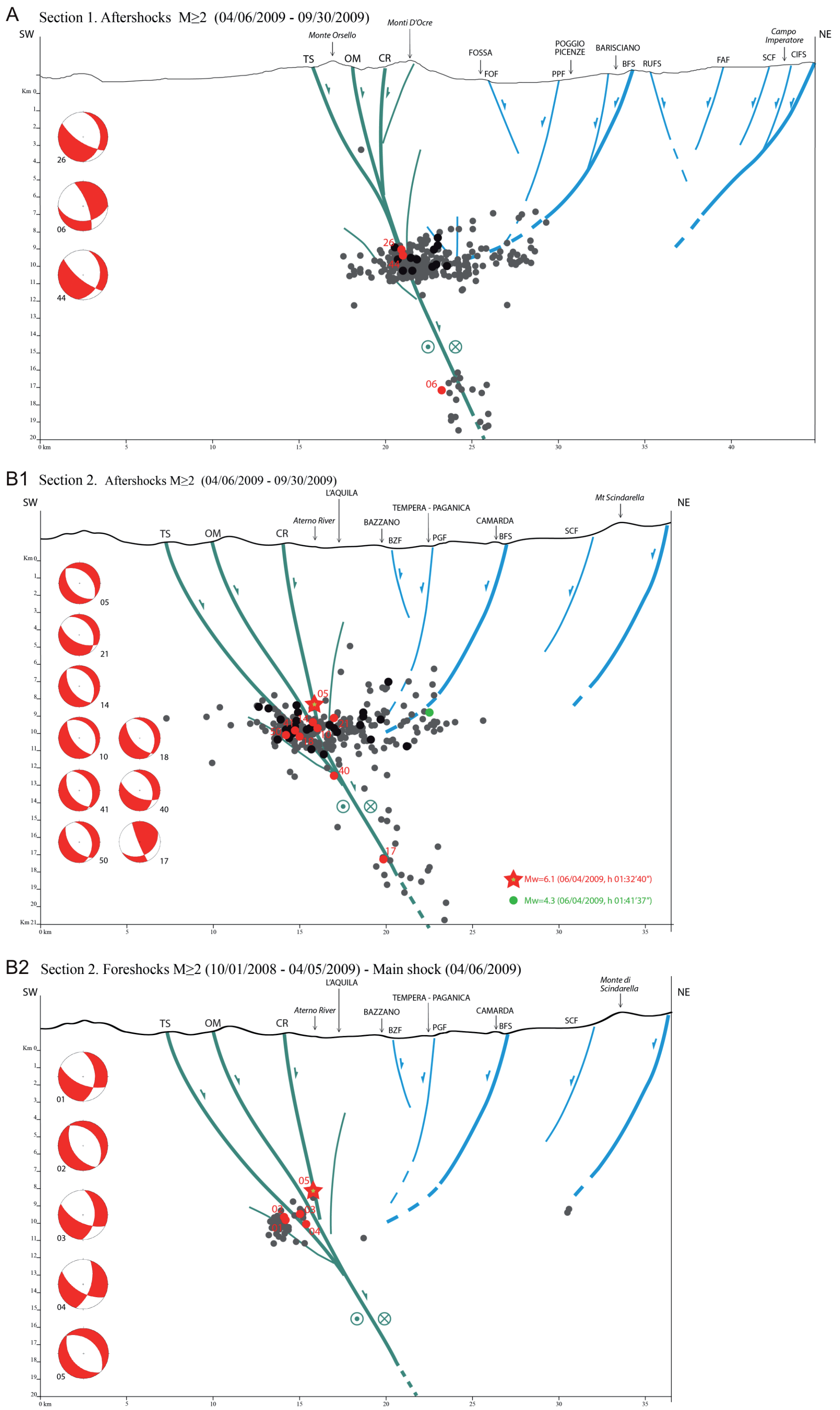

Fig. 8a-b -Structural-seismological interpretative cross-sections with beach ball. The circles are referred respectively to 2≤M<3 events (grey) and M≥3 events (black). In red the circles referred to events with focal mechanism. In Fig. 8B1 the green circle is the first event referred to BFS/STF

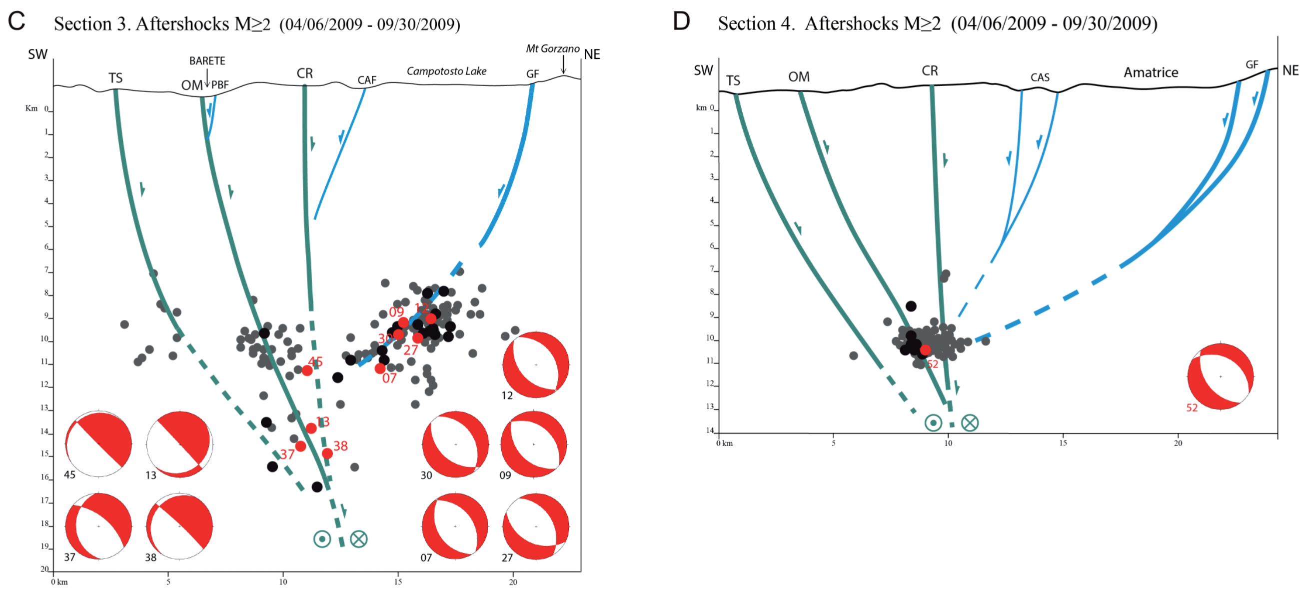

Fig. 8c-d -Structural-seismological interpretative cross-sections with beach ball. The circles are referred respectively to 2≤M<3 events (grey) and M≥3 events (black). In red the circles referred to events with focal mechanism.

the TS and OM branches of the CCFS at a depth of around 9 km. Focal mechanisms indicate alternate episodes of extension and prevailing left transtension along NE-dipping fault planes, in the medium and high angle.

To sum up, in Section 1 and 2 (Fig. 8a e 8b-1) the seismic sources are marked by the presence of two well-defined clusters of hypocenters with very low dispersion. The first fits the CCFS fault plane or planes (a larger number of hypocenters occurs at the joining or approaching branches of the CCFS flower structure), while the second fits the deep part and low angle of the BFS/STF fault plane. In addition, in Section 1, the seismic source located on the fault plane of the CCFS seems to be divided into two parts: the first stands at a depth of between 8 and 10 km, the second between 12 and 20 km. In Section 2 (Fig. 8b-1), there is a "continuum" at depths between 7-8 and 20 km. Besides in the seismic sequence of foreshocks, there were only the earthquake clusters of 8-10 km on the CCFS fault planes with alternate left transtensional and extensional focal mechanisms without any significant involvement of the adjacent and eastern Barisciano Fault System (BFS). Instead, in the sequence of aftershocks of the southern seismic box, extensional earthquakes were prevalent in the range of 8-10 km, while in the range below only left transtensional earthquakes were present, and always on the CCFS fault planes.

The most important structures of the intermediate and northern seismic boxes are to the SW, the three branches, high-angle and NE-dipping, of the CCFS, and to the NE, the SW-dipping Capitignano (CAF) and Mt. Gorzano (GF) faults (Fig. 2). All these structures are shown in Sections 3 and 4 (Figs. 8c and 8d). The Mt. Gorzano Fault is high-angle up to about 6 km and then gradually flattens until about 10 km; we have identified it on the basis of the original re-interpretation of seismic sections presented by Ciaccio *et alii* (2010) and Bigi *et alii* (2013).

In Section 3 (Fig. 8c), the hypocenters are arranged in three distinct and separate clusters: the first one is located at depths of 7-11 km near the fault plane of the inner branch (TS) of the CCFS; the second one is parallel to the deep part of the high-angle OM and CR branches of the CCFS between 8 and 16 km in depth; and the third one is located in the low angle part of the Mt. Gorzano Fault plane between 6-7 and 11 km of depth. Five of the earthquake hypocenters with focal mechanism are located at high angle fault planes of the OM branch (CCFS), while another five are on the GF fault plane (Fig. 8c). The five earthquakes lying on the OM fault plane have mainly normal kinematics (very weakly right transtension); the planes of four beach balls, consistent with the geometry of the CCFS branches, are high angle to vertical NE dipping (Fig. 8c). Five hypocenters of earthquakes with focal mechanism lie on a low angle and SW-dipping deeper part of the GF fault plane. They have normal kinematics and are consistent with the geometry, structural features and NW-SE trend of the GF fault plane on the surface. To sum up, in Section 3 (Fig. 8c), the seismic sources are marked by three well-defined and distinct clusters of hypocenters. The first and the second ones are located near the planes of the branches TS and OM (CCFS), the third one near the deep and low angle GF fault plane. Focal mechanisms indicate that there is extension (or weak mainly right transtension) along high-angle NE-dipping CCFS fault planes and extension along low-angle, SW-dipping GF fault plane.

In Section 4 (Fig. 8d), the earthquake hypocenters of M=>2 are located predominantly in the range of 8-11 km at the junction of the OM and CR branches (CCFS). In sections 20 and 21 of Valoroso *et alii* (2013) a number of hypocenters lies along a low-angle, SW-dipping plane between about 6 and 9 kilometers; it is a cluster of earthquakes of M< 2, not taken into account in our study. This sequence of very small earthquakes might be linked to the deep part of the GF fault plane as in Section 3, where, however, the earthquakes were of greater energy (up to M=5). It is noteworthy that in sections 20 and 21, clusters of earthquake hypocenters with a high angle NE-dipping arrangement are evident but have not been taken into account by the some authors (Valoroso *et alii*, 2013; Falcucci *et alii*, 2015). The only earthquake hypocenter with focal mechanism indicates extension or weak left transtension along a NW-SE striking and NE-dipping medium-angle fault plane, in agreement with the strike of the OM/CR branches on the surface. So in Section 4, the main seismic source is located near the joining planes of the OM and CR branches of the CCFS, with mainly extensional kinematics. However, according to the data of Valoroso *et alii* (2013), a weak (M<2) seismic source can be present also on the deep GF fault plane.

In all sections, the different earthquake clusters show more or less prominent dispersion; this can be due to unavoidable errors in the earthquake positioning and/or to development of new fault planes during the seismic sequence.

In conclusion, from the analysis of all five sections, it follows that the main and widespread seismic sources are those at the shallower branches of the flower structure and other along the deep fault plane of the CCFS. Other local seismic sources are in the deep, low-angle part of the BFS/STF (southern seismic box) and in the deep, low-angle part of the GF (intermediate seismic box).

Furthermore, from the analysis of the space-time evolution of the seismic sequence, it is likely that a local seismic source was also present at the NE-SW transversal S.Vittorino Fault System (SFS). On the one hand, this structure confined the southern seismic box sequence of the early hours after the main shock to the N (Fig. 6a) and on the other hand it determined (beginning about 22 hours after the main shock) the rightward shift of a large part of the intermediate seismic box sequence (Fig. 5). In fact, the Holocene activity of this fault is known (Fig. 3 and chapter 2) and as mentioned above, it divides two crustal blocks that have somewhat different structural characteristics. Beginning about a few hours after the main shock, several earthquakes of M=3/3.5 occurred at this structure (Fig. 6a); of these, the focal mechanisms of three have been identified by INGV: two appear transcurrent, one transtensive (see also Bagh *et alii*, 2007). There is no evidence of seismic sources at the other transversal faults (RMF and MFS) that confined to the N and S the seismic sequence of the first two months after the main shock (southern and intermediate seismic boxes), that is, before the start of the Cittareale seismic cluster (northern seismic box). The northern transversal fault TFS does not also shows evidence of seismic activity.

The distribution of hypocenters in Sections 1, 2, 3 and 4 on the whole fits with similar distributions reported in the sections published by Chiaraluce *et alii* (2011b) and Valoroso *et alii* (2013), who indicate the same orientation and similar positioning, but offer different interpretation of the data.

Therefore according to the results illustrated above, the main seismotectonic structure of the area was the left transtensive NW/NNW-SE/SSE striking and NE-dipping CCFS.

The following reasons support this seismotectonic correlation:

- the CCFS was the main structure of the seismic sequence area in term of continuity, regional development and the depths to which it extends.
- It was the only structure that was activated in all three seismic boxes identified, and its activation always occurred before that of other structures. Also, in the northern seismic box it was the only structure to be active.
- the sequence of foreshocks (Fig. 8b-2) clearly indicates that the 2009 L'Aquila seismic sequence began in the southern seismic box by activation of the CCFS fault planes at the junction depth of the flower branches, with left transtensive and extensional movements, just west of the town of L'Aquila. Also, the main shock (M_W=6.1) was located in the same position (Fig. 8b-2);
- The largest aftershock (M_W=5.4) occurred at the deep plane of the CCFS and many aftershocks are placed in "continuum" at its superficial and deep planes.
- towards the SW the earthquake clusters related to the BFS/STF and GF are abruptly interrupted against the high-angle CCFS planes at a depth of about 10 km because BFS/STF and GF are antithetic of the main CCFS; indeed, only along the CCFS fault planes there were earthquakes of depths exceeding 20 km. This sudden interruption is also shown in Valoroso *et alii* (2013) sections.
- during the foreshocks sequence, the main shock included, there was no evident seismogenic activation of other structures.

Other seismogenic structures were the BFS/STF for the southern seismic box, the GF for the intermediate seismic box and the transversal VFS between the southern and the intermediate seismic boxes. The BFS/STF is a normal SW-dipping fault system with high-angle (at surface) and low-angle (in depth) fault planes (Fig. 4b). The STF is the northwestward continuation of the BFS interrupted by the RF transversal fault. Many hypocenters were located in the deep (about 7-11 km) and more flattened plane of this structure and far fewer in its synthetic and anthitetic splays (PAF, PPF and PGF) (Figs. 8a-b; sections in Valoroso *et alii* (2013). The GF is a SW-dipping normal fault of the intermediate seismic box; many hypocenters were located in the deep (about 7-11 km) and more flattened plane of this structure (Fig. 8c, Section 3) with extensional kinematics. As mentioned previously, comparison of data from the reconstructions (Figs. 5, 6a, 7 and 8) and from the ISIDe Database/Bollettino sismico (2009) indicates that the sequences of earthquakes associated with the BFS/STF, GF and SFS structures started later than that caused by the CCFS. Focal mechanisms for the BFS/STF are not present in the traces of sections 1 and 2; just outside the traces there were earthquakes with extensional focal mechanisms along the NW-SE direction, consistent with the geometry and kinematics of these structures in outcrop.

All these seismogenic structures delimited the earthquake clusters and are shown in Figs. 5, 6 and 7.

SPACE-TIME EVOLUTION OF THE SEISMOGENIC STRUCTURES

During the 2009 L'Aquila seismic sequence, the seismogenic structures (CCFS, BFS/STF, GF and SFS) were not active at the same time and as a whole, but were staggered and in segments. The BFS/STF, GF and SFS were local faults that progressively become seismogenic only after activation of the adjacent CCFS segment.

As shown by the presence of three distinct and successive clusters of earthquakes (Figs. 5 and 7), during the 2009 L'Aquila seismic sequence, three segments of the CCFS structure (from south to north) were activated staggered and at different times: the first (foreshocks, the 4/6/2009 main shock and the early aftershocks occurred along a narrow SE-NW belt, W of the L'Aquila Town) in the southern seismic box, the second in the intermediate seismic box (about one hour after the main shock with two deep earthquakes) and the third in the northern seismic box (about two months after the main shock). All three activated segments were characterized by fault planes from medium/high angle (flower branches: NE and SW-dipping up to about 10 km deep) to high-angle (NE-dipping over 10 km of depth). In addition, the different segments of the CCFS became seismogenic, with earthquakes marked by different kinematics and depths.

The earthquakes generated by activation of this structure were characterized by extensional and left transtensive focal mechanisms. In particular, left transtensive earthquakes were present in the foreshock sequence and in the deepest fault planes of the southern seismic box, while some weakly transtensive earthquakes, interspersed with prevalently extensional ones, were also present in the shallow fault planes. Earthquakes with prevailing extensional (weakly right transtensional) focal mechanism were present in the intermediate seismic box and extensional (weakly left transtensional) focal mechanism in the northern seismic box. Therefore, the different segments of Celano-Cittareale Fault System, activated at successive times, moved independently and differently from each other because they were divided by sub-vertical, NE-SW transversal faults, probably as deeply rooted as the CCFS itself; in fact, these faults divide crustal blocks marked by different structural features since their early structuring (Fig. 1 and chapter 2). For this reason, some of these faults very clearly delimited the whole seismic sequence, as shown in Figs. 5, 6a and 7. The alternation of extensional and left transtensive focal mechanisms that occurred in the more superficial part of the southern CCFS segment may have resulted from reciprocal and different accommodation movements between the flower structure branches. Indeed, within the aftershock sequences, there were quick alternations between left transtensive and extensional focal mechanisms in the shallowest part (<10 km depth) of the CCFS southern segment; this is in agreement with its kinematics observed in the outcrops where at the fault plane of CCFS branches deep-slip and oblique striae are present and superimposed (see chapter 2).

The BFS and STF are the other seismogenic structures of the southern seismic box; these structures are more superficial and antithetical to the CCFS.

The Mt. Gorzano Fault (GF) is the other seismogenic structure of the intermediate seismic box (Campotosto Fault in Valoroso *et alii*, 2013). This structure, antithetical to the CCFS, began to be active through accommodation about 22 hours after the main shock with an earthquake of M_W=5.0 (Fig. 8b-1). The GF structure is dozens of kilometers long (Figs. 1 and 2), but only a segment of it was activated during the L'Aquila earthquake sequence, namely, the one between the transversal faults SFS and MFS. The GF was considered by previous authors to be the only seismogenic structure of this area. Also in this case, we have shown that the GF is neither the only nor the main seismogenic structure of the intermediate seismic box. In fact, in this area, the intermediate segment of the CCFS was activated first, about one hour after the main shock; the first earthquake in this area was more than 15 km deep and thus it can only be correlated with this structure (Fig. 8c, Section 3). Instead, the earthquakes related to the GF were shallower (<11 km) and occurred later (the first was about 22 hours after the main shock, Fig. 6a).

In the northern seismic box, the CCFS segment that activated about two months after the main shock caused a sequence of shallow earthquakes (<11 km) of low energy (M <4) that occurred only on the CCFS fault plane (Fig. 8d).

Finally, on the basis of the arrangement of epicenter clusters and the development of the seismic sequence, we posited a dual role for the transversal S.Vittorino Fault System (SFS). In the initial stages of the seismic sequence this fault acted as a passive seismic barrier (Fig. 6a) and then it began to activate as a right transfer fault, becoming itself seismogenic (Fig. 5). This is in agreement with the hypothesis of Bagh *et alii* (2007) that secondary structures located at the tips of the main NW-SE faults could be activated as transfer faults with strike-slip kinematic to accommodate part of the extensional deformation.

There is no evidence of seismogenic activation during the 2009 L'Aquila seismic sequence of the RMF, TRF and MFS transversal faults. However, they clearly confined (RMF and TRF) or separated (MFS) the seismic sequence, and then had only a passive role, acting at successive times as a seismic barrier (*sensu* Aki, 1979 and Pizzi & Galadini, 2009; Figs. 5 and 7).

Thus according to our reconstruction of the seismic sequence, the temporal activation characteristics and relationships between the different seismogenic structures were the following:

- The first to be activated was a part (from W L'Aquila to Preturo) of the CCFS segment in the northern-central area of the southern seismic box;
- Later (about 10 minutes after the main shock) a segment of the SW-dipping BFS/STF faults were also activated with an M_W=4.3 earthquake (Figs. 6a and 8b). This was also the largest energy earthquake caused by the activation of these structures. The very short time was probably due to the progressive destabilization of the BFS/STF fault planes caused by the sequence of foreshocks, which occurred over at least six months and had 75 seismic events of M≥2.
- About one hour after the main shock, the intermediate segment of the CCFS also began to activate, with low energy (Mmax=3.1) sequence earthquakes, two of which were 15.4 and 16.1 km deep (Fig. 6a, red dots). The activation of the segment continued in the following days with a significant increase in shallow and deep events.
- About 22 hours after the main shock, the southeastern part of the GF between San Vittorino Fault System and Vomano Fault, began to be activated (Mt. S. Franco cluster in Fig. 6a, green dots). Also, there was an increased presence of earthquake hypocenters more than 12 km deep along the fault planes of the southern CCFS segment, with consequent seismic source migration SE to NW and up to down along the fault planes of the southern CCFS segment. The up to down migration started about half a hour after the main shock in the southern segment: the earthquakes of the foreshock sequence, the main shock and the early aftershock sequence were less than 10 km deep. Instead, the activation of the CCFS intermediate segment came with a deep earthquake followed by a few shallower ones (down-up migration). Also within the southern segment of the CCFS there was a seismic source migration from NW to SE.
- Thus, during the 2009 L'Aquila seismic sequence three segments of the CCFS, separated from the transversal faults RMF (to the south), SFS and MFS (in the middle area) and TFS (to the north) were activated successively from south to north and then, by accommodation, the eastern BFS/STF and GF adjacent structures.
- The seismicity in the early hours after the main shock occurred in the southern seismic box and focused along a NW-SE belt about 25 km long between the RMF and SFS transversal structures (Figs. 6a-b). By the correlations M_W/length of Galli *et alii* (2008), one might assume that the initial rupture or rather the activation of a fault plane already existing affected one part of about 10-12 km of the southern segment of the CCFS, just to the west of the town of L'Aquila. This is consistent with what is highlighted previously on the basis of the main shock and earliest aftershocks epicenters localization (between W L'Aquila to Preturo for a length of about 10 km and with source migration from SE to NW). So the activation of this part of the CCFS segment (probably the OM branch) gave rise to the 2009 L'Aquila seismic sequence.
- Afterwards, the rupture or fault reactivation propagated towards the SE and in depth, affecting the whole southern segment of the CCFS.

In summary, on the basis of the all the data, results and considerations, we can postulate the following kinematic mechanism. The most important parts (foreshocks, main shock and aftershocks) of the 2009 L'Aquila seismic sequence were generated by activation of the southern segment of the Celano-Cittareale Fault System, with an initial rupture about 10-12 km long for the main shock; the kinematics of this segment was characterized by alternate left transtensional and extensional episodes. As a result, the movements along the NE-dipping fault planes of the CCFS caused destabilization of the eastern adjacent structural block, released through transversal faults, and its progressive sliding towards SW, as well as the seismogenic extensional activation of the Barisciano Fault System and the Stabiata Fault (BFS/STF) by accomodation. The SW-sliding of this block occurred also in the past as shown by the compressional pop-up structure in the middle area between the CCFS and BFS fault planes (Fig. 4b).

Later, at successive times, the CCFS intermediate and northern segments activated, mainly with extensional kinematics. We postulate a kinematic mechanism between the intermediate CCFS segment and the GF, similar to that between the CCFS and BFS/STF in the southern segment. In the northern area, given that there were no recorded earthquakes of M≥2 at the GF fault plane (Fig. 8d, Section 4), it is reasonable to suppose that it was not significantly activated. However, as previously mentioned, in sections 20 and 21 of Valoroso *et alii* (2013), there were some very low energy earthquakes (M<2) along the presumed deepest low-angle GF fault plane, which would indicate weak seismogenic involvement of this structure.

DISCUSSION AND CONCLUSIONS

According to Chiaraluce *et alii* (2011a, b), Lavecchia *et alii* (2012), and many other authors, the Paganica Fault (PGF) or the similar Aquila Fault of Valoroso *et alii* (2013) was the main seismogenic fault of the 2009 L'Aquila seismic sequence and directly responsible for the main shock (M_W=6.1); also, according to these authors, the Mt. Gorzano fault (GF) was the other seismogenic fault. These seismogenic faults were both marked by extensional kinematics. This statement is in disagreement with the results of this study, which instead shows that the 2009 L'Aquila seismic sequence started mainly by activation of some CCFS segments with extensional and left transtensive kinematics; futhermore the PGF is a synthetic fault or secondary splay of the main BFS/STF that is an antithetic, more shallow, fault of CCFS (Fig. 4b); the earthquake of greatest energy and also the first of the seismic subsequence caused by the BFS/STF seismogenic activation was M_W=4.3 and occurred later, after the main shock (Fig. 8b-1). Chiaraluce *et alii* (2011a, 2011b), Lavecchia *et alii* (2012) and Valoroso *et alii* (2013) noted in this area a further seismic source on the NE-dipping and deepest fault plane ("deep antithetic fault" of Chiaraluce *et alii* 2011a, 2011b; "hidden Monti d'Ocre seismic source" of Lavecchia *et alii*, 2012) but they did not clearly identify or define the seismogenic structures, nor did they explain the seismotectonic context. Even some of the more superficial earthquakes clusters (high-angle and NE-dipping), reported in sections of Chiaraluce *et alii* (2011a, 2011b) and Valoroso *et alii* (2013), fell outside the PGF and GF fault planes, but this "anomaly" was not taken into account or discussed.

Our reconstruction is also supported by the statements of Roberts *et alii* (2010), namely: "The Paganica Fault, although clearly an important active structure, is not slipping fast enough to accommodate all of the 3-5 mm/yr of extension across this sector of the Apennines; other neighbouring range-bounding active normal faults also have a role to play in the seismic hazard". Maybe the Paganica Fault has been considered to be the main seismogenic fault since the beginning of the seismic sequence because it is close to the epicenter on the surface, Quaternary in age and extensional (as was the main shock). Also, the most pronounced coseismic effects were detected in correspondence with it (EMERGEO, 2009), along with the most significant lowering of the ground level (by GPS and INSAR) and the greatest damage to civil structures. At the fault planes of the CCFS and BFS and other faults in the surrounding area, no coseismic effects of particular significance were detected, probably because the continental deposits are absent or very thin. Instead, at the Paganica-Poggio Picenze-Prati D'Ansidonia-S. Demetrio Faults, there are extensive thick continental clastic and unconsolidated deposits (APAT 2006a, Improta *et alii*, 2012; De Martini *et alii*, 2012; Porreca *et alii*, 2016) concurrently with widespread groundwater, factors that may have amplified locally the coseismic effects and the damage to infrastructures. In fact the INSAR maps show that the maximum lowering has occurred in these areas. In the early days after the main shock, these factors led many to the common and somewhat hasty conclusion that the Paganica Fault was the main cause (and the only one for the southern area) of the 2009 L'Aquila earthquake sequence.

Mt. Gorzano Fault was the other seismogenic fault of the 2009 L'Aquila seismic sequence. Interpretation of some reflection seismic sections induced Bigi *et alii* (2013) to propose a shallower GF fault plane (max. about 5/6 km deep) that consequently would stand above a part of the cluster of earthquake hypocenters of the intermediate seismic box. This led Bigi *et alii* (2013) to hypothesize that there is a low-angle seismogenic layer below the Mt. Gorzano fault plane. This assumption was not confirmed in our study, because the GF fault plane was (in accord with Ciaccio *et alii*, 2010) deeper (about 10 km) than that suggested by Bigi *et alii* (2013) and therefore the earthquake hypocenters fall mainly near the deep, low angle GF fault plane (see Fig. 8c).

According to Lavecchia *et alii* (2012), the only seismogenic structure of the northern seismic box was the Capitignano-Configno Fault (CAF) (Fig. 2); this is not confirmed in Section 4 of our study (Fig. 8d).

Pondrelli *et alii* (2010) reported that the focal mechanisms of the deeper earthquakes were transtensive, but did not specify the exact positioning, geometry or kinematics of the seismogenic fault planes; even so, their statement partially agrees with the results of our work because transtensional mechanisms were present only in the southern segment of the CCFS and not only in deep earthquakes.

Finally, the geometric, kinematic and evolutionary characteristics of the study area structures and the development mechanism of the 2009 L'Aquila seismic sequence and of other main historical seismic sequences (Pierantoni *et alii*, 2015) suggest that: the CCFS is a high-angle, NE-dipping, left transtensive, crustal brittle shear zone and one of the main active Quaternary structures of the Central Apennines. In this study, it was identified from the Fucino Plain to Cittareale, but most likely it continues south of the Fucino Plain and farther north than Cittareale. In fact Deschamps *et alii* (1984; 2000), at first, supposed that the 19 September 1979 Umbrian earthquake was generated by the activity of some deep, high-angle, NE-dipping master faults, with associated minor listric, SW-dipping anthitetic faults (see Fig. 15, page 65 of Cello *et alii*, 1997). The intense Quaternary activity of this structure caused significant displacement; in the Fucino Plain the amount of this displacement can be quantified. In this area, the main Quaternary faults identified are a NNW-SSE fault system, which extends along its eastern edge, and the ENE-WSW buried Tre Monti Fault system in the central-northern edge. The NNW-SSE fault system is the southern continuation of the left transtensive Cittareale-Celano Fault System (Figs. 1 and 2) and joins to the NNW-SSE Fucino Plain fault system near Celano town. A similar correlation was already proposed by Salvi & Nardi (1995). The buried Tre Monti Fault (BTFS, Figs. 1 and 4c) is the southern branch of the Tre Monti Fault system (western segment of Avezzano-Bussi Fault System; Vezzani & Ghisetti, 1998) and it stops to the east against the NNW-SSE system (CCFS). The Avezzano-Bussi Fault System, near S. Iona-Celano, has been suddivided by CCFS in two segments (Tremonti Faults System and Celano-Bussi Fault System) by a 3 km left/trastensive displacement, occurred during the Early Pleistocene stages. Instead the extensional 1 km displacement of CCFS in the Fucino Plain is linked to the more recent Middle–Upper Pleistocene stages. This is in agreement with that described in the Geological Setting.

Finally, numerous paleoseismic studies on segments or individual faults of this structure have found repeated seismogenic activations during the Quaternary that have generated earthquakes of even M=7 and perhaps even greater. According to Cello *et alii* (1997, 1998) and Tondi (2000), this system is a SW-dipping, negative flower structure, indicative of a N-S left shear-zone, with a remarkable seismogenic potential, being responsible of the past seismic Central Apennines seismicity. This structure is, for the great part, the same of CCFS. Pierantoni *et alii* (2015 a.r.t.) have also shown that the 2009 L'Aquila seismic sequence resembles the disastrous events in this area in 1703 and 1915 in many ways, including the space-time migration of seismogenic sources and activation by segments delimited by transversal faults. This structure therefore has high seismogenic potential and for all these reasons, CCFS should be defined in great detail and adequately monitored.

To sum up on the basis of the all the data, results and considerations, the following conclusions can be made:

- In the area of the 2009 L'Aquila seismic sequence, there are many Quaternary faults (Fig. 2 and chapter 2) that are potentially seismogenic, but only a few have actually been activated.
- The main seismogenic structure was the Celano-Cittareale Fault System (CCFS). The CCFS is a regional and crustal left transtensive shear zone of Apennine trend, for the most part high angle and NE dipping. A more superficial part of this structure, as far as 10 km deep, has NE and SW dipping branches (flower structure).
- Others seismogenic structures were (Fig. 5): the NW-SE, SW-dipping BFS/STF, the NW-SE, SW-dipping GF and the NE-SW transversal SFS.
- Three CCFS segments became active at different times from south to north, confined by NE-SW transversal faults.
- The main shock (M_W=6.1) of the 2009 L'Aquila seismic sequence was generated by activation of a part of the southern segment of the CCFS with an initial fault rupture about 10-12 km long.
- The main shock was preceded by a foreshock sequence located at flower branches of the southern segment of the CCFS between 8.5 and 11 km in depth, with transtensional and extensional kinematics.
- At the CCFS fault planes of the southern segment, there was a series of earthquakes alternating between left transtensional and extensional (left transtensional at depths as far as 20 km, and extensional at depths as far as 10 km). In the other segments of the CCFS fault planes the earthquakes were mainly extensional.
- The seismogenic activation of the CCFS segments caused the progressive extensional seismogenic activation of adjacent and local structures by accomodation, in particular the Barisciano Fault System and the Stabiata Fault (BFS/STF) at the southern CCFS segment and the Mt Gorzano Fault (GF) at the intermediate segment; moreover, these faults are interrupted against the CCFS fault plane.
- The main earthquake (M_W=6.1) and the highest number of earthquakes occurred in the rock volume between the CCFS fault plane and the deep part of the Barisciano/Stabiata and Mt. Gorzano fault planes, where there are the major geological dishomogeneities and roughness.
- Finally, it is important to point out that the periodic activation of CCFS for more or less long segments triggered the most important ancient, historical and recent seismic sequences of the Central Apennines.

The transversal/oblique faults (mainly NE-SW striking) assume an important role in the Upper Pliocene-Quaternary structural evolution of the Apennines. These faults mainly reactivated already existing structural elements, and bound the intramontane tectonic depressions and the seismic boxes on the south and north. As such, they may act as transfer seismogenic elements, or as barriers.

In addition, it was found that these transversal faults and numerous other present in the Central (see Geological setting) even within the same sequence may act in a different way; for example, SFS has first acted as a passive barrier to the propagation northwards of the seismic sequence of 2009 L'Aquila and subsequently has been bypassed and has become a seismogenic transfer fault. During the recent seismic sequence of Accumoli-Amatrice (2016) the NE-SW transversal fault system of Norcia-Castelluccio (NCFS) at first it confined to the North that sequence, characterized by a main shock of M_W=6.0, due activation of a CCFS segment (Chicco *et alii*, 2017); subsequently it was also bypassed allowing the activation of a greater segment which caused the M_W=6.5 earthquake. So it seems likely that within the same seismic sequence or within other, the same transversal faults may take on different roles.

ACKNOWLEDGEMENTS

This research was funded by University of Camerino in the frame of the project "FAR – Pierantoni 2016.

Reviews by an anonymous referee, the Guest Editor Alberto Prestininzi and the Editorial Staff of the IJEGE greatly helped to improve the quality of this manuscript.

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Received April 2017 - Accepted November 2017

