STATE-OF-THE-ART OF ACTIVE FAULT STUDIES IN ITALY

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Summary

Re-evaluation of existing data and new studies have allowed us to map and categorize surface structures capable of damaging earthquakes for a large part of the Italian territory, [that] including the known most severe events (central and southern Italy, part of oriental Alps). The compilation is still incomplete for the submarine areas and those areas (southern Alps, Po plain) where blind thrusting may give only subdued or no evidence of surficial deformation. All the relevant information is available to scientists in a relational text and GIS database and through the web in a simplified version.

Introduction

According to Wallace (1986), "tectonic movements expected to occur within a future time span of concern to society" should be considered active. The recognition that a fault is alive and the determination of the parameters characterizing its activity (e.g., geometry, kinematics, seismicity, slip rate, recurrence interval, segmentation, etc.) are essential for correct geodynamic and seismic-hazard evaluations. Only crustal faults that rupture the ground surface (defined as *capable,* e.g., IAEA 1991) have been described in specific detail. Generally, these faults are also the source of the most destructive earthquakes. Therefore, careful surface studies, possibly coupled with geophysical exploration, can lead to reliable identification and description of active structures. Conversely, a more limited amount of information is provided on buried faults, which are recognizable only from their subdued surface deformation or seismicity.

In general, a first screening of active faults should be based on the possibility for the fault to move or not under the current stress regime, being that any fault now quiescent can simply be reactivated during a future earthquake. Proofs of activity include displacement of sediments and landforms younger than a given time limit, because this suggests a high chance for renewed slip in a near future. Seismicity clearly located along a fault and geodetic evidence for accumulating strain also suggests activity, but instrumental seismicity alone may not indicate capability. The time limit for defining a fault as "active" ranges from the whole Quaternary (1.8 m.y.) of Japanese researchers (Kaizuda *et al.* 1992) to the more widely accepted 35-50 ky. Trifonov and Machette (1993) accept 10 ky as the upper limit for activity, but consider faults younger than 750 ky as possibly active and deserving attention.

We can try to obtain the age and style of the last movements by means of paleoseismological analyses. Sometimes the elapsed time is very short, as in the case of historical earthquakes or Holocene surface faulting; more often the age of the last activity cannot be well constrained and it is only possible to state that it occurred after, for example, the beginning of middle Pleistocene or, even less accurately, during the Quaternary.

Our forecast of future behavior (in terms of when, how, how much) is essentially based on statistical data, even if there is clear evidence of concentrating stress. In fact, only an incomplete sample of the past behavior of the fault is generally available, because the information provided by historical, paleo-seismological and geological studies are necessarily limited, either in space and time. Moreover, only rarely convincing regularities in the fault behavior are demonstrated. Therefore, all the empirical definitions of activity proposed are necessarily somewhat arbitrary, although necessary to constrain the problem for practical purposes of reduction of seismic risk.

Detailed maps and databases of active faults have been completed or are in progress in many countries, being necessary for a) evaluation of seismic hazard, b) geodynamic interpretation, c) understanding of evolving landscape, and d) land use planning. This is also the case for the densely inhabited Italy, a country where, until a few years ago, the areal distribution of many high-intensity historical earthquakes was not matched by the recognition of a comparable pattern of active faults with surface evidence. Such surface faults were believed not to be possible in the complex structural fabrics of the substratum of the Apennines and southern Alps orogens, where most of the earthquakes have been concentrated. The occurrence of surface faulting during the Irpinia earthquake in 1980 and the recent recognition of repeated Holocene surface events on faults in several areas of the Apennines has reversed this opinion.

The database project of active/capable faults in Italy was started at the beginning of 1990's, but has evolved significantly only in the last years, due to the projects of ANPA (ITHACA, i.e. ITaly HAzard from CApable faults database) and GNDT, Italian Group for Defense from Earthquakes, which aims to soon issue a state-of-the-art seismotectonic atlas of Italy for seismic-hazard reduction. Previously, the only effort to map active faults was that of Castaldini and Panizza (1991) for a sector of northeastern Italy, which had followed the general criteria set forth by the ILP project *World Map of Major Active Faults* (Trifonov and Machette 1993).

Here I briefly outline the methodological approach for the compilation of the ITHACA database, and also present a short overview of the available data related to active faulting in Italy.

Methodological approach and structure of database

In Italy, known fault slip rates are generally slower than 1 mm/yr. The recurrence intervals of major earthquakes can be in the range of thousands or even tens of thousands of years. So, the search for evidence of activity must span at least part or all of the last glacial period (at least 50–80 ky).

For the aims of the present project, evidence for capability of a fault are (ordered by decreasing relevance): historical coseismic slip, creep, recognition of paleoseismic events (Holocene-latest Pleistocene), displacement of 1) Holocene-latest Pleistocene deposits and/or landforms, 2) late-middle Pleistocene deposits and/or landforms, 3) Quaternary deposits and/or landforms, which include faults active in the middle-lower Pleistocene (labeled as elements deserving attention, until proven inactive).

Not all the suspected faults can be exhaustively investigated in the field, often due to the morphoclimatic agents, vegetation cover and human disturbance, which hinder the finding of good outcrops or suitable sites for trenching. In this sense, the Japanese criterion of activity appears reasonable: active faults displace Quaternary morphologic features based on the observation of historical reactivation along structures lacking any verifiable evidence of previous Holocene or late Quaternary movement (Kaizuda *et al.* 1992). As well, we adopt a cautious criterion in the screening process, based on the "resemblance" of a fault without direct proof of activity with other faults undoubtedly proven as active, located in the same region and stress regime.

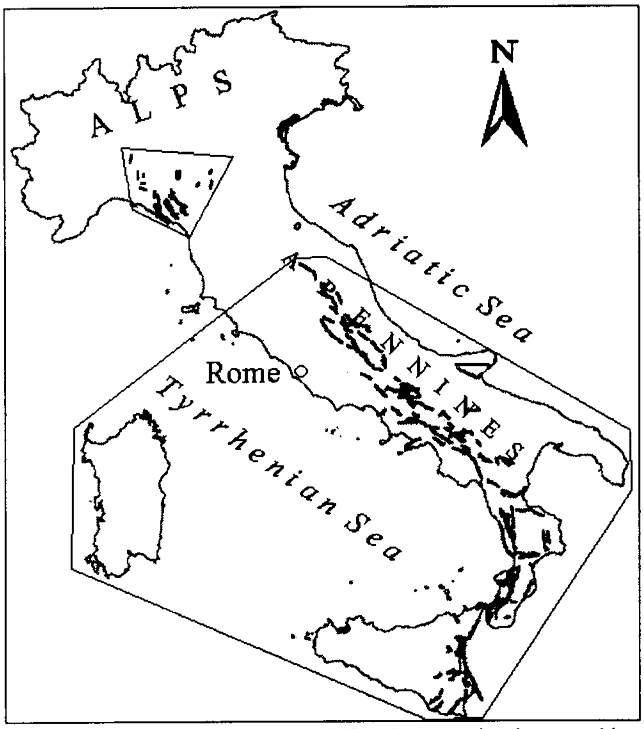

Fig. 1 – Active faults in Italy. Boxes define the areas already covered by the project.

The creation of the database has followed these steps:
- collection of all relevant published source materials, and extraction of all data dealing with active tectonics;
- critical evaluation of all information, with discussion, when and where possible, with scientists involved in active tectonics to find non-published data and to validate inferred interpretations;
- development of database structure and GIS applications;
- compilation of database, following the criteria listed below;
- field check on the suspected structures.

The database is structured as relational tables; there are hierarchical elements: *fault systems*, *faults* and *fault units*. A fault has its own tectonic and morphologic identity (for example, a fault bordering a tectonic basin) and is composed of n-units: single fault branches at the mapping scale, which can be described separately; and a set of faults tectonically connected form a fault system. This hierarchical subdivision is clearly "unnatural", being often geometric and structural features of faults scale-invariant: thus, when does a fault become a system? This tentative separation has been introduced to try to distribute the descriptive parameters according to rupture behavior during a seismic event, when one or more fault units break, the sum of which often, but not necessarily, represent the total fault. So, paleoseismic results apply to a unit and may not fully describe the fault history and its seismic potential. Faults composing a system should break in some ordered manner.
Other related tables list the *references* and the *seismic catalog*, and report paleoseismic data: *trench descriptions, dating information, and inferred paleoseismic events*. A quality factor (A to D) provides a rude estimate of the level of confidence of several parameters in the database tables.
The georeferenced items are GIS (geographical information system) layers under the widely diffused ArcView package. Other useful layers , such as a digital terrain model, geographic data (boundaries, rivers, lakes, etc.), and lifelines are also included.

Brief tectonic outline of Italian region

The continental collision of the Africa and Eurasia plates along the former Tethys basin has controlled the evolution of the Alps and Apennines orogenic chains and the opening of the Tyrrhenian oceanic basin (Royden *et al.* 1987; Laubscher 1988). In particular, the Southern Alps and the Apennines are fold and thrust belts composed of several thrust sheets piled upon one another mainly in Neogene times, in south- and northeast-verging directions, respectively (Cassano *et al.* 1986; Mostardini and Merlini 1986).
Since the late Pliocene to early Quaternary, intense extensional tectonics has affected a large part of the peninsular territory, dissecting the orogenic belt, and sometimes also reactivating inherited compressional structures (Ambrosetti *et al.* 1987).
Weak compressional tectonics still affects the outer (eastern) border of the Apennines, having deformed late Quaternary deposits of the Padanic-Adriatic foredeep and the southern margin of the eastern Prealps, from the Garda zone to the Veneto-Friuli plain (Ambrosetti *et al.* 1987; Slejko *et al.* 1987).
The highest thermal anomalies and the weakest seismic activity (e.g., Pasquale *et al.* 1993) are located on the Tyrrhenian side, affected by volcanic activity since the late Pliocene. Volcanism is still active in southern regions of Italy: Campania Province, Eolian Islands and submarine volcanoes, and Etna.
Many alluvial plains on the Tyrrhenian coast have sustained large vertical tectonic subsidence through the late Quaternary, but now display no appreciable seismic activity. The elevations of dated sea-level indicators (e.g. Antonioli *et al.* 1999) show that some faults are still moderately active.
The present-day strain in Italy is monitored by GPS and VLBI networks; as well, geodetic surveys across active or suspect faults are now in progress, but more time is needed to obtain reliable data owing to the low strain rates. Geological vertical strain rates in the Apennines are in the range of 0.1-1.0 mm/y for single faults. Estimates of the rate of extension across the entire peninsula, based on still incomplete sets of data, range between 1 and 4 mm/y for the southern Apennines (Westaway 1992; Pantosti *et al.* 1993, and references therein).

Historical seismicity and palaeoseismic evidence

The well documented seismic catalogs now available (Boschi *et al.* 1999, and references therein) indicate that Italy has been characterized by moderate seismicity in the past century, with highest magnitudes reaching 6.9-7.0 (1908 Messina, 1915 Fucino, 1980 Irpinia). The largest historical earthquakes before the XX century probably had similar magnitudes. The time window useable for probabilistic seismic hazard estimation spans about 500 years (i.e., 10% probability in 50 yrs).
Hypocenters of major shocks are generally confined to the upper crust, most of them concentrated along a relatively narrow belt running down the Apennines to eastern Sicily (Fig. 2). Their focal mechanisms generally have a dominant normal component. Scattered seismicity characterizes the Alps, except in the southern central and eastern Alps, where the intensity is comparable to that of peninsular Italy and focal mechanisms are dominantly compressional (Slejko *et al.* 1987).
The analysis of geological effects can significantly improve the estimation of parameters for many events. Some of the largest events have descriptions of ground failures clearly suggestive of

surface faulting (e.g., Michetti *et al.*, 2000a), but only a few of them have been clearly proven (Table I).

Table I - *Main characteristics of historically documented surface ruptures during earthquakes in Italy*

Event	End-to-end rupture length (km)	Maximum offset (cm)	Intensity + M (if available)
Crotonese 1638	15-20 ?	50 ?	X
Norcia+L'Aquila 1703 (1)	50	?	X
Calabria 1783 (2)	> 50	?	XI
Fucino 1915 (3)	23 (end to end)	100	XI 6.9
Friuli 1976 (4)	14 (*sec. features?*)	?	IX-X 6.5
Irpinia 1980 (5)	38 km	115	IX-X 6.9
Umbria-Marche 1997 (6)	8-9	8	VIII-IX

(1)Blumetti 1995; (2)Tortorici *et al.* 1995; (3)Michetti *et al.* 1996; (4) Martinis and Cavallin 1978; (5)Pantosti *et al.* 1993; (6)Vittori *et al.* 2000.

A careful search or re-examination of historical records may allow the recognition of surface ruptures for at least some of these earthquakes since they occurred in the same tectonic environment and had similar earthquake magnitudes as those with recognized surface faulting. Often in historical sources there are generic references to ground failures; although generally they are attributable to non-tectonic phenomena, some evidence can be found of true tectonic faulting. For example, field search of the ruptures reported by contemporary chronicles of the Norcia-L'Aquila earthquakes (1703) allowed the identification of faults that were probably reactivated by the earthquakes (Blumetti 1995). The descriptions by contemporary sources of the ruptures of the 1638 Crotonese and 1783 Calabria earthquakes strongly point to the occurrence of surface faulting, which are still to be studied in the field. In the 1908 Messina earthquake, strong surface deformation took place, but it is still debated whether the fault ruptured the ground (Valensise and Pantosti 1992).

Besides a few exceptions, all the paleoseismic research in Italy so far have addressed the Apenninic mountain range. Here many normal faults border elongated intermontane depressions that display morphological and geological evidence of late Quaternary reactivation (e.g., Bosi 1975; Blumetti *et al.* 1993). Many cases of supposed coseismic surface faulting that have been documented occurred since the latest Pleistocene and even in historical times (Rieti, Fucino, Rivisondoli, Norcia, Gran Sasso, Irpinia, etc.) (Giraudi 1988; Blumetti *et al.* 1993; Pantosti *et al.* 1993; Giraudi and Frezzotti 1994; Michetti *et al.* 1996; Michetti *et al.* 2000a, 2000b; Pantosti *et al.* 1996; Galadini *et al.* 1997).

Some recently discovered surface fault ruptures are of special interest, because they are located in areas of low historical seismicity, such as the Pollino massif (Michetti *et al.* 1997). Limited or very subdued faulting has affected the most recent earthquakes in the Apennines: Umbria-Marche in 1997 and Lauria in 1998, providing useful constraints on the magnitude threshold for these areas (Michetti *et al.* 2000b, Vittori *et al.* 2000). So, our present knowledge suggests that in the Apennines true *surface faulting* can occur above magnitude 5.8-6.0, whereas only *subordinate ruptures* are triggered at lower magnitude values (Michetti *et al.* 2000b).

Many historical earthquakes have occurred along the same tectonic and seismic belts in the Apennines, having intensities and macroseismic fields comparable to or larger than the Fucino and Irpinia events. Therefore, also their magnitudes have ranged from 6.5 to possibly slightly above 7.0. This requires that surface faulting has occurred more frequently than presently documented. No creeping normal faults are known, except in the volcanic areas of Italy. Therefore, it is reasonable and prudent to assume that all the examples of prehistoric surface faulting events in the Apennines record palaeoearthquakes rather than fault creep.

Gravity-driven deep-seated landslides can sometimes have display shapes similar to normal fault scarps in mountain areas. Being preferentially triggered by earthquakes, they are still useful for active tectonics studies, but their parameters (rupture length, slip) are not directly related to the magnitude of the seismic event, as is true for seismic surface faulting.

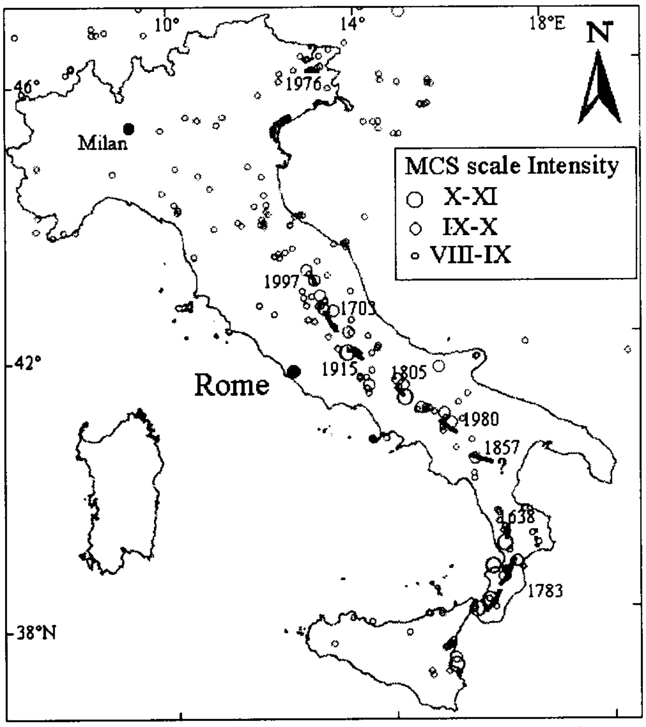

Fig. 2 – Historical seismicity in Italy (Boschi *et al. 1999)* and known cases of historical surface faulting.

Although evidence of surface faulting does exist in the southern border of the eastern Alps, buried structures (blind thrusts) probably play an important role, particularly beneath the Po Plain (e.g., Cassano *et al.* 1986), thus making the recognition of the active structures an arduous task. In the western Alps, a few cases of recent fault activity are also inferred, e.g. in the Aosta-Chatillon line, where a slightly higher level of seismicity concentrates.

Discussion

The mechanisms and rates of deformation in the Italian territory are still poorly constrained. Certainly, the tectonic processes appear less active now than during the Tertiary and the early Quaternary, but seismicity and earthquake geology data confirm that these structures are still alive.

Although some deformation zones tens of kilometers long have been recognized (e.g., Westaway 1992), the "seismogenic" portion of Italian territory (northeastern Italy, most of the peninsula and eastern Sicily) is generally characterized by a large number of relatively short faults (Fig. 2), which is a probable legacy of the multiphased tectonics that have affected the area during the Cenozoic. During major seismic events, commonly several fault segments rupture over time intervals ranging from a few seconds to months, making it difficult to identify fault segments and establish a reliable seismic hazard model. The historical account and the geological and morphological evidence of tectonic and seismic activity define at least the minimum thresholds. A comparable style of deformation characterizes Greece, except that the strain rates are much higher than in peninsular Italy.

The ITHACA database, which I briefly introduced here, provides the essential constraints (mainly kinematics, slip rates and geometry of active structures) for geodynamics studies. For practical purposes (i.e., seismic risk reduction), it will lead to more reliable and documented evaluation on a geological basis.

For a large number of lineaments or fault lines, recent activity is only suspected on the basis of morphological evidence. Careful field checking often discovers evidence of activity, i.e. the offset of recent deposits and/or landforms. Thus, the inventory aims to be an updated state-of-the-art tool to provide a basis for adequately characterizing the already known active faults and those still waiting to be found.

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