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NEOTECTONICS AS A PROCEDURE TO UNCOVER ACTIVE SEISMOGENIC FAULTS: THE PRESENT EFFICACY OF THE ITALIAN APPROACH MATURED IN 1970-1980

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ABSTRACT: Studies on active and capable faults produce data that presently have a key role in the broad field of earthquake geology, as well as in planning engineering works and land use. In regions with high deformation rates, the approach through paleoseismology could be sufficient to collect data necessary to depict active faults behavior. By contrast, a similar approach may be inappropriate in tectonic domains which are characterized by slower deformation rates, like Italy. In such areas, Neotectonics as expressed by Carlo Bosi in 1992 - "integrated set of researches with the aim to define the Plio-Quaternary tectonic evolution defined through a temporal scan of hundreds of thousands of years" - provides valuable insights into studying active tectonics and related faulting. Indeed, through the evolutionary perspective, which goes far beyond a "static" multidisciplinary approach, Neotectonics appears as a necessary procedure to define the active faulting setting of a region, representing the effect of the current tectonic regime. Hence, the structural settings produced by Neotectonics represent the basis for seismotectonic settings, as they incorporate those faults that are active seismogenic, which can be capable or not. Overall, this has effects in terms of definition: a fault can be considered active if it exhibits evidence of movements within a time frame consistent with the ongoing tectonic regime of the region, unless it is sealed by deposits and/or landforms not younger than a time span (from the present) whose duration encompasses a significant number of seismic cycles on the respective fault. Neotectonics, defined as a procedure, permits to connect active faults to their "engine", that is tectonics. This sets the basis for its methodological predictive effectiveness in seismotectonic studies.

Keywords: Neotectonics, active fault, seismogenetic source, Italy, Carlo Bosi.

1. INTRODUCTION

Active faults are manifestations of the stress regime acting in a given region. While there are a few known cases of creeping faults (excluding those connected to volcano-tectonics), faults that determine "slow earthquakes", or the still poorly understood phenomenon of sympathetic fault slip, movement of active faults typically results in the sudden release of stress accumulated in rock masses, leading to the generation of earthquakes. This category of geological structures is here addressed.

Decades of modern research, at least since the first half of the 20th century, have defined the key role of the geological and geomorphological investigations along the surficial expressions of active faults to collect information concerning surface displacement/ deformation hazard, seismogenic sources and related implications in terms of ground shaking.

Considering the relevant consequences of this branch of study, fundamental question raises, such as: what defines an active fault? Which characteristics must a fault display to be considered active and seismogenic?

To answer these questions, the concept of "active fault" is very often associated with the terms "Paleoseismology", "Active tectonics", "Neotectonics", defined according to views expressed in milestones of the dedicated literature. Among the reference publications, McCalpin (2009) stated the difference between paleoseismology and the other study fields, indicating the former as a "*subdiscipline within the much broader fields of neotectonics, active tectonics and earthquake geology*". Within this light, paleoseismology completes Neotectonics: "*paleoseismic histories* […] *help us understand many aspects of neotectonics, such as regional patterns of seismicity and tectonic deformation as well as the seismogenic behavior of specific faults*". This represents a logic definition, since Neotectonics is considered as "*the study of the post Miocene structures and structural history of the Earth's crust*".

An explicit chronological constraint is provided by Caputo & Helly (2008) who defined Neotectonics as a discipline contributing to the study of earthquake geological records in the past (few) millions of years up to the last hundreds of thousand years, after which other disciplines contribute more effectively, such as paleoseismology, archaeoseismology, historical research, etc.

Another current of thought defines consistency with the present tectonic regime (Machette, 2000). Indeed, the author defined that "*Neotectonic faults are thought of herein as those formed during the current stress regime; that is, the one presently causing earthquakes and surface deformation in an area*". A consequence is that Neotectonics should not be applied within a specific chronological interval valid everywhere, considering the variability of the tectonic domains.

This has been more recently confirmed by Wu & Hu (2019), who stated that "*the time scale of Neotectonics is closely related to the geodynamics of a particular region focusing on the geological processes at time scales from Ma to ka, and 'past and present' tectonic movement*", while "*Active Tectonics places much more attention on the geological-morphological processes since 100-150 ka BP, and it is more oriented to understand the 'present and future' tectonic deformation*". Other points important for our work, raised by Wu & Hu (2019), are related to the time scale of Neotectonics, which "*could be relatively broad*". A consequence is that "*limits exist when it is applied to study the latest tectonic activities*", since Pliocene or Miocene faults may not activate within the framework of the current tectonic regime. And also "*Active Tectonics is a significant branch and extension of Neotectonics and the latter can be considered as the basis of understanding of the former*". Therefore, on one side, these authors define chronological constraints since a broad time span of investigation is attributed to Neotectonics, longer than that attributed to Active Tectonics, considering its practical application in the past 100-150 ka BP. On the other side, the same authors consider the study of Neotectonics as a starting point to investigate active tectonics and invoke the possibility that faults derived from Neotectonics may be presently inactive.

As for the chronological aspects, the not univocal interpretation may also depend on the term "Neotectonics" itself, as it basically "sounds" like the study of the "new" tectonics, or "recent" tectonics, intuitively in contraposition to an "old" Tectonics. This linguistic aspect has been pointed out in the already mentioned work by Wu & Hu (2019), who highlighted that "*the word neotectonics originated from Greek, and refers to 'the youngest, latest or on-going crustal tectonics or movement process on the earth', i.e., the latest tectonic processes in geological history. Therefore, this term inherently does not specify a period or limit in time, which may cause confusion in application due to different understandings*".

Whichever definition is used, nonetheless, Neotectonics is evidently connected to the study of the faults that can generate earthquakes, as they are "the" active faults.

This conceptual premise is necessary to introduce the present work, since it deals with the experience on Neotectonics matured in Italy, starting from the "lesson" learned during the Italian national project "Progetto Finalizzato Geodinamica" ("Italian Geodynamics Project", hereinafter PFG), conducted in the 1970s and 1980s with methods, procedures, and results summarized by Carlo Bosi(1) in 1992, as coordinator of the sub-project "Neotectonic Map of Italy".

Our goal is *i*) to describe the perspective of Neotectonics defined in the above-mentioned Italian project, *ii*) to provide a solution to the ambiguity in the use and definitions of the term, and *iii*) to show the unreplaceable effectiveness of Neotectonics for studying active and seismogenic faulting in Italy. The Italian seismotectonic framework is particularly suitable for this aim. Indeed, in regions characterized by high deformation rates (in the order of few-to-several centimeters per year) such as those including plate boundaries, faults may display unmistakable geological evidence of activity and a "simple" paleoseismological approach may suffice to investigate them. On the contrary, in intraplate tectonic domains like indeed Italy, characterized by *i*) slow rates of deformation, *ii*) recent inception of the current tectonic regime, *iii*) faint superposition of active faults on the structural framework inherited from past tectonic phases, and *iv*) exogenous modification of the landscape with rates comparable to those related to tectonics, the detection and definition of active faults are more complex and the paleoseismological approach may result not sufficient to define appropriate seismotectonic pictures. We will show that in such tectonic domains, Neotectonics can result fundamental to define settings of active faults, once the methodological perspective we discuss is adopted.

After a paragraph dedicated to the definitions of "active tectonics", "active faults" and "capable faults" over the past decades, we present the Italian experience on Neotectonics. Afterward, we will discuss the implications of applying Neotectonics to evaluate the time interval required for assessing active and capable faulting in the context of the Italian tectonic framework for engineering practices. Subsequently, we will examine some examples to demonstrate the effectiveness of Neotectonics in assessing active and seismogenic faulting, as well as the negative consequences of not applying. In the discussion and concluding remarks, we will summarize the key aspects of the Italian experience in Neotectonics, from which general implications will be derived, related to the investigation of active and seismogenic faults in any seismotectonic framework.

2. DEFINING "ACTIVE TECTONICS", "ACTIVE FAULTING", AND "CAPABLE FAULTING": A CRITICAL REVIEW

Scientific papers, technical reporting, and guidelines for engineering practices include a multitude of definitions regarding the categories mentioned in the title of this section, partly reported in Appendix A (only available in the online version of the manuscript). The long list suggests that a commonly agreed-upon view is lacking.

The plethora of definitions allows us to derive some general aspects and criticalities that probably did not permit to get to a commonly accepted view of what defines active tectonics and active faulting to date:

1) Characterizing active tectonics and active faults can-

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1) - Carlo Bosi (1935-2018), geologist, has been Director of Centro di studio per la Geologia Tecnica and Istituto di Ricerca sulla Tettonica Recente of the (Italian) National Research Council (CNR); Coordinator of the Neotectonic Map of Italy (within the framework of Progetto Finalizzato Geodinamica sponsored by CNR); President of AIQUA (Italian Association of Quaternary Studies). Among the first Italian researchers, he used Quaternary Geology to investigate active faults in the central Apennines, greatly contributing to the methodological advancement and the progress of knowledge in this field. His works made between the Seventies and the Nineties of the past century are still fundamental sources of geological data and milestones for the analytical approach that deserve to be considered still valid and irreplaceable. The authors owe him their personal expertise in the arguments discussed in the present paper.

not solely rely on an investigation approach based on instrumental monitoring (such as instrumental seismicity and/or modern geodesy, and/or satellite remote sensing), aimed to define what are the current effects of ongoing tectonic forces.

2) The key role of the chronological constraints to define current activity usually emerges from the different scientific and technical contributions; the various definitions are based upon time intervals that are influenced by local geological and tectonic characteristics (e.g., high slip rates and/or short recurrence intervals of fault activation) or by the lifespan of engineering infrastructures (from residential buildings to dams to nuclear plants), or by the available methods used by geologists to chronologically constrain tectonic activity or inactivity.
3) It is evident that a comprehensive geological approach is necessary to assess tectonic/fault activity, as it may take place over time intervals typical of the geological analysis, i.e., on the scale of thousands or hundreds of thousands of years.
4) It is also evident that a definition of "active fault" that is suitable for one specific territory or tectonic framework may not be as applicable or effective in another tectonic context, i.e., a general and comprehensive time interval to assess fault activity cannot be determined.

Since the 1970s, alternative approaches have based the definition of tectonic and fault activity on the characteristics of the ongoing tectonic regime. Regimes vary from one region to another and are characterized by different kinematics of faults, deformation rates, and recurrence time of fault actvation (Slemmons & McKinney, 1977; Muir Wood & Mallard, 1992). According to Slemmons & McKinney (1977), a fault can be considered active if it activated during the current seismotectonic regime and, consequently, may be responsible for future dislocation events.

Within this light, an active fault is essentially the manifestation of the current tectonic regime, which serves as the underlying cause, as the "engine" for the fault activity. Fault activation during strong earthquakes and the geological traces of its movements at the surface represent direct and visible evidence of ongoing tectonic activity, i.e. of the ongoing tectonic regime.

Therefore, since the concepts of "active tectonics" and "active faulting" inherently relate to the characteristics of the ongoing tectonic regime, it becomes clear that defining this regime is essential to assess active faulting. Furthermore, considering that the characteristics of the tectonic regime differ from one region to another, it follows that the definition is inherently tied to specific territories. Each region has its own time span within which a given fault must show evidence of movements in order to be considered active.

The current tectonic regime represents the most recent phase of the tectonic evolution in a given region. By defining this history, using methods and techniques typical of the geological investigation, we can uncover the ongoing tectonic process in an area and, importantly, we are able to determine when it began.

On these grounds, the time interval for investigating tectonic behavior appears crucial. It must be sufficiently long to "sample" significant variations in deformation rates, kinematics, and style of tectonic deformation (e.g., from extensional to compressive tectonic regime).

On the whole, understanding of the current tectonic regime and, therefore, the characteristics of active tectonics implies the analysis of geological and tectonic events, as well as the structural evolution of areas, regions, faults or folds over time intervals as long as to guarantee a geologically wider view of the tectonic behavior. By taking a broader geological perspective, we can gain a comprehensive understanding of the short-term tectonic behavior, which provides the ground to assess hypotheses on the future behavior of faults. In Italy, this type of information is obtained from the analysis of time spans including late Pliocene and Quaternary.

Similar conclusions about the necessity to define active fault settings, i.e., those faults that are genetically related to ongoing tectonic regimes through the reconstruction of the kinematic evolution, have to be also drawn for the capable faults, considering that, on the whole, they can be included in the category of the active faults. Indeed, there is not a capable fault that cannot be classified as an active fault (while, by contrast, not all active faults may be considered as capable). In short, capability cannot be separated from the concept of activity, because activity connects to the engine that moves a (an active) capable fault, that is, tectonics. This is clear from IAEA SSG-9 (IAEA, 2022), one of the main references for the definition of capable faults, whose content has been summarized in Appendix A. There, following the well-known paradigm in which a capable fault is "*an active fault that has a significant potential for displacement at or near the ground surface*", IAEA defines three conditions to assess capability, i.e., *i*) the evidence of past movement (e.g., significant deformations and/or dislocations) within such a period that it is reasonable to conclude that further movements at or near the surface might occur over the lifetime of the site or the nuclear installation; *ii*) the structural link of a fault with a known active fault; *iii*) a relationship with a seismogenic structure which may cause earthquakes with magnitude large enough to trigger fault motions in a certain area.

Criterion 1 indeed highlights the significance of considering a geological time period that is sufficiently long to account for the style and rate of deformation. This time is directly related to the current tectonic regime and the age of its inception. Criterion 2 introduces the concept of a structural relationship between a given fault and another fault that satisfies criterion 1 to assess the capability of the former. However, criterion 2 does not provide a clear definition of what constitutes a "structural relationship". In this regard, for example, "soft linkage" is a kind of "structural relationship" among fault segments, but this kind of relation does not imply that the kinematic characteristics on one segment can be applied to the others, since "soft linkage" implies kinematic independence (e.g., Walsh & Watterson, 1991). Moreover, criterion 2 is ultimately dependent on criterion 1, thus reinforcing the importance of understanding of the ongoing tectonic regime.

Regarding the third criterion, although IAEA SSG-9 does not explicitly specify the relationship a fault should have with a seismogenic source to be considered capable, the definition of the seismotectonic framework - of which a seismogenic source is part - of a region relies once again on understanding the ongoing tectonic regime and the relevant time span for this definition. Comparably to criterion 2, also criterion 3 is implicitly associated to criterion 1.

In summary, the concept of fault capability and its determination relies on considering time as the primary factor to define the ongoing tectonic setting. Indeed, the other criteria mentioned for defining fault capability are not independent of a chronological criterion. The assessment of fault capability cannot be considered in isolation from activity. Therefore, while a fault can be active but not capable, a capable fault is inherently active, that is, connected to the causative tectonic regime. Fault capability and activity are therefore interconnected concepts that cannot be dissociated from the chronological criterion. Therefore, criteria 2 and 3 of IAEA SSG-9 are actually sub-criteria with respect to criterion 1.

Hence, if the definition of the tectonic regime is crucial to fully characterize the geometric and kinematic characteristics of seismogenic active and active/capable faults, connected to this regime, the next fundamental step is "how" to effectively analyze the tectonic regime. In this regard, the Italian experience on Neotectonics offers unreplaceable insights, particularly through the theoretical and epistemological synthesis proposed by Carlo Bosi discussed in the following section.

3. NEOTECTONICS IN ITALY BETWEEN THE 1970s AND THE 1990s

The studies on Neotectonics in Italy received great impulse and formal organization in the second half of the 1970s, within the framework of the Italian Geodynamics Project sponsored by the National Research Council (the above mentioned PFG). The aim of this great initiative of research was the evaluation and reduction of seismic and volcanic risks, through the collaboration of geologists, geophysicists, seismologists, and engineers. PFG is still considered as the greatest Italian effort of multidisciplinary studies, as it involved more than 1,000 scholars from universities and research institutes, organized in sub-projects and working groups, with expertise ranging from the different fields of Geology to Seismology, Volcanology, and Seismic Engineering (Barberi, 2020; Stucchi, 2023, personal communication). It produced an impressive number of scientific publications and reports, technological products, and operating manuals. The most famous releases, still used today as milestones of the research history, are the "Structural Model of Italy" (Bigi et al., 1990), the "Neotectonic Map of Italy" (Ambrosetti et al., 1987), an earthquake catalog (Postpischl, 1985; see Camassi, 2004 for a review of the Italian catalogs and a description of the PFG catalog), and the first seismic classification of the Italian territory (CNR-PFG, 1980a). According to Barberi (2020), PFG had the merit to lay the foundation of a culture of prevention in Italy regarding seismic and volcanic risks (an example of the PFG effort in this perspective is the intervention of G. Grandori and F. Barberi at the Senate of the Republic following the 1980 earthquake in southern Italy; Grandori & Barberi, 1980).

The sub-project dedicated to the Neotectonic Map of Italy was coordinated by Carlo Bosi, a Quaternary geologist of the National Research Council. The progress of the research is testified by various publications (e.g., CNR-PFG, 1980b; 1982), permitting to understand the characteristics of the Italian approach to Neotectonics and still having the role of invaluable data sources.

The range of definitions available worldwide for Neotectonics (some and significant examples have been reported above) makes the description and discussion of this approach necessary to estimate the current effectiveness of the methods adopted in Italy. In this perspective, an important document is represented by the Introduction to the workshop "La Neotettonica in Italia a dieci anni dalla fine del Progetto Finalizzato Geodinamica" (*Neotectonics in Italy ten years after the Italian Geodynamics Project*), held in Rome on 2nd-3rd March 1992 (Bosi, 1992). The text was written in Italian, and, in the following lines, we will propose the translation of those parts (within quotation marks and in italic, bold italic for the most important passage, in our text) that cast light on methodological aspects.

In his contribution, Bosi firstly retraced the state of the art at the beginning of PFG, in the half of the 1970s, mentioning the general belief of that time, i.e., "*that the formation of the Alpine and Apennine chains ended in the Miocene or in the Lower Pliocene and that Quaternary tectonics, in the few areas where evidence was collected, only represented a dampening consequence of older events. The few data reported in the sparse works dealing with this topic were considered as anomalous traces of crustal motions rather than elements of a general deformative pattern*". Considering this starting point, "*the Neotectonic Map of PFG represented an important, but necessarily defective and incomplete, first step towards an appropriate definition of the Plio-Quaternary tectonic evolution in the Italian territory*".

After a long discussion concerning the limits of the Neotectonic Map, the introductory text to the workshop goes on with the second section dedicated to the research in the decade following the end of PFG, i.e., during the 1980s and the beginning of the 1990s. According to Bosi, a key-role in the growth of the studies in Neotectonics in that period was played by Structural Geology "*which, in different ways, positively influenced the development of research* […] *This occurred in a way which I may define 'direct', i.e., by stimulating scholars working out of Neotectonics to follow a line of reasoning in terms of tectonic evolution (through 'phases' related to specific states of stress). Other effects of Structural Geology may be defined 'indirect', since growth of this discipline clearly demonstrated the impossibility to define the tectonic evolution of the mountain chain areas solely based on structural studies. This limit is due to the scarcity of Plio-Quaternary deposits which may represent the object of (typical, we may add) structural analyses*". Two important aspects derive from this passage: *i*) a first (but not in-depth) warning to the main role played by the tectonic evolution (better defined in the next) and *ii*) the qualities and limits, if taken alone, of Structural Geology in contributing to Neotectonics. As for the limits mentioned in point "*ii*", the warning was probably motivated by the tendency of researchers to get around the difficulties to perform serious (and time-consuming) studies by integrating different disciplines.

The third and last section, dedicated to "*Current issues and perspectives*", is the most important for the methodological aspects regarding Neotectonics. A fundamental discussion concerns the meaning of the term "Neotectonics", as Bosi recognized that "…*a clear and widely accepted definition is not available. The problem is by no means trivial, since the choice of one or another definition (Neogene Tectonics? Quaternary Tectonics? Last phase of the tectonic evolution? Neotectonics as a field of research clearly distinguished from Paleotectonics? etc.) has important consequences both on the content of the research related to Neotectonics and in its inclusion in one or another disciplinary field of Earth Sciences*". It is here that Bosi produces, synthetically and successfully, a clear definition of Neotectonics, which appears particularly effective for the investigations in the Italian territory: "*A more serious proposal is the attribution of an essentially practical content to the term. In this perspective, Neotectonics may be intended as an integrated set of studies with the aim to define* the Plio-Quaternary tectonic evolution *through* a temporal scan of hundreds of thousands of years*. The noteworthy aspects of this definition are represented by the evolutionary perspective and by the chronological framework on which the investigations should be based. This aspect may give its own individuality to Neotectonics and define its nature greatly interdisciplinary*" [*please note that the "normal style" has been here adopted for terms that Bosi published in italic*]. This passage expresses the evolutionary perspective, the 4D view, which animated the studies merged in the Contributions to the Neotectonic Map of Italy (e.g., CNR-PFG, 1980b; 1982) and in the map itself (Ambrosetti et al., 1987). The reconstruction of the kinematic evolution is necessary "*to define the current tectonic regime and the age of its inception. This definition has a main role in seismotectonic evaluations, since it firmly constrains detection and characterization of seismogenic structures*". This explicitly defines the consistency of the faults, which cause the earthquakes with the current tectonic regime and finds comparable approaches in other contributions of the past (as in the above-mentioned works of Slemmons & McKinney, 1977; Muir Wood & Mallard, 1992).

The definition proposed by Bosi has operational effects, since *i*) a structural setting related to the current tectonic regime includes the active faults and excludes the inactive ones (even those apparently consistent with the ongoing tectonic regime but which became inactive, for different reasons, such as fault abandonment and displacement re-organization owing to interaction of fault segments in a fault array; on this aspect see the works of Gawthorpe & Leeder, 2000; Cowie et al., 2000; Finch & Gawthorpe, 2017) and *ii*) the definition of a certain fault as active implies that it must be consistent with the current tectonic regime.

Point *i*) may represent an answer to the third criterion expressed by IAEA for fault capability, i.e., the attribution of capability to a fault affecting an area where a seismogenic structure may cause earthquakes with magnitudes large enough to trigger motions on other faults. This definition does not specify the relationship between a fault and a seismogenic source and implies that each fault kinematically and geometrically compatible with the active seismotectonic setting may be capable, using a precautionary approach. The view of Neotectonics expressed in point *i*) allows to overcome this cultural bias, as it not only helps defining when a fault is active and capable but also allows to verify when it is not (or no longer) active and capable.

However, in the same intervention, Bosi underlined the tendency to underestimate the importance of the "evolutionary perspective" intrinsic to Neotectonics "*also due to a certain (perhaps excessive) superficiality which feeds the assumption of a steady tectonic regime also during long time intervals*".

In 1992, it was already clear that studies in this complex field can be successful only by "*processing data from different disciplines such as structural geology, stratigraphy and geomorphology (with integration of data from paleo-pedology, pale-ecology, …), sedimentology, geodesy and geochronology*".

The very long and difficult investigations concerning Neotectonics may suggest defining recent fault activity by taking shortcuts, i.e., by adopting superficial and hastier approaches. However, results of similar procedures "*cannot produce chronologically well-defined pictures of Plio-Quaternary tectonic evolution* […] *and may give, at best, the scheme of a whole geological structure related to the entire chronological interval above mentioned*". For example, also inactive normal faults with a displacement history limited to Pliocene-Early Pleistocene may be considered active with an approach avoiding the reconstruction of the fault history. A presumed evidence of fault activity considered by Bosi as a shortcut is represented by the interpretation of bedrock fault scarps as sufficient condition to assess very recent activation: "*in most cases, the elements composing the different settings, when viewed alone, are purely circumstantial and may result (and often result) insignificant as for the perspectives of Neotectonics. For example, this occurs for quite common geological features as fault scarps, whose origin is often related to both tectonic motions and morpho-selective processes*". However, the role of these geomorphic features as indicators of Late Pleistocene-Holocene motions raises continuously in the geological literature (e.g., Piccardi et al., 1999; Palumbo et al., 2004; Roberts & Michetti, 2004; Papanikolaou et al., 2005; Tesson et al., 2016; Mildon et al., 2022).

In the conclusive part of this introduction to the 1992 workshop, Bosi indicated some of the perspectives of the future research. Among those of thirty years ago, two points appear still topical, regarding deontological issues and applications, which are strictly related: *i*) "*the first concerns the necessity to favor closer confrontations among scholars, also to hinder the tendency, sometimes evident in published works, to propose evaluations and deductions unsupported by data. In this perspective, I want to underline that, in the field of Neotectonics, the complexity of the cognitive process itself makes the serious scientific dialectics necessary*"; *ii*) "*the other aspect concerns the opportunity to promote greater attention for Neotectonics in planning major engineering works. The importance of neotectonic estimations, presently almost non-existent, should drastically increase, at least for those elements of active tectonics (mainly faults) which may affect the safety of the works*". It seems clear that the reliability and earnestness quoted in the first point represent an unmissable prerequisite for the massive use of geological data invoked in the second point.

In the perspective of the present paper, the most important concept defined in this section, as derived from

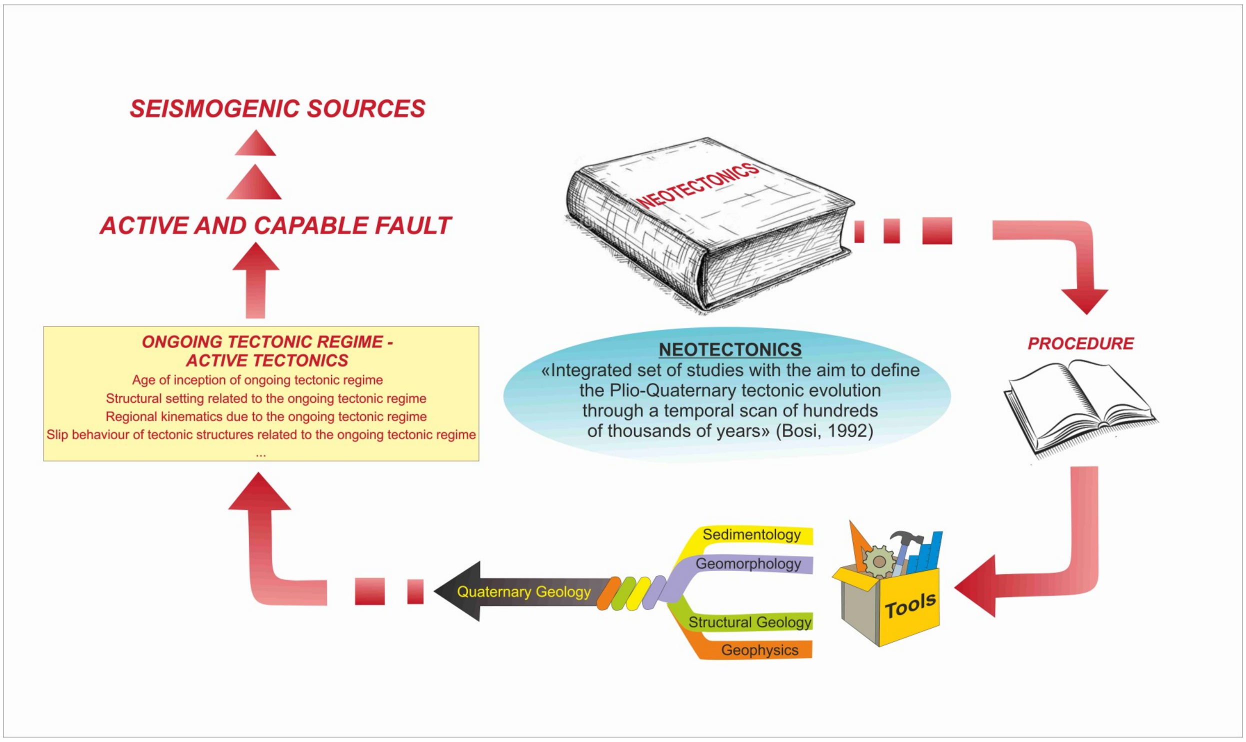

Fig. 1 - Block diagram showing the conceptual path linking Neotectonics to the identification of active and capable faults and to seismogenic sources.

Bosi's contribution, is certainly the correspondence of Neotectonics with the integrated set of studies due to different disciplines, having the aim to define the recent tectonic evolution with decisive consequences as for seismotectonics and the identification of active and capable faults and seismogenic sources (Fig. 1). In the next sections we will propose case studies which illustrate the application of the "evolutionary criteria" above discussed and the negative consequences of the non-application.

4. THE ADOPTION OF BOSI'S APPROACH TO NEOTECTONICS IN THE STUDY OF ACTIVE AND CAPABLE FAULTS IN ITALY

The Neotectonics definition by Bosi, with its evolutionary character, is hinged on "time" for investigating the tectonic evolution of a region, to assess the ongoing tectonic regime and to ultimately define fault activity and capability (see previous section). Quaternary geological investigations, with their multidisciplinary nature, play a pivotal role in Neotectonics, by providing the chronological foundations through the integration of disciplines such as sedimentology, stratigraphy, geomorphology, and various dating methods (Fig. 1).

Two active tectonic domains mainly characterize the Italian territory: *i*) the axis of the Apennine chain is affected by extensional tectonics, while *ii*) the outer sectors of the northern-central Apennine chain and the southern sectors of the Alps are characterized by compressive tectonics.

Based on Bosi's perspective on Neotectonics, i.e., considering the recent tectonic evolution of the Italian territory, Galadini et al. (2012) proposed that, in the extensional domain of Italy, a fault can be considered active and capable if it exhibits evidence of activity since the Middle Pleistocene unless it is sealed by deposits or landforms not younger than the Last Glacial Maximum (henceforth LGM; about 25-15 kyr). Middle Pleistocene was chosen since the extensional tectonic regime attained its present configuration in that time. The choice of the LGM is supported by two key factors: *i*) considering slip rates and recurrence intervals of the Italian normal faults (derived from paleoseismological studies, e.g., Galli et al., 2008), the last 25-15 kyr define a sufficiently long time span to assess inactivity once lack of motion is documented by geologic and geomorphic evidence related to the LGM; *ii*) the LGM is the last period of the recent geological history responsible for the significant morphogenetic processes (erosion and sedimentation) driven by climatic forcing. The effects of these processes, including the accumulation of sedimentary sequences and the formation of depositional/erosional surfaces, are pervasive throughout the Italian landscape, making them valuable for fault activity (or inactivity) assessment.

As for the compressive domain, Galadini et al. (2012) proposed that a fault can be considered active and capable if it shows evidence of movement throughout the entire Quaternary. Differently from the extensional domain, the choice of the entire Quaternary derives also from an operational criterion. Indeed, many Italian thrust faults are blind, and commercial reflection seismic profiles are necessary for their study. The commercial profiles usually have limited resolution as for the detection of the recent stratigraphic units, and a whole, undifferentiated Quaternary is generally depicted as the most recent stratigraphic unit. As in the case of the extensional tectonic domain, to be considered inactive, a Quaternary reverse/thrust fault should be sealed by deposits and/or landforms not younger than the LGM, based on the same geological rationale as the extensional faults.

Importantly, very similar chronological references are adopted by the above-mentioned Italian Guidelines for Seismic Microzonation (Technical Commission for Seismic Microzonation, 2015). Indeed, these guidelines state that a fault should be deemed potentially active and capable if it exhibits evidence of activation after the Middle-Late Pleistocene. Moreover, a fault should be deemed active and capable if it shows evidence of activity over the past 40 kyr. This period is similar to the LGM defined by Galadini et al. (2012). However, the past 40 kyr represent a sort of technical constraint, being related to the limit of radiocarbon dating applicability, while the use of the LGM in the work by Galadini et al. (2012) derives from geological and seismotectonic evidence. Moreover, in the Guidelines for Microzonation, the last 40 kyr are to assess activity in case of displacement of younger deposits and landforms, while the LGM is proposed by Galadini et al. (2012) to argue fault inactivity if deposits and landforms having that age or being older seal the fault.

5. CASE STUDIES OF BEST PRACTICES IN NEOTECTONICS AND NEGATIVE CONSEQUENCES OF NON-APPLICATION

In the following lines, we will deal with some case studies from the central Apennines of Italy to highlight the practical value and significance of applying Neotectonics as a procedure to assess active faulting.

1) As mentioned above, the presence of bedrock fault scarps is sometimes considered in itself a reliable geomorphic indicator of fault activity. This view assumes that the exposure of bedrock fault scarps results from fault activation, particularly in extensional tectonic environments. In the past two decades, researchers employing this view have utilized methods to date the exposure of fault planes (e.g., Palumbo et al., 2004; Tesson et al., 2016). These dating methods rely on the accumulation of cosmogenic nuclides on fault planes, which begins after fault plane exposure, presumably caused by a surface-rupturing earthquake on the considered fault.

However, this perspective is not universally accepted in the scientific literature, as other studies suggest that fault scarps may be exposed also due to non-tectonic processes such as erosion or gravitational phenomena (e.g., Bosi et al., 1993; Galadini & Messina, 2001; Galadini, 2006). This viewpoint challenges the confidence in the method and its ability to soundly assess fault activity solely based on fault plane exposition. An interesting example of this scientific debate concerns the WNE-ESE trending fault that bounds a central Apennine intermontane basin to the SSW, where the village of Leonessa is located (Fig. 2). The Leonessa fault has been the object of various studies that have resulted in still conflicting interpretations regarding its activity.

On one hand, some authors (e.g., Michetti & Serva, 1990; Cello et al., 1997; Roberts & Michetti, 2004; Papanikolaou et al., 2005) suggested that the fault plane exposure at the base of the fault scarp, in a sector located SSW of the village of Leonessa, resulted from repeated fault slip episodes occurred after the Last Glacial Maximum. Based also on the height of the exposed fault plane, some of the mentioned works derived fault slip rate and maximum credible magnitude of earthquakes that the Leonessa fault could generate, i.e., approximately M_W 6.5.

On the other hand, in syntheses of active faults of the central Apennines (Barchi et al., 2000; Galadini et al., 2001), the activity of the Leonessa fault is indicated as debated, since different research groups which contributed to these syntheses have not reached a consensus on the Late Pleistocene-Holocene activity of the tectonic structure. Fubelli et al. (2008; 2009) performed geological and geomorphological field observations in the whole Leonessa basin and along the fault-related slope, aimed at defining the Quaternary evolution of the adjacent basin from a neotectonic perspective. The authors recognized that the exposure of the Leonessa fault plane is very localized and that all of the sites where the plane crops out coincide with sectors of the fault scarp where non-tectonic processes occur, e.g., erosion or landsliding of the scree deposited at the base of the limestone scarp. Furthermore, the authors argued that the fault is sealed by sets of alluvial fans dating back to the Middle and Late Pleistocene (which is a time span long enough to consider the fault not capable, according to the chronological criteria defined by the above described work of Galadini et al., 2012). Hence, Fubelli et al. (2009) did not rule out that the Leonessa fault may have been active in the early stages of the central Apennine extensional tectonic regime, i.e., in the Early Pleistocene, but its activity strongly reduced or even ceased since the Middle Pleistocene.

The above described scientific debate holds significant implications for assessing the seismic potential associated with the Leonessa fault. According to the former viewpoint, this tectonic structure could potentially be responsible for large-magnitude earthquakes (up to about M_W 6.5). Conversely, according to the latter viewpoint, the Leonessa fault may not (or no longer) be able to produce earthquakes large enough to produce surface faulting as the magnitude threshold for producing surface faulting, on the Apennine extensional active faults is around M_W 5.5-6 (e.g., Michetti et al., 2000; Falcucci et al., 2016).

Following Bosi's (1992) viewpoint on the neotectonic significance of bedrock fault scarps, discussed in a specific work in 1993 (Bosi et al., 1993), the authors highlighted the challenges associated with interpreting bedrock fault scarps from a neotectonic perspective. They pointed out that various processes can contribute to the exposure of fault scarps. While some scarps are clearly of tectonic origin, others may result from unearthing of buried and inactive structures due to landslides or erosion, and other from a combination of tectonic and non-tectonic processes. The authors emphasized that a comprehensive analysis of bedrock fault scarps requires a detailed examination of their stratigraphic, structural, and geomorphological settings, i.e., a thorough neotectonic investigation in the territory affected by the fault. This approach is essential to ensure reliable interpretations concerning the origin of these geomorphic features and, consequently, regarding the seismic potential associated with a specific fault.

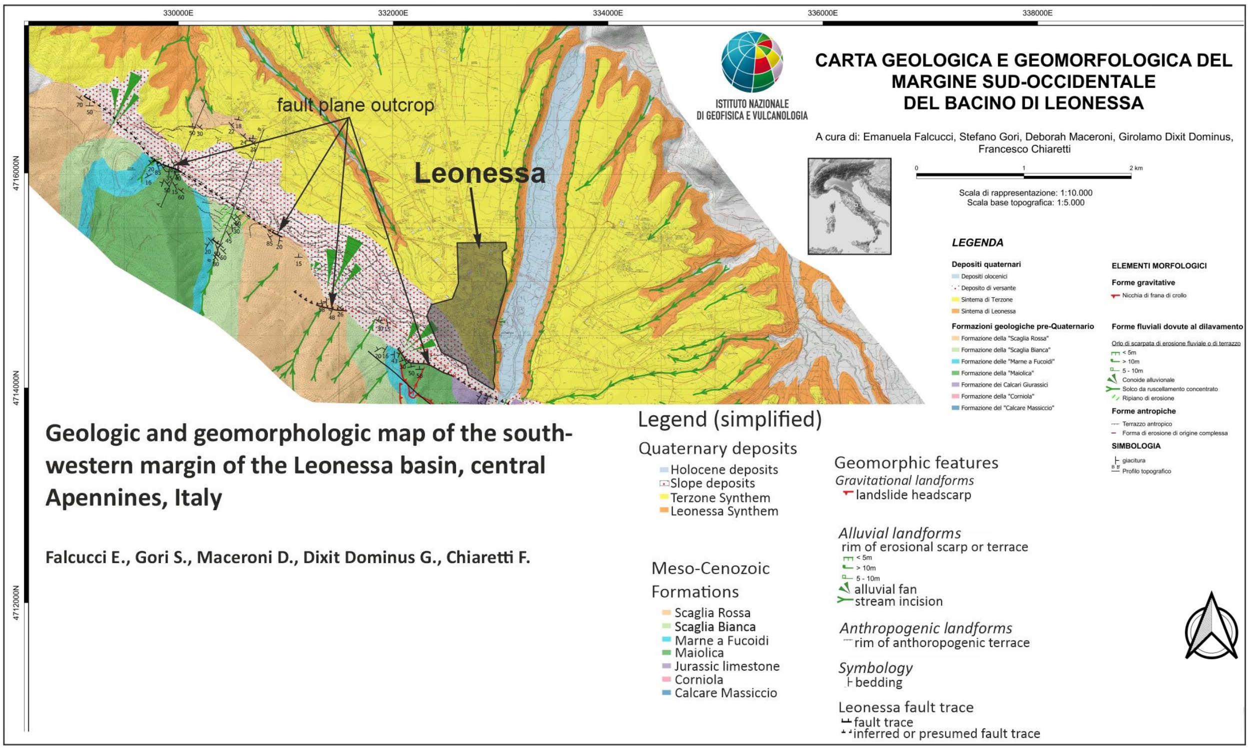

Fig. 2. - Geological map of the southern margin of the Leonessa basin. As for the legend, see the original text and figures at the website https://sisma2016data.it/faglie-attive-e-capaci/

From a broader perspective, Bosi's statements suggest that even fault scarps exposed by tectonic fault slip in continental environments should be approached with caution when conducting active faulting analyses based on the exposure and dating of the fault planes. In continental environments, particularly, deposition is naturally intermittent due to climatic influences. As a result, erosional and depositional processes can periodically conceal and expose faults, and the extent and duration of the related effects remain uncertain. Consequently, fault planes, even if active, may undergo unknown episodes of exposition and burial, thereby influencing the local fault scarp exhumation history and thus potentially affecting the tectonic significance of fault exposure dating. Hence, as the occurrence of these phenomena cannot be never completely ruled out, Neotectonics helps to place in a safe position from these uncertainties, as this approach is focused on the definition of the whole tectonic history of a given fault, allowing to overcome the above described unknowns.

2) The Sulmona basin, in the Abruzzi region of the central Apennines, is a tectonic depression whose formation and evolution throughout the Quaternary has been strongly shaped by the activity of the Mt. Morrone-Sulmona normal fault (hereafter MMF). The MMF is a NW-SE trending and SW dipping basin-bounding normal fault, widely recognized as an active and capable fault (e.g., Gori et al., 2011). It represents the surface expression of a major seismogenic source potentially responsible for earthquakes with magnitudes up to 7 (e.g., Bordoni et al., 2022). The studies above mentioned have provided evidence of displaced continental deposits spanning the whole Quaternary along the fault. Archaeoseismological and paleoseismological investigations revealed that the last episode of activation occurred approximately 1,800 years ago (Ceccaroni et al., 2009; Galli et al., 2015).

The MMF consists of two major branches that affect the southwestern slope of Mt. Morrone, with the eastern branch located at the intermediate sector of the slope and the western at the base of the relief (Fig. 3a).

The excavation of a building foundation in the fault hanging wall, a couple of km west of the western fault branch, uncovered the alluvial plain deposits widespread in the Sulmona basin. The depositional top surface of this sequence consists of a wide sub-horizontal terraced landsurface, known as the “Sulmona surface”, representing an ancient paleo-base level of the basin. The uppermost portion of the sequence and the depositional top surface have been aged at about 30-40 kyr BP, through chronostratigraphic, geomorphic and tephro-stratigraphic analyses supported by radiometric dating (e.g., Gori et al., 2011; Galli et al., 2014). The rivers that fed the alluvial deposits are presently embedded in the “Sulmona surface”, which is suspended over the thalwegs by some tens of meters.

The analysis of the excavation walls revealed a shear zone consisting of several shear planes affecting the entire sequence, showing a normal sense of motion (Fig. 3b, c). The excavation permitted a 3D view of the shear planes, showing that they mostly stroke in the N-S and NW-SE direction, which is oblique to the orientation of MMF.

The up-to-5-m high excavation walls allowed us to investigate the attitude and characteristics of the shear

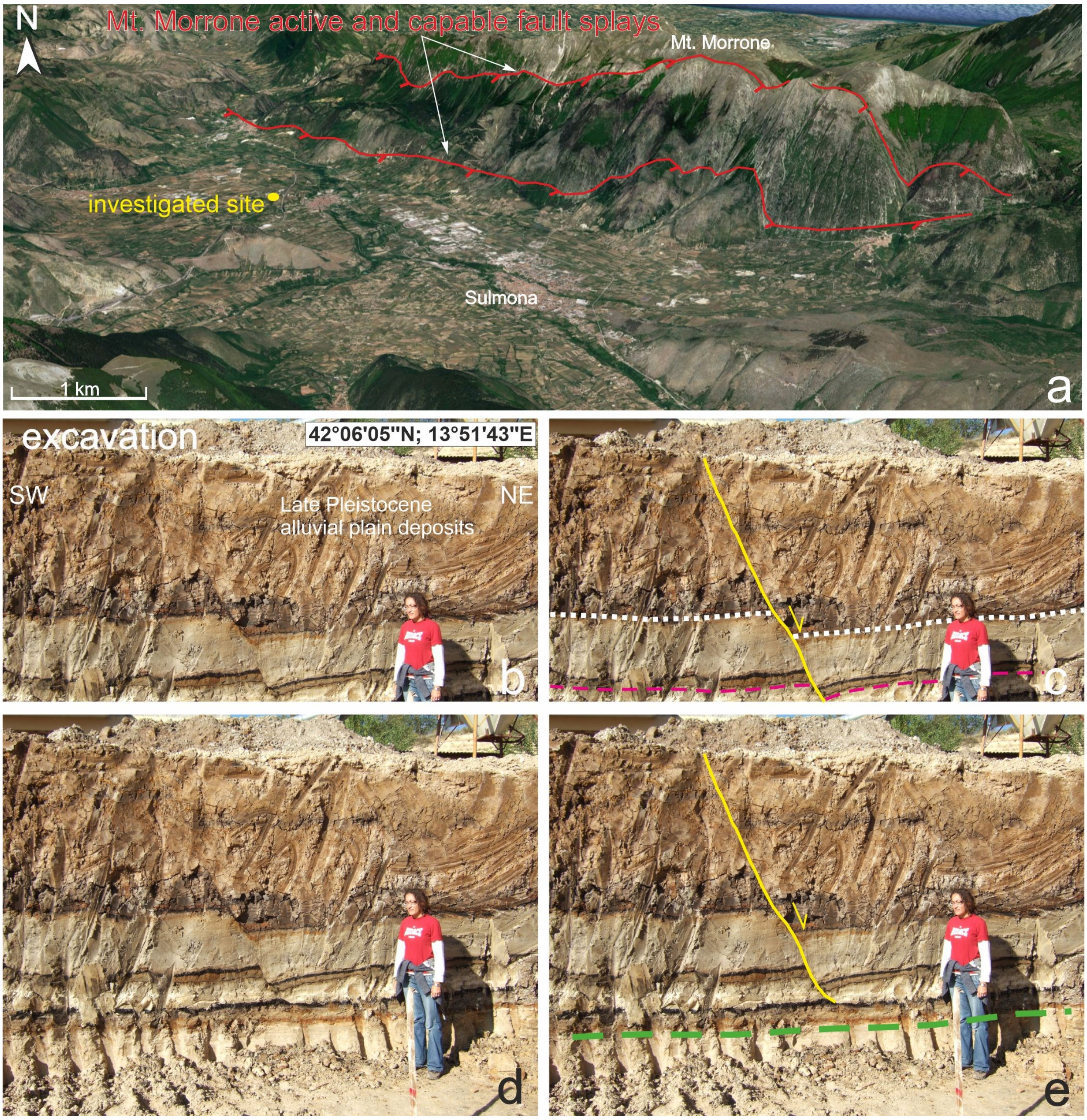

Fig. 3 - a) a) View from South of the Sulmona basin, showing the south-western flank of Mt. Morrone and the traces of the active normal fault splays. b) c) d) e) Wall of the investigated excavation; the yellow line marks the investigated shear planes; the blue dashed line marks the unfaulted sand layer.

planes some meters at depth, showing that they terminated a few meters below the surface, with the lowermost alluvial layers showing no displacement (Figs. 3d, 3e). Moreover, the amount of offset decreased with depth. In one instance, the deepest sandy layer displaced by the shear plane exhibited varying thickness across the plane, suggesting that it underwent differential compaction after deposition.

This example shows that basing on paleoseismological trenching and the analysis of the related few-meters-high outcrops these non-tectonic shear planes might have been conceivably interpreted as composing a tectonic shear zone related to the MMF. By contrast, the outcrop shown in figure 3 showed that the shear planes are the result of geotechnical processes, such as the differential compaction of the alluvial layers or liquefaction. As in most cases it is not possible to dig paleoseismological trenches so deep to obtain outcrops as high as that represented in figure 3, the investigated case suggests caution in attributing systematically a conclusive diagnostic value to just paleoseismology.

But more importantly, geological observations appear fundamental to discern the nature of the shear planes even if outcrops so high are lacking. Indeed:

i) The reduction of displacement with depth contradicts the expected behavior of a fault rupture caused by coseismic slip propagation from hypocentral depth to the surface. Indeed, if the observed shear planes were associated with surface faulting of an active, capable, and seismogenic fault, the offset should have increased with the age of the deposits. The examined case demonstrates a different pattern, where the displacement decreases with depth. This inconsistency strengthens the argument that the observed shear planes are not related to surface faulting.

   In this perspective, it must be underlined that the geological evidence of displaced deposits along the MMF branches (e.g., Gori et al., 2011; Galli et al., 2014) showed that offset affecting Early Pleistocene deposits is larger than offset of younger (up to the Holocene) deposits. This confirms that displacements of the Quaternary units along the MMF result from the primary (sensu IAEA TECDOC 1767, 2015) upward propagation of the coseismic rupture, whilst the displacement determined by the described shear planes in the investigated excavation cannot be related to tectonic faulting.

ii) Even more importantly, evidence of displacement or geomorphic anomalies due to fault activation does not affect the “Sulmona surface” across the investigated shear zone. The landsurface displays a sub-horizontal attitude with the original, gentle dip towards SW. The lack of displacement or disruption in this landform suggests that the uppermost portion of the alluvial sequence has not been affected by tectonic displacements since at least 30-40 kyr BP. This reinforces the conclusion that these shear planes, even if they were of tectonic origin - which they are not - should not be considered active and capable according to the chronological criteria proposed by Galadini et al. (2012) and the Italian Seismic Microzonation regulation. Apart from the non-tectonic origin of the observed displacement, the discussed case indicates the necessity to include a single piece of evidence of recent displacement in the wider perspective of the geological and tectonic evolution of an area defined by Neotectonics. This perspective, in the specific case here represented, defines inactivity of the detected shear planes.

3) The seismic sequence that occurred in central Italy in 2016 included three mainshocks: the first, of Mw 6.1, on August 24; the second, of Mw 5.9, on October 26; and the third and strongest one, of Mw 6.5, on October 30, as well as a sequence of aftershocks that lasted for years. It has been caused by the activation of extensional tectonic structures (e.g., Tinti et al., 2016; Chiaraluce et al., 2017; Cheloni et al., 2017; 2019), i.e., the Mt. Vettore -Mt. Bove fault (hereafter MVBF), to the north, and the Laga Mts. Fault (hereafter LMF), to the south. These faults had been extensively studied prior to the sequence by geological investigations and were already defined as active and capable (e.g., Galadini & Galli, 2003). Specifically, paleoseismological analyses conducted along their surficial expression revealed that they activated probably more than 1,000 years ago. The faults have been defined able to generate surface-rupturing earthquakes, of magnitude around M_W 6.5-6.6. This has been unfortunately confirmed by the seismic sequence of 2016.

Detailed geological investigation along the LMF allowed Galadini & Messina (2001) to identify two distinct sectors of the fault with substantial differences, despite it seems a single, long fault-related mountain front. The authors identified a southern fault section, about 20 km long, located in the area of Campotosto village, that exhibits an evident fault scarp at the base of the Laga Mountains' SW slope. Sequences of alluvial fans, alluvial terraces and slope deposits, Late Pleistocene to late Holocene in age, are evidently displaced along this fault. On the other hand, the northern sector of the Laga Mountains' SW slope, affected by the Amatrice fault section, does not display an evident scarp due to recent activity and no late Quaternary deposits or landforms are here displaced. According to Galadini & Messina (2001), the northern Amatrice section of the LMF did not control the late Quaternary evolution of the adjacent basin, and the fault here displayed no or subtle evidence of capability (Falcucci et al., 2018). Consequently, Galadini & Galli (2003) and Falcucci et al. (2018) issued that the southern fault can be considered active and capable, and potentially responsible for M~6.6 earthquakes; the northern Amatrice fault, instead, was supposed not capable, that is, not able (or no more able) of producing surface-rupturing earthquakes, that is, earthquakes not larger than Mw~6.

This segmentation of the seismogenic faults in the area was further supported by more recent investigations that defined the geological evolution of the region between the MVBF and the Amatrice and Campotosto sectors, in the perspective of Neotectonics (Falcucci et al., 2018; Fig. 4).

The 2016 central Italy seismic sequence aligns with the seismotectonic setting above described. Indeed, the seismogenic rupture of the mainshock on August 24, 2016 occurred both in the southernmost section of the MVBF and in the Amatrice fault. However, surface faulting was only observed along the former and not along the latter. Seismological and geodetic coseismic data (e.g., Tinti et al., 2016; Cheloni et al., 2017) confirmed the presence of two distinct ruptures, the larger one being consistent with the southern part of the MVBF, with a seismic moment corresponding to a magnitude of Mw 6.1. The smaller southern rupture, consistent with the Amatrice fault, released a seismic moment corresponding to a magnitude of Mw 5.8-5.9, not enough to generate surface faulting. These observations hence confirmed the long-term geological data.

Moreover, it is worth noting that, as outlined by Falcucci et al. (2018), the aftershocks following the mainshock ended towards the south where the geological separation of the Amatrice fault section from the Campotosto section occurs. This further supports the segmentation based on neotectonic analyses and the related inferences on the different seismic potentials and capability.

6. DISCUSSION AND CONCLUDING REMARKS

The assessment of the two main hazards associated with seismogenic faults, namely ground shaking and/or surface faulting, entails the comprehension of the on-

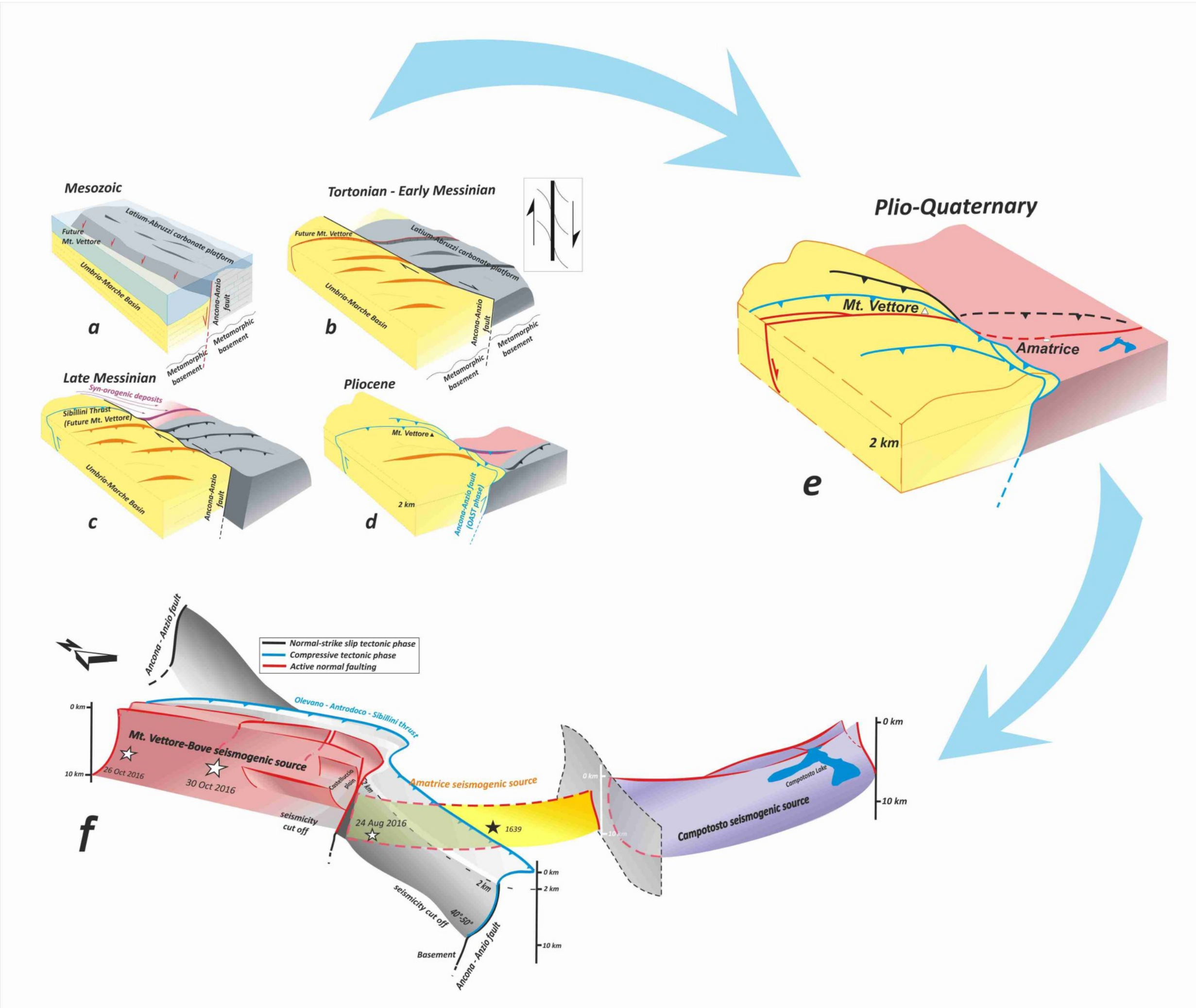

Fig. 4 - a-e) Reconstruction of the geologic and structural evolution from the Miocene to the Quaternary of the epicentral area of the 2016 seismic sequence in central Italy; f) consequent segmentation of the seismogenic faults (modified from Falcucci et al., 2018).

going tectonic regime to which structural settings of active faults are genetically connected.

Various authors (such as Slemmons & McKinney, 1977; Muir Wood & Mallard, 1992) have proposed that the attribution of activity to a fault is related to its consistency with the ongoing tectonic regime in each region. The grasp of this regime, in turn, implies the reconstruction of the tectonic history which may define cases like those summarized in the sketch of figure 5.

Among the many but not univocal definitions and declinations, Neotectonics, as defined by Bosi (1992), is a procedure whose aim is the reconstruction of the tectonic evolution and the definition of structural settings consistent with the current tectonic regime. This evolutionary perspective represents the strength of Neotectonics proposed by Bosi (1992), as a procedure going beyond the "static" multidisciplinary two- or three-dimensional analysis of a specific territory or fault. Indeed, it is by introducing evolution through time that Neotectonics allows to assess whether a fault, a fault segment, or a fault section, also apparently consistent (geometrically and kinematically) with the current tectonic regime, can be considered active.

In this perspective, one of the significant epistemological outcomes of Neotectonics is the definition of an active and capable fault (see below). It should be noted that we always refer to "capable" faults in conjunction with "active" because, as explained in Section 2, capability, regardless of the specific feature being considered (such as discrete faulting, primary or secondary, localized folding, or broadband folding), cannot be genetically separated from fault activity, as the “engine” that moves capable faults is inherently the tectonic regime.

On the whole, the main conclusive remarks emerging from the previous pages may be summarized in the following points.

1) It is evident that, in terms of chronology, each region, each territory, with its own tectonic evolution, has its specific chronological criterion for defining an active

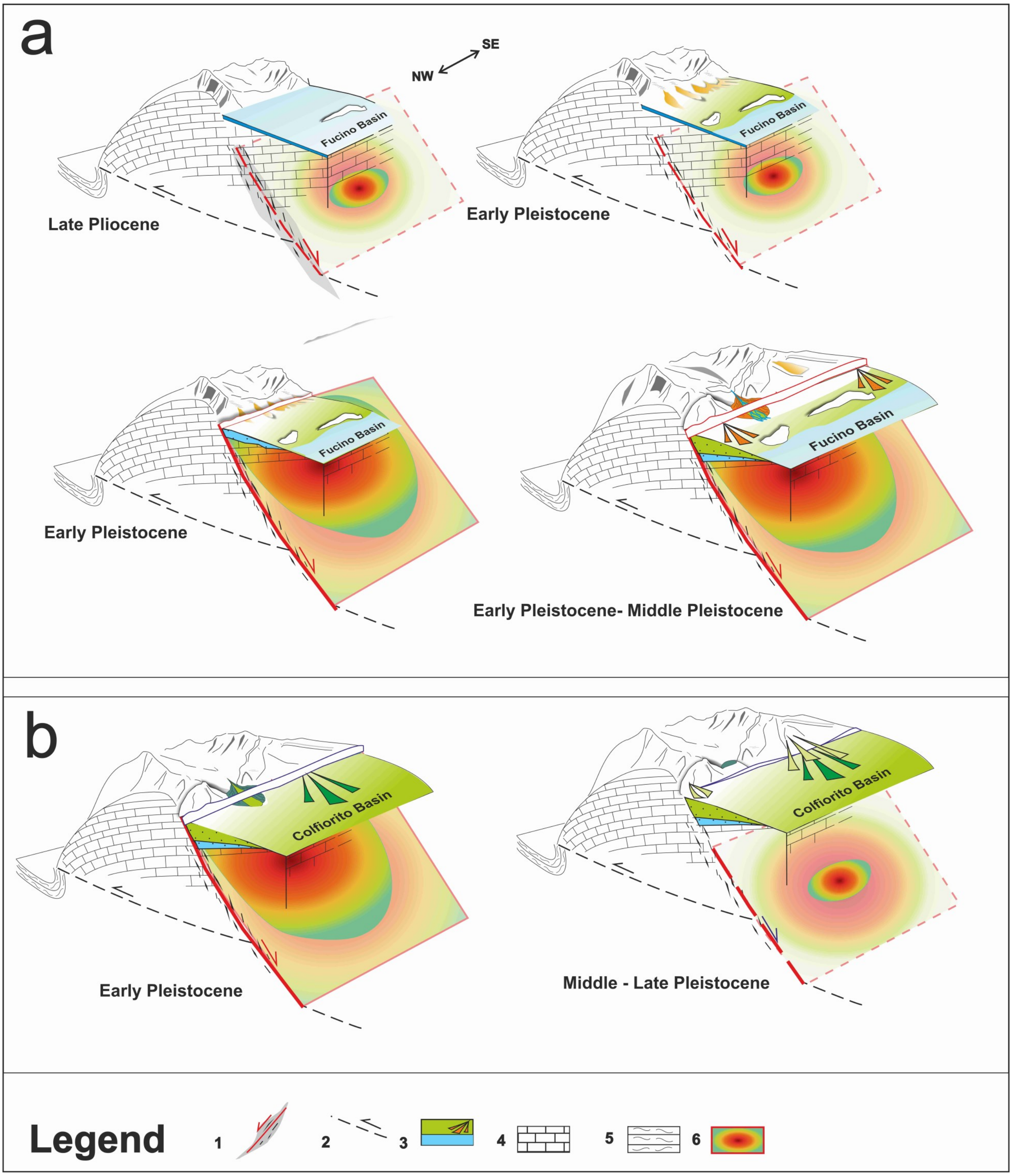

Fig. 5 - Reconstruction of geological and structural evolutions since the late Pliocene of a typical normal fault-bounded relief in the central Apennines. 1) active fault and related shear zone, 2) inactive thrust fault, 3) Plio-Quaternary deposits, 4) and 5) pre-Quaternary bedrock, 6) rupture along the active and seismogenic fault in the active extensional tectonic regime. The example depicted in the first four sketches (a) may define the tectonic history of the Magnola Mountains Fault, in the Fucino basin area (central Apennines, Abruzzi region), according to reconstructions proposed by various authors (Gori et al., 2007; Galli et al., 2012); the example of the last two sketches (b) may represent the tectonic history of the Colfiorito fault system in the Umbria region (central Apennines), according to the reconstruction by Messina et al. (2002).

fault. Only after establishing this criterion can any further assessment of fault activity and capability be conducted.

Thus, from a broader perspective, a fault can be considered active and capable if it exhibits evidence of activity within a time frame that is consistent with the ongoing tectonic regime of the region. By contrast, inactivity derives from the evidence that a certain fault is sealed by deposits and/or landforms not younger than a time span (from the present) whose duration includes a significant number of seismic cycles. This brings together another fundamental aspect, in an engineering perspective, directly connected to the concept of capability: since not all of the faults or fault segments that are structurally consistent with the ongoing tectonic regime (as for geometry and kinematics) are necessarily active and capable (as in the case of the Amatrice fault), it implies that it is necessary to operate in the manner that fault activity must be proven, through Neotectonics. The sole "structural" and "seismotectonic" criteria may not suffice to hypothesize fault activity and capability. In this regard, even considering a precautionary approach (especially in an engineering perspective), one may otherwise risk to deem a fault active (and capable) on just circumstantial factors.

2) The sole use of paleoseismology might not permit solving the problem of the causative factors of a displacement that occurred along a shear plane. This is because paleoseismological studies, which focus on specific sites, can be limited in their ability to provide a comprehensive understanding of the broader tectonic context. In this perspective, an active and capable fault should not be simply defined as a plane separating two rock blocks with differential motion. Merely considering the dislocation or differential motion is too simplistic and inadequate because it overlooks the underlying engine that generated it. For instance, a normal fault can displace two blocks with a dip-slip motion, but the same motion can also result from a rotational landslide, a sinkhole, or differential sediment compaction. Although both a tectonic active fault and a landslide may cause vertical displacement of rock blocks, the key difference lies in their distinct origins, even if their manifestations may appear similar. The example shown in the Sulmona basin testifies to this.

This is the reason why, in this view, a "capable" fault does not exist by itself as it cannot be separated from the cause that generated it, that is, tectonics, which has its own rules and processes.

The exclusion of causes other than tectonics in the motion of shear planes often results from geomorphologic analysis. However, Neotectonics defines the relationship of a shear zone with an active fault system and its role within the local structural setting consistent with the current tectonic regime. Within this light, especially in domains characterized by slow tectonic deformation rates, paleoseismology should be considered as a conclusion and completion of Neotectonics.

3) Similar arguments may be outlined for those geomorphic features that Bosi considered "*purely circumstantial and may result (and often results) insignificant as for the perspectives of Neotectonics*" as the bedrock fault scarps. Indeed, apart from the choice of sites that may be suitable for specific analyses to date the exposure of a fault plane, it is the recent activity of the fault itself that should be based on detailed geologic investigations preceding site analyses.

The reason for such a rigorous approach is clear since the Bosi's words of 1992, dealing with the perspectives of Neotectonics, considering the necessity to drastically refute evaluations and deductions unsupported by data. This priority seemed necessary at that time, when the perspective was «*to promote greater attention for Neotectonics in planning major engineering works*» and to give inputs concerning «*active tectonics (mainly faults) which may affect the safety of the works*». Considering the key role these inputs have progressively gained in the past decades, the significance of this warning is greater today than at the time Neotectonics needed promotion.

In conclusion, Neotectonics is a procedure that provides a 4D view of tectonically active regions, or of a fault, or fault segment, as it allows the reconstruction of the influence that the evolution of tectonic activity has left and still leaves on the landscape. This comprehensive understanding provides the most solid foundation for seismotectonic analysis and the assessment of hazards associated with earthquakes.

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