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ACTIVE FAULTS AND RELATED HAZARDS: NEW INSIGHTS ON THE CENTRAL APENNINE SEISMOTECTONICS AND SURFACE FAULTING ZONATION

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EXTENDED ABSTRACT

Lo studio delle faglie attive e capaci (FAC) risulta essere importante per un duplice aspetto. Il primo aspetto riguarda la valutazione della pericolosità da fagliazione di superficie, una pericolosità locale che trova applicazione negli studi di microzonazione sismica. Tale pericolosità viene trattata nelle "Linee Guida per la gestione del territorio interessato da faglie attive e capaci" in cui viene spiegato il significato di FAC e FPAC (faglia potenzialmente attiva e capace) e viene proposta una zonazione per FAC finalizzata ad una disciplina d'uso del territorio. Il secondo aspetto riguarda la possibilità di definire la geometria e la cinematica di sorgenti sismogenetiche profonde, ottenendo elementi utili per la realizzazione di scenari di scuotimento e la definizione di magnitudo massima attesa, considerati dati di input per stime di pericolosità sismica di base per scopi applicativi. Di seguito vengono riportati due casi studio dell'Appennino centrale interessati dalla presenza di FAC. Queste faglie possono essere considerate l'espressione superficiale di sorgenti sismogenetiche profonde in grado di generare terremoti di magnitudo tra 6.0-7.0, manifestazione dell'attuale regime tettonico estensionale che interessa la catena appenninica a partire dal Pliocene. Il primo caso di studio si trova nei pressi del comune di Venere dei Marsi (AQ) interessato da un segmento della faglia "San Benedetto dei Marsi – Gioia dei Marsi" appartenente al sistema di faglie attive del bacino del Fucino. Questo segmento di faglia ha registrato fagliazione di superficie durante il terremoto del 13 gennaio 1915 (Mw = 7.0) ed è stato oggetto di precedenti analisi paleosismologiche da parte di diversi autori. Le attività di campagna hanno evidenziato la presenza di una scarpata in roccia associata ad una faglia secondaria posta a 15 m al letto della faglia principale. Nonostante fossero assenti depositi continentali che avessero potuto registrare eventi di attività recenti lungo questa faglia, l'evidenza di fagliazione di superficie durante il terremoto del 1915 lungo la sua prosecuzione meridionale ha permesso di considerarla una faglia attiva e capace. Le Linee Guida propongono la presenza di una sola Zona di Rispetto (ZR) ampia 30 m (rapporto letto – tetto 1:4) attorno alla FAC sottoposta al livello massimo di approfondimento (indagini paleosismologiche). La presenza della faglia secondaria che non rientra nei 6 m previsti al letto nella ZR, invece, mostra la necessità di inserire una Zona di Suscettibilità (ZS), ampia 160 m (rapporto letto – tetto 1:4), che eviti l'esclusione di faglie secondarie che si possono formare a breve distanza dalla FAC principale. Il secondo caso di studio si trova nell'area di ricostruzione dell'Abbazia di Sant'Eutizio, a Preci (PG). L'area è interessata dalla presenza della "faglia di Campi", prosecuzione più settentrionale del sistema di faglie di Norcia, considerata espressione superficiale della sorgente sismogenetica del terremoto del 1703 (Mw = 6.8). Le indagini in corso sono finalizzate alla verifica della presenza di FAC nell'area di ricostruzione dell'Abbazia di Sant'Eutizio associate alla "faglia di Campi". Inoltre, le indagini volte a chiarire l'attività quaternaria della faglia di Campi permetteranno di definire meglio la geometria e la cinematica della sorgente sismogenetica responsabile del terremoto del 1703.

ABSTRACT

The term active and capable fault (ACF) defines an active tectonic structure able to rupture permanently the ground surface. When an ACF represents the expression at surface of a seismogenic source, the study of an ACF involves a twofold aspect: one concerns surface faulting hazard, with engineering implications regarding infrastructures crossing the trace of a ACF, the other concerns the definition of geometric and kinematic characteristics of seismogenic sources, with implications regarding the definition of the seismogenic potential of a given active tectonic structure. Here, we show the results of geological investigations regarding two case studies in the central Apennines. The first site is located near the village of Venere dei Marsi (AQ), where the detailed characterization of geometry and kinematics of a fault splay connected to "San Benedetto dei Marsi – Gioia dei Marsi" active fault segment, allowed us to verify the effectiveness of the ACF territory zonation proposed in "Guidelines for the management of territories affected by Active and Capable Faults" promulgated by the Dipartimento della Protezione Civile Nazionale of Italy in 2015. The second case study is located close to Preci (PG), where field geological investigations were aimed to verify the presence of an ACF in the area of the Sant'Eutizio Abbey severely damaged by the 30 October 2016 Mw 6.5 seismic event, for retrofitting activities, and to characterize the Campi fault segment in terms of recent activity. This allowed to better define the geometric and kinematic characteristics of seismogenic source, responsible for the 2 February 1703 (Mw = 6.8), nucleated by the Norcia active faults system.

KEYWORDS: *active and capable faults, seismogenic sources, surface faulting hazard, Central Apennine, Quaternary.*

INTRODUCTION

The individuation and the characterization of active and capable faults (ACF) are important for dual aspect. First, the presence of ACF allows to define areas prone to surface faulting. This represents a further geological hazard connected to the occurrence of an earthquake, besides ground shaking, that is an ACF can rupture permanently the ground surface and interfere with infrastructures crossing the fault trace. Therefore, this hazard represents one of the geological criticalities that should be considered in the Seismic Microzonation studies, aimed at a correct management of territories and land use planning. In light of this, the Dipartimento della Protezione Civile Nazionale (DPC) of Italy promulgated in 2015 the "Guidelines for the management of territories affected by Active and Capable Faults". The Guidelines define zoning of territory affected by an ACF, with buffers across the ACF trace with variable sizes depending on the degree of uncertainty of the trace and of the recent (<40ka) activity. An ACF can also represent the expression at surface of a deep seismogenic source able to generate earthquakes which, in the Apennines, are larger than M5.5-6 (e.g. FALCUCCI *et alii*, 2016). The seismogenic sources represent the manifestation of the active extensional tectonic regime that affects the central Apennines since the Pliocene (e.g. GALADINI & GALLI, 2000). The geological, geomorphological and structural investigations made along ACFs can therefore allow to define the geometric and kinematic characteristics of deep seismogenic sources. This allows to achieve information useful to define the maximum expected magnitude of an earthquake generated by a given fault and to studies concerning ground motion scenarios and, hence, for engineering practices.

In this work, we present two case studies in the central Apennines: the first near Venere dei Marsi (AQ) and the second near Preci (PG).

The village of Venere dei Marsi (AQ) is located at the SE margin of Fucino basin, along one of the major segments of the seismogenic Fucino Fault, responsible for the 1915 M 7 earthquake, i.e. the "San Benedetto dei Marsi – Gioia dei Marsi" segment (e.g MICHETTI *et alii*, 1996; GALADINI *et alii*, 1997). The deformation zone related to this active segment has been investigated to improve the knowledge about possible areas affected by ACF and to verify the effectiveness of ACF zonation criteria proposed in Guidelines mentioned above.

The second case study is located NE of Norcia town, where the Sant'Eutizio Abbey, close to Preci (PG), has suffered severe damage due to the 30 October 2016 M 6.5 earthquake.

The current geological knowledge suggests the possible presence of an ACF across the site of the Abbey, related to Campi fault, that may represent the northern segment of the Norcia active faults system (GALLI *et alii*, 2005). This system could represent the expression of surface of seismogenic source responsible of 2 February shock (M 6.8) of the 1703 seismic sequence (ROVIDA *et alii*, 2016). According to GALLI *et alii*. (2005), the 1703 earthquake was caused by the activation of the extensional fault system bordering the eastern margin of the Norcia basin. Our investigations aim at 1) verifying the presence of an ACF across the Sant'Eutizio Abbey site, as input geological information before retrofitting activities of the building and 2) better defining the late Quaternary activity of the Campi fault. Indeed, geological and geomorphological evidence along this fault segment were not yet detected (GALLI *et alii*, 2005), although the Campi – Preci sector is affected by widespread historical and instrumental seismicity (e.g. the M 6-6.4 1328 seismic event; GALLI & GALADINI, 1999; ROVIDA *et alii*, 2016).

METHODS

A multidisciplinary approach was used for ACF study. First of all, aerial photo analysis was performed to detect morphological elements in the study areas possibly associated to the presence and activity of ACFs. For example, continuous scarps along the carbonate slopes, related to the surface trace of primary faults, land-surfaces suspended over the present valley bottom, or landforms connected to Deep Seated Gravitational Slope Deformations (DSGSD) were detected. Moreover, aerial photos analysis has been useful to identify the sites to focus detailed geological studies. In both study areas, field geological survey aimed to detect continental Quaternary deposits and to define their relationship with tectonic features. This allowed us to evaluate the recent activity of faults that characterize the structural framework of the areas.

In the case of the *Venere dei Marsi* we test the zonation proposed by the "Guidelines for the management of territories affected by Active and Capable Faults", promulgated by the *Dipartimento della Protezione Civile Nazionale* (DPC) of Italy. The Guidelines define an ACF as the fault that shows evidence of activitation at least once in the last 40 ka and produces the permanent rupture of the ground surface. On the other hand, the "potential" active and capable fault (PACF) is defined as the fault that shows Middle Pleistocene – Late Pleistocene activity, but not necessarily in deposits younger than 40 ka. The third level of seismic microzonation proposed by the Guidelines is here considered for the case study of Venere dei Marsi. Particularly, we consider zonation of an ACF with defined trace and for which paleoseismological investigations have been carried out. This zonation prescribes only "Respect Zone" (ZR) 30 m wide (1:4 footwall – hanging wall shape ratio) across the defined trace of the fault.

RESULTS

Venere di Marsi (AQ)

The village of Venere dei Marsi (AQ) is located at the base of reliefs made of Meso-Cenozoic limestone sequence, bordering the eastern side of the Fucino basin. The Fucino basin is one of the largest intermountain depressions of the central Apennines; most of these depressions formed by the activity of extensional faults active since Pliocene-early Quaternary. The eastern side of the Fucino basin is affected by an active fault system which led the geological and structural basin evolution, and which has been responsible for the 1915 M 7 earthquake (e.g. GALADINI *et alii,* 1999). Venere dei Marsi is located along one of the major segments of the seismogenic Fucino fault, i.e. the San Benedetto dei Marsi – Gioia dei Marsi segment. It has been the object of several paleoseismological studies (e.g MICHETTI *et alii*, 1996; GALADINI *et alii*, 1997; 1999), among which the studies performed by SAROLI *et alii* (2008). Here, we investigate the same site analysed by these authors. Here, besides the fault plane investigated by SAROLI *et alii* (2008), which showed evidence of activity during the past few millennia, we identified a further fault branch (or fault splay) located at 15 m (planar distance) in the footwall of the already investigated fault branch (Fig.1). No deposits that could have recorded the recent activity of this structure are present, as in this place the fault plane places into contact just bedrock sequences. Nonetheless, according to eye witnesses (SERVA *et alii,* 1986), surface faulting took place along this plane owing to the 1915 earthquake. Hence, we can define this branch as active and capable only thanks to direct observation of coseismic surface faulting.

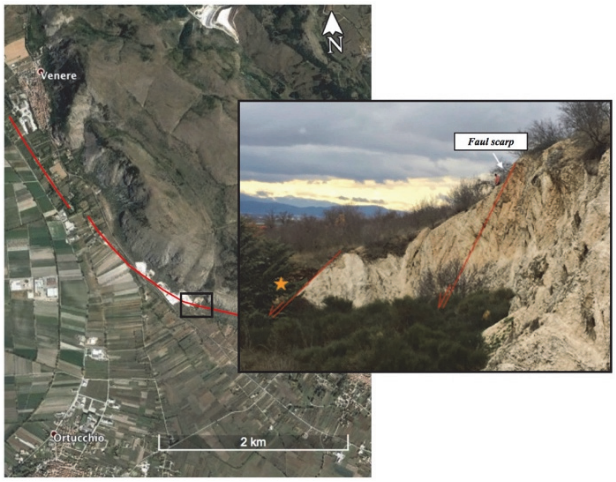

Fig. 1 – Venere dei Marsi geographic setting (Google Earth). The red line represents the trace of San Benedetto dei Marsi – Gioia dei Marsi fault. The black square indicates the site in which the fault branch is detected. The yellow star represents the area investigated by Saroli et alii., 2008

Preci (PG)

Preci (PG) is located at the southernmost sector of the Umbria region, along the Campiano river valley, within the National Park of Sibillini Mountains. The Sibillini Mountains are the highest mountain group of the Umbria-Marche Apennines. The reliefs are made of Meso-Cenozoic whose lithology have a high clay component, unlike limestone litologies that are present in the Lazio-Abruzzi Apennines. Close to the village of Piedivalle, south of Preci, the Sant'Eutizio Abbey is located. This is a religious building that has suffered severe damage owing to the 30 October 2016 Mw 6.5 earthquake. Field geological surveys carried out SE of Preci, allowed to identify shear planes in the Sant'Eutizio Abbey area. Particularly, a bedrock fault plane, NW – SE striking, was identified close to village of Campi. The surface trace of this fault plane results to be continuous for a few kilometers toward Norcia (Fig. 2A and B). Northwards, the Campi fault, which locally displays an E-W trend, placed into contact Meso-Cenozoic bedrock (in the fault footwall) with slope deposits (Fig. 2C). These are affected by some synthetic shear planes, having N 100° - 110° trend, testifying to the probably late Quaternary activity of fault segment, which has been only hypothesised in the available literature to date. Further analyses are ongoing to verify the presence of a splay of the Campi fault in the area of the Sant'Eutizio Abbey.

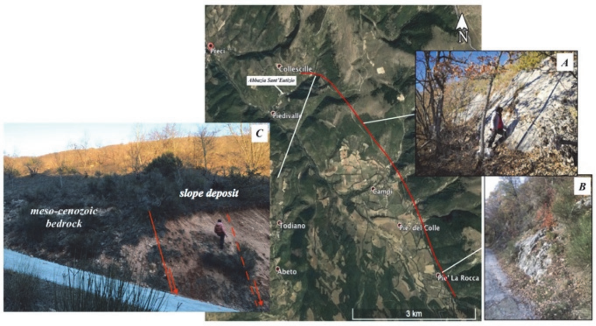

Fig. 2 – Southern area of Preci geographic setting (Google Earth). The red line represents the trace of Campi fault. The white arrows show the outcrops of bedrock fault plane (A – B) and recent surface faulting evidence in slope deposit (C)

DISCUSSION AND CONCLUSIONS

The investigations carried out along the San Benedetto dei Marsi – Gioia dei Marsi fault segment of the Fucino fault showed that to trace just a narrow, 30 m-wide "Respect Zone" across a given ACF in seismic microzonation studies, as proposed by the Guidelines, may not include some other fault branches that might undergo surface faulting and whose traces could be just few meters beyond the Respect Zone (RZ). This is the case of the fault splay located at 15 m in the footwall of the fault plane investigated by Saroli *et alii*, (2008), that is about 10 m off the RZ. The fault splay has produced surface rupture during the 1915 earthquake that can only be accounted thanks to eye-witnesses. Owing to the absence of displaced deposits aged <40 ka, this fault branch can be considered a PACF. Overall, this suggests that in order to include any other possible synthetic or antithetic splay located at short distance from the main fault plane, a "Susceptibility Zone" (SZ) 160 m wide, already proposed by Guidelines to include secondary fault splays when the knowledge on a given fault is not complete, should actually be traced in any case containing the Respect Zone.

Moreover, the ACF zoning proposed by the Guidelines for seismic microzonation studies consider a single active tectonic element, whose surface trace is geomorphologically detectable. However, on the one hand, the RZ and SZ width mentioned above allow to include the synthetic and antithetic fault splays located at few meters from the main fault plane; on the other hand, surface faulting can also occur along new fault splays, whose surface traces were not visible before, some tens to hundred meters far from the main fault plain, and they could not therefore be included within the RZ and SZ.

Evidence of this has been provided by the October 30 seismic event (Mw 6.5), nucleated along the Mt. Vettore-Bove active normal fault system, which caused surface faulting along previously known and detectable fault branches as well as along some fault splays whose geomorphic evidence before the quake were subtle or even absent. Moreover, another noteworthy aspect is that an earthquake can produce surface faulting even along faults that are not the earthquake faults which are defined as sympathetically activated. According to Gori *et alii* (2018), after the October 30 seismic event (Mw 6.5), hundreds of meters long surface fractures were surveyed in the Norcia basin. Paleoseismological analyses made across these fractures, allowed the authors to observe that the ground offset corresponded to a synthetic and antithetic splay of Norcia fault system, testifying at its sympathetic slip, that broke the surface.

These sympathetic fractures can contribute to the earthquake surface deformation field and represent a further geological hazard connected to the occurrence of an earthquake. These features should be also taken into consideration in terms of surface faulting hazard and could be somehow considered when dealing with surface faulting hazard issues.

The results obtained from geological investigations carried out along the Campi fault, in the area of Sant'Eutizio Abbey, show the displacement of probably late Quaternary continental deposits along the tectonic structure. More detailed studies to assess the Holocene activity of the Campi fault are still needed.

Detailed studies are still ongoing to verify the presence of ACF in the Abbey area as prerequisite for the retrofit practices of the building.

The results of the ongoing studies will be useful to improve the knowledge about the geometry of the seismogenic source responsible for the 2 February shock of the 1703 earthquake.

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