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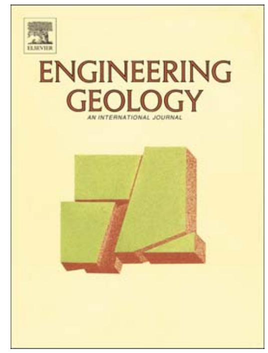

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Time intervals to assess active and capable faults for engineering practices in Italy

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Abstract

The time span necessary to define a fault as ‘active and capable’ can mainly be derived from the framework of the regulations and the literature produced since the 1970s on risk estimation in engineering planning of strategic buildings. Within this framework, two different lines of thought can be determined, which have mainly developed in the USA. On the one side, there is a tendency to produce ‘narrow’ chronological definitions. This is particularly evident in the regulatory acts for the planning of nuclear reactors. The much more effective second line of thought anchors the chronological definitions of the terms active’ and, therefore ‘capable’, to the concept of ‘seismotectonic domain’. As these domains are different in different regions of the World, the chronological definition cannot be univocal; i.e., different criteria are needed to define fault activity, which will depend on the characteristics of the local tectonic domain and of the related recurrence times of fault activation. Current research on active tectonics indicates that methodological aspects can also condition the chronological choice to define fault activity. Indeed, this practice implies the use of earth science methods, the applications of which can be inherently limited. For example, limits and constraints might be related to the availability of datable sediments and landforms that can be used to define the recent fault kinematic history. For the Italian territory, we consider two main tectonic domains: (*a*) the compressive domain along the southern margin of the Alpine chain and the northern and northeastern margins of the Apennines, which is characterised by the activity of blind thrusts and reverse faults; and (*b*) the extensional domain of the Apennines and the Calabria region, which is often manifest through the activity of seismogenic normal and normal-oblique faults. In case (*a*), the general geomorphic and subsurficial evidence of recent activity suggests that *a reverse blind fault or a blind thrust should be considered active and potentially capable if showing evidence of activity during the Quaternary (i.e., over the last 2.6 Myr), unless information is available that documents its inactivity since at least the Last Glacial Maximum (LGM) (ca. 20 ka).* The choice of the LGM period as the minimum age necessary to define fault

inactivity is related to practical aspects (the diffusion of the LGM deposits and landforms) and to the evidence that *ca.* 20 kyr to assess fault inactivity precautionarily includes a number of seismic cycles. In the extensional domains of the Apennines and Calabria region, the general geological setting suggests that the present tectonic regime has been active since the beginning of the Middle Pleistocene. Therefore, we propose that *a normal fault in the Italian extensional domain should be considered active and capable if it displays evidence of activation in the last 0.8 Myr, unless it is sealed by deposits or landforms not younger than the LGM*. The choice of the LGM as the minimum age to ascertain fault inactivity follows the same criteria described for the compressive tectonic domain.

Keywords: Active fault; capable fault; surface faulting; seismic risk; Italy

1. Introduction

Dealing with active faults generally refers to the geological investigations necessary to define current fault behaviour (e.g. McCalpin, 2009). The definition of the behaviour has different perspectives, which are mainly related to the estimation of the earthquake probability in a region and the risk of surface faulting for engineering purposes. The latter point – addressed in this report – implies the use of the concept of 'fault capability', meaning that the motion of a fault that is active and capable might cause rupture of the surface and displacement of buildings and lifelines. Within this context, two main fields of investigation need to be considered: (*i*) the study and modelling of the faulting effects on structures (e.g. Kelson et al., 2001; Takada et al., 2001; Ulusay et al., 2002; Dong et al., 2003; Honegger et al., 2004; Pamuk et al., 2005; Faccioli et al., 2008; Gazetas et al., 2008; Paolucci et al., 2010); and (*ii*) the discussion of the surface faulting hazard, on both a general territorial perspective (Guerrieri et al., 2009a) and from a more local point of view, including the areal extent of the fault set backs, to avoid building at all or to reduce the effects of any faulting by geotechnical or structural engineering interventions (Bray, 2001; Bryant and Hart, 2007; Zhou et al., 2010; Boncio et al., in press).

For the Italian territory, although sparse, the geological literature on active and capable faults for engineering practices has discussed the impact of surface faulting on urban settlements, and particularly on engineering works (Budetta and De Riso, 1987; Serva, 1990; Bosi and Galadini, 1995; Faccioli et al., 2008; Guerrieri et al., 2009a; Paolucci et al., 2010; Boncio et al., in press). Within this framework, (*i*) estimations of the surface faulting risk have been made, using indices that define the areas that are potentially prone to faulting and the level of exposure of urban and industrial settlements (Guerrieri et al., 2009a); (*ii*) aspects inherent to the distribution of surface faulting within a certain fault zone have been discussed, considering the experience of the L'Aquila earthquake (Mw 6.3) that occurred on 6 April, 2009 (Boncio et al., in press); and (*iii*) detailed studies on the effects of surface faulting on engineering works have been carried out recently (Faccioli et al., 2008; Paolucci et al., 2010; with both reporting on Italian cases).

On the whole, the literature mentioned above discusses cases of ascertained fault activity, arising from historical evidence of activation or geological data that have indicated motion over the last few millennia. However, the available Italian literature that deals with the meaning of an ‘active and capable fault’ from a chronological point of view is sparse, and the definition of temporal grounds for the attribution of activity and capability is therefore not easy. This means that giving answers to the fundamental issue of “whether a fault is, or is not, active” (Muir Wood and Mallard, 1992) is quite difficult. This aspect is by no means trivial, considering that the definition of an active and capable fault in a territory represents a step that precedes all of the interventions necessary according to the engineering perspectives mentioned above. Considering that the determination of a fault as capable is still partly anchored to so-called ‘expert judgement’ (e.g., Magri and Serva, 1986), the aspect that is certainly more obscure and misleading is represented by the age of such a fault; i.e., the chronological time span of the activity that defines a certain fault as potentially dangerous or not.

The present study addresses the chronological issues related to the definition of active and capable faults within the framework of the surface-faulting risk in the Italian territory. The engineering perspective justifies the precautionary approach, expressed in considering as active and capable not only those faults that show evidence of surficial displacement over the last few thousand years, but – for particularly obscure case studies – even those showing general Quaternary traces of motion. Since capability implies activity, in many cases the discussion will deal with active faults, which means that statements and conclusions need to be extended to the capable faults.

After a review of the international literature on the argument (mainly in the USA), the two main aspects that condition the choice of the time span will be discussed; i.e., the characteristics of the present tectonic regime, and the constraints from operational aspects inherent to active tectonics investigations. These two aspects have key roles in the definition of the time span necessary to define the state of activity of the compressive and extensional faults in the Italian territory. As the choice of these chronological intervals strictly reflects the present knowledge of Italian active tectonics and the current operational limits in earth sciences methods, we believe that our proposal can be adopted by research aimed at the definition of active/ capable faults for engineering practices, as related to the reduction of the surface faulting risk in Italy.

2 Assessment of fault activity as a function of the tectonic domain and the operational practice

We summarise here what is extensively reported in Appendix 1, where we illustrate the two operational aspects that can be discerned from the literature dealing with the time span necessary to assess the current activity and capability of a fault. The first of these deals with the definition of numerical chronological constraints, and this is evident in the production of regulations that relate to the siting and planning of strategic buildings. For example, to mention potentially the most known cases, the US regulations for nuclear power plants define a capable fault as one that has moved at least once in the past 35 kyr, or more times in the past 500 kyr (US NRC, 2010); and the ‘Alquist-Priolo Fault Zoning Act’, which prevents building close to the surficial emergence of active faults, defines capable the faults that have ruptured the surface over the past 11 kyr (Bryant and Hart, 2007).

Many numerical time constraints are now available, as in the literature cited in Appendix 1, which range from 5 ka to 1.8 Ma. This is probably the effect of the difficulties in the application of a worldwide univocal time span for the assessment of fault activity. Indeed, another practice discussed since the 1970s proposes a definition of ‘activity’ and ‘capability’ as strictly related to the characteristics of the seismotectonic domain (Slemmons and McKinney, 1977). The current tectonic regimes have different characteristics in the different regions of the World, and they are manifest through different tectonic rates and recurrence times of fault activation (Muir Wood and Mallard, 1992). These aspects condition the choice of the time spans used to ascertain current fault activity or inactivity. Indeed, the chronological interval defined in the Alquist-Priolo Act (the past 11 kyr) might be appropriate for California, USA, where the tectonic rates are high and the recurrence times are short; i.e., in the order of a few centuries or millennia (e.g., Machette, 2000), as a result of plate tectonic motion in the order of 40-50 mm/yr across the Coast Ranges and San Andreas fault system (Argus and Gordon, 2001; Bennett et al., 2003). Larger chronological intervals are necessary for the Basin and Range province, since the recurrence times per fault can be in the order of millennia or tens of thousands of years (e.g., Bell et al., 2004), as a consequence of current strain rates significantly lower than those affecting the coastal Pacific area, manifested in GPS velocities related to extension in the order of some mm/yr across the active zones (Bennett et al., 2003; Niemi et al., 2004; Hammond and Thatcher, 2005; 2007; Kreemer and Hammond, 2007). Finally, and still dealing with the North American continent, an intraplate fault certainly necessitates the reconstruction of the fault history through time intervals that include tens to hundreds of thousands of years, in order to define its activity or inactivity, based on the very long recurrence times (Adams et al., 1992; Crone et al., 1997).

Moreover, the definition of the time span that is necessary to ascertain current fault activity and capability is also depending on some practical aspects that are related to the operational limits of the earth science methods and to the geological characteristics of a region (Machette, 2000; Galadini et al., 2001a; Gruppo di Lavoro MS, 2008; Shlemon, 2010). Among the most recurrently limiting issues, we can define: (*i*) the absence of sediments and landforms that can record fault activity/ inactivity; (*ii*) the sparse availability of numerical ages that support the assessment of fault activity/ inactivity, considering that the most widely used radiocarbon method has a commercial limit of *ca*. 45 ka; and (*iii*) the sparse availability of subsurface data that can cast light on recent fault behaviour, in the case of blind and buried faults.

On the whole, two aspects appear to be fundamental for the choice of the time interval that is necessary to assess fault activity/ capability: (*a*) the dependence of this interval on the characteristics of the current tectonic regime, which are different in the different tectonic domains; and (*b*) the dependence of this interval on factors external to, although partly conditioned by, the tectonic regime, which are mainly related to methodological aspects and to the operational characteristics of the tools presently used in active tectonics research.

3 The Italian situation

3.1 The available literature

The literature relating to the time interval for the assessment of fault activity/ capability in Italy is sparse, and pioniering papers that dealt with methodological aspects inherent to the siting of nuclear power plants also do not approach this problem (D'Offizi, 1986; Magri and Serva, 1986). Within the framework of the Ithaca database (Italy hazard from capable faults; available at *www.apat.gov.it/ithaca/)*, Vittori et al. (1997) took into account the International Atomic Energy Agency (IAEA) definition of 'capable fault' that was available from the beginning of the 1990s (and which was basically not different from that reported in IAEA, 2010) to draw up the operational criteria for fault investigation. Vittori et al. (1997) defined as capable those faults showing: (*i*) historical evidence of surface faulting; (*ii*) paleoseismological evidence of surface faulting; (*iii*) geomorphological and/or stratigraphic evidence of movement in the latest Pleistocene-Holocene; i.e., after the Last Glacial Maximum (LGM; ca. 24-16 ka); (*iv*) geomorphological and/or stratigraphic evidence of movement within extensional Quaternary basins; and (*v*) geomorphological evidence of movement along fault-related slopes that border the Quaternary extensional basins. In the case of point (*ii*) here, although it was not specified by the authors, the chronological time span is probably a few tens of thousands of years. This is related to issues concerning the application of paleoseismological methods, which are generally conditioned by the above-mentioned limit of the radiocarbon method. The criteria expressed in points (*iv*) and (*v*) are instead less univocal, since general evidence of Quaternary activity does not appear conclusive for the definition of capability. Indeed, a fault whose activity has conditioned the evolution of a basin in the Early Pleistocene might be presently inactive (e.g., Messina et al., 2002, 2011).

The chronology of 'active faults' is clearly exposed in Tondi (2000), who considered as active the faults that originated and/or were activated as a response to the current regional stress field. As the present tectonic regime began in the early Middle Pleistocene, Tondi (2000) defines as active those faults that show evidence of activation after 0.7 Ma. We will see that this definition can be largely shared for mitigation of the surface faulting risk.

An inventory of the active faults in the Italian territory by Galadini et al. (2001a) (and also a study specifically dedicated to the central Apennines, by Galadini and Galli, 2000) includes structures that show surficial evidence of activation during the Late Pleistocene-Holocene (after the LGM; point (*iii*) of the procedure defined by Vittori et al., 1997). Galadini et al. (2001a) stated that: (*i*) the faults in Italy with evidence of activity during this time interval are certainly related to the present tectonic regime, and therefore they have to be considered active; and (*ii*) larger Quaternary time intervals for estimation of activity do not prevent the possibility that the selected fault is inactive and is not representative of the present tectonic regime. The choice was also conditioned by practical aspects, which always have consequences at the operational level (as indicated in the previous section). In particular, Galadini et al. (2001a) recalled that most Italian faults affect mountainous areas and are often responsible for displacement of slope deposits and related landforms. It is generally agreed that the most significant recent morphogenetic events along the Alpine and Apennine reliefs occurred in periglacial environments during the LGM (e.g., Dramis, 1983; Orombelli, 1983; Blumetti et al., 1993; Giraudi, 1996). As a consequence, the thick successions of slope deposits that are related to the above-mentioned chronological interval represent significant sources of data on the activity of many faults. However, this approach might be ineffective: indeed, LGM deposits and landforms cannot be detected everywhere along the mountain slopes, and therefore the fault activity cannot be conclusively defined. For this reason, faults characterised by general geological evidence of Quaternary activity were also reported in the study by Galadini et al. (2001a). The inclusion of these faults was based on geological features that suggested possible Late Pleistocene-Holocene fault activity – mainly the relationships between faults and intermontane basins that were also characterised by tectonically controlled geological evolution during the late Quaternary – and/or on the evident relationship with the local seismicity.

A wider time interval for assessing activity was considered by Boncio et al. (2004) in their central Italy fault inventory (i.e., the entire Late Pleistocene-Holocene, since 0.125 Ma). In this study the authors based their approach on one of the time intervals that was defined by Machette (2000) and did not elaborate a time span specifically fitting the Italian situation.

Finally, active and capable faulting in Italy has been included within the framework of the instabilities that need to be considered for seismic microzoning. The guidelines for this practice define as active any fault that has moved in the last 40 kyr. Once again, this choice has been conditioned by an operational criterion, which is represented by the above-mentioned operational limit of the radiocarbon dating (Gruppo di Lavoro MS, 2008).

Further studies on the risk related to surface faulting and capable faults did not discuss the chronological aspects that are the object of the present study (e.g., Bosi and Galadini, 1995; Guerrieri et al., 2009a, b; Boncio et al., in press).

3.2 The chronological interval for the assessment of activity/ capability

The geological structure of Italy (Fig. 1) has resulted from complex interactions between the Adria microplate – a sort of northern 'African' promontory – and the Eurasian plate (e.g., Crescenti et al., 2004). This interaction conditioned the evolution of the main structural domains: (*i*) the Alps, a collisional orogenic chain (Castellarin and Transalp Working Group, 2004; Carminati et al., 2010); (*ii*) the Po Plain, which represents the onshore portion of the Adria microplate (e.g., Bosellini, 2004); (*iii*) the Apennines, which resulted from the eastward flexural retreat of the Adria plate, with the migration of the thrust systems towards the NNE (Po Plain sector) and NE (Adriatic sector) (Malinverno and Ryan, 1986; Patacca et al., 1990; Doglioni, 1991; Patacca and Scandone, 2004a;

Barchi, 2010; Carminati et al., 2010; Cosentino et al., 2010) and the uplift of the present chain – the back of the migrating fronts (Dramis, 1992; D'Agostino et al., 2001; Bartolini et al., 2003; Galadini et al., 2003; Schiattarella et al., 2003); and (*iv*) the peri-Tyrrhenian area, due to the widespread back-arc extension (Carmignani et al., 2004; Barchi, 2010).

Tectonic activity was persistent during the entire Quaternary (e.g., CNR-PFG, 1987). The main tectonic domains of the Italian territory where the recent tectonics is manifest through surficial fault displacement and seismicity are (Fig. 1): (*i*) the central-eastern Southern Alps (which includes the pre-Alpine sector and the Po, Venetian and Friulian plains); (*ii*) the 'external' (i.e. northeastern and eastern) Apennine tectonic domain (i.e., the northern Apennines foothills, the Po Plain and the peri-Adriatic sectors); and (*iii*) the axial belt of the Apennine chain and of the Calabria peninsula. The domains of points (*i*) and (*ii*) are characterised by compressive tectonics and reverse/ thrust faulting, while that of point (*iii*) results from extensional tectonics expressed by normal and normal-oblique faults.

The definition of these domains is corroborated by the indicators of the current state of strain. Indeed, the large scale deformation patterns from GPS data indicate a shortening trend in the northern Apennines (related to the Po Plain) of about 2 mm/yr in a 50-70-km-large belt (Devoti et al., 2011). A similar shortening rate has been defined along the southern margin of the Alps (Devoti et al., 2011). As for peninsular Italy, the extension rate across the Apennines ranges between 2 and 3 mm/yr (Devoti et al., 2011). Current deformation in Calabria is less defined, due to the short time-window of GPS data acquisition. In this case, the extension rate may be in the order of 1.5 mm/yr, but it has to be related to an area narrower than that of the Apennines. In the whole, the gradient of the strain across the different active areas of peninsular Italy is comparable. The focal mechanisms available in the Italian centroid moment tensor dataset indicate mainly extensional mechanisms in the axial belt of the Apennines and the Calabria region (Chiarabba et al., 2005; Pondrelli et al., 2006; 2011). By contrast, compressive solutions (thrust and transcurrent mechanisms) have been defined for the Po Plain and Adriatic sectors of the Apennines and the southern margin of the Alps

(Chiarabba et al., 2005; Pondrelli et al., 2006; 2011). In the whole, this evidence is consistent with the available knowledge on the current state of stress. Indeed, the stress map of Italy shows that the minimum horizontal stress (Shmin) related to thrust tectonics is parallel to the Po Plain and Adriatic margins of the Apennines and to the southern border of the Alps (Montone et al., 2004). Shmin related to normal faulting in the inner sector of the Apennines are tipically orthogonal to the main axis of the chain, indicating an extensional regime acting across the Italian peninsula.

In short, the available data on the current strain and stress regime in the Italian territory are consistent with the definition of the seismotectonic domains here proposed.

Further domains may probably be defined (e.g., the western Alps, eastern Sicily, northern Apulia; Fig. 1), but knowledge of their tectonic characteristics is not detailed enough to allow any general inferences. In the western Alps, much of the evidence of Quaternary faulting is indirect and is related to the interpretations of the origin of gravitational deformations (Collo, 1994; Giardino and Polino, 1997; Malaroda, 1998). Moreover, the recent kinematic framework is not clear at all, in terms of the two faults that have attracted the attention of the geologists over the last decades. These are (Fig. 1): (*i*) the E-W trending Aosta-Ranzola fault (Carraro et al., 1994; Giardino, 1996; Bistacchi et al., 2000, 2001); and (*ii*) the NW-SE trending Plio-Quaternary Saorge-Taggia fault in the Maritime Alps (Giammarino et al., 1978; Eva et al., 1990, 2000; Courboulex et al., 1998; Larroque et al., 2001). In eastern Sicily, there is activity along normal faults that coexists with the compressional tectonics that is manifest in the growth of folds (Catalano et al., 2007, 2008). In contrast, northern Apulia appears to be affected by the most evident strike-slip fault of the whole Italian territory (e.g., Piccardi, 2005; Tondi et al., 2005), although, overall, tectonic knowledge of this region is sparse. Generally speaking, the rates of Quaternary fault motion in these sectors are comparable to those of the other, above-mentioned, domains (fractions of mm/yr: Piccardi, 2005; Tondi et al., 2005; Ridente et al., 2008; Catalano et al., 2010). This means that the recurrence interval per fault, which is defined paleoseismologically as variable between a few centuries and a few millennia in the Apennines (Galli et al., 2008), is probably similar throughout the active Italian territories. As this seismogenic parameter reflects the seismotectonic behaviour and characteristics of the present stress regime, we conclude that inferences related to the above-mentioned main tectonic domains are probably applicable to all of the Italian tectonic domains.

Considering that the compressive provinces are characterised by faults with comparable characteristics and problems of investigation, the discussion of the three main domains (central-eastern Southern Alps; northeastern and eastern Apennines; axial belt of the Apennines and Calabria) can be reduced to two subsections. Indeed, as indicated above, the shortening rates of the Apennine and Alpine compressive fronts are comparable, together with the main thrust geometries and the geomorphological superficial expressions, represented by continuous deformation of the landscape. Considering the scope of the paper, especially this aspect suggests that these two tectonic domains can be properly discussed together. For this reason, the following subsection is dedicated to the compressive tectonic regime that is responsible for the activation of reverse and thrust faults in the Southern Alps and in the external Apennine sectors. The later subsection is dedicated to the extensional tectonic regime that is responsible for activation of the Apennine normal faults.

The Italian situation will be addressed taking into account the two main factors that condition the definition of the time interval necessary to assess fault activity; i.e., dependence on the characteristics of the tectonic regime and on the constraints of current procedures of analysis, instead of the application of regulations drawn up for seismotectonic domains that are not comparable to the Italian ones.

3.2.1 The compressive tectonic regime of the Alps and Apennines

The compressive tectonic regime in Italy is responsible for the activation of blind reverse faults that show expression at the surface that is well documented in the available literature (e.g., Galadini et al., 2005; Livio et al., 2009a; Toscani et al., 2009). This can be summarised as: (*i*) continuous deformation (gentle flexure of the topographic surface); and (*ii*) secondary faulting (Fig. 2a).

For this first point, the surface expression of most Italian reverse and thrust faults is represented by sporadic topographic reliefs that emerge in the plain zones (Fig. 3) or by gently dipping scarps (Fig. 4) (e.g., Desio, 1965; Burrato et al., 2003; Galadini et al., 2005; Livio et al., 2009a). In such cases, the deformation affects limited sectors (i.e., some hundreds of metres wide), at the transition between the relief and the plain.

Secondary faulting is generally represented by extensional displacements along the hinge of the growing anticline in the fault hangingwall; i.e., at the top of the related topographic relief (e.g., Galadini et al., 2001b; Berlusconi et al., 2008) (Figs. 3, 5). Also, non-tectonic faulting (*sensu* Hanson et al., 1999) has been observed along the frontal sectors of hills, which is mainly represented by gravity-driven displacements (Fig. 6). In all cases, the superficial features are considered as secondary effects of compressive blind faults based on the reconstruction of the geometry and kinematics of the whole structure (e.g. by means of subsurface data) (e.g. Livio et al., 2009a).

The activity of the reverse/ thrust faults that mainly affect northern and peninsular-periadriatic Italy can be defined by subsurface data (Fig. 7), and to a lesser extent by surface geological or geomorphological information (Figs. 4, 5). Usually, the whole dataset allows it to be hypothesised that certain reliefs and their related scarps that emerge in plain territories result from the growth of blind faults. However, the landforms surveyed at the surface show continuous deformation of the landscape, plus the effects of exogenous actions; i.e., of erosion from the relief and deposition in adjacent lower areas. Within this picture, the study of the relief is rarely conclusive for the current tectonic activity or the age of the tectonic inception. Inferences from sediments deposited in the lower areas are even more complicated, as these sediments are generally buried below the surface, and hence their analysis with traditional methods of geological surveys are hindered. On the whole, some examples from northern Italy (Fig. 3) are illuminating: (*i*) the Apennine relief of San Colombano is made of sediments that have been attributed to the Early and Middle Pleistocene (Gelati, 1971; Pellegrini et al., 2003); (*ii*) the Alpine relief of Romanengo is made of sediments that have been attributed to the Middle Pleistocene (Cremaschi, 1987); (*iii*) the Alpine relief of Mount Netto is made of sediments that have been attributed to the Middle and Late Pleistocene (Cremaschi, 1987; Livio et al., 2009b); and (*iv*) the Alpine relief of Montello is made of deposits that have been attributed to the Messinian and Early Pliocene (Massari et al., 1986; Massari, 1990). Apart from the case of Mount Netto (Fig. 5), where the deformation of the Late Pleistocene sediments suggests that uplift has been persistent in geological times that are recent enough to hypothesise current fault activity, the other cases are inconclusive. How can a relief formed by Messinian or Middle Pleistocene deposits be considered as the result of currently persistent fault activity? To solve this issue, we need particular geological conditions that are rarely available. In the case of Montello, recent activity has been hypothesised through a geomorphological study of the terraced landforms that are carved into the Messinian substratum (Ferrarese et al., 1998; Benedetti et al., 2000). These landforms record the progressive uplift of the relief during the Quaternary (since the Middle Pleistocene, according to Benedetti et al., 2000); as the process also occurred during the Late Pleistocene-Holocene, the Montello fault can be considered as active (e.g., Galadini et al., 2005).

However, as indicated, data such as these that are available for the Montello terraced landforms are sparse. For this reason, if they are solely based on surface data, precise chronological limits for the definition of ‘active/ capable faults’ in the Italian compressive tectonic domains cannot be proposed. Indeed, many buried faults that might have been characterised by recent activity (e.g., on the basis of the structural relationship with the regional tectonic setting) do not show such surficial expression that can define their recent tectonic history. For example, the southern Alpine Thiene-Bassano and Bassano-Cornuda faults were responsible for the deformation of pre-Quaternary sediments, and the attribution of recent activity here is based on historical seismicity (the Bassano-Cornuda fault), morphological evidence (inconclusive), and the knowledge that they are part of a longer system of faults that are certainly active (Galadini et al., 2005).

In practical terms, the aforementioned cases of points *i-iv* indicate that the motion of some of the compressive faults that are considered active occurred at least since the Middle Pleistocene, although the data available do not usually define the persistency of the activity in the last few tens of thousands of years. Moreover, the information on the various faults does not cast light on the period of inception of the present tectonic regime, which might be suitable for discriminating between active *versus* inactive faults.

It is evident that only through high-resolution seismic-reflection surveys it is possible to better define the recent tectonic activity of blind faults. Nevertheless, most of the kinematic information on the thrusts of the Italian territory derives from reports and publications that are based on the results of commercial seismic lines (i.e., made for industrial purposes; see in Galadini et al., 2005; Picotti and Pazzaglia, 2008; Toscani et al., 2009). In the active tectonic perspective, these data rarely provide conclusive information on fault activity during the late Quaternary. A positive example is the Castenedolo hill (Brescia province, central-southern Alps; Fig. 3), where Livio et al. (2009a) used subsurface information to identify more episodes of uplift since 1.6 Ma. This age might represent the beginning of the activity for this still active fault. In contrast, in the case of Montello hill, the seismic sections that are available allow the definition of the sub-surficial thrust geometry and the Quaternary fault activity (Fig. 7), but they do not allow the reconstruction of the different recent tectonic episodes and the definition of their ages (Galadini et al., 2005).

Two aspects of the thrust analysis seems important to address the chronological issue of the active faults: (*i*) the tectonic information available and the cases described above clarify that the activity of many faults that are considered active has been persistent at least over a wide Quaternary time interval (of hundreds of thousands of years); (*ii*) seismic-reflection surveys rarely allow chronological resolution better than the general Quaternary. For these reasons, with a precautionary approach followed, the scientific information available and the methodological limits indicate that a fault in the Italian compressive tectonic domains can be defined as potentially active and capable if it shows evidence of movement during the Quaternary (the last 2.6 Ma). This conclusion is similar to the procedure adopted by Lettis et al. (1997), who compared the distribution of historical compressive earthquakes with the geometry of thrusts that show evidence of often undefined Quaternary activity. This practice should be adopted when further information is lacking, and particularly in those cases where high-resolution reflection surveys have not been performed across the structure. Indeed, this kind of subsurface data can confirm persistency of activity also over the last few tens of thousands of years, and therefore they can strengthen an initial hypothesis of activity. In contrast, high-resolution seismic-reflection surveys may show that a fault is sealed by undeformed Late Pleistocene-Holocene layers, and therefore that the initial hypothesis of activity should be rejected.

When considering the chronological constraints for the definition of a Quaternary fault as inactive, we can take into account the slip rates of Italian compressive structures that may be potentially or have been responsible for moderate-to-large magnitude earthquakes. These rates (fractions of mm/yr; e.g., Galadini et al., 2005) are consistent with seismic cycles of not longer than a few millennia (e.g., Galli et al., 2008). Adopting a conservative approach, we can define *ca*. 20 ka as the minimum age for the definition of a fault as inactive, as the time span from *ca*. 20 ka to the Present certainly includes more than one seismic cycle per fault. Practical reasons again favour this chronological choice. Indeed, the last significant and ubiquitous morphogenetic phase was related to the LGM (e.g., Orombelli, 1983; Fliri, 1988). During this period and in the following deglaciation phase, sediment accumulation was certainly much more significant than it was subsequently. Although these LGM-related sediments and landforms are discontinuously distributed, they are present both in the Piedmont areas of the Alps and the Apennines, and in the plain areas (e.g., Orombelli, 1983; Forcella and Jadoul, 2000; Di Dio et al., 2005; Zanferrari et al., 2008a, b, c; Gasperi and Pizziolo, 2009). Detailed subsurface investigations can reveal these features and define their geometry; i.e., whether the stratigraphic units are deformed or not.

In short, a Quaternary (reverse and blind) fault can be considered inactive if it is sealed by deposits and landforms related to the LGM or older. An example of inactivity that was determined in this way is the Monferrato arc, which is the western-most Apennine compressive structure in the Po Plain sector (Fig. 1). Analysis of a well-dated Quaternary sequence in the Cerrina valley allowed the definition of tectonic activity during the Early Pleistocene. The tilted sediments, which were attributed to the Jaramillo subchron (1.07-0.99 Ma), are overlaid by undeformed sediments that were attributed to the Brunhes chron (≤0.78 Ma; Giraudi et al., 2003). The whole geological picture allowed it to be concluded that the Quaternary activity of the Monferrato thrusts is not younger than the beginning of the Middle Pleistocene.

Therefore, the operational choice for engineering practices that are aimed at the reduction of surface faulting risk in the Italian territory can be summarised as follows: *a reverse blind fault or a blind thrust should be considered active and potentially capable if it shows evidence of activity during the Quaternary (2.6 Ma), unless information is available that documents inactivity since a period not later than the LGM.*

3.2.2 The extensional tectonic regime of the Apennines and the Calabrian Arc

The tectonic domain that includes the Apennine chain and the reliefs of the Calabria region is characterised by Quaternary normal faults, the activity of which has strongly conditioned the recent geological evolution at the local scale (CNR-PFG, 1987). Often, these faults are characterised by evident surface expression (i.e., fault scarps in the bedrock and unconsolidated sediments), and are located at the borders of intermontane basins, and along slopes that have morphological features that can be ascribed to the effects of tectonic activity (e.g., Blumetti and Guerrieri, 2007) (Figs. 2b, 8). Therefore, many active faults of peninsular Italy can be considered as capable, as they might generate primary surface faulting as a result of propagation of the seismogenic rupture towards the surface. Moreover, due to the complexity of the tectonic setting and the fault zones, secondary and branch faulting (*sensu* Bonilla, 1967) can affect a territory. Apart from the cases of surface faulting that are known from historical documents or from surveys after historical and recent earthquakes (e.g. Sarconi, 1784; Oddone, 1915; Bollettinari and Panizza, 1981; Westaway and Jackson, 1984;

Cotecchia et al., 1986; Serva et al., 1986; Pantosti and Valensise, 1990; Galadini et al., 1999; Falcucci et al., 2009; Guerrieri et al., 2009b), evidence of coseismic surficial displacement can also be derived from numerous paleoseismological studies that have been performed since the end of the 1980s (Galli et al., 2008, and references therein).

The Apennine active faults often show evidence of Late Pleistocene-Holocene motion. This justifies the methodological approach in the fault inventories compiled at the beginning of this century (Galadini and Galli, 2000; Galadini et al., 2001a), where structures characterised by activity over the last 20 kyr were mapped. However, the use of this time span to ascertain the present state of fault activity has the already mentioned operational limits related to discontinuous distribution of chronological markers in sectors characterised by active faulting. Moreover, in those cases where the slip rate of a fault is significantly lower than the rate of exogenous geomorphic modelling over the last millennia, evidence of recent tectonic activity can be minimal, and hence hardly recognisable. Therefore, although we can consider a fault with evidence of activation in the past 20 kyr as active (as it has moved recently and consistently with the present tectonic regime), the above-mentioned limitations suggest that a longer time span should be defined to draw a picture of the active faults of peninsular Italy that is as complete as possible. In this case, the adoption of the characterisation of the present tectonic regime to define activity/ inactivity (Slemmons and McKinney, 1977; Muir Wood and Mallard, 1992) appears to be the correct way to solve this issue. Once the present tectonic phase has been chronologically defined, all of the faults that are consistent with this, as those that show evidence of activation in the current tectonic regime, should be considered as active, unless evidence of inactivity is recognised.

The available data on the Quaternary geological history of peninsular Italy testify to an evident kinematic change since the beginning of the Middle Pleistocene. For example, investigations into the uplift history of the Apennines have defined a probable acceleration of this process since the final Early Pleistocene or the earlier Middle Pleistocene (Dramis, 1992; Bartolini et al., 2003; Schiattarella et al., 2003). Structural and geomorphological data on the Apennines indicate that there has been a change in the tectonic regime in peninsular Italy, with a substantial kinematic variation along the main Quaternary faults since the Middle Pleistocene (Cinque et al., 1993; Pantosti et al., 1993; Hyppolite et al., 1994; Calamita et al., 1995; Cello et al., 1997; Galadini, 1999; Galadini and Messina, 2001; Valensise and Pantosti, 2001; Di Bucci and Mazzoli, 2002; Patacca and Scandone, 2001, 2004b; Tondi et al., 2005). Concurrent with this, the activity of some central Apennine faults that strongly conditioned the geological evolution of large sectors of the Apennines during the Early Pleistocene ended, or showed a strong decrease (Galadini and Messina, 2004). Finally, the main alkaline potassic magmatic phase of the peri-Tyrrhenian area began in the earlier Middle Pleistocene (e.g., Peccerillo, 2005) as a result of significant geodynamic modifications in the back-arc sector of peninsular Italy.

Overall, present knowledge of the tectonic history of the Italian territory that is characterised by extensional tectonics refers the beginning of the present tectonic regime to the transition between the Early and the Middle Pleistocene (about 0.8 Ma). Therefore, for engineering practices that are related to mitigation of surface-faulting risk, we suggest that *a fault should be considered active and capable if it shows evidence of activation in the last 0.8 Myr, unless deposits not younger than the LGM seal the fault, thus showing that the post-0.8 Ma activity ended during the later Quaternary*. Similar to the case of reverse faults, to state that a fault is inactive, we consider the need for 20 ka as the most recent age of the sealing deposits. Taking into account the slip rates, consistent with the plurisecular-to-a-few-millennia-long recurrence intervals per Italian normal fault, this time span certainly includes more than one seismic cycle.

Based on the importance given to the definition of the present tectonic regime, and considering the above-defined time interval, our conclusion is comparable to that expressed by Tondi (2000), who defined as active all faults that show evidence of motion subsequent to 0.7 Ma.

4 Concluding remarks

As indicated by the available literature, a univocal chronological definition of an 'active and capable fault' that will have worldwide application cannot be proposed. The chronological limits of the activity that defines a fault as active or inactive depend on the characteristics of the tectonic domain related to the present tectonic regime. All of the faults consistent with the current tectonic phase, which is defined as those faults that have moved after the inception of the present tectonic regime, should be considered as active, unless conclusive evidence of inactivity is available. In practical terms, the beginning of the tectonic phase can be considered as the age that divides the field of active faults from that of inactive faults.

Moreover, the choice of the chronological limits is also dependent on methodological issues that involve the tool operation in the tectonic analysis. These methodological aspects are also different across the various tectonic domains, depending on the fault geometry and kinematics, and on the relationships between these features and the recent geological evolution of the sectors investigated.

The dependence on operational aspects might have a key role in the determination of the time span for the anchoring of the definition of an active fault in the compressive domains of the Italian territory; i.e., in the central and eastern southern Alps, Po Plain and peri-Adriatic sectors of the Apennines. These areas are characterised by active reverse faults that have been buried by thick successions of Quaternary sediments. In most cases, surface investigations can confirm Pleistocene fault activity, although they cannot define a detailed chronological framework. Moreover, most of the information on thrusts in the sectors mentioned here can be derived from the seismic-reflection surveys that are carried out for industrial purposes (e.g., for oil and gas extraction), even though these are not targeted at the definition of the active tectonics. This geophysical information only provides evidence of a general Quaternary activity. Therefore, for the sectors of the Italian territory that are characterised by thrust tectonics, we suggest that the blind faults that display evidence of activity over the last 2.6 Ma (Quaternary) can be considered as active and potentially capable. This precautionary choice should be applied if more detailed subsurface information is lacking regarding a hypothesis of activity or a definition of fault inactivity. Fault inactivity should be determined based on a lack of displacement and deformation over the past *ca*. 20 kyr or more; i.e., when a fault is sealed by undeformed sediments with ages not younger than 20 ka. This minimum time interval, which includes the important morphogenetic phase of the LGM and the related landforms and deposits that are easily detectable and datable, certainly covers more than a single seismic cycle of a single fault. This represents, therefore, a precautionary minimum age to ascertain a fault as inactive.

In the case of the extensional domain of the Apennines and the Calabrian arc, active faults that are potentially responsible for earthquakes with M >6 usually reach the surface, and so they can originate primary surface faulting. Branch and secondary faulting usually accompany the primary faulting. Normal faults are considered as active if they show evidence of activation in the past *ca*. 20 kyr. Due to recurring surface faulting, displacement episodes can often be recognised through paleoseismological investigations. However, the discontinuous distribution of recent datable deposits can hinder the assessment of recent fault activity, including the prominent and relatively diffuse geomorphic and stratigraphic markers of the LGM. For this reason, we suggest that characterisation of the present tectonic regime should govern the definition of active faulting in the above-mentioned domains. At least in sectors characterised by extensional tectonics, this regime began in the earlier Middle Pleistocene. On this basis, we suggest to consider active those faults of the Apennine and Calabrian extensional domains that show evidence of activation over the last 0.8 Ma, unless geological information is available that indicates that the post-0.8 Ma activity ended during the later Quaternary, and not younger than the LGM period, as in cases of compressive tectonics.

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Appendix 1

1. 'Time' and 'fault activity/ capability'

The 'time' of activation has often been considered a key element in the definition of an 'active and capable fault'. Since the beginning of the 20th century, this issue has attracted interest in geological discussions (Wood, 1916; Willis, 1923). Both Wood (1916) and Willis (1923) emphasised the importance of historical evidence of fault motion to define fault activity. Moreover, these authors defined the detection of geomorphic evidence of 'recent' fault activation as a fundamental procedure in the study of active faults. This line of thought of referring to the 'recency' of a fault then persisted through later studies. For example, Louderback (1937) defined a fault as active if it showed "evidence of repeated movements during Quaternary time, up to and including very recent offsets, as, for example, in very young alluvium". Here, 'time' is still mentioned in a general way, but the necessity to anchor 'fault activity' to a temporal reference system is evident in the use of terms such as 'recent', 'historical', 'Quaternary' and 'young'.

This blurred time definition continued through later studies. For example, Allen et al. (1965) stated that faults with "sufficiently recent movement to displace the ground surface are usually considered active by geologists simply because the ground surface is a very young and ephemeral feature", and in a study dedicated to active faulting in Alaska, Brogan et al. (1975) stated that "generally recent fault displacements are post-glacial in mountainous parts of Alaska, but may be as old as early Quaternary".

Since the 1960s, most of the widely known definitions were formulated within the framework of regulatory and legal perspectives, as they became related to the estimation of surface faulting and seismic hazard, especially for the siting of strategic engineering works. In this case, the time of activity is quantified. There was a wide review of the definitions of an 'active fault' in the 1970s by Slemmons and McKinney (1977). In their inventory, assumptions of current activity can be found, such as those related to the evidence of repeated activation in the past 5,000 years, or if a single movement occurred in this period, of repeated motion in the past 50,000 years. Actually, a quantitative perspective is seen in numerous studies of several decades ago. For example, Allen et al. (1965) reported, “if stream offsets and scarps in alluvium are to be used as criteria for activity of faults, then the term ‘active’ must apply to events dating well back into the Pleistocene epoch, perhaps as much as 100,000 years”.

In the USA, the regulations for nuclear sites clearly express the definition of a capable fault. During the 1970s, the US Atomic Energy Commission considered that a fault is capable if it shows evidence of at least one displacement in the last 35,000 years or recurrent movements in the past 500,000 years (Coulter et al., 1973; Sherard et al., 1974). However, we know that in planning reactors during the 1960s, faults that also showed evidence of activation in the past 180,000 years were considered capable (Bonilla, 1991). More recently, the upper limit was changed to 50,000 years (US NRC, 1996). The two time intervals (50,000 and 500,000 years) were maintained in the regulatory guidelines over the following years, and were cited in a report dedicated to the techniques for the identification of active faults by Hanson et al. (1999).

The choice of the lower limit has been criticized from an operational point of view, as it largely exceeds the previous commercial limit (about 40,000 years) of the radiocarbon analysis; i.e., the most widely used method to obtain numerical ages (Machette, 2000). However, the same intervals were confirmed by the US NRC (2007), and then only recently the original time spans (35,000 and 500,000 years) were proposed again (US NRC, 2010). Within this framework, it is worth noting that part of the literature on active tectonics research considers 500,000 years as a time span suitable for defining ‘activity’. Indeed, this time span includes a portion of the geological history that can reliably shed light on the tectonic rates, styles and patterns that depict the present regime (e.g., Wallace and Geophysics Study Committee, 1986).

Other countries have generally followed the US nuclear regulations (e.g., Terrier et al., 2002, for France; Diamond, 2007, for Australia). However, the Japanese regulations (NSC, 2006) established a larger chronological interval that corresponds to the entire Upper Pleistocene (about 130,000 years).

The problem of the chronological constraints of the activity has also been addressed for purposes different from nuclear siting. For example, the experience of the San Fernando earthquake in 1971 prompted the drawing up of the ‘Alquist-Priolo Earthquake Fault Zoning Act’ (1972), to prevent building close to the surficial expression of active faults in the State of California, USA (California Geological Survey, 1972). A fault was considered active if evidence can be collected for motion in the past 10,000 years. The Alquist-Priolo Act was more recently updated in Bryant and Hart (2007), who defined as active a fault that was characterised by motion in the last 11,000 years (i.e., during the Holocene). However, according to Shlemon (2010), considering the calibrated ages normally used in active tectonics research, the actual chronological limit should be 13,500 years. The term ‘capable fault’ is also included in the glossary of the US Bureau of Reclamation (2010), where following the nuclear regulations, they referred to a fault that had at least one activation in the last 35,000 years.

With reference to the Basin and Range tectonic province of the USA, WSSPC (1997, 2008; see also Machette, 2000) tried to overcome the issues related to tight chronological constraints by defining: (*i*) Holocene faults (motion in the last 10,000 years; 11,500 years BP cal. age); (*ii*) Late Quaternary faults (motion in the last 130,000 years); and (*iii*) Quaternary faults (motion in the last 1,800,000 years; or 1,600,000 years in WSSPC, 1997, and Machette, 2000). This choice is certainly dependent on the fact that the Holocene tectonic characterization in the Basin and Range province is not enough to define active faults in this domain, where recurrence intervals can be in the order of tens of thousands of years (e.g., Bell et al., 2004). Comparable periodizations can be found in Boschi et al. (2006) and Trifonov and Machette (1993). Boschi et al. (2006) indicated 125,000 years as the time span that is useful to define fault activity for seismic hazard assessment, while Trifonov and Machette (1993) defined 10,000 years and 125,000 years as the two time intervals for the storing of the information in the “World Map of Major Active Faults Project”. In this case, however, the authors adopted different time intervals for continental areas that are characterized by slow rates of tectonic activity, i.e., the Middle Pleistocene (interval considered, 700,000-100,000 years BP) and the Quaternary (interval considered: the last 1,600,000 years). This includes, for example, a vast region of the eastern hemisphere, which is represented by the countries of the former Soviet Union. There, indeed, about 1,000,000 years was the chronological interval considered to assess fault activity (Serva, 1992).

The available literature offers other definitions for the chronological time scale. For example, a bedrock fault sealed by Late Pleistocene surfaces was considered inactive (not 'critical') in the Rhinegraben area of Europe by Loew et al. (1989). Similarly, in a discussion about fault capability related to dam siting, Allen and Cluff (2000) concluded that the absence of surficial displacements during the Late Pleistocene is a sort of guarantee against future activation, also if microseismicity can be associated to the fault. Otherwise, a fault with evidence of activity during the Quaternary should be considered potentially active, while inactivity should be attributed to the faults for which Quaternary evidence is lacking (Keller and Pinter, 2002).

This numerical jungle and the difficult application of univocal statements has probably stimulated further definitions. Due to the variability of the tectonic regime, the already mentioned concepts of 'Holocene active faults', 'Late Quaternary active faults' and 'Quaternary active faults' should be considered, leaving to the user the ability to decide which category of fault is dangerous (e.g., Yeats et al., 1997; Machette, 2000; WSSPC, 2008). This represents a specification of the "degree of activity through a stipulation of the time of most recent movement" (Yeats et al., 1997), and this is considered to be much more adherent to the geological reality (Yeats et al., 1997; Allen and Cluff, 2000).

More recently, an evident change of course saw the definition of 'hazardous faults', as the opposite to 'non-hazardous faults' (Shlemon, 2010). This approach emphasizes the hazard related to the fault activity in terms of the expected amount of displacement, instead of the probability of activation (which is strictly dependent on the chronological aspects). In such a case, engineering planning to reduce the effects of limited throw has a major role (e.g. Bray, 2001; Faccioli et al, 2008; Gazetas et al., 2008).

2 The time span for the assessment of active and capable faults as a function of the tectonic domain and the constraints of operational practice

The previous section showed that the chronological definitions of ‘active faults’ and ‘capable faults’ are ambiguous. Indeed, numerous time spans have been mentioned (5,000, 10,000, 11,000, 11,500, 13,500, 35,000, 50,000, 100,000, 125,000, 130,000, 180,000, 500,000, 700,000, 1,000,000, 1,600,000, 1,800,000 years), following an approach that arose as a response to the regulatory and legal necessities. Meanwhile, adjectives such as ‘young’, ‘recent’ or ‘historical’ are commonly used. This chronological chaos has already been stressed and criticized in other reviews on the subject (e.g., Wallace and Geophysics Study Committee, 1986; Yeats et al., 1997; Castaldini and Ilies, 2005) and is evidently recalled by the engineers who need to use the geological data (e.g., Coulter et al., 1973; Allen and Cluff, 2000; Ulusay et al., 2002; Gazetas et al., 2008). It is possible that these issues have partly conditioned recent engineering approaches, avoiding the need to face the problem of the activity/ capability by the *a-priori* planning of fault-safe engineering works in fault zones, despite conclusively demonstrated current fault activity/ capability (Gazetas et al., 2008).

Besides the definitions of activity and capability linked to the numerical dating or to the geological time scale, we can find other studies and documents that have used definitions that are not directly time anchored. Within this framework, the mention of ‘activity’ can be seen as something that might occur in a time interval of interest for society (e.g., Wallace and Geophysics Study Committee, 1986; Keller and Pinter, 2002), or that might have potential for future fault motion without the need to specify the chronology of the past/ last activity (CNSC, 2007; Roshan et al., 2008; IAEA, 2010). Naturally, these definitions cannot be used directly as part of the regulatory perspective or for engineering purposes, where numerically defined time spans are necessary. However, the vagueness of these definitions is also a sort of response to the problematic application of precise chronological constraints.

Considering these open issues, the geologist can appraise another line of thought, which links the concept of activity to that of the tectonic regime (Slemmons and McKinney, 1977; Muir Wood and Mallard, 1992). In this approach, a fault is defined as active if it has moved within the framework of the present tectonic regime. This evidence guarantees that the fault will probably activate in the future. The vagueness here is only apparent, as such an approach implies tectonic investigations that will also chronologically define the current tectonic regime of a region. Moreover, in contrast to numerical constraints, reference to the tectonic framework makes the definition more widely suitable in practical terms. Indeed, this admits that the current activity of a fault pertaining to a certain tectonic domain can be ascertained by the consideration of a specific time interval that is related to that tectonic domain. If the present tectonic regime has been, or might be still, responsible for the fault activation, all of the faults consistent with that regime should be considered active. This shifts the target of the investigations from the single fault (studied to understand if it has moved during one of the previously mentioned time intervals) to the entire tectonic domain (to reconstruct the tectonic history and to define the characteristics of its latest phase and the faults consistent with it).

Therefore, since the second half of the 1970s, and in parallel with the definition of activity by the expression of precise chronological constraints, we find that the problem of active faulting is also approached from a more general point of view; i.e., of tectonic studies at the regional scale. These conclusions have a ‘local’ value that is related to that specific tectonic domain, but which is not exportable to other domains. This widely usable approach was later reasserted (Wallace and Geophysics Study Committee, 1986; Terrier et al., 2002; ANS, 2008; IAEA, 2010). For example, IAEA (2010) stated that when geological data indicate that the present seismotectonic regime is characterised by short seismogenic cycles, the fault capability can be estimated by considering time spans in the order of thousands or tens of thousands of years (e.g., Late Pleistocene-Holocene). In contrast, in areas affected by lower seismicity, the estimation should be based on larger time intervals. Indeed, it is evident that due to the different tectonic rates and styles, the time intervals necessary to characterise active transcurrent faults in California, USA (recurrence intervals from a few centuries to a few millennia; e.g., Machette, 2000), is certainly different from that necessary to define active normal faults of the Basin and Range (recurrence intervals also in the range of tens of thousands of years; e.g. Machette, 2000; Bell et al., 2004), or that related to the intraplate tectonic domains (e.g., Adams et al., 1992; Crone et al., 1997).

Practically speaking, operational constraints also significantly contribute to the choice of the time interval for the assessment of fault activity. The impact of the operational factors is evident in the approach by WSSPC (2008). Indeed the chronological limit for the Late Quaternary faults (130,000 years) was fixed because it represents the transition between the isotopic stages 6 and 5, i.e., a climatic event where the geological and geomorphological signature is widespread. Similar considerations were made by Terrier et al. (2002) in their report on the Antilles and the faults active during the Holocene. This is a period characterised by well-known deposits, in terms of their precise dating and for the sedimentary environment. Similarly, Galadini et al. (2001a) defined as active those faults responsible for the displacement of recent deposits that are not older than the LGM, considering the quite wide distribution of the LGM deposits (although outcrops are strongly discontinuous) along the Apennine-fault-related slopes in Italy. Moreover, we have already mentioned the main criticism to the choice of 50,000 years as the chronological limit of an active fault in the regulations for nuclear sites, which arises as it is far beyond the commercial limit of the radiocarbon method (Machette, 2000). The use of this dating method clearly conditions the choice of the time span to assess active faulting in the Italian guidelines for seismic microzoning (40,000 years) (Gruppo di Lavoro MS, 2008).

Other operational constraints derive from the current practices of investigation. For example, one of the criticisms of the chronological range of the Alquist-Priolo Act by Shlemon

(2010) is represented by the difficulties and the costs of digging geognostic trenches in California, USA, that reach the depth necessary to uncover stratigraphic units older than about 5,000 years. Also for this reason, Shlemon (2010) proposed a time interval to ascertain fault activity of the order of 4,000-6,000 years, instead of 11,000 years.

The operational constraints probably have major roles in numerous other situations. One of these cases can be seen by blind faults, which are introduced here because they are quite diffuse in Italy and define part of the Italian case study. These faults are characterised by faint surficial evidence, which are possibly hidden by the effects of depositions with high sediment accumulation rates (e.g., for the Italian cases, Desio, 1965; Burrato et al., 2003; Galadini et al., 2005; Picotti and Pazzaglia, 2008; Livio et al., 2009; Toscani et al., 2009). In terms of 'capability', these faults are important because of the flexural deformation they can undergo at the surface along quite a narrow belt, and because of secondary extensional faulting and 'non-tectonic', gravity-driven faulting that is potentially related to the growth of thrust-related folds. In the case of low tectonic rates and high erosion/ sediment accumulation rates, the definition of these surface tectonic features can be difficult. For this reason, ascertaining the fault activity might only be possible through the collection of subsurface geological data. Most of these data can usually be derived by the processing of seismic-reflection profiles. However, apart from specific cases of fault investigations, most surveys are usually performed for industrial purposes that are not related to the analysis of active tectonics. For this reason, most of the available subsurface information does not provide the detail necessary to define the recent fault activity. If high-resolution seismic data are not available, the recent activity of a buried fault can only be assessed without significant chronological detail for the most recent times; e.g., the general evidence of Quaternary deformation will be emphasised. This means that in most cases of blind faults (usually thrust faults), the time span chosen for the assessment of the activity can be very large, and can thus cover hundreds of thousands of years.

In conclusion, two aspects appear to be fundamental for the choice of the time interval necessary to assess fault activity/ capability: (*i*) the dependence of this interval on the characteristics of the current tectonic regime, which are different in the different tectonic domains; and (*ii*) the dependence of this interval on factors external to (although partly conditioned by) the tectonic regime, which are mainly related to methodological aspects and to the operational characteristics of the tools presently available in active tectonics research.

Captions

Figure 1. Main Italian tectonic domains. 1) Compressive domain of the central and eastern Southern Alps, which is mainly affected by blind thrust and reverse faults. 2) Compressive domain of the central-northern external Apennines, which is mainly characterised by blind thrust and reverse faults. 3) Extensional domain of the inner Apennines and Calabria. The location of the areas represented in Figs. 3, 5, and 8 is reported. Focal mechanisms are also drawn for some key-sectors of the seismotectonic domains; the solutions have been obtained by Meletti et al. (2008) from the cumulative moment tensor related to a large number of instrumental earthquakes and represent, therefore, average kinematic properties.

Figure 2. Three-dimensional schemes that illustrate the capability of compressive and extensional faults in the Italian tectonic domains. a) Compressive tectonic domain: blind thrusts might be responsible for secondary extensional faulting along the extrados of fault-related folds. b) Extensional tectonic domain: fault motion is responsible for the formation of primary and secondary faulting; primary faulting often borders intermontane basins and affects mountain slopes.

Figure 3. Location map of the topographic reliefs traditionally interpreted as the result of the growth of thrust faults. Stars define the location of the hills discussed in the text, close to the projection at surface of the related thrust faults; faults are indicated by the black lines and the teeth marks at the hanging walls.The grey lines represent the isobaths of the base of the Pliocene sediments, clearly displaced the Apennine thrusts.

Figure 4. The Colle Villano thrust, along the Susans-Tricesimo thrust system, at Megredis in the province of Udine (see Fig. 1 for location). A) The surficial expression of the blind thrust is represented by gentle scarps at the limit between the Friulian plain and the Prealpine reliefs. Dashed

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Figure 5. Mount Netto relief in the province of Brescia, central southern Alps (see Fig. 3 for location). A, B) General view of the folded area, with intense deformation in the hinge zone. Dashed circle, sector enlarged in C. C) Detail of the hinge zone with evidence of extrados extensional faulting. Dashed circle, sector enlarged in D. D) Minor extensional faults responsible for small displacements. See Livio et al. (2009b) for complete description of this case study.

Figure 6. Mount Baldo, in the province of Verona, central southern Alps (see Fig. 1 for location). A, B) Fault plane that borders the narrow Naole valley that is located at the top of the relief formed by the doubling of the crest as a result of deep-seated gravitational motions. C) The deep gravitational displacements have been interpreted as a secondary effect of the thrust-related fold growth. (Modified after Galadini et al., 2001b).

Figure 7. Typical seismic image of a blind thrust in the Italian eastern southern Alps: the Montello blind thrust. White arrow, the folded sediments attributed to the Quaternary (Q) are only visible in the right corner. Detailed information about the Quaternary deformations cannot be derived. Pli, Pliocene layers. Dashed white lines define the base of the Quaternary and of the Pliocene deposits. (Modified after Galadini et al., 2005).

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system, which was responsible for the 1915 earthquake (M 7). The impressive bedrock scarp affects the middle portion of the slope. The fault plane is exposed along the scarp and places the carbonate bedrock in contact with slope deposits that are mainly related to the Late Pleistocene, and are due to depositional episodes that occurred during the LGM (e.g. Galadini and Messina, 1994). C) Magnola Mountains Fault, as part of the Fucino fault system. The bedrock fault scarp is located in the lower portion of the slope. Along the scarp, the fault plane places the carbonate bedrock in contact with Pleistocene and Holocene slope deposits (e.g. Galadini and Messina, 1994). D) Middle Aterno valley fault in the zone of Tione degli Abruzzi. As in the other cases, the fault plane places the carbonate bedrock in contact with Late Pleistocene (LGM)-Holocene deposits (e.g. Falcucci et al., 2011). E) Mount Morrone fault in the zone of Roccacasale. The surficial expression of the fault is an easily detectable bedrock scarp. The repeated Quaternary fault motion generated the Sulmona basin, which is partly visible on the right side of the photograph (e.g. Gori et al., 2010). F) Paganica fault, at the base of the low relief in the background of the photograph. The fault generated the 6 April, 2009, L'Aquila earthquake (M 6.3). The repeated fault motion was repsonsible for the formation and evolution of the Paganica-San Gregorio basin, which is visible in the foreground (Galli et al., 2010).

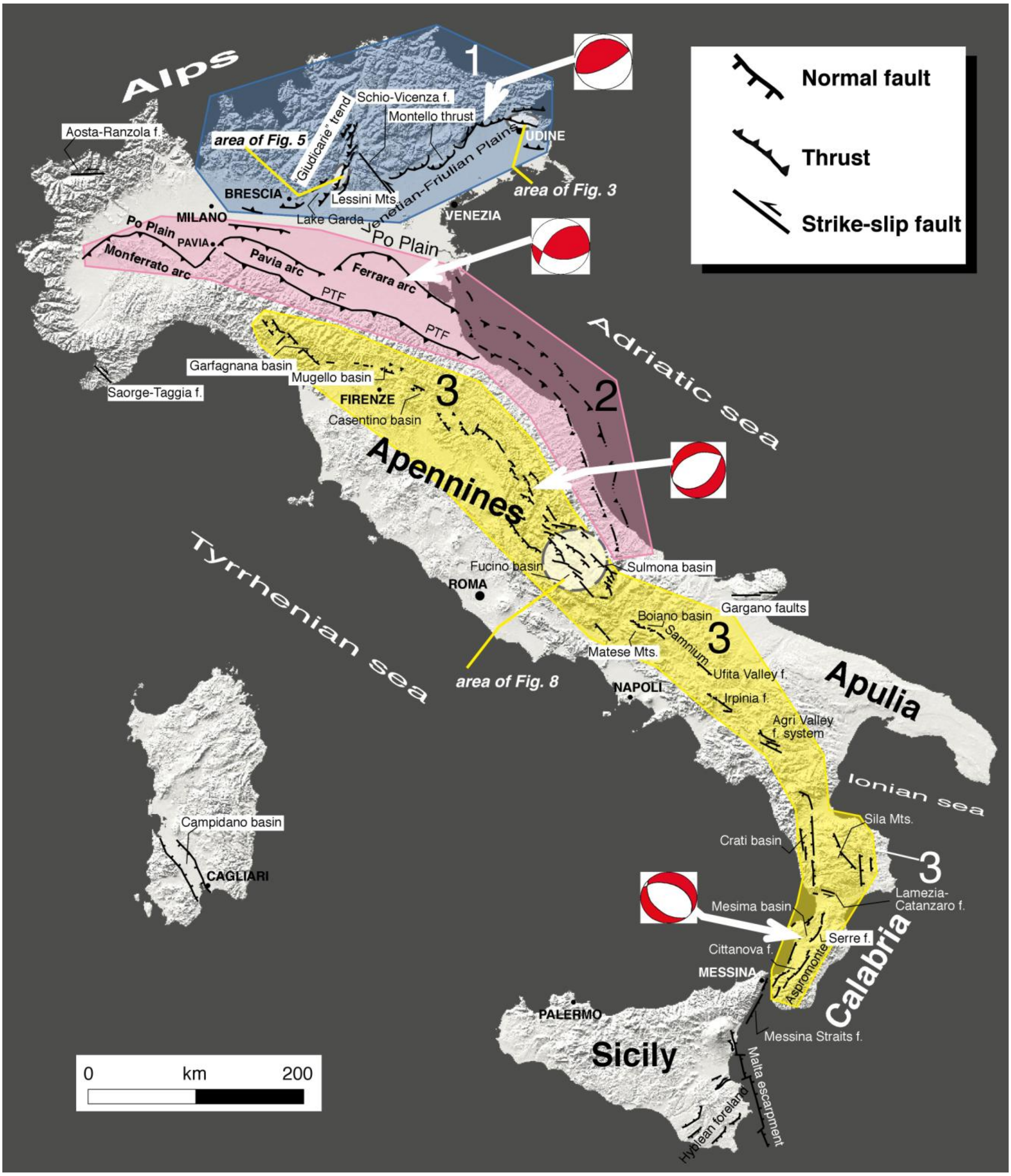
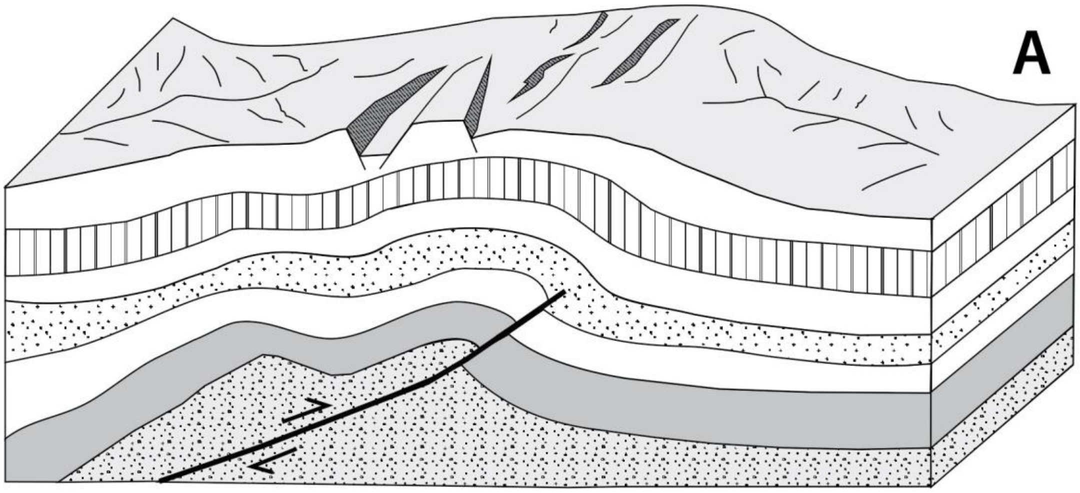

Alps
1
2
3
Normal fault
Thrust
Strike-slip fault
Aosta-Ranzola f.
Schio-Vicenza f.
Montello thrust
area of Fig. 5
"Giudicarie" trend
Venetian-Friulian Plains
UDINE
area of Fig. 3
BRESCIA
Lessini Mts.
Lake Garda
MILANO
VENEZIA
Po Plain
PAVIA
Monferrato arc
Pavia arc
Ferrara arc
PTF
Adriatic Sea
Garfagnana basin
Mugello basin
FIRENZE
Casentino basin
Saorge-Taggia f.
Apennines
Tyrrhenian sea
Fucino basin
Sulmona basin
ROMA
Gargano faults
Boiano basin
Samnium
Matese Mts.
area of Fig. 8
NAPOLI
Ufita Valley f.
Irpinia f.
Apulia
Agri Valley f. system
Ionian sea
Sila Mts.
Crati basin
Lamezia-Catanzaro f.
Mesima basin
Serre f.
Cittanova f.
MESSINA
Aspromonte
Calabria
PALERMO
Messina Straits f.
Sicily
Malta escarpment
Hyblean foreland
Campidano basin
CAGLIARI
0 km 200

Figure 1



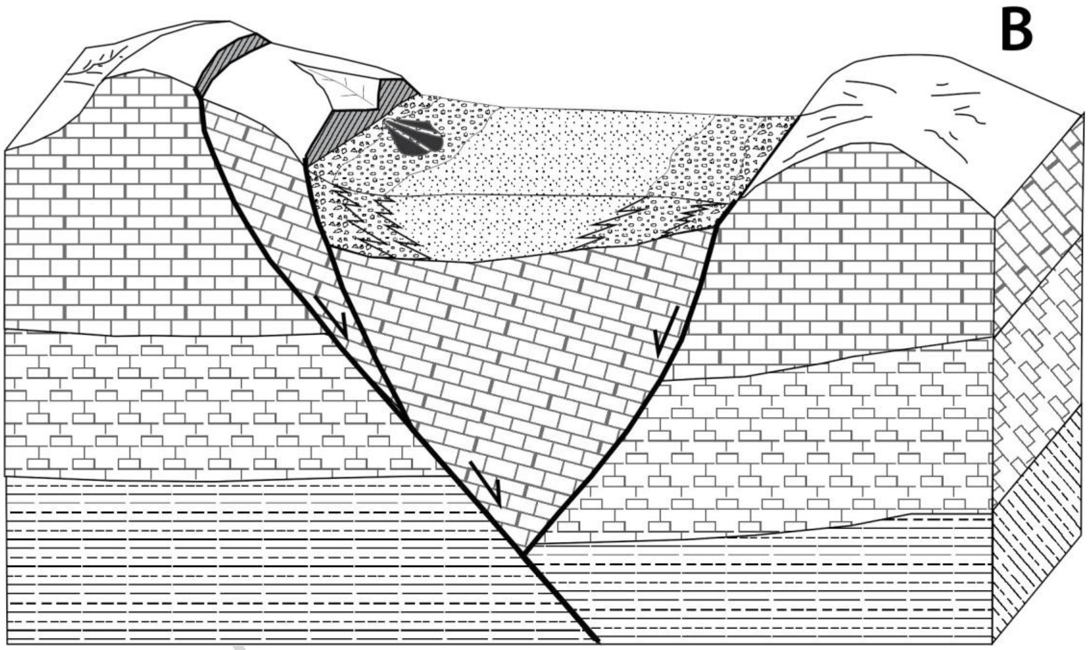


Figure 2

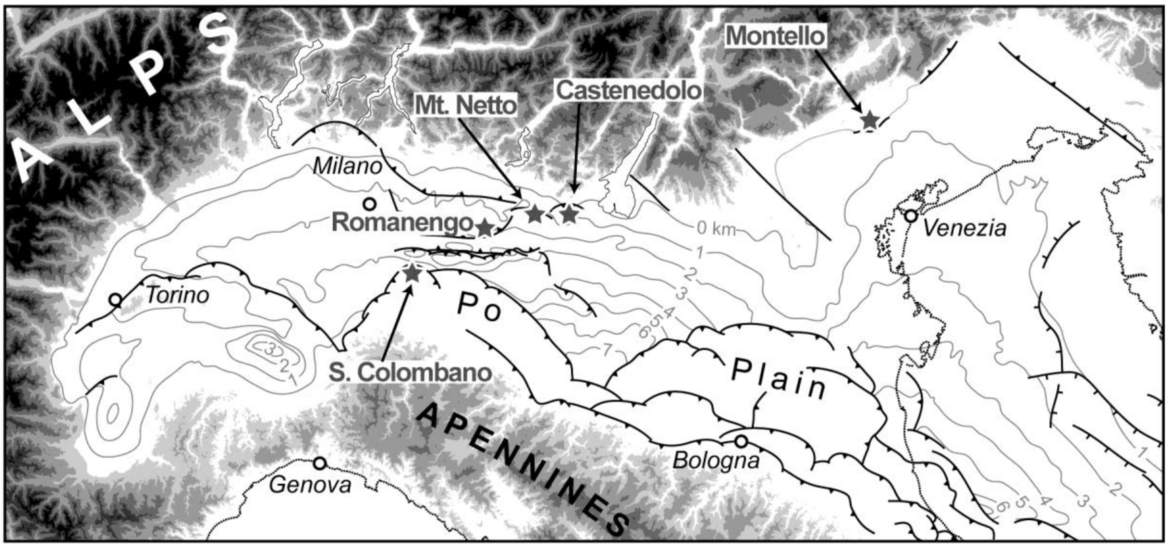

ALPS
Montello
Mt. Netto
Castenedolo
Milano
Romanengo
0 km
Venezia
Torino
S. Colombano
Po
Plain
APENNINES
Bologna
Genova
Figure 3

Figure 4

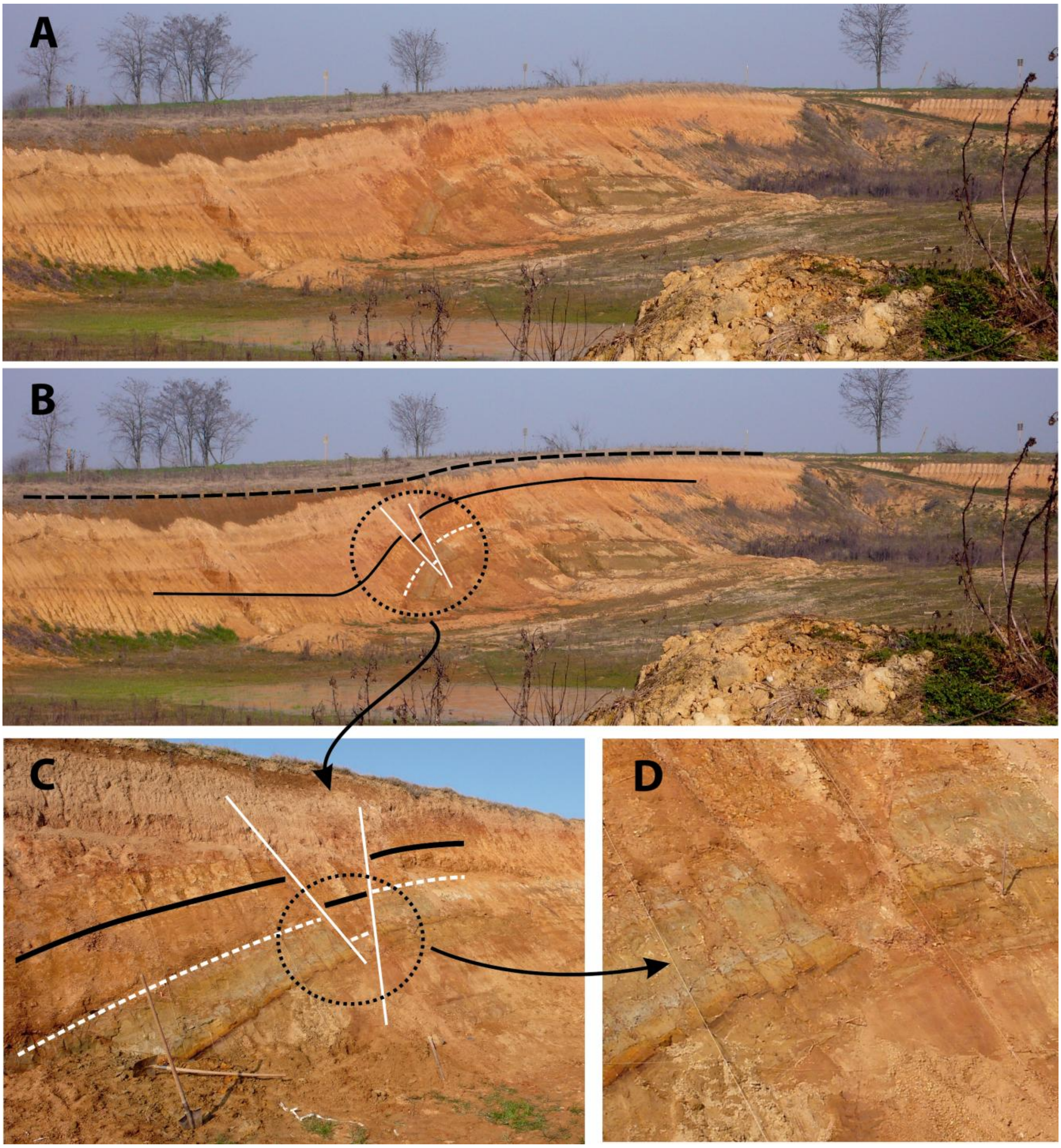


Figure 5

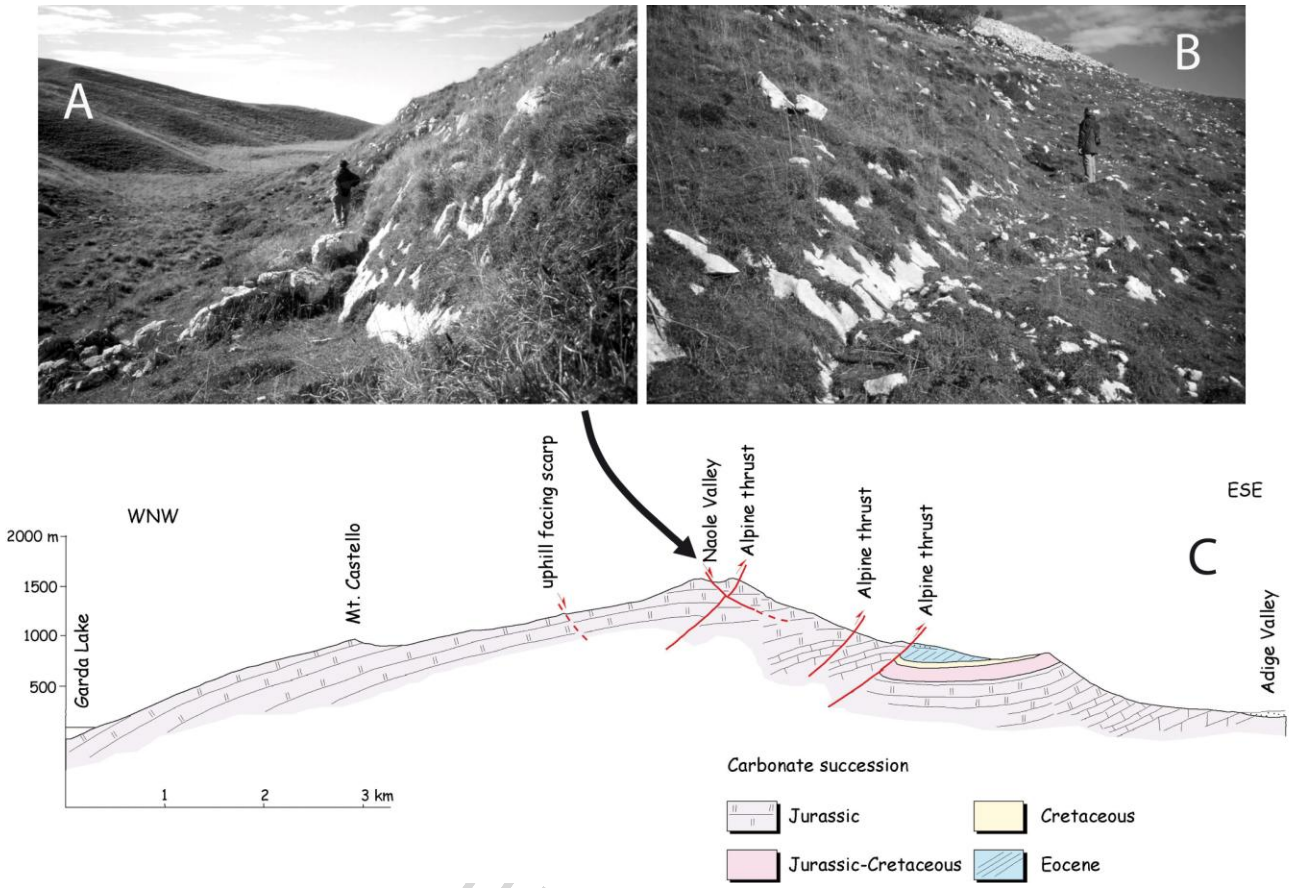

A
B
C
WNW
ESE
2000 m
1500
1000
500
Garda Lake
Mt. Castello
uphill facing scarp
Naole Valley
Alpine thrust
Alpine thrust
Alpine thrust
Adige Valley
1
2
3 km
Carbonate succession
Jurassic
Cretaceous
Jurassic-Cretaceous
Eocene

Figure 6

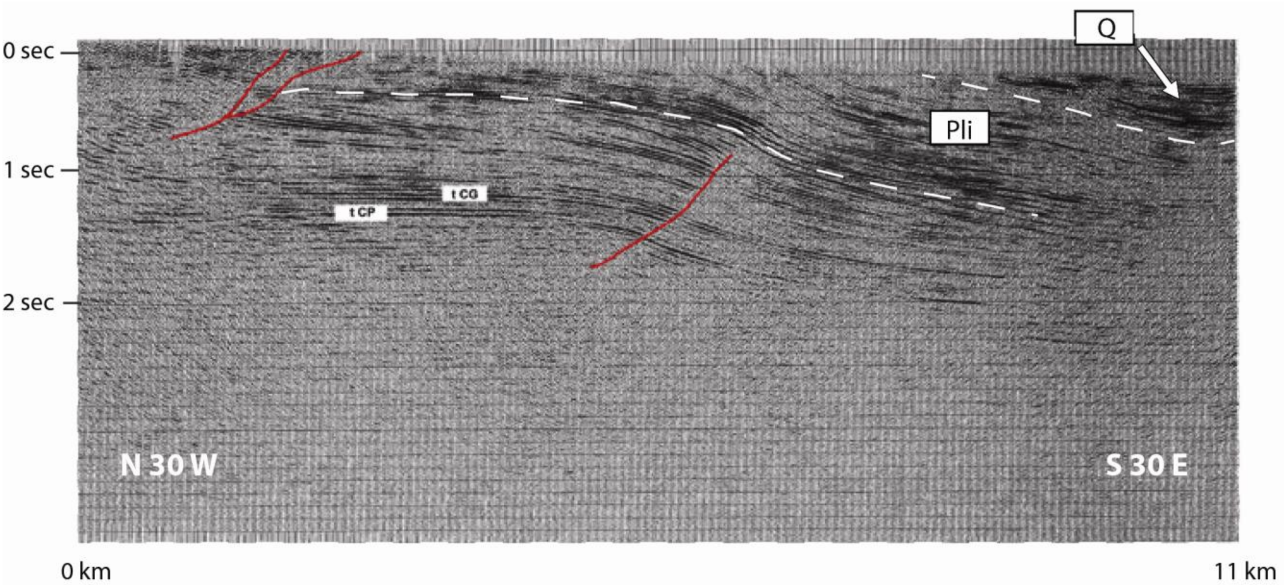
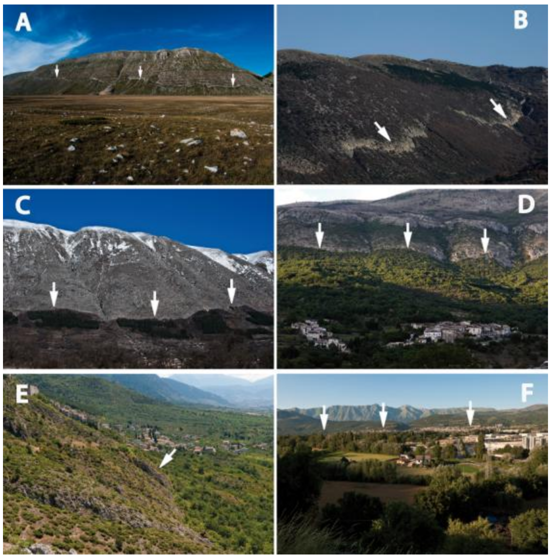


Figure 7



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Highlights

- We discuss the literature dealing with the time span to define a fault as active
- We examine the Italian tectonic domains to chronologically define a fault as active
- We conclude that methods of analysis condition the time choice to define Italian thrusts as active
- We conclude that the present tectonic regime defines the time choice for normal faults in Italy