DOI: 10.4408/IJEGE.2021-01.S-12

CAPABLE FAULTS AND SEISMOGENIC SOURCES: ASSESSING ACTIVITY AND SEISMOGENIC BEHAVIOR FOR ENGINEERING PRACTICES. CASES FROM CENTRAL ITALY

Deborah MACERONI(*;**), Emanuela FALCUCCI(**), Stefano GORI(**), Fabrizio GALADINI(**), Marco MORO(*,**) & Michele SAROLI(*;**)

(*)Università degli Studi di Cassino e del Lazio Meridionale - DICeM - Cassino, Italy
(**)INGV - Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy
Corresponding author: deborah.maceroni@unicas.it

EXTENDED ABSTRACT

L'espressione "faglia attiva e capace" (FAC) definisce una faglia in grado di produrre dislocazioni/deformazioni permanenti della superficie topografica, mentre per "sorgente sismogenetica" (SS) si intende una struttura tettonica in grado di generare terremoti. Tuttavia, qualora la rottura cosismica in profondità di una SS raggiunga la superficie del suolo, essa è in grado di dislocarla/deformarla in maniera permanente.

Di conseguenza, i due concetti geologici possono essere relazionabili fra loro in quanto una FAC può rappresentare l'espressione diretta in superficie di una SS, in funzione delle caratteristiche geometriche, cinematiche e della magnitudo di un terremoto da essa generato. Nel caso di FAC che siano espressione superficiale di SS, sarebbe possibile definire attraverso studi di "superficie" le caratteristiche delle SS e di conseguenza valutarne il potenziale sismogenetico e di fagliazione. Le sequenze sismiche dell'Italia centrale del 2009 e del 2016-2017 sono state causate dall'attivazione di SS estensionali.

Queste hanno generato rotture superficiali lungo faglie che mostrano attività Quaternaria e tardo-Quaternaria in superficie, testimoniata dalla dislocazione di depositi e/o forme del paesaggio e riconducibile a ripetute attivazioni delle relative SS profonde nel corso di decine o centinaia di migliaia di anni. Queste faglie potevano, quindi, essere definite FAC già prima delle sequenze sismiche. Alcune rotture superficiali prodotte dalle sequenze sismiche hanno coinvolto strutture antropiche, fra le quali l'acquedotto del Gran Sasso e il Viadotto "Vigne Basse", durante il terremoto del 6 aprile 2009 (MW 6.2) che attraversano la faglia di Paganica, oppure la Galleria di San Benedetto che attraversa una delle faglie antitetiche del sistema di faglie del Mt. Vettore-Mt. Bove, in occasione del terremoto del 30 ottobre 2016 (MW 6.5).

La raccolta e l'analisi dei dati di letteratura delle SS responsabili degli eventi sismici dell'Italia centrale mostra che ancora non vi è accordo nella comunità scientifica nel porre in relazione le FAC con le SS e nel definire quali FAC rappresentino effettivamente l'espressione superficiale delle singole SS. Ad oggi, in Italia, esistono due database distinti: il Catalogo delle Faglie Capaci (ITHACA), realizzato dall'ISPRA, che consente di ricavare informazioni utili a valutazioni sulla pericolosità da fagliazione di superficie ed il Database delle Sorgenti Sismogenetiche (DISS), realizzato dall'INGV, che fornisce altresì informazioni utili alla definizione delle magnitudo massime attese in una determinata area del territorio nazionale. La netta separazione dei due database comporta che non sia esplicitamente affrontato il tema della correlazione dei concetti di FAC e SS. Come menzionato sopra, nonostante i due database esprimano concetti geologici relazionabili fra loro, dalla loro consultazione emergono alcune difformità concettuali e criticità che rendono problematica la loro sovrapposizione concettuale e fattuale.

La lettura di ITHACA, a volte, non consente, ad esempio, di comprendere pienamente quali siano i criteri utilizzati per definire una faglia come capace e come questa possa essere l'espressione in superficie di una SS. Per ciò che riguarda il DISS, per contro, per un utente non è di sempre facile discernimento su come sia stata definita una SS in una determinata area. Questo comporta la necessità di definire un approccio metodologico chiaro e ben definito che permetta di valutare se una FAC possa essere espressione superficiale di una SS. Per esempio, prima della sequenza sismica del 2016-2017, studi geologici, geomorfologici e paleosismologici avevano permesso di considerare il sistema di faglia Mt. Vettore-Mt. Bove come FAC espressione di una SS dalla quale ci si poteva attendere un terremoto di magnitudo circa 6.5. Effettivamente, tale sistema di faglia si è attivato in occasione della sequenza sismica del 2016-2017 e, in particolare, ha generato la scossa principale del 30 ottobre 2016 di MW 6.5, appunto.

L'approccio utilizzato ha permesso agli autori di considerare una certa faglia come una FAC e, in funzione della lunghezza dell'espressione in superficie, di associargli un certo potenziale sismogenetico.

Di conseguenza, tale approccio permetterebbe di realizzare un catalogo che concettualmente unisca le principali FAC dell'Appennino centrale con le SS, con ciò giustapponendo parametri sismogenetici a informazioni inerenti le dislocazioni permanenti del suolo, in termini di distribuzione ed entità.

ABSTRACT

An active fault is defined capable (FAC) when, in fact, it is capable of offsetting the ground surface; while a seismogenic source (SS) is a tectonic structure that generates earthquakes and, under certain conditions, displaces the ground when the deep coseismic rupture propagates up to the surface. Therefore, the FACs may be considered as the surficial expression of SSs. The seismic sequences of central Italy in 2009 and 2016-2017 showed the importance to define and locate "in advance" FACs and SSs in any given area. However, the analysis of the scientific literature shows that the conceptual difference between the FAC and the SS is still marked in Italy. This is demonstrated by the availability of two distinct national databases, that deal separately with the FACs (ITHACA) and the SSs (DISS). This article analyses ITHACA and DISS in the 2009 and 2016-2017 seismic sequences epicentral areas and identifies possible conceptual differences and similarities between FAC and SS. It highlights the need of a well-defined methodological approach that can define and map a FAC as a surficial expression of a SS, to which a certain seismogenic and surface faulting potential can be associated.

Keywords: *active and capable faults, seismogenic sources, central Apennines, seismic sequences, methodology*

INTRODUCTION

The 2009 and 2016-2017 seismic sequences of central Italy were caused by the activation of extensional seismogenic sources (SS) that caused impressive surface ruptures along normal faults showing evidence of Late Quaternary activity. These coseismic ruptures have confirmed the results published by some authors, regarding the seismogenic behaviour and potential of these faults, prior to the seismic events, especially that of Mt.Vettore-Mt.Bove fault system and the Amatrice fault. This work examines the geological information available on normal faults in the epicentral areas. It investigates the conceptual difference between the active and capable fault (FAC) and the SS that still exists in the Italian practice. In Italy, two databases separately deal with the FACs and the SSs, ITHACA (ITaly HAzard from CApable faults), compiled by ISPRA (Istituto Superiore per la Protezione Ambientale), and DISS (Database of Individual Seismogenic Sources), compiled by Istituto Nazionale di Geofisica e Vulcanologia (INGV), respectively. In several cases, these databases show the conceptual and factual differences and difficulties in relating FAC and SS to each other. Here we analyse the information in ITHACA and DISS regarding the FACs and the SSs located in the epicentral areas of the 2009 and the 2016-2017 seismic sequences, while highlighting the differences and criticalities that do not always guarantee the clarification what the conceptual and factual bases are for the proposed definition of FACs and SSs in any given area. A robust multidisciplinary approach for assessing the "actual" relation between the two "subjects" is necessary to achieve a reliable superposition of FACs and SSs. This would allow to define the seismic behaviour and the seismic potential of a given FAC, considered as the surficial expression of a SS. This methodology would allow to create a future map that shows how and why FACs can be related to SSs and provide useful information for assessing the surface faulting hazard together with input parameters necessary for the definition of the seismic action.

GEOLOGICAL AND SEISMOTECTONIC BACKGROUND

The geological and structural setting of the Central Apennines derives from the superposition of two subsequent geodynamic phases. The compressive phase began in the Oligocene with the formation of NE-verging thrust fronts, which placed the Meso-Cenozoic successions in contact with the Miocene clayey-arenaceous flysch (e.g. Cipollari & Cosentino, 1995; Cosentino *et alii*, 2010). The extensional phase began in the Late Pliocene-Early Pleistocene with the formation of NW-SE trending and mainly SW dipping normal faults, which displaced the pre-existing compressive structures and have been responsible for the formation of intermontane basins filled by Plio-Quaternary continental sediments (e.g. Galadini & Messina, 2004). Some of the normal faults showing geological evidence of Late Pleistocene-Holocene activity have been responsible for the strongest earthquakes of the past centuries reported in the Italian seismic catalogue (Rovida *et alii*, 2020), such as those that occurred on January 13, 1915 (~Mw 7.1) in the Fucino area, January 14, 1703 (~Mw 6.9) in the Norcia basin and in February 2, 1703 (~Mw 6.7) in the L'Aquila basin (e.g. Galadini & Galli, 2000; Barchi *et alii*, 2000; Boncio *et alii*, 2004; Galli *et alii*, 2008; Galadini *et alii*, 2018) (Fig.1). Faults showing evidence of Late Pleistocene-Holocene activity are generally considered as surficial expression of SSs able to generate Mw ≥5.5-6.0 earthquakes (e.g. Galadini & Galli, 2000; Galadini *et alii*, 2001; Boncio *et alii*, 2004; Galli *et alii,* 2008; Falcucci *et alii*, 2016; Valentini *et alii*, 2017; Galli, 2020).

The 2009 and 2016-2017 seismic sequences were caused by SSs to which known Quaternary normal faults can be related. The Paganica fault is characterized by Quaternary activity (e.g. Bagnaia *et alii*., 1992; Vezzani & Ghisetti, 1998) and it is presently considered the source of the April 6, 2009 earthquake (MW6.2) (e.g. Boncio *et alii,* 2010; Galli *et alii,* 2010; Gori *et alii,* 2012). Before the earthquake, the fault was not considered as the surficial expression of a SS potentially able to generate Mw> 6.5 earthquakes (Galadini & Galli, 2000; Galadini *et alii,* 2001), while other authors defined it as a single 13-km-long independent fault segment, which probably became active during the 1461 (Mw 6.5) and 1762 (Mw 5.5) earthquakes (e.g. Boncio *et alii*, 2004).

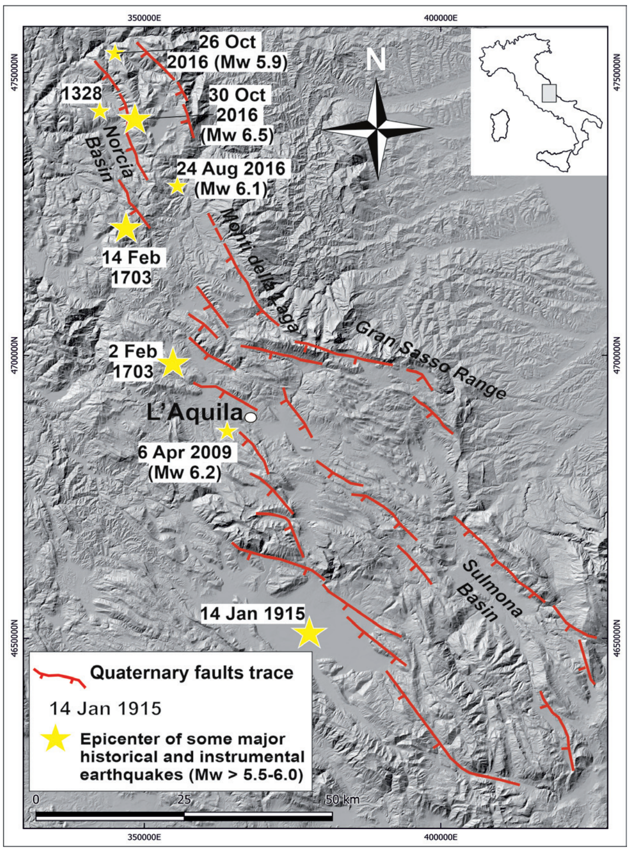

Fig. 1 - Digital Elevation Model (DEM) (Tarquini & Nannipieri, 2017) on which the Quaternary faults trace was reported (e.g. Galadini & Galli, 2000; Boncio et alii, 2004; Falcucci et alii, 2011). The yellow stars indicate the epicenters of some major historical and instrumental earthquakes occurred in the central Apennines

The August 24, 2016 earthquake (MW 6.18) was partly caused by the Amatrice fault rupture, defined inactive or with reduced activity during the Late Quaternary and for this reason not "capable" (Galadini & Messina, 2001). On the contrary, the Campotosto fault, which affects the southern sector of the south-western flank of the Laga Mts., is considered an active fault potentially able to generate Mw ~ 6.6 earthquakes, and related surface faulting (e.g. Galadini & Galli, 2003). However, according to other authors the Amatrice and Campotosto faults were the surficial expression of a single SS, able to generate Mw ≥ 6.5 earthquakes (Boncio *et alii*., 2004; Blumetti & Guerrieri, 2007; Valentini *et alii*, 2017).

The October 30, 2016 earthquake (MW6.5) was caused by the Mt. Vettore-Mt. Bove fault system, whose Late Quaternary-Holocene activity was defined by several authors (e.g. Calamita & Pizzi, 1992; Coltorti & Farabollini, 1995; Cello *et alii.*, 1997, Galadini & Galli, 2000; 2003; Boncio *et alii*, 2004), and potentially able to generate MW~6.5 earthquakes (Galadini & Galli, 2003). No historical earthquake was associated with this fault, suggesting it to be considered as "silent" prior to the October 30, 2016 earthquake.

FACS AND SSS: CASES STUDY FOR THE 2009 AND 2016 EARTHQUAKES

Many geological, seismological and geodetic data state that the Paganica fault is the FAC that represents the surficial expression of the SS of the April 6, 2009 (Mw 6.2) earthquake (e.g. Galli *et alii,* 2010; Gori *et alii*, 2012; Lavecchia *et alii*, 2012; Moro *et alii*, 2013). Evidence of coseismic surface rupture was detected along this FAC after the 2009 seismic event. Two of the most impressive effects of surface ruptures were the displacement of the Gran Sasso water pipeline and of the "Vigne Basse" viaduct along the motorway between L'Aquila and Teramo (e.g. Falcucci *et alii*, 2009). For the sake of completeness, Bonini *et alii* (2014) considered the coseismic surface ruptures not directly related to the motion of the seismogenic source. They maintained that the Paganica SS was a blind fault, with the coseismic breaks being just secondary effects. After the 2009 earthquake, the surface trace of the Paganica fault was defined by several authors, with a length that ranged between ca. 10-13 km (e.g. Falcucci *et alii*, 2009; Boncio *et alii*, 2010; EMERGEO Working Group, 2010; Gori *et alii*, 2012) and ca.19 km (including the San Demetrio ne'Vestini fault: e.g. Galli *et alii*, 2010; Giaccio e*t alii*, 2012; Civico *et alii*, 2015).

On August 24, 2016, two separated synchronous ruptures occurred (Tinti *et alii*., 2016): the larger one, to the north, was caused by the slip of the southern tip of the Mt.Vettore-Mt.Bove fault system (that released a seismic moment of MW 6.0), and the smaller one, to the south, involved the Amatrice fault (that released a seismic moment of MW 5.9) (e.g. Cheloni *et alii*, 2017). Surface faulting occurred along the southern sector of the Mt. Vettore-Mt. Bove fault system, whereas no evidence of surface rupture was detected along the Amatrice fault (EMERGEO Working Group, 2016). These observations were consistent with the long-term kinematic history defined for both faults by previous geological data (Galadini & Messina, 2001; Galadini & Galli, 2003).

On October 30, 2016, the Mt. Vettore-Mt. Bove fault system became active again, producing a MW 6.5 earthquake, in accordance with the results published 20 years before by Galli & Galadini (1999) and Galadini & Galli (2003). After this earthquake, surface faulting was detected along the Mt.Vettore-Mt.Bove fault system, along a number of segments and splays composing the tectonic structure. Among these, there was an antithetic branch which ruptured the San Benedetto Gallery along the National road 685 (Cheloni *et alii*, 2018; Galli *et alii,* 2019).

On April 9, 2009 and January 18, 2017, the Campotosto fault generated some moderate seismic events (Mw 5.0-5.5). Some authors defined the Campotosto fault as the surface expression of a deep SS, with seismogenic potential able to generate earthquakes with Mw~6.5 (e.g. Galadini & Galli, 2003; Falcucci *et alii*., 2018; Cheloni *et alii*., 2019). Other authors defined that the deep Campotosto seismogenic fault might not be connected to the fault at surface, significantly reducing the seismogenic potential of this fault (Bigi *et alii*, 2013; Buttinelli *et alii*, 2018; Tondi *et alii*, 2020).

ITHACA AND DISS: ANALYSIS AND COMPARISON OF TWO DATABASES

The available literature data about FACs and SSs related to the 2009 and the 2016-2017 seismic events show that part of the scientific community disagrees on two aspects: i) to relate the surficial FACs with a related deep SS and ii) to define which FACs represent the surficial expression of the same, single SS. This dual aspect represents a fundamental prerequisite for the assessment of the seismic and surface faulting potential of a FAC/SS, since the seismogenic parameters can be derived from studies at surface only if the relationship between FAC and SS have been previously stated. This seems to be the only way to obtain information suitable for engineering purposes.

Presently, two Italian databases, dealing with FACs and SSs, are available. The ITHACA database includes information about potential FACs and the related surface faulting hazard. The terminology used in ITHACA derives from the IAEA Technical Guidelines (IAEA, 2010; 2015), that define as capable a fault which produced surface displacement in the last 125ka. It is, therefore, supposed to be consistent with the present tectonic regime. In ITHACA, the FACs are defined as "primary" or "secondary". According to the IAEA, "*Earthquake effects*, *Primary"* is defined as "*The surface expression of seismogenic tectonic source (including surface faulting, surface uplift and subsidence). Primary effects gave place to characteristic tectonic landforms (e.g. fault scarps, pressure ridges) and eventually, particular landform assemblages of seismic origin (i.e. seismic landscapes)"*.

The *"Earthquake effects, Secondary"* are instead defined as *"Phenomena generally induced by seismic ground shaking, including e.g. liquefaction, mass movements and tsunamis. (See earthquake environmental effects). Exclude coseismic displacement on the earthquake source (main/primary) fault and on the structurally associated secondary structures"*. In this latter definition, the IAEA defines the primary fault as the earthquake fault.

The DISS, instead, provides seismotectonic information (e.g. geometry of the source and expected maximum magnitude) from which data for the assessment of seismic hazard, or expected ground shaking, can be derived (e.g. Valensise & Pantosti, 2001a; Basili *et alii*, 2008; Basili *et alii*, 2009). The mapped SSs in DISS are identified as: i) Individual Seismogenic Sources (ISS), characterized by defined kinematic and geometric parameters, and assumed to be sources of specific coseismic energy release. An ISS is identified by a rectangle representing the fault projection at surface, as well as a line representing the interception of fault at surface, automatically calculated from fault geometry and parameters; ii) Composite Seismogenic Sources (CSS) are drawn in areas where SS of specific geometry and related to earthquakes of specific size cannot be traced, according to DISS's compilers. The associated magnitude is estimated using information available in the seismic catalogue; iii) Debated Seismogenic Sources (DSS), include some of the active faults defined as potential seismic sources in the scientific literature, but are not considered by the DISS's authors reliable enough for representation in the database. The reliability of geometric and kinematic parameters of ISS and CSS is based on the data quality and type. However, the reliability gradually decreases from: 1) literature data (LD), 2) original unpublished data (OD), 3) empirical relations (ER), 4) analytical relations (AR) (i.e. those that derive from the equation of the seismic moment) and 5) expert judgment (EJ) (Basili *et alii*, 2008).

ITHACA and DISS collect tectonic and structural information that is largely complementary to both: a primary FAC of ITHACA might represent the surficial expression of an ISS included in DISS. However, taking into consideration the 2009 and 2016-2017 seismic sequences epicentral areas, a spatial and consequently conceptual overlap between FACs of ITHACA and SSs of DISS not always appears. For example, not only a primary FACs of ITHACA (defined to be the direct manifestation of a SS, according to IAEA Guidelines) coincide with the supposed surficial trace of a ISS of DISS in the L'Aquila-Paganica basin (Fig.2 a,b,c), but secondary FACs geometrically also match the supposed surficial trace of a ISS of DISS. Moreover, in other cases (Amatrice basin and Campotosto area; Mt. Vettore-Mt. Bove southern-western slopes), primary FACs of ITHACA match DSSs in DISS, while these should be related to an ISS if they adopted the same approach (Fig.2 d,e). Therefore, the simple overlap of elements in ITHACA and DISS hinders the direct assumption of the FACs as the surficial expression of SSs in any given area.

In order to understand which grounds the definition of FACs and SSs in ITHACA and DISS is based on, we analysed the two databases for the epicentral areas of the 2009 and 2016-2017 earthquakes, in the L'Aquila-Paganica and in the Amatrice-Campotosto basins, respectively. The information about some FACs in the L'Aquila-Paganica and Amatrice-Campotosto basins, deriving from ITHACA, has been reported in Tab. 1.

The analysis of ITHACA shows that some fundamental works, dealing with the evidence of Late Quaternary-Holocene activity of the faults bounding the L'Aquila and Paganica basins, (e.g. Moro *et alii,* 2002; Falcucci *et alii*, 2009; Galli *et alii*,

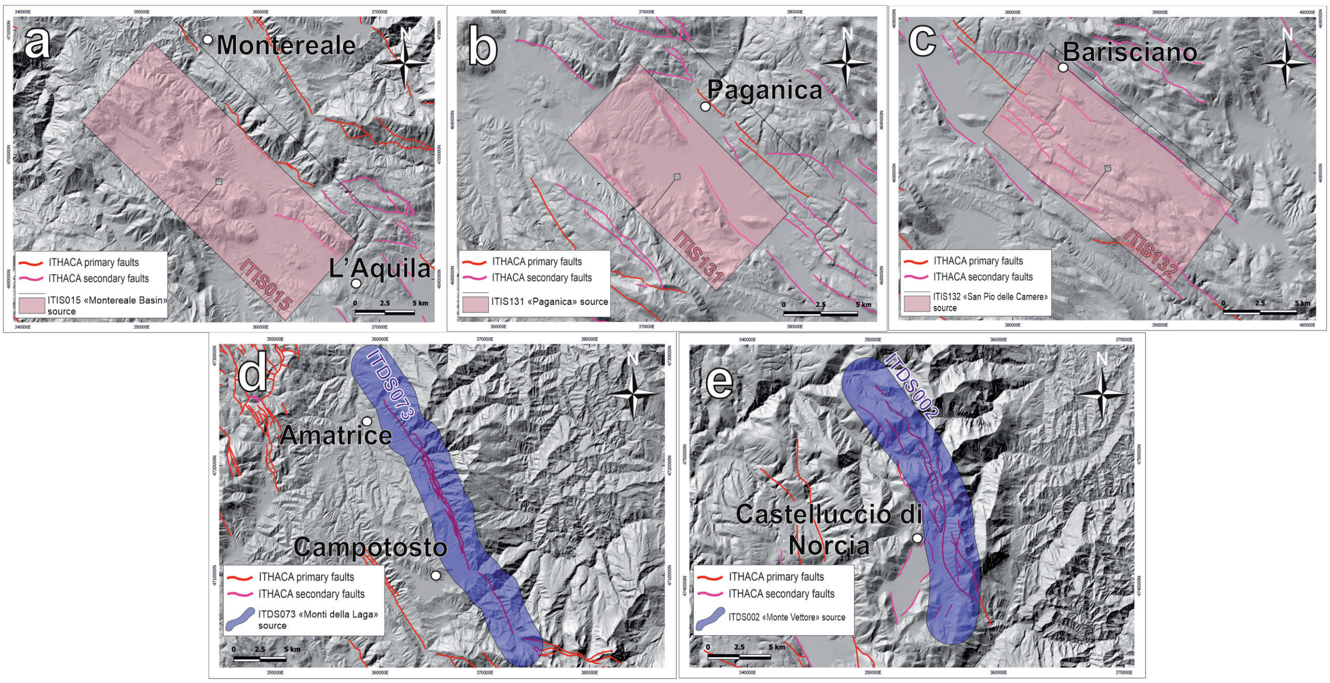

Fig. 2 - Overlap between a) the primary FACs of ITHACA and the "Montereale Basin" source of DISS; b) the primary FACs of ITHACA and the "Paganica" source of DISS; c) the secondary FACs of ITHACA and the "San Pio delle Camere" source of DISS; d) the primary FACs of ITHACA and the "Monti della Laga" source and e) the primary FACs of ITHACA and the "Monte Vettore" source

2011; Giaccio *et alii*, 2012; Gori *et alii*, 2015; Moro *et alii*, 2016) lack in the Reference section. As for the Amatrice and Campotosto basins, the 1639 earthquake is associated to both the Amatrice and Campotosto FACs and the "Slip Parameters" section presents all the fields filled in. In this case too, some works that deal with the Amatrice and Campotosto faults are missing in the Reference section (e.g. Galadini & Messina, 2001; Falcucci *et alii*, 2016; 2018).

The L'Aquila and Paganica basins are characterized by three ISS in DISS. The "Montereale Basin" source was represented by the compilers as faults activated during the February 2, 1703 earthquake (Blumetti, 1995; Cello *et alii*, 1998). In this case, most of the Quality parameters that indicate the degree of reliability of the chosen information, especially that which describe the seismogenic behavior of the source, are considered of low quality. OD parameters not supported by any data are also included. Only Length, Min. Depth, Strike and Dip parameters are "Based on geological data from various authors" with LD quality, without specifying the source-literature. Surprisingly, Moro *et alii* (2002) has not been included among the cited papers, despite this being the only reference that deals with paleoseismological evidence of fault activity (such as the 1703 event), published before the last update of the source, not even the work by Galli *et alii* (2010) published after the last update.

Kinematic and geometric parameters of the "Paganica" source are mainly characterized by a LD quality and are defined on seismological, geodetic and geological data, published after the earthquake of April 6, 2009. However, only for Max Depth, Strike and Slip Rate parameters the references are defined (e.g. Atzori *et alii,* 2009; Chiarabba *et alii*, 2009; Cinti *et alii*, 2010). Compilers indicate that a consensus can be recognised in the scientific community regarding the fact that the deep SS propagated the coseismic rupture up to the surface along the Paganica fault. They also state that "this fault, however, did not display a well-defined morphotectonic evidence". By contrast, literature pointing out that the coseismic surface ruptures, that should be attributed to secondary effects and not related to the direct seismogenic displacement of the seismogenic fault (e.g. Bonini *et alii*, 2014), are not mentioned in the text, but are mentioned in the References.

The "San Pio delle Camere" ISS is defined in DISS on the basis of Di Bucci *et alii* (2011) and most of the parameters (Length, Rake, etc…) present a LD (that is, high quality). Nonetheless, the Slip per Event, Slip Rate, Recurrence and Magnitude parameters have a low Quality, defined as ER and EJ quality. However, it is worth noting that all the indication of activity of this fault claimed by Di Bucci *et alii* (2011), have been confuted by Messina *et alii* (2011), on the base of geological surface data.

The "Monti della Laga" source is represented in DISS as a DSS. Following the 2016-2017 seismic sequence, the compilers state that, given the contrasting evidence about surface ruptures along the Monte Gorzano fault, they "see no reason to modify

Fault Code	Rank	Reference	Mapping Scale	Last Activity	Evidence For Capability	Applied Tecnique	Study Quality
21402-21406 (Capitignano faults)	Primary	No	No	No	No	No	High
21401 (Montereale fault)	Primary	Yes	No	Prehistory-Neolithic (3,000-9,000) *	Displacement of Quaternary deposits and/or land forms	No	High
22500-22502 (Mt.Marine faults)	Primary	Yes	Yes	Prehistory-Neolithic (3,000-9,000) **	Earthquake	Field Studies (absent supporting data)	High
22100 (Mt.Pettino fault)	Secondary	Yes	No	Latest glacial (9.000-15,000) ***	Earthquake	No	High
23101 (Paganica fault)	Primary	Yes	Yes	Historical (< 3,0000) ****	Earthquake	Paleosismology (absent supporting data)	High
23110,23117, 23111,22106	Secondary	No	No	No	No	No	Low
23120,23129, 23100 (San Pio delle Camere faults)	Secondary	No	No	Latest glacial (9,000-15,000)	Displacement of Latest Pleistocene-Holocene deposits and/or landforms	Field Studies (absent supporting data)	Fair
22000-22024 (Campotosto faults)	Primary	Yes	Yes	Holocene generic (<10,000)	Displacement of latest Pleistocene - Holocene deposits and/or landforms".	Paleosismology (absent supporting data)	High
22025-22028 (Amatrice faults)	Primary	Yes	Yes	125,000-300, 000	Displacement of middle-late Pleistocene deposits and/or landforms	Paleosismology (absent supporting data)	High

*The Note field specifies "The Norcia earthquake of 14th January 1703". **The Note field specifies "The Norcia earthquake of 14th January 1703 and 19th September 1979 according to Blumetti (1991)". This latter is not present in the Reference section. ***The Note field specifies "effects of the Aquila earthquake of February 2, 1703 (Bagnaia *et alii*, 1996). ****The Note field specifies "the 2009 and 1703 earthquakes"

Tab. 1 - The information content of ITHACA capable faults of the L'Aquila-Paganica and Amatrice-Campotosto basins

the assignment of the Mt. Gorzano fault to the Debated source category". In the References section, some works are missing, e.g. Galadini & Messina (2001) and Falcucci *et alii* (2016), published before the last update of the source.

DISCUSSIONS AND CONCLUSIONS

The analysis of the two databases reveals some unclear aspects both for the FACs of ITHACA and for the SSs of DISS. The critical issues identified with ITHACA's analysis can be divided into two categories. The first one covers missing available data – which should not be expected when we consider the compilation nature of the database – which allows users to understand the reason why a given FAC is reported. The authors state that the database "*is constantly updated and can never be* *considered complete or definitive*". However, some works are missing in the provided literature, even after the latest update. Moreover, although the compilers state that the database "*does not represent the totality of capable faults potentially present on the national territory, but only those for which there is a study, even at a minimum level and therefore a bibliographic reference*", Tab. 1 clearly shows that references are lacking for several FACs. For this reason, it is not always clear which elements have been used to represent those FACs, reported in the database, for which the related literature has not been reported. This issue is rarely solved in the database through other information provided by the compilers. Moreover, the detail of mapping of the different faults in the catalogue, as the authors explain, is based on the scale at which the data were published, represented as "Mapping Scale" field; furthermore, the compilers state that "[...] *the maximum resolution at which being able to use the data cannot in any case be higher than the mapping scale* ". However, as shown in Tab. 1, the "Mapping Scale" field is sometimes incomplete. Therefore, information, that is often necessary for users, may be absent. Among the substantial missing information, as shown in Tab. 1, there may also be the data ("Applied Technique" field) that support the identification and mapping of a given FAC.

The second category covers the absence of criteria for assessing reliability and hierarchization of the faults for some FACs. The compilers state that "[...] *The detail is a function of the quality of the surveys that have been carried out (reported in the Study Quality field)"*. This suggests that the "detail" relates to the "Applied Technique" field and to the "References" section, necessary to understand the reliability of the data. This could mean that a fault that has an "Applied Technique" field and a "References" section that reports several works should have a High "Study Quality". This occurs, for example, for all faults in the Amatrice and Campotosto sectors (Tab. 1). However, the primary Capitignano faults also have a High "Study Quality" even though both the "References" section and the "Applied Tecnique" field are missing at the moment of writing this paper (Tab. 1). Therefore, the basis of the classification as "High" of the Study Quality are not always clear. The difference between the knowledge about- and the information available regarding the Capitignano faults, and those regarding the Campotosto and Amatrice faults, is presently unclear. Furthermore, it has been observed that some FACs, for instance, the 23110, 23117, 23111 and 22106, have a Low "Study Quality" despite having an information content similar to that of the Capitignano faults (Tab. 1). Consequently, the grounds for attributing the quality as "Low" and the difference with faults defined as "High" are unclear. Another issue concerns the hierarchization of the FACs in "primary" and "secondary". One may consider three factors. Firstly, the Study Quality and information content. The Capitignano faults are represented as "primary" despite having an incomplete information content, but a High "Study Quality". The same rank is attributed to the Paganica fault which, on the contrary, shows a complete information content, evidence for associated earthquakes and a High "Study Quality" (Tab. 1). Hence, since the same "primary" rank attributed to the Capitignano faults and Paganica fault does not depend on the differently compiled fields, it may seem to depend only on the "Study Quality" fields, which is defined as High for both structures. Nonetheless, as expressed above, it is not clear how the compilers attributed the same "Study Quality" to the faults, without having the field compiled with the same detail (or not compiled at all). Secondly, the length of the FACs. Faults 21401 and 22100 in the L'Aquila-Paganica basin, displaying highly comparable information contents, are classified as primary and secondary, respectively. However, they have different lengths, i.e. the primary FAC shorter than the secondary one. The fault length appears to have no role in defining a FAC as primary or secondary. Another example is FAC 25000, defined as primary, whose length is the same as the 22100, defined instead as secondary, despite both having a highly comparable information content. Thirdly, the distinction as "primary" or "secondary" is based on the reference literature. Fault 22100 (Mt. Pettino fault) is classified as secondary (in the notes, "*Effects of the L'Aquila earthquake of February 2, 1703;* Bagnaia *et alii* 1996) (see Tab.1). This could suggest that the reason for the classification as "secondary" of the Mt. Pettino fault is probably a consequence of information reported in Bagnaia *et alii* (1996). However, Bagnaia *et alii* (1996) defined Mt. Pettino fault as primary. Consequently, the reason why fault 22100 has been represented as secondary does not lie in the associated literature. Finally, ITHACA uses IAEA definitions. Considering the ambiguities in ranking as primary or secondary a FAC in ITHACA, it is not clear whether and how ITHACA considers the primary FACs in relation to a possible SSs.

Two main issues derive from the analysis of DISS information content. First of all, the criteria used to distinguish the SSs. Although analysed by paleoseismological investigations, the "Monti della Laga" source was ranked as a DSS prior to the 2016-2017 seismic sequence. Considering the disagreement about the nature of the surface ruptures, which formed in 2016-2017 along the Mt. Gorzano fault, its category (i.e. DSS) was not changed after the seismic sequence. However, from the analysis of the "Comments" and "Questionnaire" sections regarding this source, the reasons for defining it as DSS before the seismic sequence are not stated by the compilers. In this light, a further unclear issue arises from the comparison of this case with that of the "San Pio delle Camere" source, in the L'Aquila basin, since scientific disagreement also concerns the reliability of the latter. In fact, in the "Comments" section of the "San Pio delle Camere" source, the compilers acknowledge that "*Messina et alii (2011) raised a number of issues that would invalidate the conclusions of Di*

Bucci et alii (2011a) on the existence and activity of the San Pio delle Camere source. In their response, Di Bucci et alii (2011b) showed recent lacustrine silts tilted toward the fault depocentre, and other lines of geological and geomorphological evidence supporting the recent activity of the source". Despite this, the SS is represented as an ISS and not as a DSS, as one would expect. Moreover, in the "Comments" and "Open Questions" sections, the criteria to define the "San Pio delle Camere" source as ISS used are unclear. The DISS compilers did not clearly state why the geological evidence and data reported to define the "San Pio delle Camere" fault, as a direct primary surface expression of an ISS, are more "reliable" than those reported in the literature for the Monti della Laga fault. The latter has the geological evidence with a comparable degree of uncertainty, but which were not considered "reliable" enough to be defined as an ISS.

Another issue concerns the geometric representation of the ISSs. The seismogenic boxes, that represent the surface projection of ISSs, are characterized by rectangles and lines; the latter define "*the ancillary geographic features calculated automatically from the fault geometry and parameters. […] They are the traces of surface-breaking faults and traces of fold axes identified by a supplemental ID that is simply an ordinal number* " (Basili *et alii*, 2009). Therefore, considering the above-mentioned ISS cases, the line paralleling the seismogenic box could/should approximate the surface expression of the SS. The automatic calculation gives little information about the real geometry of a surficial expression of an ISS. Indeed, in the case of the "Paganica" source, the DISS compilers mapped the active Paganica fault trace in red, basing this on the 2009 surface ruptures provided by EMERGEO Working Group (2009). However, the line representing the surface-breaking fault trace of the seismogenic box is located NE of the Paganica fault trace, because the line is traced as the straight projection of the planar seismogenic fault plane to the surface. This means that the surficial expression of the Paganica SS, calculated automatically by DISS from geometrical and kinematic parameters, does not match the fault path that results from geological investigations and from the coseismic surface evidence. In this light, the DISS compilers provide the low deep angle of the rupture plane as a support element to a "complex" relation between the deep SS and the surface Paganica fault that does not allow the projection of the SS with the surface Paganica fault to match. By contrast, the "San Pio delle Camere" ISS displays a trace of the surface-breaking fault that appears coinciding with the "geological" fault mapped in red, defined active by Di Bucci *et alii* (2011) because, in this case, these authors did not simply prolong the SS straight to the surface with its low deep angle, but they "impose" a verticalization of the fault plane in the last 1 km, allowing for the surface-breaking fault to match the "geological" fault. Consequently, the different approach used in the two cases described above is not clear and not stated. On the whole, we can see that the geometrical (and consequently kinematic) relationship between surface breaking faults, automatically calculated, and the fault traces at surface, known from geological data may seem quite arbitrary.

The analysis of the two databases highlights the fact that some choices in the definition of FACs and SSs are not clear and not fully explained by compilers. This suggests that expert judgment has an important and undeclared role. Consequently, some choices may appear subjective, thus hindering the attempts to establish a clear and initially declared relationship between FACs and SSs (the former being the surficial expression of the latter) reported in ITHACA and DISS, respectively.

These issues indicate that a reliable product juxtaposing FACs and SSs cannot easily be defined. Some attempts have been made in the available literature, such as those made by Falcucci *et alii* (2016), Valentini *et alii* (2017), and Faure-Walker *et alii* (2021) who defined those surface faults that can be the expression of seismogenic sources.

The evidence from the area of the 2009 and 2016-2017 earthquake sequences can provide some grounds for defining a methodological procedure, based on geological (neotectonic), seismological and geodetic data. This would be useful to draw such a unified and agreed-upon database, where the criteria are clearly stated, fully respected, univocal and univocally applied. A first approach to creating of such a database was attempted at the end of the 20th century and summarized by Galadini *et alii*, (1999), which took into consideration the available surface geological data to associate the seismic potential to each mapped fault.

AKNOWLEDGMENTS

The revisions of an anonymous reviewer improved the manuscript. The present work was carried out as part of XXXIV Ph.D. cycle, co-fi 50% INGV and 50% University of Cassino and Southern Lazio.

REFERENCES

Atzori S., Hunstad I., Chini M., Salvi S., Tolomei C., Bignami C., Stramondo S., Trasatti E., Antonioli A. & Boschi E.(2009) - *Finite fault inversion of DInSARcoseismic displacement of the 2009 L'Aquila earthquake (central Italy)*. Geophysical Research Letters; Doi: 10.1029/2009GL039293.

Bagnaia R., Blumetti A.M., De Luca G., Gorini A., Marcucci S., Marsan P., Milana G., Salvucci R. & Zambonelli E. (1996) – *Morfotettonica dei rilievi a nord della conca aquilana.* Il Quaternario, Italian Journal of Quaternary Sciences, **9** (1): 287-292.

Bagnaia R., D'epifanio A. & Sylos Labini S. (1992) – *Aquila and subequan basins: an example of Quaternary evolution in central Appennines, Italy.*

Quaternaria Nova, II: 187-209.

Barchi M, Galadini F., Lavecchia G., Messina P., Michetti A.M., Peruzza L., Pizzi A., Tondi E. & Vittori E. (2000) – *Sintesi delle conoscenze sulle faglie attive in Italia Centrale: parametrizzazione ai fini della caratterizzazione della pericolosità sismica*.CNR-GNDT, volume congiunto dei prog. 5.1.2 e 5.1.1, Roma, 62 pp.

Basili R., D'amico V., Meletti C. & Valensise G. (2017) - *Linee Guida per la redazione e le istruttorie degli studi sismotettonici relativi alle grandi dighe.* Accordo tra INGV e Direzione Generale Dighe, Ministero Infrastrutture e Trasporti (Circolare DG Dighe 27 settembre 2017).

Basili R., Kastelic V., Valensise G & Diss Working Group 2009 (2009) – *DISS3 Tutorial series: guidelines for compiling records of the database of individual seismogenic sources, version 3*. Rapporti tecnici INGV, anno 2009, numero 108.

Basili R., Tiberti M.M., Kastelic V., Romano F., Piatanesi A., Selva J. & Lorito S. (2013) – *Integrating geologic fault data into tsunami hazardstudies.* Nat. Hazards Earth Syst. Sci., **13**, 1025–1050, 2013 www.nat-hazards-earth-syst-sci.net/13/1025/2013/Doi:10.5194/nhess-13-1025-2013.

Basili, R., Valensise, G., Vannoli, P., Burrato, P., Fracassi, U., Mariano, S., Tiberti, M. M., Boschi & E. (2008) - *The Database of Individual Seismogenic Sources (DISS), version 3: summarizing 20 years of research on Italy's earthquake geology.*Tectonophysics, Doi:10.1016/j.tecto.2007.04.014.

Bigi S., Casero P., Chiarabba C. & Di Bucci D. (2013) - *Contrasting surface active faults and deep seismogenic sources unveiled by the 2009 L'Aquila earthquake sequence (Italy)*.Terra Nova, **25:** 21–29.

Blumetti A. M. & Guerrieri L. (2007) - *Fault-generated mountain fronts and the identification of fault segments: implications for seismic hazard assessment*. Boll. Soc. Geol. It. (Ital. J. Geosci.),**126** (2): 307-322.

Blumetti A. M. (1995) - *Neotectonic investigations and evidence of paleoseismicity in the epicentral area of the January-February 1703, Central Italy, earthquakes.* In: Serva L. & Slemmons D. B. (eds.): Perspectivesinpaleoseismology. Association of Engineering Geologists, spec. publ. **6**: 83-100.

Blumetti, A. M., F. Dramis & A. M. Michetti (1993) - *Fault-generated mountain fronts in the Central Apennines (Central Italy): geomorphological features and seismotectonic implications.* Earth Surf. Proc. Land., **18**: 203-223.

Boncio P., G. Lavecchia & B. Pace (2004a) - *Defining a model of 3D seismogenic sources for Seismic Hazard Assessment applications: the case of central Apennines (Italy)*. J. Seism., **8**, 407–425.

Boncio P., G. Lavecchia, G. Milana & B. Rozzi (2004B) - *Improving the knowledge on the seismogenesis of the Amatrice-Campotosto area (central Italy) through an integrated analysis of minor earthquake sequences and structural data*. Ann. Geophys., **47**: 1723–1742.

Boncio, P., Pizzi A., Brozzetti F., Pomposo G., Lavecchia G., Di Naccio D. & Ferrarini F. (2010) -– *Coseismic ground deformation of the 6 April 2009 L'Aquila earthquake (central Italy, Mw6.3)*. Geophys. Res. Lett., **37**, L06308, 10.1029/2010GL042807.

Bonini L., Di Bucci D., Toscani G., Seno S. & Valensise G. (2014) - *On the complexity of surface ruptures during normal faulting earthquakes: excepts from the 6 April 2009 L'Aquila (central Italy) earthquake (Mw 6.3)*.Solid Earth, **5**: 389–408.

Buttinelli M., Pezzo G., Valoroso L., De Gori P. & Chiarabba C. (2018) - *Tectonics inversions, fault segmentation, and triggering mechanisms in the central Apennines normal fault system: insights from high-resolution velocity models.* Tectonics, 37. https://doi.org/10.1029/2018TC005053

Cello G., Mazzoli S. & Tondi E. (1998) – *The crustal fault structure responsible for the 1703 earthquake sequence of central Italy*. J. Geodynamics, **26** (2): 4443-460, 1998.

Cheloni D., D'agostino N., D'anastasio E., Avallone A., Mantenuto S., Giuliani R., Mattone M., Calcaterra S., Gamibino P., Dominici D., Radicioni F. & Fastellini G. (2010) – *Coseismic and initial post-seismic slip of the 2009 Mw 6.3 L'Aquila earthquake, Italy, from GPS measurements.* Geophys. J. Int., **181**:1539–1546. Doi: 10.1111/j.1365-246X.2010.04584.x.

Cheloni D., D'agostino N., Scognamiglio L., Tinti E., Bignami C., Avallone A., Giuliani R., Calcaterra S., Gambino P. & Mattone M. (2019) – *Slip behaviour of the Campotosto normal fault (central Italy) imaged by geodetic and seismological data: insights from the 18 January 2017, M<5 events.* Conference Paper, GNDT, November 2019, Rome.

Cheloni D.,et al. (2017) – *Geodetic model of the 2016 Central Italy earthquake sequence inferred from InSAR and GPS data.* Geophys. Res. Lett., **44**: 6778-6787. Doi:10.1002/2017GL073580.

Chiaraluce, L., Chiarabba C., De Gori P., Di Stefano R., Improta L., Piccinini D., Schlagenhauf A., Traversa P., Valoroso L. & Voisin C. (2011) - T*he 2009 L'Aquila (central Italy) seismic sequence*. Boll. Geof. Teor. Appl., **52** (3): 367-387, 10.4430/bgta0019.

Cipollari P. & Cosentino D. (1995) - *Miocene unconformities in the central Apennines: geodynamic significance and sedimentary basin evolution*. Tectonophysics, **252**: 375-389

Civico R., Pucci S., De Martini P.M. & Pantosti D. (2015) – *Morphotectonic Analysis Of The Long-Term Surface Expression Of The 2009 L'aquila Earthquake Fault (Central Italy) Using Airborne Lidar Data*. Tectonophysics, **644–645**: 108–121.

Cosentino D., Cipollari P., Marsili P. & Scrocca D. (2010) - *Geology of The Central Apennines: A Regional Review*. Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142

Di Bucci D.,Vannoli P., Burrato P., Fracassi U. & Valensise G. (2011) - *Insights from the Mw 6.3, 2009 L'Aquila earthquake (Central Apennines)*

- *unveiling new seismogenic sources through their surface signatures: the adjacent San Pio Fault*. Terra Nova, **23** (2): 108-115, 10.1111/j.1365-3121.2011.00990.x.

Diss Working Group (2018) - *Database of Individual Seismogenic Sources (DISS), Version 3.2.1: A compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas.* http://diss.rm.ingv.it/diss/, IstitutoNazionale di Geofisica e Vulcanologia; Doi:10.6092/INGV.IT-DISS3.2.1.

Emergeo Working Group (2010) - *Evidence for surface rupture associated with the Mw 6.3 L'Aquila earthquake sequence of April 2009 (central Italy)*. Terra Nova, **22**: 43-51

Emergeo Working Group, 2016 - *Terremoto di Amatrice del 24 agosto 2016: Effetti Cosismici*. Doi: 10.5281/zenodo.61566

Falcucci E. & Gori S. (2014) – *The origin of scarps in urban areas affected by active and capable normal faulting: only faults? Examples from the 2009 L'Aquila earthquake region (central Italy)*. Conference paper, January 2014, Doi: 10.1007/978-3-319-09048-1_198.

Falcucci E., Gori S., Bignami C., Pietrantonio G., Melini D., Moro M., Saroli M. & Galadini F. (2018) –*The Campotosto seismic gap in between the 2009 and 2016-2017 seismic sequences of central Italy and the role of inherited lithospheric faults in regional seismotectonic settings.* Tectonics, July 2018. Doi: 10.1029/2017TC004844.

Falcucci E., Gori S., Galadini F., Fubelli G., Moro M. & Saroli M. (2016) – *Active faults in the epicentral and mesoseismal Ml 6.0 24, 2016 Amatrice earthquake region, central Italy. Methodological and seismotectonic issues.* Annals of geophysics, **59**, Fast Track 5; Doi:10.4401/ ag-7266.

Falcucci E., Gori S., Moro M., Pisani A.R., Melini D., Galadini F. & Fredi P. (2011) - *The 2009 L'Aquila earthquake (Italy): What's next in the region? Hints from stress diffusion analysis and normal fault activity.* Earth and Planetary Science Letters, **305**: 350–358.

Faure Walker J., Boncio P., Pace B., Roberts Gerald, Benedetti L., Scotti O., Visini F. & Peruzza L. (2021) – *Faults 2SHA Central Apennines database and structuring active fault data for seismic hazard assessment.* Scientific Data **8**: 87|https://doi.org/10.1038/s41597-021-00868-0.

Galadini F. & Galli P. (2000) – *Active tectonics in the Central Appennines (Italy) – Input Data for Seismic Hazard Assessment*. Natural Hazards., **22**: 225-270.

Galadini F. & Galli P. (2003) – *Paleoseismology of silent faults in the Central Apennines (Italy): the Mt. Vettore and Laga Mts. faults*. Annals of Geophysics, **46:** 815-836.

Galadini F. & Messina P. (2001) - *Plio-Quaternary changes of the normal fault architecture in the central Apennines (Italy).* Geodinamica Acta, **14**: 321-344.

Galadini F. & Messina P. (2004) - *Early–Middle Pleistocene eastward migration of the Abruzzi Apennine (central Italy) extensional domain.* Journal of Geodynamics, **37**: 57–81

Galadini F., Falcucci E., Gori S., Zimmaro P., Cheloni D. & Stewart J.P. (2018) – *Active faulting in source region of 2016-2017 central Italy event sequence.* Earthquake Spectra, Vol. **34** (4): 1557-1583.

Galadini F., Meletti C. & Vittori E. (2001) – *Major active faults in Italy: available surficial data*. Netherlands Journal of Geosciences/Geologie en Mijnbouw, **80** (3-4): 273-296.

Galadini F., Meletti C. & Vittori E. (1999) – *Stato delle conoscenze sulle faglie attive in Italia: elementi geologici di superficie*. Risultati del progetto 5.1.2 "Inventario delle faglie attive e dei terremoti ad esse associabili".

Galadini F., Messina P. & Sposato A. (2000) – *Tettonica quaternaria nell'Appennino centrale e caratterizzazione dell'attività di faglie nel Pleistocene superiore* – Olocene. Attività di ricerca del GNDT.

Galli P. & Galadini F. (1999) – *Seismotectonic framework of the 1997-1998 Umbria-Marche (central Italy) earthquakes*. Seismological Research Letters, Volume **70**, Number 4, July/August 1999; Doi: 10.1785/gssrl.70.4.417.

Galli P. (2020) – *Recurrence times of centrale-southern Apennine faults (Italy): Hints from palaeoseismology*. Terra Nova, 2020 – Wiley Online Library. Doi: 10.1111/ter.12470.

Galli P., Galadini F & Pantosti D. (2008) – *Twenty years of paleoseismology in Italy*. Earth-Science Reviews **88** (2008) 89–117.

Galli P., Galderisi A., Martino M., Mugnozza S. & Bozzano F. (2019) – *The coseismic faulting of the San Benedetto tunnel (2016, Mw 6.6 central Italy earthquake).* Tunnels and Underground Cities: Engineering and Innovation meet Archaeology, Architecture and Art-Peila, Viggiani & Celestino (Eds), 2019 Taylor & Francis Group, London, ISBN 978-1-138-38865-9.

Galli P., Galderisi A., Peronace E., Giaccio B., Hajdas I., Messina P., Pileggi D. & Polpetta F. (2018) – *The awakening of the dormant Mount Vettore fault (2016 Central Italy Earthquake, Mw 6.6): paleoseismic clues on its millenial silences*. Tectonics, Doi: 10.1029/2018TC005326.

Galli P., Giaccio B. & Messina P. (2010) - *The 2009 central Italy earthquake seen through 0.5 Myr-long tectonic history of the L'Aquila faults system.* Quaternary Science Reviews, **29**: 3768-3789.

Galli P., Peronace E., Bramerini F., Castenetto S., Naso G., Cassone F. & Pallone F. (2016) – *The MCS intensity distribution of devastating 24 August 2016 earthquake in central Italy (Mw 6.2).* Annals of Geophysics, **59**, fast track 5; Doi: 10.4401/ag-7287.

Giaccio B., Galli P., Messina P., Peronace E., Scardia G., Sottili G., Sposato A., Chiarini E., Jicha B & Silvestri S. (2012) – *Fault and basin* *depocentre migration over the last 2 Ma in the L'Aquila 2009 earthquake region, central italian Apennines.* Quaternary Science Reviwes*,* **56**: 69-88.

Gori S., E. Falcucci, S. Atzori, M. Chini, M. Moro, E. Serpelloni, G. Fubelli, M. Saroli, R. Devoti, S. Stramondo, F. Galadini & S. Salvi (2012) - *Constraining primary surface rupture length along the Paganica fault (2009 L'Aquila earthquake) with geological and geodetic (DInSAR and GPS) data*. Italian Journal of Geosciences (Boll. Soc. Geol. It.), **131** (3): 359-372.

Gori S., Manufo' I., Falcucci E., Moro M., Saroli M., Malagnini L. & Galadini F. (2019) – *Active faulting and seismotectonics in central Italy: Lesson learned from the past 20 years of seismicity.* Engineering clues. Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri&Moraci (Eds). 2019 AssociazioneGeotecnicaItaliana, Rome, Italy, ISBN 978-0-367-14328-2.

Iaea Ssg-9 (*Seismic Hazards in Site Evaluation for Nuclear Installations*. Specific Safety Guide. IAEA Safety Standards. Series SSG-9, 2010) (https://www-pub.iaea.org/MTCD/publications/PDF/Pub1448_web.pdf).

Iaea Tecdoc 1767 (*The Contribution of Palaeoseismology to Seismic Hazard Assessment in Site Evaluation for Nuclear Installations*, IAEA TECDOC 1767, 2015) (https://www-pub.iaea.org/MTCD/Publications/PDF/TE-1767_web.pdf).

Ithaca Working Group (2019) - ITHACA (ITalyHAzard from CApable faulting), *A database of active capable faults of the Italian territory.* Version December 2019. ISPRA Geological Survey of Italy. Web Portal http://sgi2.isprambiente.it/ithacaweb/Mappatura.aspx.

Lavecchia G., F. Ferrarini, F. Brozzetti, R. De Nardis, P. Boncio, L. & Chiaraluce . (2012) - *From surface geology to aftershock analysis: constraints on the geometry of the L'Aquila 2009 seismogenic fault system*. Ital. J. Geosci. (Boll. Soc. Geol. It.), **131** (3): 330-347. Doi: 10.3301/IJG.2012.24.

Messina, P., Galli P. & Giaccio B. (2011) - *Comment on 'Insights from the Mw 6.3, 2009 L'Aquila earthquake (central Apennines) to unveil new seismogenic sources through their surface signature: the adjacent San Pio Fault'* by Bucci et al. (2011). Terra Nova, **23**, 4: 280-282, 10.1111/j.1365-3121.2011.01010.x.

Moro M., Bosi V., Galadini F., Galli P., Giaccio B., Messina P. & Sposato A. (2002) – *Analisi paleosismologiche lungo la faglie del M.Marine (Alta Valle dell'Aterno): Risultati preliminari.* Italian Journal of Quaternary Sciences, **15** (2): 259-270.

Moro M., Falcucci E., Gori S., Saroli M. & Galadini F. (2016) - *New paleoseismologic data in the sector between the 2016 Amatrice and 2009 L'Aquila seismic sequences (central Apennines): the Mt.Marine Fault.* Annals of Geophysics, **59**, fast track n. 5, Doi: 10.4401/ag-7260.

Moro M., Gori S., Falcucci E., Saroli M., Galadini F. & Salvi F. (2013) – *Historical earthquakes and variable kinematic behavior of the 2009 L'Aquila seismic event (central Italy) causative fault, revealed by paleoseismological investigations.* Tectonophysics, **583**: 131-144.

Rovida A., Locati M., Camassi R., Lolli B. & Gasperini P. (2020) - *The Italian earthquake catalogue CPTI15. Bulletin of Earthquake Engineering*, **18** (7): 2953-2984. https://doi.org/10.1007/s10518-020-00818-y.

Tarquini S. & Nannipieri L. (2017) - *The 10 m-resolution TINITALY DEM as a trans-disciplinary basis for the analysis of the Italian territory: Current trends and new perspectives.* Geomorphology, **281**: 108-115.

Tinti E., Scognamiglio L., Michelini A. & Cocco M. (2016) – *Slip heterogeneity and directivity of the Ml 6.0, 2016, Amatrice earthquake estimated with rapid finite-fault inversion.* Geophys. Res. Lett., **43**, 10: 745-10,752, Doi: 10.1002/2016GL071263.

Tondi E., Jablonska D., Volatili T., Michele M., Mazzoli S. & Pierantoni P.P. (2020) – *The Campotosto linkage fault zone between the 2009 and 2016 seismic sequences of central Italy: Implications for seismic hazard analysis*. GSA Bulletin; https://doi.org/10.1130/B35788.1.

Valensise G. & Pantosti D. (Eds.) (2001a) - *Database of potential sources for earthquakes larger than M 5.5 in Italy*. Annali di Geofisica, **44** (4): 797–964.

Valentini A., Visini F., & Pace B. (2017) - *Integrating faults and past earthquakes into a probabilistic seismic hazard model for peninsular Italy*. Nat. Hazards Earth Syst. Sci., **17**: 2017-2039, https://doi.org/10.5194/nhess-17-2017-2017.

Valoroso L., Chiaraluce L., Piccinini D., Di Stefano R., Schaff D. & Waldhauser F. (2013) - *Radiography of a normal fault system by 64,000 high-precision earthquake locations: The 2009 L'Aquila (central Italy) case study*. J. Geophys. Res.: Solid Earth, **118**, 3: 1156-1176, 10.1002/jgrb.50130.

Vezzani L. & Ghisetti F. (1998) - *Carta geologica dell'Abruzzo.* Scala 1:100.000, S.El.Ca., Firenze

Received February 2021 - Accepted May 2021