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A fresh look at the seismotectonics of the Abruzzi (Central Apennines) following the 6 April 2009 L'Aquila earthquake (Mw 6.3)

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A fresh look at the seismotectonics of the Abruzzi (Central Apennines) following the 6 April 2009 L'Aquila earthquake (M_w 6.3)

Uno sguardo d'insieme alla sismotettonica abruzzese all'indomani del terremoto de L'Aquila del 6 aprile 2009 (M_w 6.3)

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ABSTRACT

This work aims at providing an updated and augmented view of present-day tectonics and seismogenic sources of the Abruzzi Apennines, focusing on its extensional domain. This paper was spurred by the 6 April 2009, L'Aquila earthquake (M_w 6.3), an event from which geologists learned important lessons – including rather surprising ones. Although the earthquake was not major compared with other catastrophic events that occurred in Italy and elsewhere, this destructive earthquake led to a thorough review of the geometry - and style, in some instances - that characterises earthquake faulting in this region. The poorly expressed field evidence of the 6 April event, especially in light of the damage it caused in the mesoseismal area, stressed the intrinsic limitation of the earthquake geologists' toolbox.

Abruzzi is the region of a true "seismological paradox": despite the rather long earthquake history available for the region, the number of potential sources for earthquakes of $M \geq 6.0$ proposed in the literature is two to five times larger than the number of events that appear in the full earthquake record. This circumstance is made even more paradoxical by recent palaeoseismological work that proposed recurrence times of only a few centuries for individual seismogenic sources. Do the evident faults mapped by previous workers all correspond to potential seismogenic sources?

We aim at addressing this paradox by drawing an updated seismotectonic model of Abruzzi based on the lessons learned following the 2009 earthquake. The model is based on selected geological, geomorphological, seismological, historical and geodetic data and will ultimately feed an updated version of the DISS database (http://diss.rm.ingv.it/diss/).

KEY WORDS: *6 April 2009 L'Aquila earthquake, Active faults, Seismogenic Sources, Active tectonics, Seismic hazard, Abruzzi region, Central Apennines.*

1. INTRODUCTION

Having a potential for shallow M 7 earthquakes, the Abruzzi Apennines comprise one of the most threatening seismogenic regions in Europe. Until recently, the active tectonics of this part of the Apennines belt was believed to be especially well understood, which was seen as the basis for an effective mitigation of the local seismic risk. The Abruzzi landscape is criss-crossed by a number of faults of all sizes, and many of them show both evidence for sustained activity and credible relationships with one of the many earthquakes that have struck this region historically.

The 6 April 2009, M_w 6.3 L'Aquila earthquake challenged this belief. The surface expression of its causative source turned out to be a barely visible fault mapped by only a few investigators, while the more obvious faults nearby were not involved. Many scientists were taken by surprise also by the geometry of the fault rupture, as the earthquake was caused by slip over a plane dipping around 45° while most of the faults seen at the surface dip from 60° to subvertical, and by its depth which, from aftershock data, extended from about 2.5-3.0 to 10 km.

The 2009 L'Aquila earthquake has spurred a number of studies - at least 100 papers have already appeared in the international literature in just two years - focusing on its source and the relationships with the surface geology. Nevertheless we believe this earthquake calls for a careful reconsideration of the geological and tectonic observations and models based on pre-2009 understanding of the seismotectonics of Abruzzi. Our paper aims at 1) reconstructing how this understanding has developed throughout the past few decades, 2) establishing whether the knowledge and wisdom accrued for other portions of Abruzzi is still acceptable in view of the lessons learned in 2009, and 3) verifying if there exists a model of the main seismogenic sources that is both reliable and shared by most of the earthquake geology community.

1.1. MORE FAULTS, MORE EARTHQUAKES, MORE HAZARD?

Perhaps the first scientific account on active faulting in Abruzzi is the report written by Emilio Oddone, a physicist who devoted most of his career to the investigation of the Earth geodynamics, following the catastrophic 13 January 1915, M_w 7.0, intensity XI, Avezzano (Fucino, central Apennines) earthquake (GRUPPO DI LAVORO CPTI, 2004). In the early days of seismology, when the very nature of earthquakes was still being debated, ODDONE (1915) described the formation of several strands of ground breaks that could not be explained as strictly surficial effects and that had to be somehow related with the deep earthquake source.

After 1915, Abruzzi remained seismically quiet for many years. Furthermore, similar surface effects were not reported following any of the earthquakes that occurred in the rest of the peninsula in the following decades. Nevertheless, thanks to the vicinity of Rome with its many research centers and to the beautifully exposed geology, Abruzzi became the focus of numerous geological investigations. In the context of the preparation of the 1:100,000 geological map of Italy, the region offered a perfect viewpoint for understanding how the Apennines were constructed, from the initial involvement of open sea sediments of the Tethys ocean to its current fold-and-thrust configuration. In the 1940s Abruzzi had become a playground for developing innovative tectonic models to be used in the booming oil industry, such as the theory of *tectonic wedges* ("cunei composti") by Tuscan geologist MIGLIORINI (1948). Later on, ACCORDI (1966) used observations from Abruzzi faults and folds to develop a model for the *translational tectonics* ("tettonica traslativa") that would explain the major shortening and the simultaneous creation of thrust and normal faults in a typical fold-and-thrust-belt.

In the framework of the new interest for the hazard posed by active fault to major infrastructures, in the 1970s Abruzzi became the target of new investigations on active faulting. Unlike other similarly active areas of the Apennines, where the evidence for tectonic activity is much more subdued, Abruzzi offered a large number and variety of faults that could be easily recognised even by non-geologists. BOSI (1975) and BERTINI & BOSI (1978) mapped a number of active or potentially active faults (Fig. 1) in a large region stretching from the Apennines piedmont east of Rome to the Adriatic coast. The faults shared the following characteristics:

- mostly extensional, striking NW-SE and dipping at 50°-70° to the SW;
- individual strands seldom longer than 10 km;
- observed in bedrock (limestone), often perched at high elevation over the adjacent basin/valley floor and lined by unconsolidated talus (scree);
- often marked by a white ribbon of fresh limestone ("*nastrino di faglia*", fault ribbon) contrasting with the grey colour of the rest of the fault plane and of the adjacent bedrock;
- often seen to mimic the orientation and length of the main thrusts, but never cutting beyond their ends.

The faults mapped by BOSI (1975) and BERTINI & BOSI (1978) indeed agreed with the extensional regime currently active along most of the Apennines. Yet, the mapped faults were not considered to be the source of the largest earthquake but rather "*….faults that are believed to be significant for identifying the deeper shear zone that generates earthquakes...*" (BOSI, 1975). Although in those days the perception of fault scaling relationships was crude, this belief was correct and in fact rather wise. According to current catalogues, the region under investigation suffered at least five earthquakes of M 6.0 or larger over the past four centuries, an interval for which the information on damaging earthquakes is considered complete over the entire country (STUCCHI *et alii*, 2004). Even assuming that all of these earthquakes were generated by surface-breaking faults, based on current empirical relationships (e.g. WELLS & COPPERSMITH, 1994) each one of them would justify the existence of a single fault with a length of 10-30 km. In contrast, and purely based on fault length, several maps and compilations that discuss active faulting in the extensional core of the Abruzzi Apennines show a number of potential sources for earthquakes of M ≥ 6.0 from two up to perhaps five times larger, depending on the author(s), on the size of the study area and on when the interpretation was presented (more recent papers tend to present fewer large potential sources). Notice that the above reasoning does not take into account: 1) expected fault width from scaling relationships, 2) the 3D geometrical relationships among closely-spaced faults (i.e., when lateral distance is 2-3 km or less and almost one order of magnitude smaller than fault length), and, consequently, 3) possible fault interaction and mutual stress shadow (see HARRIS, 1998; KENNER & SEGALL, 1999). If each one of these faults slips at 0.5 to 1.2 mm/a and has generated its largest earthquake every 1,000-2,000 years, as commonly accepted based on palaeoseismological studies (GALLI *et alii*, 2008; see also BASILI *et alii*, 2008; DISS WORKING GROUP, 2010, and references therein), and assuming a characteristic earthquake behaviour for simplicity (see SCHWARTZ & COPPERSMITH, 1984; WESNOUSKY, 1994), we would expect 10-15 earthquakes of M 6.0 and larger over the four-century completeness window discussed above - which is not the case. Furthermore, palaeoseismological investigations carried out in the damage area of the 6 April 2009 earthquake (CINTI *et alii*, 2011; GALLI *et alii*, 2011) propose recurrence times of only a few centuries, making the discrepancy even bigger and harder to explain.

Many investigators followed Bosi's first reconnaissance work. It is now widely accepted that the Central Apennines are cut by a large number of high-angle normal faults, most of which trend NW and dip to the SW (e.g. GALADINI *et alii*, 2000, and references therein). Typically these faults have been seen as controlling the location and evolution of the Pleistocene-Holocene intramontane basins filled by continental deposits, and are often characterised by prominent morphological scarps, well-preserved free-faces, and wide cataclasite zones. Nevertheless, the scientific community has contrasting opinions on the rate of activity of these otherwise evident faults, on their association with historical earthquakes, on the relationship between each seismogenic source and the overlying surface faults, and hence in general on their seismogenic potential.

Although it qualifies as a moderate-size event, the 6 April 2009 makes a unique case for testing and improving our seismotectonic understanding of the Apennines, thanks to the amount and quality of the data collected during and after the earthquake and to the nature of the issues it raised, most of which are shared by other central and southern Apennines earthquakes. VALENSISE & PANTOSTI

(2001a) outlined the differences between geological and seismological evidence for Italian seismicity and discussed four circumstances that make the identification of Italian seismogenic faults particularly difficult: 1) the complexity of the inherited tectonic history; 2) the large number of blind faults; 3) the relatively low rates of tectonic deformation; and 4) the recency of the latest major change in the tectonic regime. We will discuss in the following sections if and how these circumstances are relevant to Abruzzi faults and what is the knowledge that can be considered established.

2. GEOLOGICAL AND SEISMOTECTONIC FRAMEWORK OF THE ABRUZZI APENNINES

2.1. REGIONAL TECTONIC FRAMEWORK

The central Apennines thrustbelt results from the convergence between the Hercynian European plate and the westward subducted Paleozoic Adriatic lithosphere (for a summary see PATACCA & SCANDONE, 2004, and references therein). From Oligocene to Pliocene times, the development of an accretionary wedge deformed different stratigraphic sequences of Mesozoic and Tertiary age. From Oligocene time onwards, continental collision occurred against the Adriatic plate (GHISETTI & VEZZANI, 2000). Large-scale contraction at the core of the Apennines belt has been highlighted using deep seismic reflection profiles (BIGI *et alii*, 1991a, 1995; PATACCA *et alii*, 2008; DI LUZIO *et alii*, 2009), which supplied ample evidence for large, imbricate duplex systems (GHISETTI & VEZZANI, 2000; PATACCA *et alii*, 2008).

The Late Tertiary collisional system involved the entire Triassic to Upper Miocene sequence. The upper portion of the sedimentary stack was further overthrusted onto Upper Miocene to Early Pliocene syn-tectonic foreland units, made of thick siliciclastic sequences (GHISETTI, 1987). Contraction is highlighted by NE-verging thrusts and folds (thus indicating shortening roughly oriented SW-NE), while the underlying Hercynian basement was partially involved in decollément layers at various crustal depths (see BIGI *et alii*, 1991a, b, 1995; PATACCA *et alii*, 2008; DI LUZIO *et alii*, 2009).

To the west and northwest the boundary of the Abruzzi Apennines is represented by the contact between units overlain onto the Latium-Abruzzi carbonate platforms (Late Triassic to Late Miocene) and those belonging to the Umbro-Marchean Apennines; the surface trace of such contact is marked by the *Olevano-Antrodoco-Sibillini Line* (OASL; PATACCA *et alii*, 1990; BIGI *et alii*, 1991a; GALADINI, 1999; PIZZI & SCISCIANI, 2000; CENTAMORE & ROSSI, 2009; PIZZI & GALADINI, 2009; CALAMITA *et alii*, 2011; see Fig. 2b). East and southeast of the Abruzzi Apennines, Oligo-Miocene flysch units of the Molise domain are separated from Latium-Abruzzi units by the *Ortona-Roccamonfina Line* (ORL), a regional lineament straddling the full width of the boundary between the central and southern Apennines (LOCARDI, 1982, 1988; DI BUCCI & TOZZI, 1991; PECCERILLO, 2005; MILANO *et alii*, 2008; CENTAMORE & ROSSI, 2009; PIZZI & GALADINI, 2009; see Fig. 2b). Although the nature, role and degree of activity (if any) of both OASL and ORL are still debated in the literature, they indeed border the Abruzzi Apennines and its SW-dipping, normal fault systems that we discuss further on in this work.

Finally, Plio-Quaternary marine deposits seal thrusted units near the Adriatic coast and its offshore (see among others: CENTAMORE & ROSSI, 2009). This piedmont sector of the Abruzzi Apennines is a portion of the Apennines Foredeep (BIGI *et alii*, 1991b) and is thought to contain active thrusts, as shown by offshore seismic reflection and seismicity data (SCISCIANI & CALAMITA, 2009), and by regional analyses of seismic and geological cross-sections and modeling of the source kinematics of destructive historical earthquakes (LAVECCHIA *et alii*, 2010).

2.2. HISTORICAL AND INSTRUMENTAL SEISMICITY

Historical and instrumental earthquake catalogues show that the Abruzzi Apennines have been struck by numerous earthquakes (Fig. 2a; Tables 1 and 2), ranging from sparse background seismicity up to M_w 7.0 events - i.e. the 13 January 1915 earthquake. Most of the major earthquakes are concentrated in the inner extensional sector, with few yet significant exceptions.

The epicentral location and magnitude estimate of any pre-instrumental earthquake depends on the quality of the historical records, and specifically on the number of intensity datapoints available. The data are treated with automated procedures and hence bear an additionl uncertainty due to the selected analytical approach (e.g., GASPERINI *et alii*, 1999), although recent algorithms have much improved the reliability of the results (GASPERINI *et alii*, 2010). For older earthquakes - for instance, prior to and including the Middle Ages - and for events that occurred in scarcely populated areas, such as the inner Abruzzi Apennines, epicentral locations and magnitude estimates bear large uncertainties. This is the case for the 9 September 1349 multiple earthquakes, a seismic crisis that affected several regions of the central Apennines. Although historical information is certainly highly fragmentary, GUIDOBONI & COMASTRI (2005) proposed three distinct areas of maximum damage (including the region highlighted by the label in Fig. 2a) and, therefore, three distinct epicentral areas corresponding to three events, arguably related to one another.

The 5 and 30 December 1456 seismic sequence also is a very problematic case. The earthquakes affected most of central and southern Italy, causing 30,000-80,000 casualties and widespread devastation. GUIDOBONI & COMASTRI (2005) identified three main damage zones, two in the southern Apennines and a smaller yet significant one near the northern termination of the Maiella Massif. Based on this information, FRACASSI & VALENSISE (2007) subdivided the 1456 sequence into at least three large subevents, including one on the eastern border of the Abruzzi Apennines, believed by these investigators to have occurred on 30 December (blue label in Fig. 2a).

Significantly, the 1456 earthquakes occurred only five years before the 26 November 1461 Aquilano earthquake (M_w 6.5), believed by some investigators to be a twin of the 6 April 2009 event, either based on macroseismic studies (e.g. TERTULLIANI *et alii*, 2010) or on palaeoseismological trenching (CINTI *et alii*, 2011) (see § 4). Available data for the 1461 earthquake (GRUPPO DI LAVORO CPTI, 2004; GUIDOBONI & COMASTRI, 2005) show a small mesoseismal area supported by 5-6 closely spaced reports of intensity IX-X and X. The full extent of the damage field remains unknown but for very few reports of intensity IV and V. The currently accepted location of this strong earthquake raises a number of issues (for further details see DISS WORKING GROUP, 2010). Both the 1456 and 1461 earthquakes occurred at a time when restoring buildings in scarcely populated areas was not a priority for the ruling powers (the "Regno delle Due Sicile" in Naples). The macroseismic field of the 30 December 1456 Abruzzi sub-event shows that this earthquake has occurred virtually adjacent to the 1461 earthquake. Keeping in mind that a) no intermediate level damage (intensity V/VI through IX) is known for the latter event, that b) the two events are very close in time and space, and that c) the non-strategic socio-economic role of the area did not compel immediate rebuilding, one could infer that the 1456 earthquake may have partially hindered or lessened the reliability of historical accounts of the 1461 event, the ultimate effect being an apparent shift of its epicenter to the NW and possibily a reduction of its magnitude. This hard to resolve issue is crucial for assessing the earthquake potential of the seismogenic sources located SE of the region struck by the 6 April 2009 earthquake.

The 6 October 1762 (M_w 6.0) earthquake is another example of uncertain location and magnitude estimate. GUIDOBONI *et alii* (2007) reported that various localities were uninhabitable after this earthquake, and proposed a slightly larger magnitude than that (M_w 5.9) reported by GRUPPO DI LAVORO CPTI (2004) (Table 1). Similarly to the case of the 1461 earthquake, however, the damage estimates are based on 3-4 intensity datapoints only, thus leading to a poorly constrained epicentral location and magnitude estimate. Once again, whether the location of the 1762 earthquake is reliable or not is a critical issue for the assessment of local seismic hazard (DISS WORKING GROUP, 2010; DI BUCCI *et alii*, 2011a).

The 2 February 1703 earthquake (M_w 6.6), which struck the northern portion of the study area, may have shared many similarities to its 14 January predecessor (M_w 6.8), which occurred about 30 km to the northwest. The 2 February event caused major devastation in the city of L'Aquila and its currently accepted location is just north of the 6 April 2009 earthquake (for an in-depth review of this recent event, see § 4).

The 13 January 1915 (M_w 7.0) Avezzano earthquake is to date the largest event to have ever occurred in the Abruzzi Apennines, and is certainly one of the strongest earthquakes reported in the Italian historical and instrumental catalogs. Possibly preceded a decade earlier by a much smaller yet damaging earthquake located to the northwest (24 February 1904, M_w 5.7), the 1915 earthquake produced widespread devastation throughout the entire region and beyond, causing VI/VII intensity damage in Rome. As mentioned in § 1.1, several investigators have studied this earthquake based on the vast amount of available data (for a summary see: http://diss.rm.ingv.it/diss/; DISS WORKING GROUP, 2010), including detailed felt reports, instrumental recordings, geological and geodetic information.

The 7 May 1984 (M_w 5.9) earthquake and its strong 11 May aftershock occurred near the southern end of the study region. This sequence has been the topic of a number of investigations (see PACE *et alii*, 2002, and references therein) and has been recently reassessed by MILANO & DI GIOVAMBATTISTA (2011), who reanalyzed all available instrumental data; they maintain that ORL (see § 2.1) has played a key role in controlling the spatial pattern of the full sequence, including the mainshocks.

Two areas, both located in the piedmont east of the Apennines thrustbelt (Fig. 2), have been the locus of isolated earthquakes apparently unrelated with the main extensional belt responsible for the major seismicity discussed so far. The 5 September 1950 (M_w 5.7) earthquake is a relatively deep event that occurred near the city of Teramo (TERTULLIANI *et alii*, 2006). Further to the southeast, two relatively large earthquakes occurred on the eastern flank of the Maiella Mt. on 3 November 1706 (M_w 6.6) and 26 September 1933 (M_w 5.7). According to LAVECCHIA *et alii* (2010), these earthquakes have both been caused by E-verging reverse faulting underneath the Maiella Mt. (see *Composite Seismogenic Source* ITCS078 in DISS WORKING GROUP, 2010). Finally, moderate-size earthquakes have occurred further to the northeast, between the piedmont and the Adriatic coastline, the largest one being the 10 September 1881 event (M_w 5.6).

2.3. PRESENT-DAY DEFORMATION, PREVIOUS FAULT COMPILATIONS AND PALAEOSEISMOLOGICAL STUDIES OF ACTIVE FAULTS

The tectonic grain of the inner Abruzzi Apennines is defined by a number of up to ca. 10 km long, SW-dipping normal faults, broadly arranged along two to three main, NW-SE trending systems. Such arrangement and orientation reflects the current extensional regime (MONTONE *et alii*, 2004; ANZIDEI *et alii*, 2005; SERPELLONI *et alii*, 2005, 2007; D'AGOSTINO *et alii*, 2008; MARIUCCI *et alii*, 2010; D'AGOSTINO *et alii*, 2011; Fig. 2a). Since the Early Pleistocene (see among others, VEZZANI & GHISETTI, 1998; GALADINI, 1999), the extension, which trends nearly parallel to the former contractional axis, favoured the development of normal faults that have either downthrown the back-limb of the pre-existing, large thrust systems, or have somehow disrupted the landscape that resulted from the paleogeographic domains and the contractional phases we account for in § 2.1. A genetic relationship between the thrusts and the overlying normal faults is suggested by the observation that these faults appear to be contained within the thrusts themselves and are never seen to cut their terminations.

As discussed earlier, active faulting of Abruzzi has been thoroughly investigated over the past 40 years and, despite the diverse views on the rate of activity of the numerous fault segments (see Figs. 2b and 3; Table 3, and references therein), a broad consensus exists regarding the main regional trends (for a summary: GALADINI *et alii*, 2000). Unfortuntely, individual faults or fault segments (depending on the specific interpretations) are often interpreted differently by different research groups (Table 3), partial exceptions being represented by those that have long been associated with an instrumental earthquake - as is the case for the catastrophic 13 January 1915 event (M_w 7.0: WARD & VALENSISE, 1989).

In some key cases, major faults border sizable basins, as is the case for the Fucino Plain, the largest in the Abruzzi Apennines (among others: SERVA *et alii*, 1986; MICHETTI *et alii*, 1996; GALADINI & GALLI, 1999; PICCARDI *et alii*, 1999). Recent activity (i.e. since the Late Pleistocene; HIPPOLYTE *et alii*, 1994) of some of these large fault systems, however, may be markedly different from what their tectonic arrangement would suggest (GALADINI & MESSINA, 2004). Again, this is in part due to the earlier extensional stages of the Lower Quaternary that have caused major offset and large geomorphic footprint on given fault segments that may no longer be favourably oriented with respect to the current extensional trend.

A vast amount of literature has dealt with the extensional tectonics of the Abruzzi Apennines, either due to the early Quaternary phases or to present-day tectonics. Some of these works have been conducted at regional scale and hence propose a broader view (e.g. AMBROSETTI *et alii*, 1983; BIGI *et alii*, 1991b), some concentrated on specific parts of the Apennines (CELLO *et alii*, 1997), and others focused on the current activity of individual faults (e.g. SCHLAGENHAUF *et alii*, 2011). Given the volume of available literature, we selected a subset of papers that a) are representative of different research groups, and b) have addressed the seismotectonic potential of broad areas of the Abruzzi Apennines with homogeneous criteria. In Table 3 we made an attempt to portray the diversity of views among the various research groups. The reader should notice that the Paganica Fault (PA), considered by several investigators to be the surface expression of the seismogenic source of the 2009 L'Aquila earthquake (see § 4), was recognised before the occurrence of the 2009 earthquake by only a few workers. This sole fact fully explains the need for a re-examination of what was known and what was unexplored before and after the 6 April 2009 earthquake.

3. SEISMOGENIC SOURCES

3.1. DEFINITION OF A SEISMOGENIC SOURCE

Over the past 15 years, the DISS Working Group developed a strategy for identifying, characterizing and archiving in a permanent database the major seismogenic sources that occur in and around the Italian peninsula, i.e. those that are believed to be capable of producing M 5.5 or larger earthquakes (VALENSISE & PANTOSTI, 2001b; BASILI *et alii*, 2008). This strategy, which is currently being extended to the rest of Europe within the EC-funded project SHARE (BASILI *et alii*, 2010), is based on two categories of sources, identified on the basis of their hierarchical relationships and of the detailedness and quality of the associated geometrical and kinematic parameters: the *Individual Seismogenic Sources* and the *Composite Seismogenic Sources* (BASILI *et alii*, 2009; see also: *http://diss.rm.ingv.it/diss/UserManual.html*). The first category consists of well-defined individual fault segments that are often associated with a specific historical or instrumental earthquake. Conversely, the second category of sources is formed by longer fault systems that include the *Individual Seismogenic Sources* and that normally contain historical earthquakes.

The recognition and characterization of a seismogenic source is always based on original and bibliographical geological and geophysical data, on seismological constraints from historical and/or instrumental seismicity and on geodynamic considerations. DISS incorporates seismogenic sources capable of generating $M_w \geq 5.5$ earthquakes, thus including the majority of the most damaging earthquakes reported in Italian catalogues.

An *Individual Seismogenic Source* (ISS) is represented as planar rectangular fault projected onto the Earth's surface, and is characterised by a set of geometric (strike, dip, length, width and depth), kinematic (rake, average displacement and slip rate) and seismological parameters (magnitude and recurrence interval). ISSs are assumed to exhibit "characteristic" behaviour with respect to rupture length/width and expected magnitude. These sources are tested against worldwide databases for internal consistency in terms of length, width, average displacement and magnitude, and can be complemented with information on fault scarps and other surface features, when documented. This category of sources can be used for deterministic assessment of seismic hazard, for calculating the probability of the occurrence of strong earthquakes for the sources themselves, for calculating earthquake and tsunami scenarios and for tectonic and geodynamic investigations.

A *Composite Seismogenic Source* (CSS) is represented as a planar fault system projected onto the Earth's surface, and is characterised by geometric (strike, dip, width and depth), kinematic (rake, slip rate) and seismological parameters (maximum expected magnitude). Its length is equal to the entire fault system and may contain any number of ISSs. They are not assumed to be capable of a specific earthquake but their potential can be derived from existing earthquake catalogues. A CSS is essentially identified on the basis of the knowledge gained from specific large earthquakes of the past combined with regional surface and subsurface geological data. In conjunction with seismicity and modern strain data, CSSs can thus be used for regional probabilistic seismic hazard assessment and for investigating large-scale geodynamic processes (see BASILI *et alii*, 2008 for further details).

3.2. A MULTI -STEP PROCEDURE FOR CONSTRUCTING A SEISMOGENIC SOURCE

The geometric and kinematic parameters of the seismogenic sources are evaluated following a multi-step procedure that includes the original elaborations of geophysical and geological data and studies of specific instrumental and historical earthquakes. Table 4 shows a list of common analyses and procedures that may help constraining the parameters of the Seismogenic Sources.

All possible case histories in developing a Seismogenic Source can be summarised in four basic typologies:

1) the ISS is responsible for a well-studied recent instrumental earthquake, and a large amount of seismological, geodetic and geological data are jointly interpreted to obtain the location, geometry and kinematics of the source (e.g., the 6 April 2009 L'Aquila earthquake: see Table 4); the dimensions (length and width) of the source are scaled with the earthquake moment magnitude (M_w) using empirical relationships (WELLS & COPPERSMITH, 1994) and are constrained by analytical laws relating rupture area and coseismic displacement to the seismic moment (HANKS & KANAMORI, 1979);
2) the ISS is responsible for an older instrumental event (e.g., the 1915 Fucino earthquake): the location, geometry and kinematics of the source are obtained from analytical modeling of the available data constrained by geological, macroseismic, and morphotectonic analyses, and the dimensions are scaled to the M_w of the earthquake;
3) an ISS is responsible for a pre-instrumental historical earthquake (e.g., the 1703 Aquilano earthquake): its dimensions are scaled to the M_w of the earthquake obtained from macroseismic data and verified against geological observations, while its location and geometry are based on geological, macroseismic, and morphotectonic analyses;
4) an ISS identified on the basis of geological and morphotectonic analysis is not associated with any historical or instrumental earthquake (e.g., the San Pio delle Camere Source): the M_w of the hypothetical future earthquakes is derived from the geologically constrained source dimension using empirical relationships (WELLS & COPPERSMITH, 1994).

The approach used when dealing with instrumental earthquakes is to verify the consistency of the geometry and size of the faults resulting from geological field studies with the corresponding seismological parameters. This step of the procedure uses empirical and analytical relationships among length, width, slip and moment magnitude (HANKS & KANAMORI, 1979; WELLS & COPPERSMITH, 1994). In contrast, the approach taken when dealing with historical earthquakes involves the assessment of the completeness (in terms of intensity classes) and spatial distribution of the intensity data. For older and larger events, the magnitude reported in parametric earthquakes catalogues is compared with the actual macroseismic pattern to infer any complexity of the causative source in time and space. Simplified dislocation modeling is often used to constrain the location and geometry of a seismogenic source with the expected shape or trend or displacement of selected geologic and geomorphic features (i.e., attitude of sedimentary beds, drainage patterns, location and shape of syntectonic basins, fault-scale morphologies like mountain fronts or anticline axes).

Our updated seismotectonic portrait of the Central Apennines includes an ISS responsible of the 6 April 2009 earthquake. To define its geometry (see Table 4 and § 4), we analysed and selected the best constrained of all seismological parameters and geological data proposed in the literature (e.g., seismic moment; hypocentral location; strike, dip and rake from focal mechanisms; slip at depth and surface slip). Other parameters have been derived using dislocation modeling by comparing the expected surface displacement with observed geologic and geomorphic features (e.g., the location of maximum subsidence area with respect to the active sedimentary trends, the location of the line of null vertical displacement, etc.).

4. AN OVERVIEW OF THE 6 APRIL 2009 EARTHQUAKE SOURCE

The 6 April 2009 earthquake (M_w 6.3) occurred close to the city of L'Aquila in the Abruzzi Apennines and was followed by more than 20,000 aftershocks (ISIDE, 2010), the two largest ones on 7 April (M_w 5.4), and on 9 April (M_w 5.2) (CHIARALUCE *et alii*, 2011). The normal faulting focal mechanisms computed for the largest shocks agree with the tectonic regime of the region (PONDRELLI *et alii*, 2010; SCOGNAMIGLIO *et alii*, 2010; HERRMANN *et alii*, 2011). Seismological, geodetic, and geological data available for this earthquake sequence were extraordinary both in amount and quality, thus supplying fundamental insight into the source characteristics and complexity. Nevertheless, the range of the conclusions reached by different investigators is unexpectedly wide (Table 5), and some key questions remain unsolved.

There is general consensus that the upward prolongation of the subsurface rupture plane intersects the ground surface near the Paganica Fault, a poorly known tectonic feature having a subtle geomorphic expression (BAGNAIA *et alii*, 1989; PACE *et alii*, 2006) referred to as an "uncertain or buried fault" in the digital version of the official geological maps of Italy (SERVIZIO GEOLOGICO D'ITALIA, 2006). The seismological evidence that aftershocks were confined below 2 km depth (CHIARABBA *et alii*, 2009; CHIARALUCE *et alii*, 2011) suggests that only minor slip took place along the shallower portion of the fault, which agrees with surface observations (see discussion below). The fact that the deep seismogenic source may have complex relationships with the surface Paganica Fault is also suggested by the relatively low dip angle of the rupture plane (see Table 5) and by its projection in the foot-wall of the Paganica Fault itself, as seen in the seismological sections published by CHIARABBA *et alii* (2009) and CHIARALUCE *et alii* (2011).

The rupture area and slip distribution of the activated fault have been constrained by various investigators through modelling of GPS, SAR and seismological data. The subsurface rupture length varies in the range 12 to 19 km (Table 5; ANZIDEI *et alii*, 2009; ATZORI *et alii*, 2009; CHELONI *et alii*, 2010; TRASATTI *et alii*, 2011). The maximum slip at depth was about 1 m with only a few centimeters of slip predicted on the shallower portion of the fault (e.g. CIRELLA *et alii*, 2009). In contrast, field reconnaissance of surface co-seismic ruptures showed only discontinuous ground cracks and surface faulting with few centimeters of ground displacement: the total length and the geometry of the mapped surface breaks also varied greatly according to the different investigators (Table 5; see also discussion in GORI *et alii*, this issue). Accordingly, the surface evidence has been described 1) as a discontinuous 2.5 to 6 km-long segment of the Paganica Fault (EMERGEO WORKING GROUP, 2009; CINTI *et alii*, 2011; VITTORI *et alii*, 2011), 2) as three discontinuous 10 km-long *en-echelon* segments of the Paganica Fault (FALCUCCI *et alii*, 2009), 3) as three narrow discontinuous 13 km-long fracture zones (BONCIO *et alii*, 2010), 4) as three discontinuous 19 km-long sub-parallel splays of the Paganica-San Demetrio fault system (GALLI *et alii*, 2010a), and 5) as 12-13 km long surface breaks along three *en echelon* splays (GORI *et alii*, this issue).

As regards the predecessors of the 2009 event, based on the analysis of historical intensity reports, TERTULLIANI *et alii* (2010) suggested that both the M_w 6.5, 1461 and the M_w 5.9, 1762 earthquakes (Table 1) were generated by the same source as the 2009 event, or by an antithetic structure cutting through the same seismogenic volume. Palaeoseismological studies across different segments of the Paganica and San Demetrio Faults returned different results: on the one hand GALLI *et alii* (2010a; 2011) contended that the Paganica Fault ruptured during the 1461 and the 2 February 1703 (M_w 6.7) earthquakes, while on the other hand CINTI *et alii* (2011) recognised five paleo-events which include the 1461 but not the 1703 earthquake. Based on the long-term fault scarp geomorphology, however, they also suggested that the Paganica Fault could occasionally generate larger earthquakes.

This large amount of data and their interpretation have raised several issues, the main ones concerning 1) the deep source geometry and its relationships with surface active faults, 2) the repeat time of 2009-type earthquakes, and 3) the ability of the fault system to generate larger earthquakes involving simultaneous activation of adjoining segments (this last point refers to the geometry of the fault system itself).

The solution proposed in the DISS database comes from a joint reassessment of all these data. The parameters of our Paganica Seismogenic Source fit the wide range of results proposed in the literature (Tables 5 and 7). We believe that the geometry of the Paganica Source highlighted by the occurrence of the 2009 earthquakes should represent guidance for identifying correctly and characterising other nearby sources.

5. SEISMOGENIC SOURCES OF THE CENTRAL APENNINES

This section contains a description of the seismogenic sources included in the DISS database (v. 3.1.1). For each CSS and ISS we describe the geological and geophysical background derived from original and literature data that we collected and interpreted, and present the workflow we followed for defining the parameters for each source. The sources are described starting from the CSS that contains the ISS of the 6 April 2009 earthquake (ITCS013); each CSS will be described from north to south.

For the inner extensional portion of the Abruzzi Apennines DISS lists three parallel, about 100 km-long CSSs (Table 6; Fig. 3), each one including two or more ISSs (Table 7; Fig. 3). These seismogenic sources straddle the crests of the central Apennines following a regional NW-SE trend delineated by the location of the largest historical earthquakes; they dip to the SW and are characterised by normal faulting (see § 2.3). Simple consideration of the distribution of historical eartquake release in the Abruzzi Apennines shows that here tectonic extension is accommodated differently from the adjoining regions to the north and to the south. In particular, seismic release follows three independent trends and affects a much wider area across the mountain belt. The reason for this probably lies in the different rheology of the crust resulting from the presence of the thick and rigid Latium-Abruzzi carbonate platforms.

The three CSSs terminate to the northwest and to the southeast at the transverse OASL and ORL, respectively (Figs. 2b and 3; see § 2.1). These are two NNE-striking, inherited tectonic lineaments that bound paleogeographic domains and define a major change in the surface geology. They are thought to act as effective boundaries to the dynamic earthquake propagation, segmenting also the Quaternary extensional fault systems (PIZZI & GALADINI, 2009). The OASL to the north separates the Abruzzi extensional domain from the structures related to the Alto Tiberina normal fault system developed in the Umbria-Marche Apennines, and marks a change in the dip direction of the master fault (Fig. 3): northwest of OASL the extensional fault system downthrows to the NE, while to the southeast it downthrows to the SW. The ORL defines the boundary with the Southern Apennines extensional belt just southeast of the 1984 earthquake epicentral area and close to the intersection with the E-W Molise-Gondola Shear Zone (DI BUCCI *et alii*, 2010). In contrast with the Abruzzi, in the Southern Apennines a single system of NE-dipping seismogenic sources follows the hinge of the mountain chain; in its turn this system is segmented by regional E-W shear zones responsible for the earthquakes located east of the drainage divide (e.g., the 1456 seismic sequence, FRACASSI & VALENSISE, 2007). The location and geometry of the CSSs described in this section follows a careful revision of the historical and instrumental seismicity, combined with the analysis and interpretation of geological and geophysical data and of active fault trends. This diverse dataset is helpful to define in 3D the structures and fully characterise the seismogenic sources.

One of the primary lines of evidence used to identify earthquake-generating faults is basic structural mapping (see § 1.1). The main active fault systems associated with the shallower portion of the CSS are shown in bold in Figure 3. The reader must be aware that the faults associated with each seismogenic source are a selection made by the DISS Working Group among the many faults identified in the literature. For example the Gran Sasso Range, the easternmost reach of mountain building of the Abruzzi Apennines, that lies to the southeast of the ITCS028 source, has been dissected by normal faulting in the early Pleistocene (Fig. 3), but whether these faults are still active and large enough to be potentially seismogenic remains the object of a lively debate. Several workers (e.g. GIRAUDI & FREZZOTTI, 1995; GALADINI *et alii*, 2000; GALLI *et alii*, 2002) focused on the south dipping border fault of the Campo Imperatore Plain, a large depression within the Gran Sasso Range, and used palaeoseismological evidence to suggest that this is a major potential seismogenic source. H/V analyses carried out on the Holocene sedimentary filling of the Campo Imperatore Plain, however, do not show the presence of a basin associated with the Campo Imperatore master fault (FRACASSI, 2001), suggesting that the fault has not been active during the Holocene. In addition to that, a survey carried out by ROBERTS *et alii* (2009) along the main faults of the Gran Sasso Massif showed mixed soil/rock and snow avalanches and ground cracks in the vicinity of the trench excavated by GALLI *et alii* (2002). Although ROBERTS and coworkers did not rule out the possibility that these features were actual earthquake ruptures, subsequent analyses based on SAR imagery and geodetic data showed that the Gran Sasso Range lies outside the region affected by coseismic strains in 2009. One may conclude that ROBERTS *et alii* (2009) have witnessed recurrent phenomena of compaction and sliding of surficial sediments, which raises legitimate doubts on the tectonic meaning of the fault ruptures excavated by GALLI *et alii* (2002) and hence on their current state of activity. For all of these reasons the Campo Imperatore normal faults have not been associated with any CSS.

Aside from the problem of identifying correctly the active fault and separating them from inactive or non-tectonic features, the relationships between the deep seismogenic source and the faults mapped at the surface is rather complex. This is demonstrated by the M_w 7.0, 1915 Avezzano earthquake, a large historical event for which both instrumental information and field evidence exist, but also by the M_w 6.3, 2009 L'Aquila earthquake, a much smaller but extremely well documented event. The 1915 earthquake produced surface faulting on parallel, *en-echelon*, synthetic fault strands in the source hanging-wall, near the area of maximum coseismic subsidence, partly activating range-bounding faults (e.g. VALENSISE & PANTOSTI, 2001a). The 2009 earthquake was caused by a fault having a subdued morphology, such that several investigators did not include it among the main active faults and some did not map it at all (see Table 3), and produced only a few centimetres of coseismic slip along the Paganica Fault (see § 4). In both cases the earthquakes activated more than one surface fault strand, none of which are correctly scaled in length to the magnitude of the earthquake.

The lesson that must be learned from these two earthquakes is that in areas of complex geology such as the Abruzzi Apennines, where the current structural grain results from the superposition of different tectonic regimes, assuming the most visible active faults are the major seismogenic faults is often misguided. In fact the main active fault systems are discontinuous and fragmented in segments with various orientations and lengths, are often associated with synthetic and antithetic secondary faults, and their map traces cannot be taken alone to draw a geometrically coherent seismogenic model and to predict a realistic expected magnitude. We defined the parameters of our seismogenic sources following these lines of reasoning. For each source analysed in detail the structural and geologic setting at seismogenic depth and all morphotectonic phenomena at the scale of the entire investigated region, so as to unveil the source long-term activity and reduce the inherent ambiguities of bedrock geology.

5.1. ITCS013 - BORBONA-L'AQUILA-AREMOGNA COMPOSITE SOURCE

This CSS straddles the backbone of the central Apennines, including the Montereale Basin (to the northwest), the Upper and Middle Aterno Valley, the Subequana Valley, and the Cinque Miglia Plain (to the southeast, Fig. 3).

Earthquake catalogues (BOSCHI *et alii*, 2000; GRUPPO DI LAVORO CPTI, 2004; GUIDOBONI *et alii*, 2007) show a remarkable concentration of damaging and catastrophic earthquakes within this area: 26 November 1461 (M_w 6.5, Aquilano), 2 February 1703 (M_w 6.7, Aquilano; the southernmost event of the largest seismic sequence in central Italy), January 1791 (M_w 5.4, L'Aquila), 22 April 1916 (M_w 5.2, Aquilano), 24 June 1958 (M_w 5.2, Aquilano). The 6 April 2009 L'Aquila earthquake also falls within this CSS.

The Montereale basin, which includes all faults reported by BLUMETTI (1995) and CELLO *et alii* (1998) as having been activated during the 1703 seismic sequence, falls at the northernmost end of this CSS. BLUMETTI (1995) reviewed the historical descriptions of surface phenomena reported in the Norcia-L'Aquila area during the 1703 earthquakes and compared them with field evidence with the goal of locating the surface ruptures. The observed ruptures occurred close to pre-existing normal faults bounding Meso-Cenozoic ridges that are part of a 50 km-long, 5 km-wide NNW-striking belt. The surface ruptures associated with the 2 February 1703 earthquake occurred at three locations: 1) the western side of Mt. Laghetto Ridge (Cittareale Fault, west-side down), 2) the western side of Montereale basin (Montereale Fault, east-side down), and 3) the Rotigliano Plain (Rotigliano Fault, west-side down). Secondary effects were reported along the Mt. Marine Ridge (Arischia Fault, west-side down). A trench dug across the Arischia Fault at a construction site exposed a faulted stratigraphic sequence with at least two faulting events (BLUMETTI, 1995). The activity of the Pizzoli Fault is demonstrated in the Arischia area by faulted slope deposits and by the occurrence of liquefaction phenomena during the 1703 earthquake. The activity of the three major N-S striking faults is testified west of L'Aquila and south of Arischia by faulted and tilted slope deposits and faulted Quaternary fluvio-lacustrine deposits (CELLO *et alii*, 1997).

The area struck by the 6 April 2009 earthquake falls to the southeast of the Montereale Basin. For an overview of the source of this earthquake the reader may refer to a) § 4; b) Table 4 for the procedures we used to determine the parameters of the Paganica Seismogenic Source; c) Table 5 for a review of the geometrical-kinematics parameters of the source published in the literature; d) Table 7 for the parameters of the ITIS131 Paganica; and e) Fig. 3 for the projection to ground surface of the Paganica Source. This source extends from L'Aquila to around San Demetrio né Vestini; to the southeast, it dies out against a prominent geomorphologic transverse structure, where the 6 April 2009 sequence ends its south-easterly trend.

Southeast of the Paganica Source, the fault system shows an *en-echelon* pattern with the 15 to 20 km-long Middle Aterno Valley Fault. Its surface expression is represented by continuous and evident fault scarps and ribbons, well-visible along the left bank slope of the valley (BAGNAIA *et alii*, 1989), where there is no tectonic depression filled by Quaternary deposits. MORO *et alii* (2010) dug two palaeoseismological trenches along the Middle Aterno Valley slope, concluding that the penultimate rupture event occurred between 5480-5310 B.C. and 3574 B.P. while the last event occurred around 10-140 A.D. A maximum M_w 6.6 has been attributed to the Middle Aterno Valley fault by PACE *et alii* (2006).

The Middle Aterno Valley Fault is *en-echelon* to the 10 km-long Subequana Valley Fault to the southeast. The surface expression of this structure is represented by fault scarps visible along the southwestern slopes of Mt. Urano, where a tectonic depression has undergone continental deposition since the early Quaternary (BOSI & BERTINI, 1970). According to FALCUCCI *et alii* (2011), the two structures of the Middle Aterno Valley Fault and the Subequana Valley Fault overlap over a distance of about 0.5 km along a transfer fault that cut and re-used a NE-SW-trending regional shear zone known as the Avezzano-Bussi Fault. The Subequana Valley Fault is exposed in a quarry bearing displaced slope deposits. FALCUCCI *et alii* (2011) dug two palaeoseismological trenches across this fault and suggested that, along with the Middle Aterno Valley Fault, these two structures belong to the same 25 to 30 km-long fault system. The two faults represent the branching at surface of the same deep seismogenic source, which ruptured twice during the late Holocene - the last activation having occurred between the 4th and 1st century B.C. Analysis of the Coulomb stress diffusion induced by the 6 April 2009 earthquake revealed a stress increase along the Middle Aterno Valley and the Subequana faults (FALCUCCI *et alii*, 2011).

At the southeastern end of this Composite Source, the Aremogna-Cinque Miglia Fault is believed by D'ADDEZIO *et alii* (2001) to have caused two large earthquakes on 801 A.D. and 1349 A.D. (the latter probably being a series of large earthquake that hit three different areas of central Italy; see GUIDOBONI & COMASTRI, 2005). The source is located at the transition between the dominantly SW-dipping normal fault systems of the central Apennines to the dominantly NE-dipping systems seen in the southern Apennines. In his review of active faulting in central Italy, BOSI (1975) described for the first time the fault scarp of the Cinque Miglia Plain as "likely active" (Fig. 1), but this source is mainly based on the geomorphic and palaeoseismological work of D'ADDEZIO *et alii* (2001), who analysed the earthquake potential of the Aremogna-Cinque Miglia Fault and mapped a 16 km-long, up to 6 m-high complex fault scarp. In their view, this 16-km long fault is composed by two main sections, one being in the Aremogna plain, the other one in the Cinque Miglia plain. They reported a recurrence interval in the range 2140-5080 years, a Holocene throw-rate of 0.1-0.5 mm/a, a 0.3-1.0 m slip per event, and a 6.5-6.8 magnitude assuming that each of these earthquakes ruptured the entire length of the Aremogna-Cinque Miglia Fault.

5.2. ITCS025 - SALTO LAKE-OVINDOLI-BARREA SOURCE

The Salto Lake-Ovindoli-Barrea CSS straddles the backbone of the central Apennines between the Rieti Plain, to the northwest, and the higher Sangro River valley, to the southeast, stretching across the Fucino Plain. The source falls within the core of the SW-dipping, inner Abruzzo normal fault system, marking the western extensional border of the central Apennines, and includes the Salto Valley Fault, the Velino-Magnola fault system, the Fucino Basin and the Barrea fault.

Historical and instrumental catalogues (BOSCHI *et alii*, 2000; GRUPPO DI LAVORO CPTI, 2004; GUIDOBONI *et alii*, 2007) show a particularly dense level of seismicity near the damage threshold (4.5 < M_w < 5.0) in this area. This source is believed to be responsible for some complex, highly destructive earthquakes that rank among the largest in the entire Italian history i.e., the 9 September 1349 (M_w 6.5, I=X, Aquilano) and the 13 January 1915 (M_w 7.0, I=XI, Avezzano). Between the mesoseismal areas of the 1349 and 1915 earthquakes lies the epicentral area of the 24 February 1904 event (M_w 5.7, I=IX, Marsica). Finally, the 7 May 1984 (M_w 5.9, I=VIII; Appennino abruzzese) earthquake occurred near the southern end of this Composite Source.

The most significant tectonic feature at the northern end of this CSS is the SW-dipping Salto Valley Fault. According to BOSI (1975) and MARIOTTI & CAPOTORTI (1988), the fault is at least 24 km long and its fault plane is exposed along a 7 km-long bedrock scarp in the Fiamignano area. The scarp height (offsetting 18 ka sediments) varies from 10 m in the center of the fault to less of 4 m toward its tips. This is a Plio-Quaternary normal fault considered active by MOREWOOD & ROBERTS (2000), who calculated throw rates of 0.22-0.56 mm/a for the past 18 ka. GALADINI & MESSINA (2001), however, interpreted the late-Quaternary displacement evidence of the Salto Valley Fault as due to deep-seated gravitational movements rather than to tectonic displacement, and GALADINI (2006) maintained that the fault has played a passive role, since it only bounds the sliding mass and coincides with the surface expressions of the sliding plane. Also BONCIO *et alii* (2004) considered the Salto Valley Fault to be at least questionable.

According to BOSI (1975) and ACCORDI *et alii* (1986), southeast of the Salto Valley Fault the Mt. Velino-Mt. Magnola Fault cuts along the southwestern, NW-striking steep slopes of Mt. Velino and along the southern WNW-striking steep slopes of Mt. Magnola, over a length of about 21 km. According to MOREWOOD & ROBERTS (2000), the limestone fault plane is almost continuously exposed, and the scarp height reaches 5.0 m in the central part of the fault. According to FREZZOTTI & GIRAUDI (1992), NW-striking, 2.5 m-high fault scarps cut across outwash fan deposits of the Majelama Valley but do not appear to have much affected their evolution, being more recent than the main deposition phases (upper Pleistocene last glacial maximum). MOREWOOD & ROBERTS (2000) assumed an age of 18 ka and proposed rates of throw and displacement of 0.08-0.19 mm/a and 0.09-0.23 mm/a, respectively, and rates of horizontal extension of 0.04-0.17 mm/a. Other investigators, such as PALUMBO *et alii* (2004) and more recently SCHLAGENHAUF *et alii* (2011), quantified the activity of the Mt. Magnola Fault by measuring ^{36}Cl accumulation on the exposed fault plane. They found that the fault, in the last 15 ka, ruptured its entire length during at least nine large earthquakes, with maximum surface slip of 3 m. GALLI *et alii* (2010b) opened trenches at the site studied by SCHLAGENHAUF *et alii* (2011) and identified evidence of surface faulting during the late Holocene.

Based on aerial-photo interpretation BIASINI (1966) identified two faults scarps at Piano di Pezza and Campo Porcaro, to the west of the Mt. Velino-Mt. Magnola Fault. These scarps are interpreted as the surface evidence of an active normal fault that produced as much as 9 m of post-Wurm displacement. According to PANTOSTI *et alii* (1996), the Ovindoli-Pezza is a NW-striking, SW-dipping fault a generating large earthquakes with an average recurrence time of 1,000-3,300 years. Their estimated extension rates, from palaeoseismological and geomorphic observations, are 0.3-0.5 mm/a and 0.4-1.1 mm/a, respectively. A controversy exists about the kinematics of the Ovindoli-Pezza Fault, however, because GALADINI (1999) and PICCARDI *et alii* (1999) observed significant left-lateral displacements. In contrast MOREWOOD & ROBERTS (2000) described only dip-slip movement, with an offset glacial surfaces yield rates of throw and displacement of 0.13-0.16 mm/a and 0.17-0.18 mm/a, respectively. According BONCIO *et alii* (2004) the fault has a dip ranging from 45° to 80°, a length of 26.5 km, and pure dip slip to transtensional (left lateral) kinematics.

Southeast of the Ovindoli-Pezza Fault, the Fucino Basin Source is a surface-breaking, N145° striking, 60° dipping, 30 km-long normal fault. The source aligns with direct observations of the coseismic fault scarps formed during the 13 January 1915 earthquake (ODDONE, 1915), with the model fault obtained by inversion of 1915 coseismic elevation changes (WARD & VALENSISE, 1989), with palaeoseismological observations of the main fault scarps (summarised in GALADINI & GALLI, 1999). Although the exact kinematics of the fault are still debated, most workers agree that the lateral component of motion is a small fraction of the vertical. The exposure of a white ribbon of fresh limestone fault plane reported along the southwestern slope of Mt. Serrone after the earthquake is suggestive of coseismic reactivation, although it is clearly difficult to discriminate between tectonic and gravitational movements. GALADINI & GALLI (1999) regarded the Mt. Parasano and the San Benedetto-Gioia dei Marsi Faults as the main branches of a single NW-striking, SW-dipping pure normal fault. These faults slip always simultaneously with characteristic displacements per event; conversely the Trasacco and Luco dei Marsi Fault branches move only passively. There is no consensus on the present activity of the Ventrino Fault (see Table 3), considered to be an early Pleistocene fault. Based on a thorough investigation of the geometry of the depositional bodies, CAVINATO *et alii* (2002) concluded that the Fucino Basin was formed as a half-graben type structure during Plio-Quaternary extensional events.

There is a 20-km-long gap between the Fucino Basin source and the southeastern Barrea Source, parallel to the crest of the Apennines. The Barrea Source is a N152°-striking, 50°W-dipping fault rupturing between 5 and 11 km depth. This fault is characterised by prevalent normal slip, in agreement with WESTAWAY *et alii* (1989) and PACE *et alii* (2002). The distribution of the aftershocks, however, that concentrated within a cluster oriented ENE-WSW, is rather anomalous. According to PACE *et alii* (2002) they are controlled by two kinematically compatible structures: the main normal fault and a right-lateral normal oblique fault, assumed to have played the role of a transfer fault and of a barrier for the propagation of the rupture. MILANO & DI GIOVAMBATTISTA (2011) suggested that the 1984 sequence nucleated in several stages with different strain pattern. These workers also suggested that the beginning of the sequence nucleated on a NE-SW striking fault, that subsequent events nucleated along an E-W fault, and that overall the 1984 sequence originated on a fault segment belonging to ORL.

5.3 ITCS040 - BARISCIANO-SULMONA SOURCE

This CSS straddles the backbone of the central Apennines, from Barisciano to the northwest to the higher Pescara River valley to the southeast, and is the easternmost strand of the SW-dipping extensional system of the central Apennines

Historical and instrumental catalogues (BOSCHI *et alii*, 2000; GRUPPO DI LAVORO CPTI, 2004; GUIDOBONI *et alii*, 2007) show sparse intermediate ($4.5 < M_w < 5.0$) to damaging seismicity within the area. Furthermore, this source is responsible for destructive earthquakes such as the 6 October 1762 (M_w 5.9, Aquilano) and 3 December 1315 (M_w 6.0, Italia centrale) events. The large 3 November 1706 Maiella earthquake (M_w 6.6) occurred to the southeast of this source.

This CSS is located near the southeastern edge of the 6 April 2009 seismic sequence and includes the basin running from Barisciano to Civitaretenga-Navelli. According to BOSI (1975) and other investigators (see Table 3), an active fault borders the eastern slope of the valley. Through a detailed morphotectonic, geological and structural analysis, DI BUCCI *et alii* (2011a) first identified the San Pio delle Camere Seismogenic Source and defined its earthquake potential. This ISS is formed by a NW-SE-striking, 50°-dipping, 16 km-long normal fault having a potential for a M_w 6.2 shock. MESSINA *et alii* (2011), however, objected to the activity of the San Pio delle Camere Fault. In their response, DI BUCCI *et alii* (2011b) showed recent lacustrine silts tilted toward the fault depocentre and other lines of evidence supporting the recent activity of the fault.

Southeast of the San Pio delle Camere Source, the Mt. Morrone borders the Sulmona intramontane basin. The Quaternary activity of the NW-SE normal fault along the Mt. Morrone southwestern slope has been documented in different works (e.g. VITTORI *et alii*, 1995; MICCADEI *et alii*, 2002). According to GORI *et alii* (2011) this tectonic structure comprises two parallel fault segments and is responsible for earthquakes of magnitude > 6.5. They identified the displacements of alluvial fans, attributed to middle and late Pleistocene, and evaluated the slip rate of the western branch of the structure to be 0.4+-0.07 mm/a.

5.4 ITCS028 - COLFIORITO-CAMPOTOSTO SOURCE

We briefly describe this source that mostly runs outside the study area since its geometry was highlighted by the occurrence close to its southern portion of two of the strongest aftershocks of the 2009 L'Aquila earthquake and by the related sequence; one on 6 April (23:15 UTC, M_w 5.0) and one on 9 April (00:53 UTC, M_w 5.2; CHIARALUCE *et alii*, 2011).

As a whole, this CSS straddles a section of the Umbria-Marche Apennines between Gualdo Tadino (Umbria Region) to the north and the Campotosto Lake to the south, close to the western reaches of the Gran Sasso mountain range. This is the easternmost SW-dipping normal fault system of the central Apennines; it dips at a relatively low-angle and locates just west of the region where tectonic compression prevails (DISS WORKING GROUP, 2010). Most of the information on this source comes from studies that followed the 1997-98 Umbria-Marche earthquake sequence and, for its southern portion, from the analysis of the 2009 sequence. This CSS includes the three ISSs of the main shocks of the 1997-98 sequence and that associated with the 14 January 1703 earthquake (M_w 6.8: refer to Table 6 for the source parameters).

The geometry of the southern portion of this CSS was based on the lessons learned from the 2009 seismic sequence. Fault plane solutions of the largest shocks and seismicity distribution showed the activation of a 14 km-long, low-angle, deeper structure forming a right-lateral step with the source of the 6 April main shock (CHIARALUCE *et alii*, 2011). Other distinguishing features were the absence of seismicity above 5 km depth and the different strike followed by the sequence with respect to the surface trace of the Monti della Laga Fault. The 2009 sequence demonstrated that this surface fault, like many others in the region, can not be considered as the surface expression of a deep seismogenic source because 1) it strikes at an angle with respect to the trend highlighted by seismicity and 2) its high-angle geometry can hardly be reconciled with that of the seismogenic fault at depth.

6. SUMMARY

Our update of the Abruzzi extensional seismogenic sources in view of the 6 April 2009 earthquake supplies a fresh look at the seismotectonics of this stretch of the Apennines (Table 8). The first insight that can be derived from the seismogenic sources is the regularity in the pattern of present tectonic deformation. Most of the seismic moment is released along three parallel extensional, SW-dipping CSSs having similar depth of nucleation and slip rate. These extensional sources are bounded by well-known, pre-existing major tectonic lineaments that have credibly played an important role in the evolution of the Abruzzi Apennines, a region that can be considered rather uniform at least from a paleogeographic and tectonic viewpoint.

In the following we briefly summarise the main improvements and novelties:

1) an improved understanding of three parallel extensional fault systems, implying the need to define their most credible geometry and extent and to understand their mutual kinematic relationships, also as a function of their respective arrangement;
2) the greater depth of the Campotosto Source as highlighted by the newly-available seismological data, leading to a careful reconsideration of the geological evidence that used to be considered crucial for this source;
3) updates of the geometric properties of seismogenic sources and new interpretations of faults that are thought to have generated a number of historical earthquakes. In particular, we believe that the relatively shallow dip, the depth of the upper tip at 2-3 km below the ground surface, and the complex relationships with surface active faults do not represent an anomaly; instead, they must be regarded as common features of the seismogenic sources responsible for moderate earthquakes in the region;
4) the role (passive, active - any at all?) of two regional tectonic lineaments that cross the entire central Apennines edifice from the Tyrrhenian to the Adriatic Sea; OASL to the north, and ORL to the south;
5) the identification of seismic gaps along the three main CSSs. For example, the Sulmona Basin and the Subequana Valley have not been the locus of major historical earthquakes at least over the past seven centuries, and can hence be considered as two independent seismic gaps.

The revised seismogenic sources presented in this work improve the degree of completeness of the seismotectonic framework of the Abruzzi region, yielding a synoptic view of seismogenic processes in the central Apennines area. They also comprise a homogeneous database for quantifying tectonic strains and the associated seismogenic potential at regional scale.

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Figure Captions

Figure 1 - Active or potentially active faults (from BOSI, 1975, modified and adapted).

Figure 2 - *a)* Historical and instrumental earthquakes in the Abruzzi Apennines and its surroundings. Notice the concentration of the largest events along the backbone of the Apennines.

Macroseismic earthquake data from GRUPPO DI LAVORO CPTI (2004), instrumental seismicity from CASTELLO *et alii* (2006), and *Sh-min* vectors (cumulative from borehole breakouts, focal mechanisms, palaeoseismology) from MONTONE *et alii* (2004) and MARIUCCI *et alii* (2010).

The small dots locate earthquakes belonging to the sequence preceding and following the 6 April 2009, L'Aquila earthquake (M_w 6.3), as recorded from 1 April to 31 July 2009 by the INGV national seismic network (ISIDE, 2010); the epicenter of the 6 April 2009 mainshock is shown by the larger white star; the smaller black stars show the epicenters of the 7 April (M_w 5.4, to the south) and 9 April (M_w 5.2, to the north) earthquakes, respectively.

Focal mechanisms by authors listed in Table 2. Present-day extensional axis (red arrows) from SERPELLONI *et alii* (2005). Labelled earthquakes are key events (both historical and instrumental) that have occurred within the study area; those with coloured background are associated with the following *Composite Seismogenic Sources*: ITCS025 (green), ITCS013 (yellow), ITCS028 (orange), and ITCS040 (cyan), respectively (see § 5 and Fig. 3). The location of the 1456 earthquake (white text in blue label) is from FRACASSI & VALENSISE (2007).

b) Geological summary of the central Apennines and its environs (modified, from DI BUCCI *et alii*, 2006). Notice how OASL (auct., see PATACCA *et alii*, 1990) to the north, and ORL (auct., see LOCARDI, 1988) to the south border the Abruzzi Apennines and its large normal fault systems discussed in this work.

Key: 1 - marine and continental clastic deposits (Pliocene-Quaternary); 2 - volcanics (Pleistocene); 3 - clayey and carbonate turbidites (Cretaceous-Eocene); 4 - Apennines carbonate platform; 5 - Apennines slope and margin deposits (Lias-Miocene); 6 - Apulia carbonate platform and slope deposits (Trias-Miocene); 7 - Molise-Sannio-Lagonegro pelagic deposits (Meso-Cenozoic); 8 - syn-orogenic hemi-pelagic and turbiditic sequences (Tortonian-Pliocene); 9 - thrust faults; 10 - normal faults.

Figure 3 - Seismotectonic setting of the Central Apennines. Yellow box: *Individual Seismogenic Source (ISS)* projection onto the ground surface; yellow line: up-dip projection of the *ISS* onto the surface; red polygon: *Composite Seismogenic Source (CSS)* projection on the ground surface; red line: upper edge of the *CSS* (DISS WORKING GROUP, 2010); black line: active faults mentioned in Table 3; grey line: other faults.

Key to fault names: PI: Pizzoli; MP: Mt. Pettino; PA: Paganica; MAV: Middle Aterno Valley; SV: Subequana Valley; ACM: Aremogna-Cinque Miglia; FS: Fiamignano-Salto; VM: Val di Malito: VE: Velino; MA: Magnola; OP: Ovindoli-Pezza; TM: Tre Monti; SB: San Benedetto-Gioia dei Marsi; MPA: Monte Parasano; AI: Aielli; TR: Trasacco; VN: Ventrino; USV: Upper Sangro Valley; MG: Monte Greco; BA: Barrea; SP: San Pio delle Camere; SU: Sulmona; MOR: Morrone; MO: Montereale; ML: Monti della Laga. OASL: Olevano-Antrodoco-Sibillini Line; ORL: Ortona-Roccamonfina Line.

Table Captions

Table 1 - Location and parameters of earthquakes of M > 5.0 that have occurred in the study region and surroundings and for which macroseismic data are available (GRUPPO DI LAVORO CPTI, 2004). Earthquakes listed here are those labelled in Fig. 2a. Date is in YYYY MM DD format (months and days may be missing for older earthquakes); Intensity is in MCS scale; N Data is number of localities for which macroseismic data are avalaible; Source is the code of the *Composite Seismogenic Source* the earthquake has been associated with: a dash in this column indicates that no association has been made or deemed sufficiently constrained, while OS (Other Source) indicates that the earthquake has been associated to a source either lying outside the extensional core of the Abruzzi Apennines and/or not mentioned in the text.

Table 2 - Location and parameters of the largest instrumental earthquakes that occurred in the study region and for which focal mechanisms are available. Earthquakes listed here are those shown with focal mechanisms in Fig. 2a. Date is in YYYY MM DD format; Time is local (Italian); Reference(s) indicates the paper(s) used to derive the parameters; Source is the code of the *Individual Seismogenic Source* and/or *Composite Seismogenic Source* the earthquake has been associated with: a dash in this column indicates that no association has been made or deemed sufficiently constrained.

Table 3 - Synoptic view of the active faults or active fault systems reported in regional tectonic overviews. Notice the diversity of views concerning the degree of activity of any given fault system. Fault systems for which there is consensus across the various research groups are highlighted in bold. Key to fault names: PI: Pizzoli; MP: M. Pettino; PA: Paganica; MAV: Middle Aterno Valley; SV: Subequana Valley; ACM: Aremogna-Cinque Miglia; FS: Fiamignano-Salto; VM: Val di Malito: VE: Velino; MA: Magnola; OP: Ovindoli-Pezza; TM: Tre Monti; SB: San Benedetto-Gioia dei Marsi; MPA: Monte Parasano; AI: Aielli; TR: Trasacco; VN: Ventrino; USV: Upper Sangro Valley; MG: Monte Greco; BA: Barrea; SP: San Pio delle Camere; SU: Sulmona; MOR: Morrone; MO: Montereale; ML: Monti della Laga. Key to fault properties: 1 - possible; 2 - subordinate; 3 - secondary; 4 - inferred; 5 - no consensus; 6 - Quaternary faults for which no evidence of Upper Pleistocene-Holocene activity is available; 7 - doubtful longitudinal continuity and/or seismogenic role. The active faults are labelled in Fig. 3. *ITHACA database: www.apat.gov.it/site/en-GB/Projects/ITHACA_- ITaly_HAzards_from_CApable_faults/default.html.

Table 4 - Principal types of analyses, procedures or data used to determine the parameters of seismogenic sources (modified from BASILI *et alii*, 2008). The lists in the second column are not intended to be exhaustive. The analyses or procedures used to determine the parameters of 6 April 2009 earthquake source are highlighted in bold. * These data were not available in July 2010, when version 3.1.1 of the DISS was published online.

Table 5 – Geometric and kinematic parameters of the 2009 L'Aquila earthquake as proposed by various investigators. Key: 1 - strike fixed from CMT solution; 2 - available at: http://www.eas.slu.edu/eqc/eqc_mt/MECH.IT/; 3 - available at: http://mednet.rm.ingv.it/; 4 - available at: http://www.globalcmt.org/CMTsearch.html; 5 - available at: http://earthquake.usgs.gov/; 6 - variable slip models; 7 - uniform slip models; 8 - from aftershock profiles; 9 - total length of mapped surface faulting.

Table 6 – Geometric and kinematics parameters of the extensional CSSs of the Central Apennines. Explanatory notes and published source(s) for each single parameter plus a commentary and a full reference list can be found on the DISS web interface (http://diss.rm.ingv.it/diss/).

Table 7 – Geometric and kinematics parameters of the extensional ISSs of the Central Apennines. Explanatory notes and published source(s) for each single parameter plus a commentary and a full reference list can be found on the DISS web interface (http://diss.rm.ingv.it/diss/).
*These data were not available in July 2010, when version 3.1.1 of the Database was published online.

Table 8 – Main updates and changes of ISS and CSS resulting from the review of the seismotectonic regional model, according to the numerous studies that followed the 2009 L'Aquila earthquake.

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TABLES

Table 1

Date	Time	Locality	Lat (°)	Lon (°)	Intensity	M_w	N Data	Source
101 -- --	-- -- --	S. Valentino in Ab. Cit.	42.230	13.980	IX-X	6.3	1	-
1315 12 03	09 30 --	Italia centrale	42.000	13.970	IX	6.0	15	ITCS040
1328 12 01	-- -- --	Norcia	42.856	13.018	X	6.4	13	ITCS028
1349 09 09	-- -- --	Aquilano	42.170	13.380	IX-X	6.5	22	ITCS025
1461 11 26	21 30 --	Aquilano	42.308	13.543	X	6.5	10	ITCS013
1639 10 07	00 30 --	Amatrice	42.636	13.252	X	6.3	27	ITCS028
1654 07 23	00 25 --	Sorano-Marsica	41.630	13.680	IX-X	6.2	44	-
1703 01 14	18 -- --	Appennino reatino	42.680	13.120	XI	6.8	196	ITCS028
1703 02 02	11 05 --	Aquilano	42.470	13.200	X	6.7	70	ITCS013
1706 11 03	13 -- --	Maiella	42.080	14.080	IX-X	6.6	99	OS
1762 10 06	12 10 --	Aquilano	42.300	13.580	IX	5.9	6	ITCS040
1791 01 --	-- -- --	L'Aquila	42.356	13.396	VII-VIII	5.4	1	ITCS013
1838 02 14	-- -- --	Valnerina	42.875	12.886	VIII	5.6	9	ITCS028
1881 09 10	07 -- --	Abruzzo meridionale	42.230	14.280	VIII	5.6	29	OS
1882 02 12	-- -- --	Chieti	42.290	14.347	VII	5.3	8	OS
1904 02 24	15 53 26	Marsica	42.100	13.320	VIII-IX	5.7	56	ITCS025
1915 01 13	06 52 --	Avezzano	42.013	13.530	XI	7.0	1041	ITCS025
1916 04 22	04 33 --	Aquilano	42.294	13.396	VI-VII	5.2	9	ITCS013
1933 09 26	03 33 29	Maiella	42.050	14.180	VIII-IX	5.7	326	OS
1950 09 05	04 08 --	Gran Sasso	42.516	13.657	VIII	5.7	137	OS
1958 06 24	06 07 --	Aquilano	42.340	13.477	VII	5.2	14	ITCS013
1979 09 19	21 35 37	Valnerina	42.720	13.070	VIII-IX	5.9	691	ITCS028
1984 05 07	17 49 42	Appennino abruzzese	41.666	14.057	VIII	5.9	913	ITCS025
2002 10 31	10 33 00	Molise	41.694	14.925	VII-VIII	5.8	51	OS

Table 2

Date	Time	Locality	Lat (°)	Lon (°)	M_w	Strike (°)	Dip (°)	Rake (°)	Reference(s)	Source(s)
1915 01 13	06 52	Avezzano	42.01	13.53	7.0	135	63	-90	Ward & Valensise (1989)	ITIS002 ITCS025
1984 05 07	17 49	Barrea	41.66	14.06	5.8	123	48	-96	Westaway *et alii* (1989)	ITIS028 ITCS025
2009 04 06	03 32	L'Aquila	42.42	13.45	6.3	134	56	-97	Chiarabba *et alii* (2009) Pondrelli *et alii* (2010)	ITIS131 ITCS013
2009 04 07	19 47	L'Aquila	42.36	13.52	5.4	338 93	73 36	-58 -151	Chiaraluce *et alii* (2011) Scognamiglio *et alii* (2010)	-
2009 04 09	02 53	L'Aquila	42.53	13.44	5.2	136	46	-99	Chiaraluce *et alii* (2011) Pondrelli *et alii* (2010)	ITCS028

Table 3

Fault System	*Composite Seismogenic Source - ITCSXXX*	Bosi, 1975	ITHACA*	Bagnaia, *et alii*, 1989	Cello *et alii*, 1997	Piccardi *et alii*, 1999	Morewood & Roberts, 2000	Galadini *et alii*, 2000	Galadini & Galli, 2000	Pizzi *et alii*, 2002	Boncio *et alii*, 2004	Roberts & Michetti, 2004	Galadini, 2006	Pizzi & Galadini, 2009	Vezzani *et alii*, 2009	Schlagenhauf *et alii*, 2011	Falcucci *et alii*, 2011
PI	*013*	Yes	Yes	Yes	Yes	n/a	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MP	*013*	Yes	Yes	Yes	Yes	n/a	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
PA	*013*	No	Yes	Yes	n/a	n/a	No	No	No	Yes	Yes[7]	No	No	Yes	Yes	Yes	Yes
MAV	*013*	Yes	Yes[2]	Yes	n/a	n/a	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
SV	*013*	Yes[1]	No	Yes	n/a	n/a	No	No	No	Yes	No	No	No	Yes	No	Yes	Yes
ACM	*013*	Yes	Yes	n/a	n/a	n/a	n/a	Yes	Yes	n/a	Yes	Yes	Yes	Yes	Yes	Yes	Yes
FS	*025*	Yes	Yes	n/a	n/a	n/a	Yes	Yes[5]	No	No	Yes	Yes	Yes	No	No	Yes[3]	No
VM	*025*	Yes	No	n/a	n/a	n/a	Yes[4]	No	No	Yes	No	No	Yes	No	Yes	Yes	No
VE	*025*	Yes	Yes	n/a	n/a	Yes	Yes	No	No	Yes	Yes	Yes	No	No	Yes	Yes	No
MA	*025*	Yes	Yes	n/a	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
OP	*025*	Yes	Yes	n/a	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
TM	--	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No
SB	*025*	Yes[1]	Yes	n/a	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MPA	*025*	Yes	Yes	n/a	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
AI	*025*	No	No	n/a	No	Yes[3]	No	No	No	No	No	No	No	No	Yes	Yes	No
TR	*025*	Yes	Yes[2]	n/a	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No
VN	--	Yes	No	n/a	No	Yes	Yes	No	No	No	No	Yes	No	No	No	Yes[3]	No
USV	*025*	Yes	Yes[2]	n/a	n/a	Yes	Yes	Yes	Yes	n/a	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MG	*025*	Yes	Yes[2]	n/a	n/a	n/a	n/a	Yes[6]	Yes	n/a	Yes	Yes	No	Yes	Yes	Yes	Yes
BA	*025*	Yes	Yes[2]	n/a	n/a	n/a	n/a	No	No	n/a	Yes	No	Yes	Yes	Yes	Yes	n/a
SP	*040*	Yes	Yes	Yes	n/a	n/a	Yes	No	No	Yes	No	Yes	No	Yes	Yes	No	No
SU	*040*	Yes	Yes	n/a	n/a	n/a	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
MOR	*040*	Yes	Yes	n/a	n/a	n/a	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
MO	*028*	Yes[1]	Yes	No	Yes	n/a	n/a	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
ML	*028*	n/a	Yes	n/a	Yes	n/a	n/a	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 4

Parameter	**Data and methods**
Location	• **Location of** historical and/or **instrumental earthquakes**. • **Analysis of geologically, geomorphically and geodetically detected deformation.**
Length (L)	• Maps of surface active faults. • **Inversion of seismological and geodetic data.** • Geological sections across the active fault system. • Length of the area deformed by slip at depth identified as the area of 1) displaced or warped geological layers (folds) or geomorphic features (e.g. alluvial and coastal terraces), 2) forced or anomalous drainage pattern (e.g. stream/river migration/avulsion), and 3) **vertical displacements as identified by satellite geodesy**. • Scaling relationship between length and moment magnitude (e.g. LogL = a + b × Mw).
Width (W)	• Geological sections across the active fault system. • **Estimation from depth interval and dip.** • Width of the area deformed by slip at depth identified as the area of 1) displaced or warped geological layers (folds) or geomorphic features (e.g. alluvial and coastal terraces), 2) forced or anomalous drainage pattern (e.g. stream/river migration/avulsion), and 3) **vertical displacements as identified by satellite geodesy**. • **Scaling relationship between width and moment magnitude (e.g. LogW = a + b × Mw).**
Depth	• **Depth distribution of instrumental earthquakes**. • **Inversion of geodetic and seismological observations.** • Geological sections across the active fault system. • Rheological profiles of the region. • Seismic tomography of the region. • Combined analysis with the estimation of width.
Strike, Dip, and Rake	• Displacement components of geological markers in maps and cross sections. • Measures obtained on faults exposed at the ground surface. • **Focal mechanisms of the associated earthquake.** • Physical properties such as principal stress and strain axes. • **Modeling of satellite geodesy data.**
Slip Rate (SR)	• Displacement of dated geological markers.* • Displacement observed through geodetic measurements. • Displacement calculated from seismic or geodetic strain. • Calculated from recurrence time and slip per event (SR = D / RI). • **Assumed from geodynamic constraints.**
Recurrence Interval (RI)	• Time lag between successive event horizons identified in palaeoseismological trenches.* • **Derivation from long-term slip rate (RI = D / SR)**.
Slip per Event (D)	• **Based on seismological data.** • Displaced geologic or geomorphic markers. • Analytical formulation of seismic moment based on the double-couple model ($D = M_0 / \mu S$ where μ is rigidity, S is fault area, and M_0 is seismic moment).
Magnitude (Mw)	• **Magnitude of associated earthquake measured instrumentally.** • Largest magnitude of associated historical earthquake(s) estimated from intensity data. • Magnitude inferred from the area of the largest associated fault or fault set. • **Magnitude inferred from a physical model that includes deformation data of any sort (e.g. geodetic, seismic).** • Scaling relationship between magnitude and fault size.

Table 5

Reference	Length (km)	Width (km)	Min depth (km)	Strike (deg)	Dip (deg)	Rake (deg)	Max Slip(6) (cm)	Avg Slip(7) (cm)	M_o (Nm)	M_w	Method
Geodetic and seismological inversion											
Anzidei *et alii*, 2009(1)	13±0.9	15.7±1.3	--	140	55.3±1.8	-98±1.9	--	50±3	3.20e+18	6.3	GPS data inversion
Atzori *et alii*, 2009	12.2±0.4	14.1±0.7	1.9±0.2	133±2	47±1	-103±2	90	56±2	2.90e+18	6.3	DInSAR and GPS data inversion
Cheloni *et alii*, 2010	12	17.4	0.6	135.8	50.4	-98.5	100	62	3.90e+18	6.4	GPS data inversion
Chiarabba *et alii*, 2009	16	11.3	2	135	45	--	--	--	--	6.3	Relocated aftershock distribution
Chiaraluce *et alii*, 2011	16	10.4	2-3(8)	135	50±3	--	--	--	--	6.1	Relocated aftershock distribution
Cirella *et alii*, 2009	18	17.5	0.5	133	54	-102	110	--	3.50e+18	6.3	Strong motion and GPS data inversion
Guerrieri *et alii*, 2011	18.5	--	0	133-147	45	--	80	--	2.88e+18	6.2	InSAR inversion and field mapping of surface effects
Hermann *et alii*, 2011(2)	--	--	--	135	55	-95	--	--	1.97e+18	6.1	Broadband waveform inversion
Serpelloni *et alii*, 2010	12.5	15.9	0.8	138	50.6	--	110	--	2.61e+18	6.3	GPS data inversion
Trasatti *et alii*, 2011	12.5±0.5	10.8±0.8	2.3±0.7	142±2	42±2	-96±4	110-120	53±5	2.50e+18	6.2	Finite element geodetic data inversion
Walters *et alii*, 2009	12.2	10.8	3	144	54	-105	80	66	2.80e+18	6.2	DInSAR and body-waves data inversion
Focal Mechanism											
Pondrelli *et alii*, 2010	--	--	--	134	56	-97	--	--	--	6.3	Regional Centroid Moment Tensor
Scognamiglio *et alii*, 2010	--	--	--	139	48	-87	80	16.9	1.62e+18	6.1	Time Domain Moment Tensor
INGV QRCMT(3)	--	--	--	147	43	-88	--	--	3.70e+18	6.3	Regional Centroid Moment Tensor
Harvard CMT(4)	--	--	--	120	54	-113	--	--	3.66e+18	6.3	Centroid Moment Tensor
USGS(5)	--	--	--	122	53	-112	--	--	3.40e+18	6.3	Centroid Moment Tensor
USGS(5)	--	--	--	113	60	-118	--	--	2.80e+18	6.2	Body-Wave Moment Tensor
USGS(5)	--	--	--	121	43	-122	--	--	2.90e+18	6.2	WPhase Moment Tensor Solution
Surface breaking											
Boncio *et alii*, 2010	13(9)	--	--	130-140	--	--	--	--	--	--	Field mapping of surface coseismic effects
Cinti *et alii*, 2011	3(9)	--	--	130-140	--	--	--	--	--	--	Field mapping and paleoseismological trenching
Emergeo Working Group, 2010	2.5 to 6(9)	--	--	130-140	--	--	--	--	--	--	Field mapping of surface coseismic effects
Falcucci *et alii*, 2009	10(9)	--	--	130	--	--	--	--	--	--	Field mapping of surface coseismic effects
Galli *et alii*, 2010a	19(9)	--	--	130	--	--	--	--	--	--	Field mapping and paleoseismological trenching
Gori *et alii*, this issue	12-13(9)	--	--	136	50	-100	110	--	3.31e+18	6.3	InSAR and GPS inversion and field mapping of surface effects
Vittori *et alii*, 2011	2.6(9)	--	--	120-140	--	--	--	--	--	--	Field mapping of surface coseismic effects

Table 6

ID	Name	Depth (km)	Strike (deg)	Dip (deg)	Rake (deg)	Slip Rate (mm/a)	Max M
ITCS013	*Borbona-L'Aquila-Aremogna*	2.0-14.0	130-150	40-60	260-280	0.1-1.0	6.5
ITCS025	*Salto Lake-Ovindoli-Barrea*	1.0-14.5	130-150	40-65	260-280	0.1-1.7	6.7
ITCS028	*Colfiorito-Campotosto*	2.5-14.0	130-150	35-55	260-280	0.1-1.0	6.5
ITCS040	*Barisciano-Sulmona*	1.0-14.0	120-140	40-65	260-280	0.1-1.0	6.4

Table 7

ID	Name	Length (km)	Width (km)	Depth (km)	Strike (deg)	Dip (deg)	Rake (deg)	Average Slip (m)	Slip Rate (mm/a)	Latest Eq	M
ITIS002	*Fucino Basin*	28.0	15.5	1.5-14.9	135	60	270	1.06	1.2-1.7	13 January 1915	6.7
ITIS028	*Barrea*	10.0	7.5	5.0-10.7	152	50	264	0.27	0.1-1.0	7 May 1984	5.8
ITIS015	*Montereale Basin*	23.4	13.6	3.0-13.4	132	50	270	0.72	0.1-1.0	2 February 1703	6.5
ITIS131	*Paganica*	14.0	9.5	3.0-9.5	133	43	275	0.60	0.1-1.0*	6 April 2009	6.3
ITIS003	*Aremogna-Cinque Miglia*	20.0	12.2	3.0-12.3	144	50	270	0.66	0.1-0.6	800 B.C-1030 A.D.	6.4
ITIS132	*San Pio delle Camere*	16.2	10.5	0.8-8.7	127	50	270	0.50	0.1-1.0	Unknown	6.2
ITIS027	*Sulmona Basin*	20.0	12.2	1.0-11.6	135	60	270	0.66	0.6-0.7	3 December 1315	6.4
ITIS016	*Norcia Basin*	25.0	13.6	3.0-13.4	150	50	270	0.64	0.1-0.6	14 January 1703	6.5

Table 8

ID	Change	What/why
		Individual Seismogenic Source
ITIS131	New	Based on observations following the 6 April 2009 earthquake.
ITIS132	New	According to Di Bucci *et alii* (2011).
ITIS015	Modified	Minimum depth (shifted downwards), dip (lowered), strike (rotated counter clockwise).
ITIS016	Modified	Minimum depth (shifted downwards), dip (lowered), strike (rotated counter clockwise).
ITIS002	Modified	Depth (shifted downwards), strike (rotated counter clockwise).
ITIS003	Modified	Minimum depth (shifted downwards), dip (lowered), strike (rotated counter clockwise).
ITIS001	Deleted	Following reconsideration of the regional structural and seismotectonic model.
ITIS025	Deleted	Depth range not compatible with new seismological and geological data.
ITIS026	Deleted	Depth range not compatible with new seismological and geological data.
		Composite Seismogenic Source
ITCS013	Modified	Lengthened northwest-ward to include ITIS131 and ITIS015. M_w (raised), depth range (shifted downwards) and dip (lowered).
ITCS025	Modified	Shortened in its northwestern end to terminate close to Olevano-Antrodoco-Sibillini Line. Dip (lowered) and strike (counter clockwise).
ITCS028	Modified	Lengthened southeast-ward. M_w (decreased), depth range (deepened minimum depth), strike and dip.
ITCS040	Modified	Shortened in its northwestern end to include ITIS132. M_w (decreased), depth range (shifted downwards) and dip.

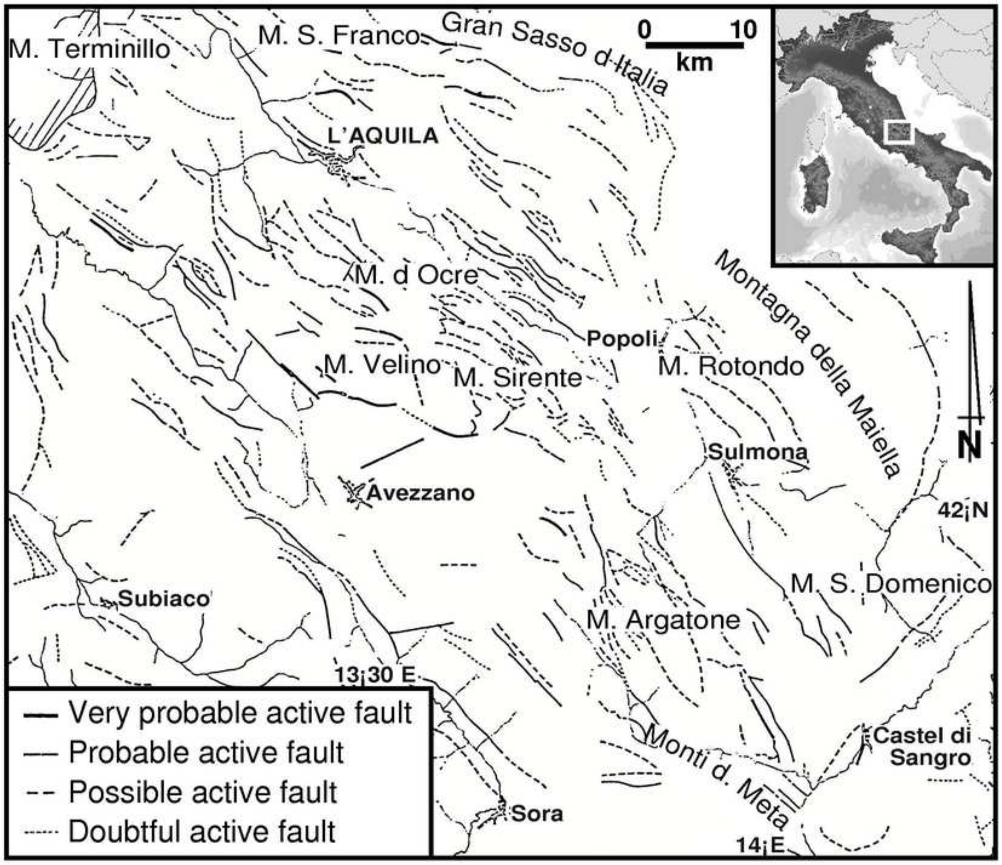

Figure 1 - Active or potentially active faults (from BOSI, 1975, modified and adapted).
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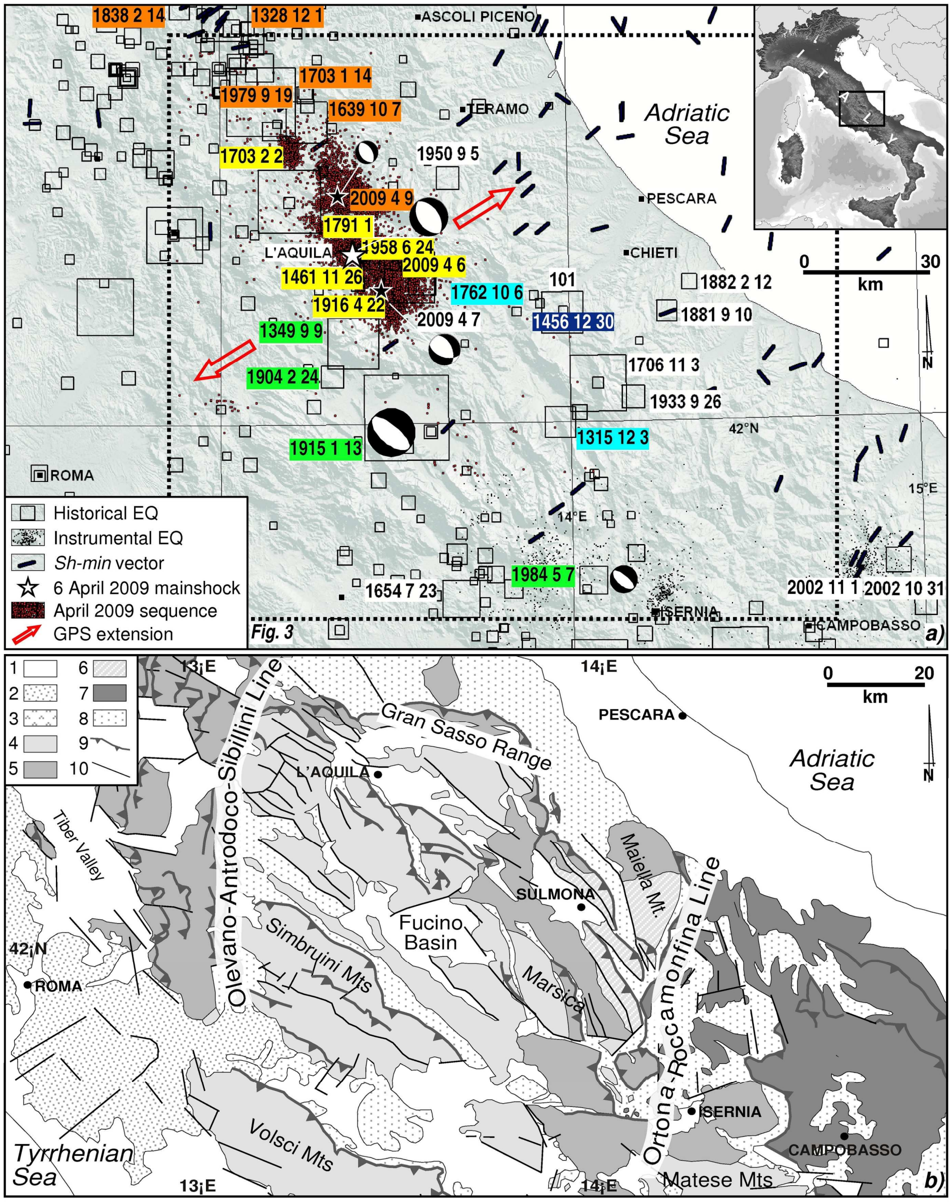

Figure 2 - a) Historical and instrumental earthquakes that have affected the Abruzzi Apennines and its surroundings. Notice the concentration of the largest events along the backbone of the Apennines.
Credits: macroseismic earthquake data from GRUPPO DI LAVORO CPTI (2004); instrumental seismicity from CASTELLO et alii (2006); Sh-min vectors (cumulative from borehole breakouts, focal mechanisms, paleoseismology) from MONTONE et alii (2004) and MARIUCCI et alii (2010).
The small dots show the seismic sequence preceding and following the 6 April 2009, L'Aquila earthquake (Mw 6.3), as recorded from 1 April to 31 July by the INGV national seismic network (ISIDE, 2010); the epicenter of the 6 April 2009 mainshock is shown by the larger white star; the smaller black stars show the epicenters of the 7 April (Mw 5.7, to the south), and of the 9 April (Mw 5.4, to the north) earthquakes, respectively.
Focal mechanisms by authors listed in Table 2. Present-day extensional axis (red arrows) arrows from SERPELLONI et alii (2005). Labelled earthquakes are the key ones (both historical and

instrumental) that have occurred within the study area; those with colored background are associated with the following DISS Composite Seismogenic Sources: ITCS025 (green), ITCS013 (yellow), ITCS028 (orange), and ITCS040 (cyan), respectively (see § 5). Location of the 1456 earthquake (white text in blue label) is from FRACASSI & VALENSISE (2007).
b) Geological summary of the central Apennines and its environs (modified, from DI BUCCI et alii, 2006). Notice how the Olevano-Antrodoco-Sibillini Line (auct., see PATACCA et alii, 1990) to the north, and the Ortona-Roccamonfina Line (auct., see LOCARDI, 1988) to the south border the Abruzzi Apennines and its large normal fault systems discussed in this work.
Key: 1) marine and continental clastic deposits (Pliocene-Quaternary); 2) Volcanics (Pleistocene); 3) clayey and carbonate turbidites (Cretaceous-Eocene); 4) Apennine carbonate platform; 5) Apennine slope and margin deposits (Lias-Miocene); 6) Apulia carbonate platform and slope deposits (Trias-Miocene); 7) Molise-Sannio-Lagonegro pelagic deposits (Meso-Cenozoic); 8) syn-orogenic hemi-pelagic and turbiditic sequences (Tortonian-Pliocene); 9) thrust faults; 10) normal faults.
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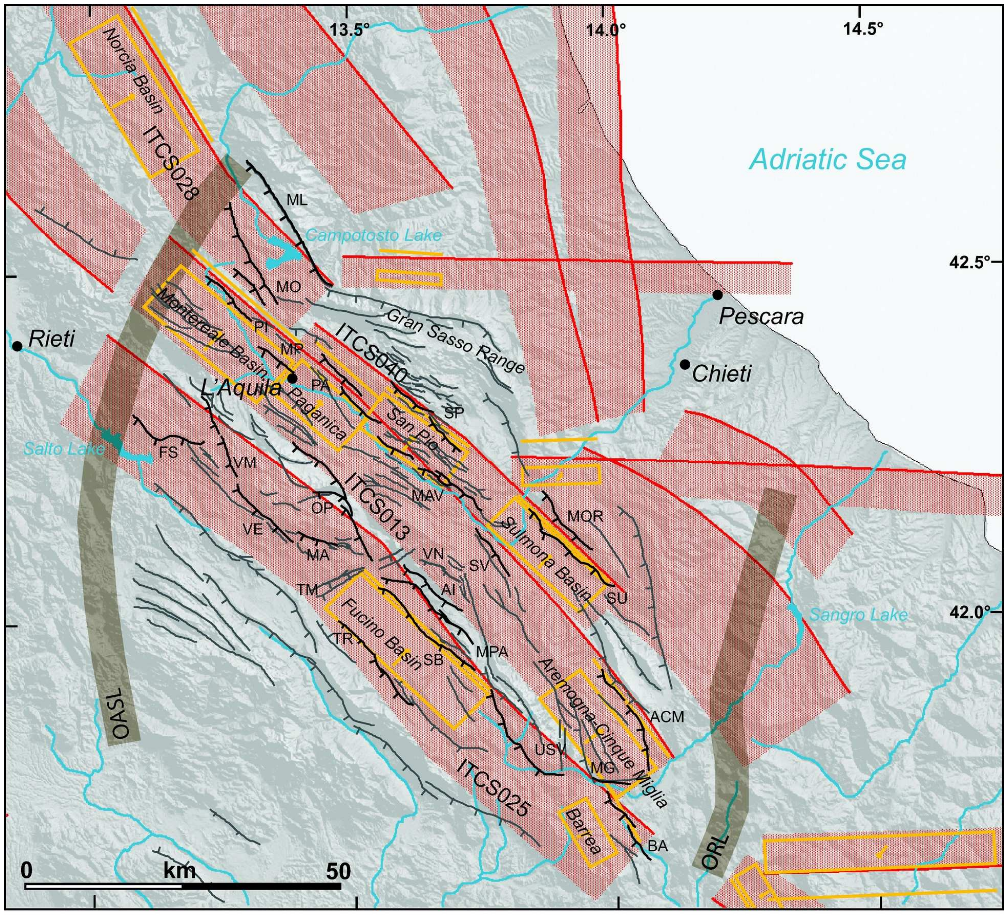

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